Cement & Concrete Composites 33 (2011) 346–352

Contents lists available at ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Anchorage and tension-stiffening effect between near-surface-mounted CFRP rods and concrete

Firas Al-Mahmoud [a,*], Arnaud Castel [b], Raoul François [b], Christian Tourneur [c]

[a] Institut Jean Lamour, Dpt CP2S, Equipe Matériaux pour le Génie Civil, Nancy Université, UMR 7198, IUT de Nancy-Brabois, CS 90137, F54601 Villers-lès-Nancy Cedex, France
[b] Université de Toulouse UPS, INSA; L.M.D.C (Laboratoire Matériaux et Durabilité des Constructions), 31077 Toulouse, France
[c] Freyssinet, 1bis rue du Petit Clarmat Vélizy – Villacoublay, France

ARTICLE INFO

Article history:
Received 18 November 2008
Received in revised form 15 October 2010
Accepted 21 October 2010
Available online 30 October 2010

Keywords:
NSM
CFRP
Rod
Strengthening
Bond strength
Tension stiffening

ABSTRACT

The aim of the experimental program developed in this work was to investigate the effects of concrete strength, filling material, groove dimensions, groove surface preparation for such CFRP rods used in the Near-Surface Mounted reinforcement (NSM) technique. Two interfaces are involved in the NSM technique: one between the reinforcing composite rod and the filling material and the other between this material and the old concrete. The coupling between the two interfaces was studied through two mechanical tests: the usual pull-out test, which assessed the anchoring capacity of the CFRP rods, and the tension member test, which simulated the behavior of the CFRP rod bond in the tensile zone of an RC-structural element.

The specimen was designed to study the specific problems of NSM: reduction of contact surface area between filling material and concrete and eccentricity of FRP rods. The rods were 12-mm-diameter carbon-epoxy pultruded FRP. The experimental results indicate that NSM technique gives satisfactory results for both anchoring and reinforced concrete flexural member strengthening.

1. Introduction

The need to strengthen civil engineering structures is becoming a serious problem for facilities owners. Composite materials offer interesting possibilities due to their high tensile strength for a low density, their absence of sensitivity to corrosion and their long fatigue life [1–4]. Under-performing structures are usually strengthened by bonding FRP sheets or plates onto the external concrete surface of the structural members. But, sometimes, this type of strengthening may be difficult or impossible to set up. For example, cantilever tension parts of structural members supporting hot bituminous mix are subjected to high temperatures which can affect the adhesive layer and so damage the bond between the concrete and the FRP sheet. In presence of longitudinal concrete cracks due to steel reinforcement corrosion, the external concrete surface is no longer suitable for the bonding of FRP sheets.

For these particular cases, the Near-Surface Mounted reinforcement (NSM) technique, where a composite rod is bonded in a pre-sawn groove in the concrete cover, can be used. This technique has attracted extensive research in recent years [5–16]. In this paper, the possibility of using a Carbon Fiber Reinforced Polymer CFRP material to strengthen concrete structures by the NSM technique is investigated. The material in question is a carbon-epoxy pultruded FRP rod 12 mm in diameter.

A satisfactory bond between the strengthening and the old concrete is a key condition and is a complex problem for the NSM technique because two interfaces are involved: that between the CFRP rod and the filling material, and that between the filling material and the old concrete. The bond between the CFRP rod and the concrete, where FRP rods were cast within concrete, has already been studied and reported in a previous work [16]. The results showed that it was necessary to improve the bond of the smooth CFRP rod with the concrete because of its very low roughness. To modify the contact surface of the initially smooth rods with the concrete, two different surface treatments were applied: surface machining and surface sand coating. These surface treatments gave a bond strength higher than that of ribbed steel reinforcing bars in the same concrete. Following the conclusions of this previous study, surface sand coated CFRP rods were used in this work.

In this study, the effects of concrete strength, filling material, groove dimensions, groove surface preparation for such CFRP rods were investigated. Two different mechanical tests were performed:

* Corresponding author. Tel.: +33 3 83 68 25 30; fax: +33 3 83 68 25 32.
E-mail addresses: firas.almahmoud@iutnb.uhp-nancy.fr (F. Al-Mahmoud), castel@insa-toulouse.fr (A. Castel), francois@insa-toulouse.fr (R. François), ctourneur@freyssinet.com (C. Tourneur).

0958-9465/$ - see front matter © 2010 Elsevier Ltd. All rights reserved.
doi:10.1016/j.cemconcomp.2010.10.016

the usual pull-out test, which characterized the anchoring capacity of the CFRP rod in the concrete, and the tension member test, which studied the bond between the CFRP rod and the tension concrete of cracked reinforced concrete beams (i.e. tension-stiffening effect). Two concrete strengths (conventional and high-strength) and two different filling materials were studied: a mortar and a resin.

