

RECENT EXPERIMENTAL INVESTIGATIONS ON REINFORCED UHPFRC FOR APPLICATIONS IN EARTHQUAKE ENGINEERING AND RETROFITTING

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Abstract

The bond capacity and characteristic behaviour of steel rebars embedded in ultra-high performance fibre-reinforced concrete (UHPFRC) has been studied. Indeed, sufficient ductility is to be ensured by proper seismic-resistant detailing of reinforced (or fibre-only reinforced) UHPFRC structures. This research is especially important for UHPFRC mixes which, due to the high fibre content, are generally used without conventional passive reinforcement, such as stirrups and ties. Rebars provided with fibre optic sensors were used to precisely quantify the strain along the steel reinforcing bars and, hence, derive the bond stress-strain relationship between UHPFRC and bars. This also assists to determine the extent of the ductile micro-cracking phase. Pull-out testing was conducted on thin plates and thick blocks, both under quasi-static monotonous loading and repeated loading cycles. The results complement current understanding of the contribution provided by rebars to crack control in UHPFRC elements.

Résumé

L'adhérence des armatures au béton fibré à ultra-hautes performances (BFUP) a été quantifiée de façon à proposer des dispositions constructives suffisamment ductiles, le cas échéant vis-à-vis des séismes, pour des structures en BFUP éventuellement armées. Cette quantification est originale pour les BFUP qui ont généralement pu être employés jusqu'ici sans armatures passives compte tenu de leur teneur élevée en fibres. L'instrumentation d'armatures par des capteurs à fibre optique a été mise au point pour mesurer précisément les déformations le long des aciers et en déduire la contrainte d'adhérence. On peut en déduire l'étendue du régime ductile de microfissuration. Cette technique a été utilisée lors d'essais d'arrachement monotones et cycliques, sur plaques minces et éléments massifs, pour quantifier la contribution du ferrailage à la maîtrise de la fissuration des éléments en BFUP.

1. INTRODUCTION

The BADIFOPS project is intended to promote possible application of UHPFRC for earthquake engineering and retrofitting, which often relies on the safe accounting for contribution of reinforcing bars (rebars) to structural ductility. BADIFOPS is a joint R&D project selected by the French Directorate in charge of incentive funds for sustainable construction, with Ifsttar (Public Works Research Laboratory), CSTB (Building Research Centre), Sétra (Highways Technical Agency) and Eiffage Company as partners. Identification of structural parts which should take benefit both from UHPFRC application and from demonstration of ductile behaviour has been carried out, especially for buildings and bridges. A certain number of parts (bridge decks, walls...) could be made of UHPFRC as an alternative to regular reinforced concrete, which helps obtaining a lighter structure with associated advantages for foundations and seismic resistance, while their behaviour shall remain in the elastic domain and ductility is not formally required. Conversely, clamped column ends, hinges made of regular reinforced concrete externally strengthened by a UHPFRC layer, turn out as mostly representative of members where ductility is searched.

Within the project, the UHPFRC to steel rebars bond characteristics are thus to be quantified, so that ductile enough and/or proper seismic-resistant detailing provisions can be proposed for UHPFRC structures. This quantification is especially new for UHPFRC available in France which, due to the high fibre content, could generally be applied till now dispensing with conventional use of passive reinforcement. Using the same UHPFRC mix for all the project, realization of bending tests on rectangular beams and of pull-out tests both on slender plates and massive bodies, under quasi-static monotonous loading and applying repeated loading cycles, associated to a careful material characteristics identification, complements the quantified understanding of rebars contribution to crack control in UHPFRC elements. Static and cyclic tests on ties and on columns submitted to axial and bending forces will help validating the local laws determined from the previous experiments. All these tests on basic structural components will help justify the design provisions in view of extending EN 1998 (Eurocode for earthquake design and retrofitting) to UHPFRC structures, as an extension of AFGC recommendations complementing EN 1992, the Eurocode for concrete structures [1].