Fig. 1. Sand coated CFRP rods used in the study.

Table 1
Composition of the vibrated concretes.

	VC30 (kg/m^3)	VC60 (kg/m^3)
Cement CEM I 52.5 N CE CP2 NF from Gargenville Calcia	280	390
Sand 0/4 SC NF Sandrancourt	768	750
Rolled gravel 4/10	324	400
Crushed gravel 10/14	839	730
Superplasticizer		10.91
Total water	176	145

Table 2
Mechanical properties of the concretes and filling materials.

Material	Compressive strength (MPa)	Tensile strength (MPa)	Elastic modulus (GPa)
VC30 (28 days)	34.0	2.6	32.2
VC60 (28 days)	65.7	5.4	43.4
Epoxy resin (7 days)	83.0	29.5	4.9
Mortar (7 days)	74.4	6.2	31.6

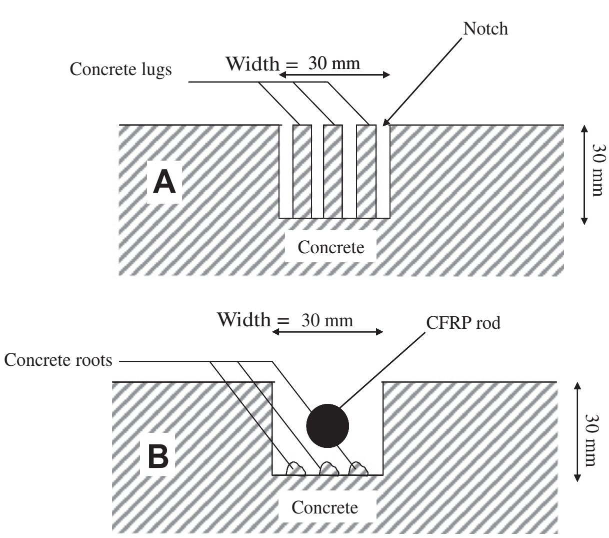

Fig. 2. (A) Groove (30 × 30 mm) after concrete notching and (B) groove after removal of the concrete lugs.

2. Experimental program

2.1. Materials

A single type of FRP rod was used: carbon-epoxy pultruded FRP with a diameter of 12 mm. This rod is made by the Soficar Company in France. The modulus of elasticity and tensile strength of the CFRP rods were determined by laboratory testing. The tensile strength and the elastic modulus were equal to 1875 MPa and 146 GPa respectively.

To modify the surface of the initially smooth rods, a surface sanding treatment was applied. The smooth CFRP rods were coated with 0.2/0.3 mm sand by sprinkling it onto a thin layer of freshly applied epoxy resin (Fig. 1). This method was developed by the Freyssinet Company.

Two vibrated concretes (VC) were studied. Their compositions are given in Table 1. The properties of the hardened concrete (compressive strength, tensile strength and instantaneous elastic modulus) were measured at 28 days on concrete cylinders (diameter = 110 mm, height = 220 mm). The specimens were removed from their molds 24 h after casting then they were immersed in normal tap water for 28 days in a confined room. The tensile strength was measured using the splitting test.

Two filling materials, epoxy resin and ready-mixed mortar, were studied for sealing, with two surface concrete states: no treatment after sawing (smooth) and sandblasted. Table 2 shows the mechanical properties obtained for both concretes and both filling materials.

2.2. Near-Surface Mounted reinforcement (NSM) test

2.2.1. Specimen preparation

Three groove sections (20 × 20, 30 × 30 and 20 × 50 mm) (Fig. 3) were tested. Two concrete strengths and two filling materials were studied.

The groove was formed by notching the specimen three, four or six times with a saw, according to the groove width (Fig. 2A). The remaining concrete lugs were removed with a hammer and hand

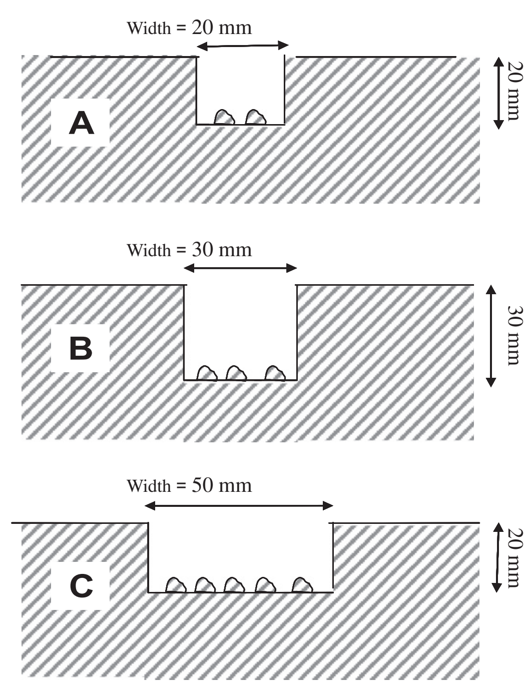

Fig. 3. Groove sections: (A) 20 × 20 mm, (B) 30 × 30 mm and (C) 20 × 50 mm.