2. CONSISTENCY OF MEASUREMENT TECHNIQUES

In a first step of the project, reinforcing bars equipment with fiber optic sensors has been developed in order to precisely quantify the UHPFRC to steel bars bond characteristics and precise the extent of ductile micro-cracking phase. This has been made necessary due to the small anticipated anchor length, and shortcomings of conventional sensors equipment along rebars (disturbed zone along the strain gauges, wires congestion, signal variations when cracks occur preventing from a sound interpretation of local information, etc.).

Reliability of the technique required optimization of several technical aspects. The optic fiber sheath was chosen thin and relatively rigid. Continuity of its fixation was ensured by embedding it in a groove machined along the longitudinal rib of the reinforcement and filled with a very fluid glue (bubbles should be avoided). After application, the glue itself (metacrylate) got rigid. Ends of the glued zone where the optic fiber separates from the rebar had to be protected to resist the concreting phase. Qualification of this fiber optic sensor implementation process included direct tensile tests and bending tests on bare bars, where the

FO signal could be compared to strain gauges, then preliminary pull-out tests on bars embedded in UHPFRC elements, then bending tests on reinforced UHPFRC beams [2-4].

From the pull-out tests with a short embedment length (Fig.1) three characteristic zones corresponding to uniform tensile stress (“pure tension zone” in Fig. 1 for the bar in its free end), unloaded part (below anchor) and a zone of variation (load transfer along the bar over a length close to 3 times the bar diameter) can be clearly distinguished, which confirms that the signal of the fiber optic sensor directly reflects the underlying bar strains, without significant signal smearing. This property was applied in monitoring a reinforced UHPFRC beam during cracking development, and strain concentrations at cracks location turned out consistent with strain gauges measurement, while these locations were confirmed using an optical micrometer survey and digital image analysis (Fig. 2). Such a successful implementation of fiber optic sensors along the bars opens the way to promising structural monitoring [2, 4].

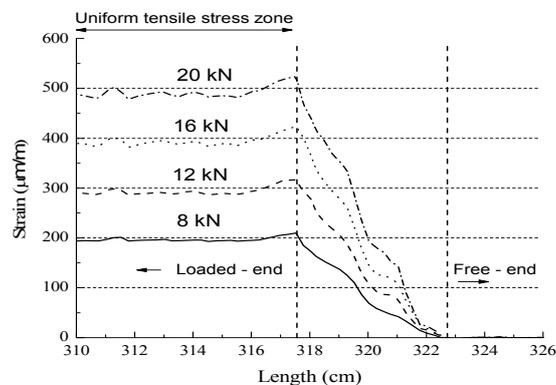


Figure 1: fibre optic sensor signal converted to strains ($\mu\text{m}/\text{m}$) in the bar vs. position (in cm) during a pull-out test

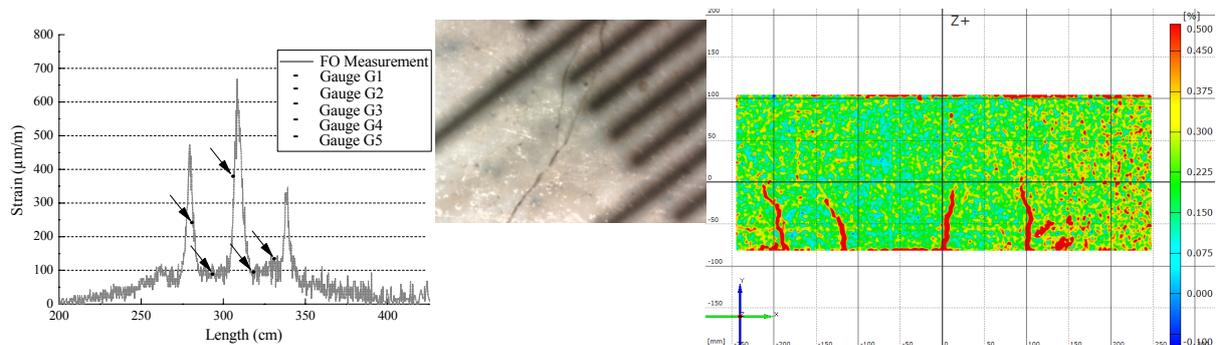


Figure 2: Consistency of cracks survey methods in a bending test: fibre optic (curve) and strain gauges (dots) signals along the bar in a bent reinforced UHPFRC beam (left), crack observation (middle) and crack width determination using digital image analysis (right)

3. ANCHOR LENGTH OF REINFORCEMENT IN UHPFRC MATERIAL

Bond of rebars within UHPFRC is critical with respect to crack control provisions at serviceability limit state, whether for a tie or a bent member, and also with respect to bearing capacity at ultimate limit state, and to guarantee of ductility in plastic hinges when considering earthquake-resistant structural design. As summarized in [5] major investigation

programs [6-8] have been mainly based on direct tensile tests on reinforced UHPFRC members. However, direct strain monitoring of rebars was not carried out, and only the peak value of the bond stress could be estimated from load measurements, cracks spacing and model assumptions. Preliminary orders of magnitude from these references lead to a peak bond stress close to 55 MPa and anchor length of about 3.2 times the ribbed steel nominal diameter [9]. A bilinear bond stress / slip law has been proposed [6], with a peak displacement of 0.1 mm and a maximum slip corresponding to the distance between successive ribs.

The fibre optic measurements were expected to help check these figures in the dedicated tests of BADIFOPS project, carried out on a UHPFRC of the BSI® type comprising polypropylene fibres in addition to 2 % vol. steel fibres. Main characteristics [10] are about 200 MPa 28-days average cylinder compressive strength, 60 GPa Young's modulus, 0.22 Poisson's ratio and 13 MPa tensile limit of linearity in a bending test.

3.1 Anchor length identified from pull-out test of bars embedded in UHPFRC blocks

Pull out tests that consist of the extraction of a bar partially embedded in a concrete block (Fig. 3) were carried out. Two bar diameters (12 and 16 mm ribbed bars) and two embedment lengths (EL = 2.5 and 8 times the bar diameter) were tested. A single UHPFRC test block containing six embedded rebars was cast for each case. Half of the rebars were pulled out stepwise or with quasi-static cycles. Measurements were performed meanwhile loading was imposed to the rebar, but during fibre optic measurement, it was necessary to maintain the load to a constant value. Strain measurement using the optic fibre sensor remained reliable up to about 0.4 %. Beyond, the fibre got broken. Main results are given in Table 1.

Table 1: Pull-out tests results. Quasi-static loadings, rebars embedded in large blocks

Ribbed bar dia. (mm)	Embedment length (mm)	Failure mode	Failure load (kN)	Equiv. stress (shear or tensile)
12	30	sliding	60.5 to 62.4	shear 54.4 MPa
12	96	bar failure (yielding)	65.8 to 66.4	tensile 585 MPa
16	40	sliding	100.9 to 122.2	shear 56.2 MPa
16	128	bar failure (yielding)	132.5 to 133.4	tensile 662 MPa