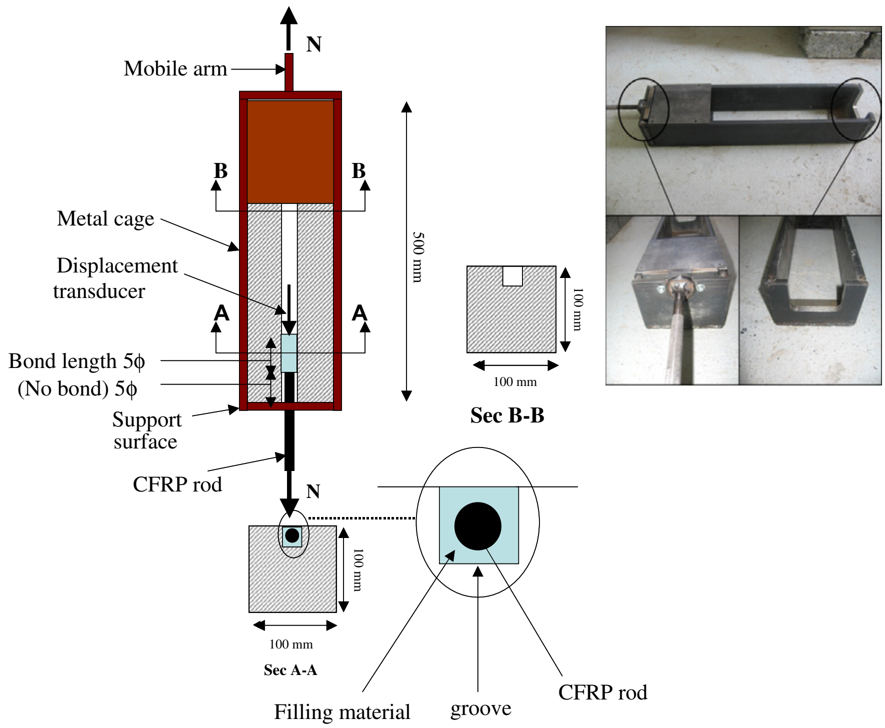

Fig. 4. Pull-out test used for the NSM.

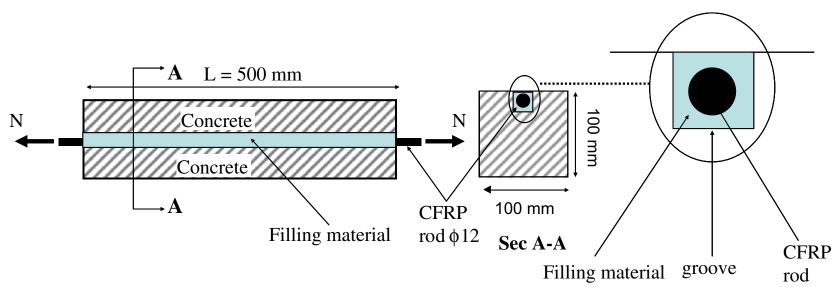

Fig. 5. Tension member specimens used for the NSM.

chisel, so that the lower surface of the groove became rough. A CFRP rod was then placed in the middle of this groove in the filling material (Fig. 2B). The specimen was left for one week to ensure the filling material strength.

To improve the bond between the mortar and the old concrete, a sandblasting operation was performed on the smooth concrete surface resulting from the concrete sawing. This technique was applied with a compressed air sandblaster. Fig. 7 shows the difference between smooth and sandblasted concrete surfaces. The result of this operation was a rough surface where the inter-aggregate mortar was removed to a depth of 2–3 mm.

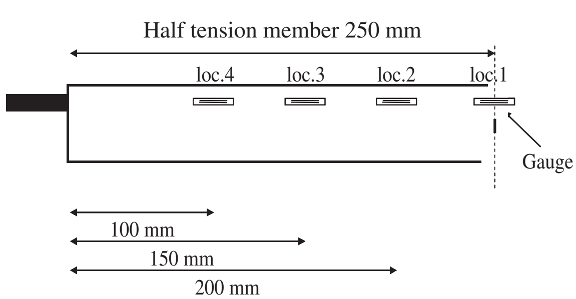

Fig. 6. Location of the strain gauges along the tension members used for the NSM.