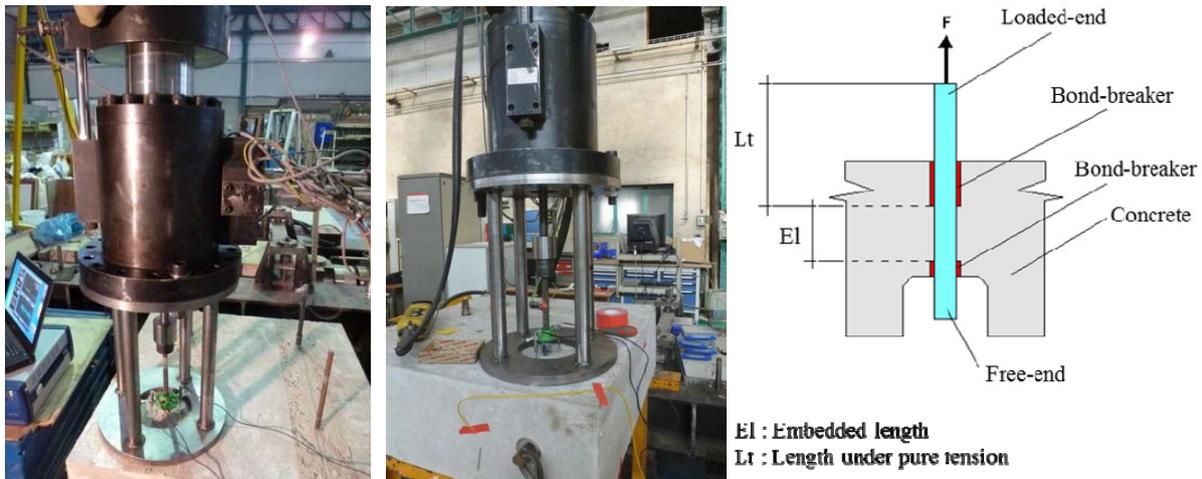


Figure 3: Pull-out test configuration (massive blocks)

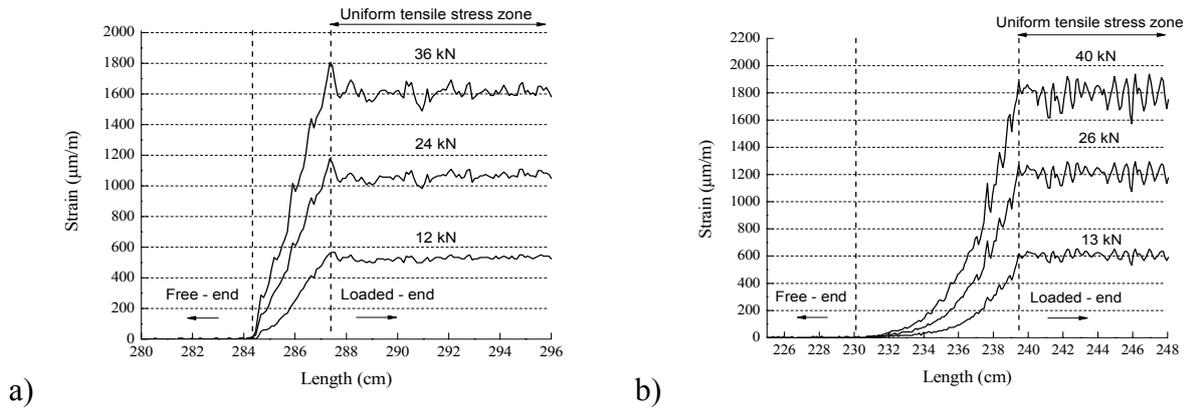


Figure 4: Strain profiles along the rebar for different loading steps
 (a) EL = 30 mm - (b) EL = 96 mm

Fibre optic sensor signals help confirming the evaluation of the anchor length. When the embedment length is lower than the anchor length (Fig. 4a), the tensile stress in the rebar varies roughly linearly which constitutes a direct evaluation of the average shear stress ensuring load transfer (Table 1, last column). It also exhibits a kind of overstress at the limit of anchoring zone, may be due to thrust of UHPFRC upon the first rib of the bar concerned with stress transfer. When the embedment length is higher than the anchor length (Fig. 4b), the stress decreases quasi-linearly with a strong variation over a first part of the embedment length, about 3 to 4 cm-long, then it decreases smoothly, maybe in continuity with tensile strains in the surrounding UHPFRC, until it gets null where the bar gets out of the concrete.

3.2 Anchor length identified from pull-out tests of bars embedded in UHPFRC plates

Since confinement is known to have a significant influence on bond characteristics, it was deemed as necessary to measure bond characteristics of bars embedded in UHPFRC representative thin elements. Covers of 20 and 30 mm were chosen, while embedment lengths of 4 to 8 times the bar diameter were tested (Fig. 5), for ribbed bars 8 and 12 mm in diameter.

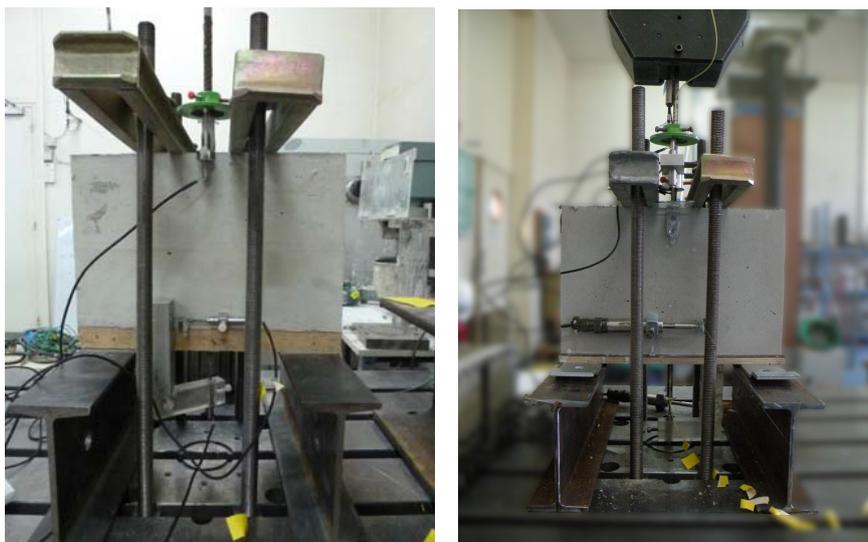


Figure 5: Pull-out test thin plates configuration

The results of stepwise and quasi-static loading tests are displayed in Table 2. Yielding of the rebar has been obtained in all configurations, except for the smaller cover and higher bar diameter, and short embedment length. Consequently the ultimate load has exhibited very low scatter, which corresponds to the average tensile stress calculated over the rebar cross-section (Table 2, last column). Even with a reduced cover the average shear strength over the embedment length, which is of course a lower bond estimate of the bond capacity, reaches at least 20 MPa. Only in the case with cover less than 1.7 times the bar diameter splitting has been observed, which corresponds to having reached the tensile strength of UHPFRC in a reduced thickness zone, possibly affected by a concreting defect.

Table 2: Pull-out tests results. Quasi-static loadings, bars embedded in thin plates

Ribbed bar dia. (mm)	Plate thickness (mm)	Embedment length (mm)	Failure mode	Failure load (kN)	Equiv. stress (shear or tensile)
8	48 (c = 20*)	32 (4 dia.)	bar failure (yielding)	30.8	tensile 613 MPa shear 38.3 MPa
8	48 (c = 20*)	64 (8 dia.)	bar failure (yielding)	31.3 to 31.4	tensile 624 MPa
8	68 (c = 30*)	32 (4 dia.)	bar failure (yielding)	30.4 to 30.6	tensile 605 MPa shear 37.9 MPa
8	68 (c = 30*)	64 (8 dia.)	bar failure (yielding)	30.8	tensile 613 MPa
12	52 (c = 20*)	48 (4 dia.)	splitting	59.6	tensile 527 MPa shear 33.0 MPa
12	52 (c = 20*)	96 (8 dia.)	bar failure (yielding)	66.3 to 66.5	tensile 588 MPa shear 18.4 MPa
12	72 (c = 30*)	48 (4 dia.)	bar failure (yielding)	66.1 to 66.6	tensile 587 MPa shear 36.7 MPa
12	72 (c = 30*)	96 (8 dia.)	bar failure (yielding)	66.1 to 66.2	tensile 585 MPa

(* c = cover in mm)

3.3 Discussion - Consistency with identification in reinforced UHPFRC members

These results confirm the orders of magnitude found in the literature, with an anchor length lower than 4 diameters of the bar and higher than 2.5 times this length, even with relatively small values of cover thickness. This corresponds to mean shear values close to 55 MPa, and certainly higher than 35 MPa. This can also be validated considering the cracks spacing in the lower flange of bent reinforced UHPFRC beams (Fig. 2, 6). Beams made of the same UHPFRC mix, comprising 2 lower rebars, either 12 or 16 mm in dia. (thus named P12 or P16, respectively), have been tested under 4 point-bending. Maximum crack spacing ranged from 7 to 10 cm, while 2 anchor lengths estimated as 3 bar diameters correspond to 72 to 96 mm.