2.2.2. Pull-out tests

The specimen length was 500 mm. Only 60 mm was filled with the filling material (Fig. 4).

Eccentricity of the CFRP rod could easily induce flexural effects during the pull-out test and change the bond behavior and the

Fig. 7. Comparison between smooth (A) and sandblasted (B) concrete surfaces.

Table 3
Summary of ultimate loads in NSM test for the three groove sections, SD: Standard Deviation for three specimens.

Filling material	Ultimate load/SD (kN)					
	Resin		Mortar with smooth concrete surface		Mortar with sandblasted concrete surface	
Concrete Groove section (mm)	VC30	VC60	VC30	VC60	VC30	VC60
20 × 20	32.5/1.1 CFRP rod pull-out	34.6/1 CFRP rod pull-out	16.9/0.4 Concrete–mortar interface debonding	19.5/0.7 Concrete–mortar interface debonding	20.9/0.7 CFRP rod pull-out	21.7/0.5 CFRP rod pull-out
30 × 30	34.5/1.3 CFRP rod pull-out + shear cracks	33.6/1.6 CFRP rod pull-out + shear cracks	19/0.3 Concrete–mortar interface debonding	19.6/0.5 Concrete–mortar interface debonding	20.7/0.4 CFRP rod pull-out + shear cracks	22/0.5 CFRP rod pull-out + shear cracks
20 × 50	23.2/1.5 Shear cracks	25.7/1.3 Shear cracks	14.6/0.3 Shear cracks	16.8/0.9 Shear cracks	17.7/0.9 Shear cracks	18.6/0.6 Shear cracks

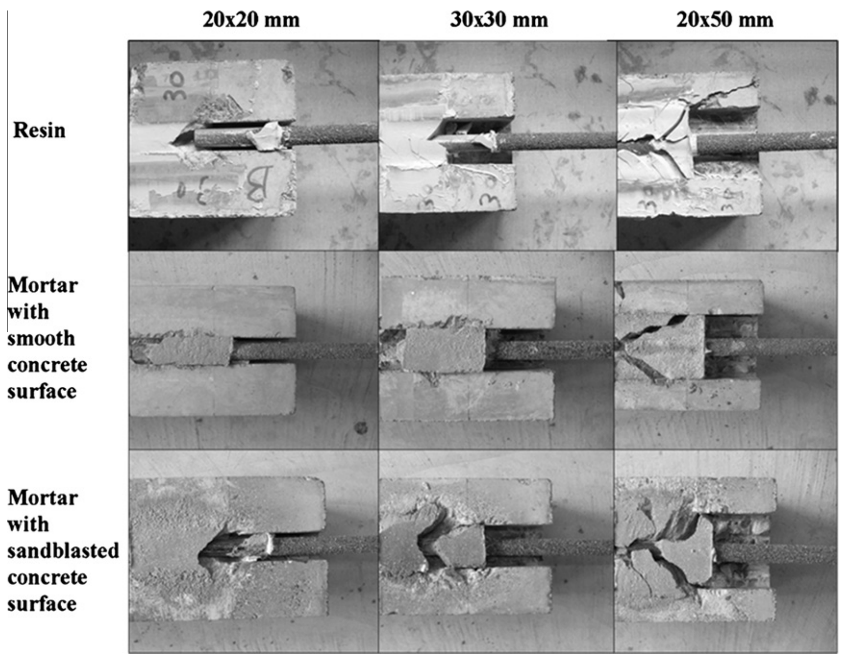

Fig. 8. NSM specimen after failure (pull-out test).

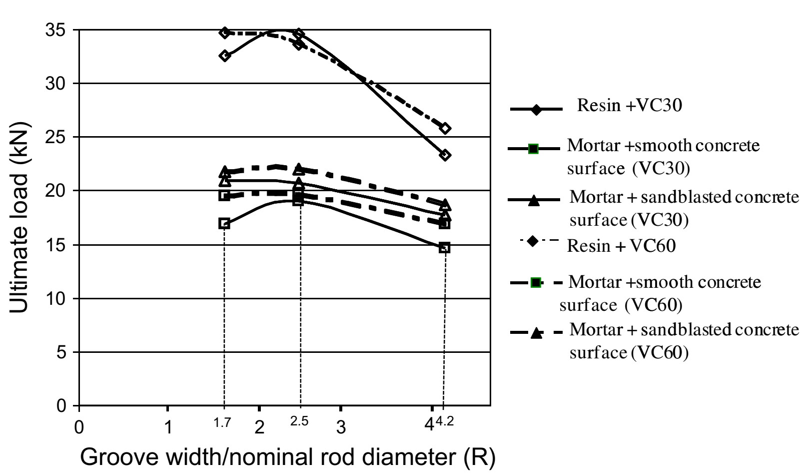

Fig. 9. Ultimate load vs groove width/nominal rod diameter (*R*) for NSM specimens filled with resin and mortar with smooth and sandblasted concrete surfaces for VC30 and VC60 concretes.

ultimate load. Therefore, a system was developed to avoid this flexural effect and offer the advantages of the direct pull-out test.