Considering a reinforced UHPFRC member under bending or tensile force at ultimate limit state, it may thus be assumed that a regular pattern of cracks can appear as stabilized, with a typical crack spacing of 5 to 6 bar diameters. If yielding of the rebars is assumed to take place, corresponding to concentrated strains of 2 to 3 %, then the UHPFRC contribution in

bending or tensile bending can be added in a cross-section capacity computation, since for sufficiently ductile UHPFRC the strain corresponding to the peak tensile capacity is higher than this 2 to 3 ‰ value. This has been recently verified in a preliminary test of a tie made of the same BSI® mix used in the BADIFOPS project. A central ribbed 12 mm in dia. bar was included, corresponding to a tensile capacity of 66 kN. The net cross-section of UHPFRC alone (60 x 60 mm²) has a 31 kN capacity. Failure has been observed for a 94 kN total load, exhibiting yielding of the bar. A multiple micro-cracking pattern has confirmed that until failure the locally hardening behaviour of UHPFRC has helped controlling the cracks opening. Processing of fiber optic signal confirming the strains in the rebar and performing of additional tests with repeated cyclic tensile loading are currently undertaken. This shall help validating the domain of applicability of additive contributions of rebars and fibers effects in reinforced UHPFRC.

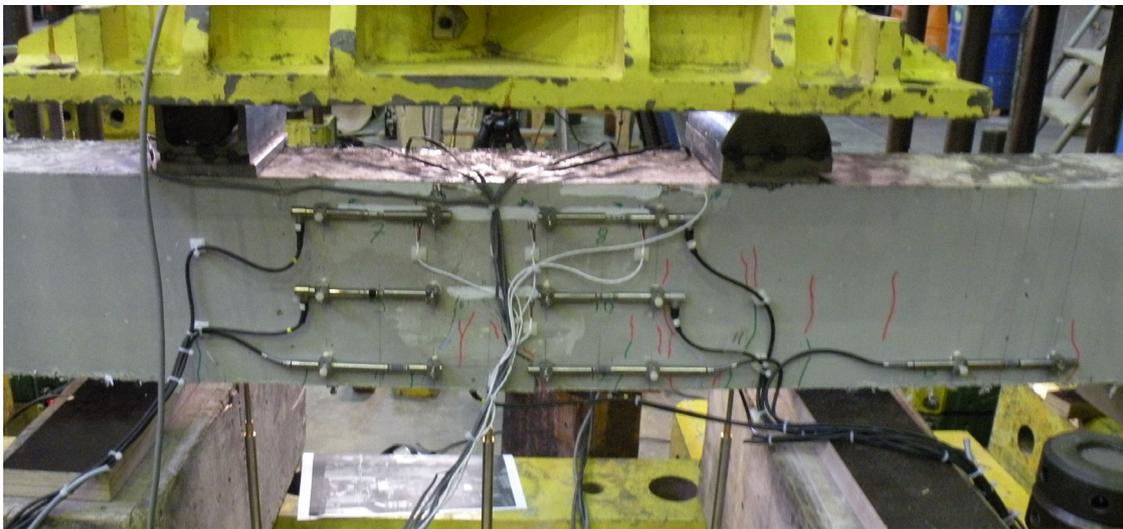


Figure 6: Four-point bending test on reinforced UHPFRC beams - cracking survey

4. EFFECT OF LOADING CYCLES REPETITION

4.1 Repeated pull-out loadings

For pull-out tests of rebars embedded in massive blocks as well as in thin plates, half of the specimens were tested according to a program including stepwise repetitions of loading cycles (Fig. 7). A possible degradation of UHPFRC to rebar interface was anticipated in case of loading repetition, and could be quantified with these tests. Main results are given in Table 3 for bulk anchorage and Table 4 for anchorage in thin elements.

Table 3: Pull-out tests results. Cyclic loadings, bars embedded in large blocks

Ribbed bar dia. (mm)	Embedment length (mm)	Failure mode	Failure load (kN)	Equiv. stress (shear or tensile)
12	30	sliding	57.9 to 59.6	shear 52.1 MPa
12	96	bar failure (yielding)	66.4 to 67.0	tensile 590 MPa
16	40	sliding	118.2 to 119.4	shear 59.1 MPa
16	128	bar failure (yielding)	131.0 to 132.4	tensile 655 MPa

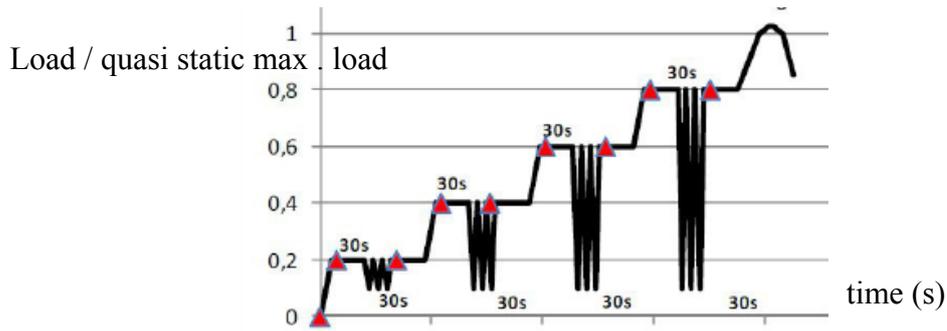


Figure 7: Pull-out tests loading program with cycles repetition

Table 4: Pull-out tests results. Cyclic loadings, bars embedded in thin plates

Ribbed bar dia. (mm)	Plate thickness (mm)	Embedment length (mm)	Failure mode	Failure load (kN)	Equiv. stress (shear or tensile)
8	48 (c = 20*)	32 (4 dia.)	bar failure (yielding)	29.8	tensile 593 MPa
8	48 (c = 20*)	64 (8 dia.)	bar failure (yielding)	30.7	tensile 611 MPa
8	68 (c = 30*)	32 (4 dia.)	bar failure (yielding)	30.6	tensile 608 MPa
8	68 (c = 30*)	64 (8 dia.)	bar failure (yielding)	31.2	tensile 621 MPa
12	52 (c = 20*)	48 (4 dia.)	bar failure (yielding)	66.2	tensile 585 MPa
12	52 (c = 20*)	96 (8 dia.)	bar failure + splitting	65.3	tensile 578 MPa
12	72 (c = 30*)	48 (4 dia.)	bar failure (yielding)	66.2	tensile 585 MPa
12	72 (c = 30*)	96 (8 dia.)	bar failure (yielding)	65.8	tensile 582 MPa

(* c = cover in mm)