This system was composed of a metal cage able to prevent specimen movement in all directions. The specimen was placed in the cage and the cage was suspended on the tension testing machine by means of a mobile steel arm which was always located perfectly opposite the CFRP rod. The CFRP rod slip was measured at the free end using a displacement transducer (Fig. 4). The loading rate was 0.1 kN/s.

2.2.3. Tension member tests

For this test, the total length of the specimen was assumed to correspond to the distance between two consecutive bending transverse cracks. The purpose was to assess the distance needed for the reinforcements to restore the full tensile force in the concrete, lost by the occurrence of the crack. This distance is called the transfer length L_t [17].

Of course, in the case of the tension member, the purpose was to measure the transfer length necessary for the CFRP rod to trans-

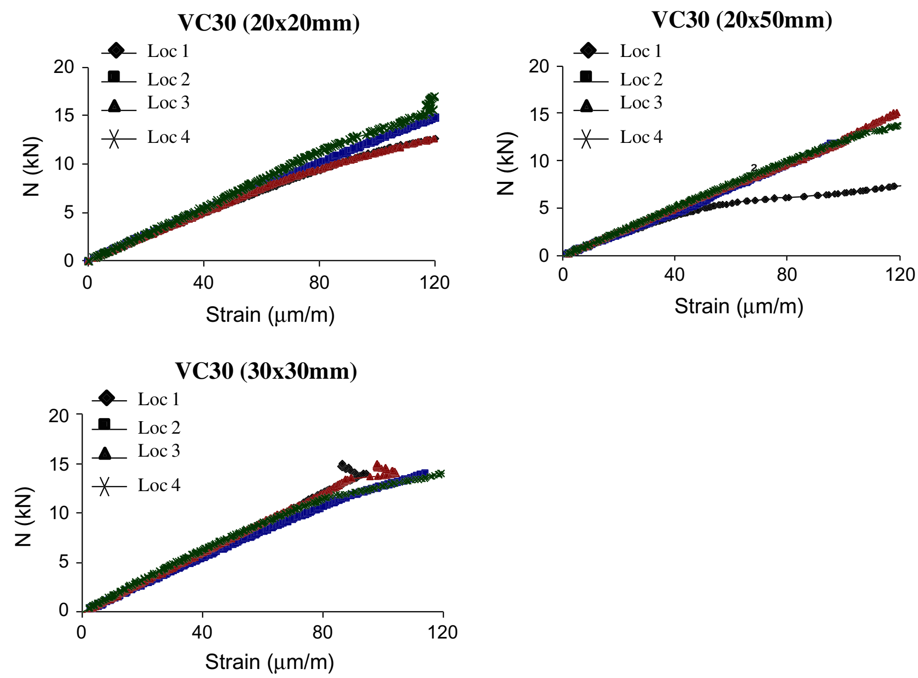

Fig. 10. Strain vs load for the two concrete strengths. Strains measured on concrete surface at different locations along the tension members filled with the resin for VC30 (Fig. 6).

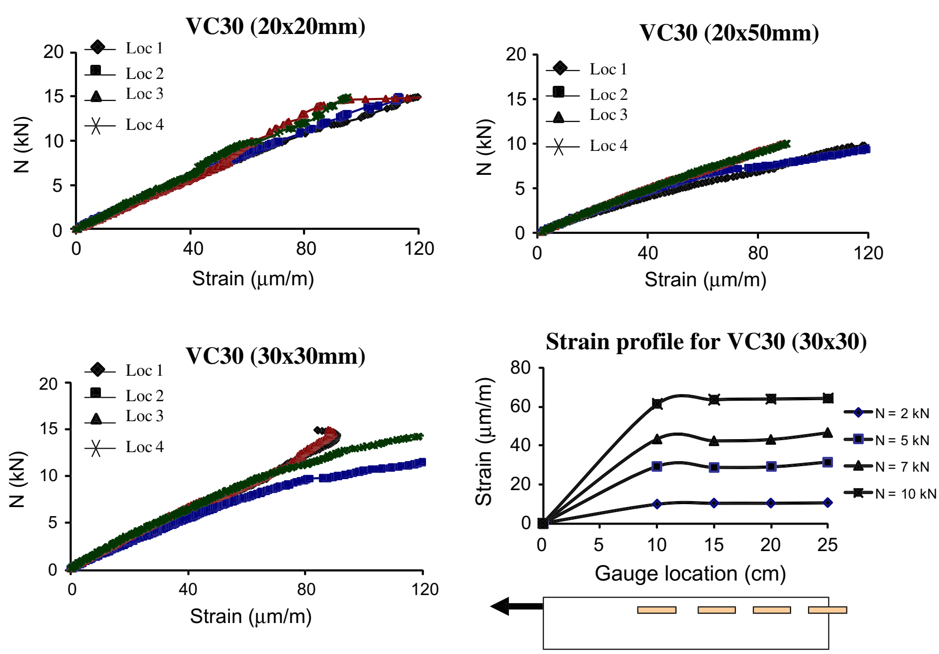

Fig. 11. Strain vs load for the two concrete strengths. Strains measured on concrete surface at different locations along the tension members filled with the mortar for VC30 (Fig. 6).

fer a part of the tensile force through the filling material in an optimal way, and then into the concrete. Beyond this length, the presence of cracks (here edges of the tension member) does not influence the behavior of the tension member, and the stress level in the CFRP rod corresponds to that in the absence of cracks. Two concrete strengths, VC30 and VC60, and two filling materials, resin and mortar, were studied.

The specimen length was 500 mm and the filling material was applied along the whole length of the tension member (Fig. 5). During loading, the strains were measured using 30-mm-long strain gauges pasted on the concrete surface at the same level as the CFRP rod, along the tension members, four on each symmetrical side of the tension member. Each strain value was taken as the average of the strains obtained on the two sides. The location of the gauges is shown in Fig. 6 (on one side only). The loading rate was 0.1 kN/s.

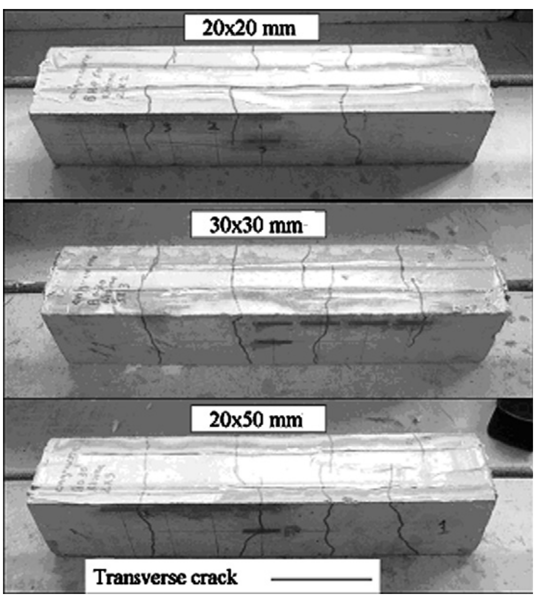

Fig. 12. NSM tension members VC30 (filled with the resin) after cracking.

3. Results

3.1. Pull-out test

Table 3 presents the ultimate pull-out loads for two concrete strengths, two filling materials (resin, and mortar with smooth or sandblasted concrete surfaces) and three groove sections. Fig. 8 shows the test specimens after failure.

3.1.1. Resin

20 × 20 mm groove. Failure occurred by debonding at the CFRP rod–resin interface (pull-out). The bond between the resin and the concrete was not affected. However, cracking of the resin layer on the outside surface was also observed. This failure of the resin layer was probably due to the thinness of the resin cover (about 2 mm).

30 × 30 mm groove. Failure also occurred by debonding at the CFRP rod–resin interface. In this case, as the resin cover was thicker, no failure of the resin layer was observed. However, some little shear cracks oriented at 45° to the load direction could be observed.

20 × 50 mm groove. The failure mode was different compared to both previous cases as failure occurred by shear cracking of the resin.

For the three groove sections, the concrete strength was not a determining parameter, which shows that the concrete–resin bond is strong enough (Table 4). This result confirms a previous study by De Lorenzis and Nanni [7].

For the 20 × 20 mm and the 30 × 30 mm grooves, the ultimate pull-out loads were comparable, due to the similar failure mode. In contrast, the ultimate pull-out load was significantly lower for the 20 × 50 mm groove because of the premature shear failure of the resin. This result is not in agreement with the studies by De Lorenzis and Nanni [7] and Novidis et al. [10], where the increase in groove section increased the failure load when failure was controlled by pull-out at the CFRP rod–resin interface. This difference was due to the difference in the groove shape: always square for De Lorenzis and Nanni [7] and Novidis et al. [10] but rectangular in our study.

3.1.2. Mortar with smooth concrete surface

20 × 20 mm groove. Failure occurred by debonding at the concrete–mortar interface at the groove lateral faces. The lower part of the mortar remained attached to the lower surface of the groove (the only rough surface of the groove) (Fig. 8).

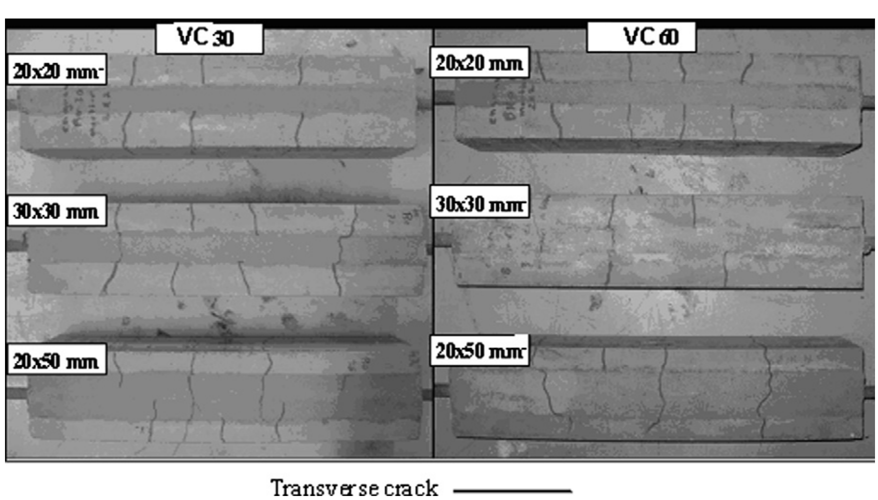

Fig. 13. NSM tension members VC30 and VC60 (filled with the mortar) after cracking.

30 × 30 mm groove. The failure mode was the same as for the 20 × 20 mm groove.

20 × 50 mm groove. Failure occurred by shear cracking of the mortar. This shear cracking was followed by debonding at the concrete–mortar interface at the groove sides, which decreased the failure load compared to the other groove sections.

3.1.3. Mortar with sandblasted concrete surface

The ultimate pull-out load increased by 2–4 kN compared with tests for which the concrete surface was smooth. New failure modes occurred in the mortar.

20 × 20 mm groove. Failure occurred by debonding at the CFRP rod–mortar interface. The bond between the mortar and the concrete was not affected.

30 × 30 mm groove. Failure occurred by debonding at the CFRP rod–mortar interface but with shear cracking of the mortar.

20 × 50 mm groove. In this case, the mortar shear cracking was more marked than in the case of the 30 × 30 mm groove. This decreased the failure load compared to the other groove sections.

Fig. 9 shows the ultimate load vs groove width/nominal rod diameter (*R*) for NSM specimens filled with resin and mortar with smooth or sandblasted concrete surfaces for both VC30 and VC60 concretes.

This figure shows that the concrete strength is not a determining parameter whatever the groove section and whatever the filling material or the concrete surface state (smooth or sandblasted). For pull-out tests, the ultimate load was always higher with the resin than with the mortar whatever the groove width or the concrete strength. This result is in agreement with the one obtained by De Lorenzis et al. [6]. Maximum bond strength was reached for *R* between 1.7 and 2.5. This ratio is in agreement with the one recommended by De Lorenzis and Nanni [7–9], whose conclusion was based on testing of specimens with CFRP deformed, spirally wound and ribbed rods.

3.2. Tension member test

Figs. 10 and 11 present the concrete strains measured at the different locations along the tension members for VC30 and two filling materials (resin and mortar with smooth concrete surface) vs load until cracking occurred. Before cracking, the strains measured at the four locations along the tension member were equal, which indicates that the transfer length was less than 100 mm whatever the groove section, concrete strength, or filling material. The cracking always occurred in a transverse direction relative to the load direction, with initiation in the concrete and propagation in the resin for both 30 × 30 mm and 20 × 50 mm grooves. The resin–concrete interface was not affected by the transverse cracks (except in the vicinity of the cracks of course) and the bond between the concrete and the resin was still active after cracking (Fig. 12). In the case of the mortar, for both VC30 and VC60, the same type of cracking (in the transverse direction) with initiation in the concrete and propagation in the mortar was observed for 30 × 30 mm and 20 × 50 mm grooves (Fig. 13).

On the contrary, for the 20 × 20 mm groove, no propagation of cracks was observed in the filling material. Groove width appears then as an important parameter in NSM technique because delay in filling material cracking leads to improve the tension-stiffening effect.

4. Conclusions

The following conclusions can be drawn from this study:

- For pull-out test, in the case of the resin, the ultimate load was always higher than that obtained for CFRP rods embedded in the concrete whatever the concrete strength (VC30, VC60) and the groove width. The failure occurred at the CFRP rod–resin interface. In the case of the mortar, the ultimate load was always only about half that obtained with the resin. The main difference with the resin results was the debonding failure at the mortar–concrete interface. Sandblasting the concrete surface increased the ultimate load by about 15% (which is still weak).
- For tension member tests, the transfer length was similar to that obtained for rods embedded in concrete (less than 100 mm), again, whatever the filling material or the concrete strength or the groove width. This is a satisfactory result.
- For tension member tests, after cracking, for both VC30 and VC60, debonding between mortar and concrete no longer occurred, probably because of the roughness of the bottom surfaces of the grooves. So, the mechanical behavior after cracking was the same as that obtained for CFRP rods embedded only in the concrete or with the resin. This means that the presence of the filling material does not affect the mechanical behavior of the tension members.
- A groove width to nominal rod diameter ratio between 1.7 and 2.5 appears to be optimal. An adequate groove section could be 25 × 25 mm for 12 mm diameter CFRP rods.

The next step of the study will be to experiment the Near-Surface Mounted reinforcement method for strengthening reinforced concrete beams using CFRP rods and the resin as filling material and to develop a models to predict the ultimate load in the case of pull-out failure modes.

References

[1] Barboni M, Benedetti A, Nanni A. Carbon FRP strengthening of doubly curved precast PC shell. J Compos Construct 1997;1:168–74.
[2] Emmons PH, Vayburd AM, Thomas J. Strengthening concrete structures, part 2. Concr Int; 1998. p. 56–60.
[3] Midwater KR. Plate bonding carbon fiber and steel plates. Construct Repair 1997;11:5–8.
[4] Nanni A. Concrete repair with externally bonded FRP reinforcement: examples from Japan. Concr Int 1995;17:22–6.
[5] De Lorenzis L, Nanni A. Shear strengthening of reinforced concrete beams with near-surface mounted fiber-reinforced polymer rods. ACI Struct J 2001(January–February):60–8.
[6] De Lorenzis L, Rizzo A, La Tegola A. A modified pull-out test for bond of near-surface mounted FRP rods in concrete. Composites 2002;33:589–603.
[7] De Lorenzis L, Nanni A. Bond between near-surface mounted fiber-reinforced polymer rods and concrete in structural strengthening. ACI Struct J 2002(March–April):123–31.
[8] De Lorenzis L, Lundgren K, Rizzo A. Anchorage length of near-surface mounted fibre reinforced polymer bars for concrete strengthening experimental investigation and numerical modelling. ACI Struct J 2004(March–April):269–77.
[9] De Lorenzis L. Anchorage length of near-surface mounted fiber reinforced polymer bars for concrete strengthening - analytical modelling. ACI Struct J 2004(May–June):375–86.
[10] Novidis D, Pantazopoulou SJ, Tentolouris 1 E. Experimental study of bond of NSM-FRP reinforcement. Construct Build Mater 2006:1–11.
[11] KRET A, Al-Mahmoud F, Castel A, François R. Corroded RC beam repaired with near-surface mounted CFRP rods. In: ICCRRR 2008: international conference on concrete repair, rehabilitation and retrofitting, Cape Town, South Africa.
[12] Al-Mahmoud F, Castel A, François R, Tourneur C. Anchorage and tension-stiffening effect between near-surface-mounted carbon fiber reinforcement polymer rods and concrete. In: Paper presented at 2nd international symposium on advances in concrete through science and engineering. Quebec City, Canada; 2006. p. 11–13 [September].
[13] Al-Mahmoud F, Castel A, François R, Tourneur C. Strengthening of RC members with near-surface mounted CFRP rods. Compos Struct J 2009;91(November):138–47.
[14] Al-Mahmoud F, Castel A, François R, Tourneur C. RC beams strengthened with NSM CFRP rods and modeling of peeling-off failure. Compos Struct J 2010;92(January):1920–30.
[15] Costa IG, Barros JAO. Flexural and shear strengthening of RC beams with composite materials – the influence of cutting steel stirrups to install CFRP strips. Cem Concr Compos 2010;32(7):544–53.
[16] Al-Mahmoud F, Castel A, François R, Tourneur C. Effect of surface pre-conditioning on bond of carbon fiber reinforced polymer rods to concrete. Cem Concr Compos 2007;29(9):677–89.
[17] Kwak HG, Song JY. Cracking analysis of RC members using polynomial strain distribution function. Eng Struct 2002;24(4):455–68.