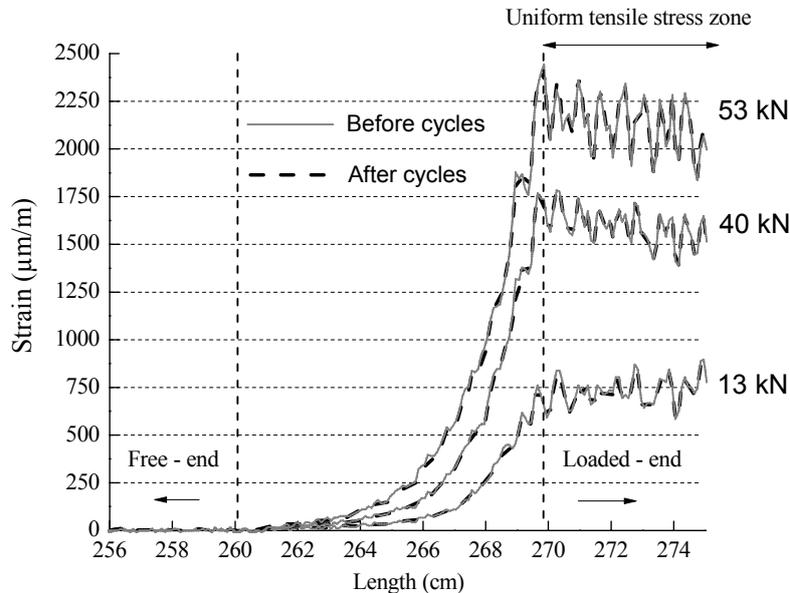


Figure 8: Strain profiles along the rebar for different loading steps, before and after the cycles series (Specimen with 12 mm bar, 30 mm cover, 96 mm embedment length)

For bulk anchorage, cycles have shown no effect on the failure mode, and the difference in estimated bond strength is hardly significant: it represents less than 5 % for a rather limited number of test samples and is positive for 12 mm in dia. rebars and negative for 16 mm in dia. rebars. From fibre optic signals, the stress variation is not changed from before to after the cycles repetition, which confirms absence of significant bond degradation during the process (Fig. 8). For tests carried out on rebars embedded in thin plates, failure has almost always been obtained with rebar yielding, so that the bond capacity has not been changed with sufficient amplitude due to cyclic loading repetition. Like in the stepwise process splitting has also been observed once for a thin plate of reduced cover (less than 1.7 times the bar diameter). However the embedment length was different. It can be assumed that correct placement of the UHPFRC was made difficult in this configuration, and statistically some specimens exhibited a lower tensile capacity due to fibres shortage in the critical zone at the edge of the bar.

4.2 Repeated bending cycles

The bending tests mentioned in section 3.3 have also been carried out both in a stepwise monotonic process, and with repeated cycles of increasing amplitude. Although such a loading process does not directly represent seismic loading effects, it may have induced accelerated bond degradation with induced difference in the cracking pattern and possibility of combining rebars and fibres contribution. In fact, no difference has been observed between specimens having been submitted to monotonic or cyclic loading processes (Fig. 9): initial and successive stiffness identifications, maximum load and post-peak capacity appear as similar whatever the reinforcement ratio. The ultimate bending moments are reasonably consistent with an additive contribution of the rebars moment at yielding and the UHPFRC contribution (compatible strains close to 3 ‰ have been measured along the bar and in the surrounding UHPFRC), taking into account a reduction in the fibres effect due to localized obstacles which have prevented correct placement of the material.

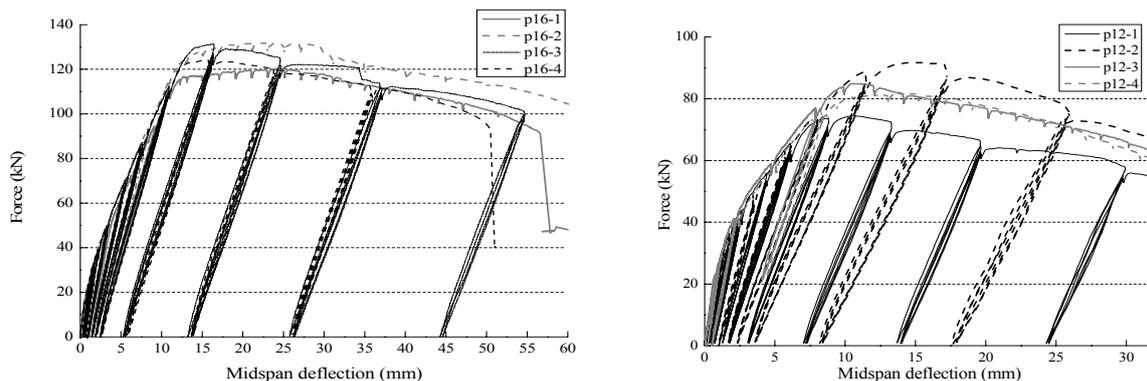


Figure 9: Applied force vs. central deflection of reinforced UHPFRC beams under 4 point-bending. Graphs correspond to P16 and P12 beams (see § 3.3), respectively. With or without repeated loading cycles similar limit curves are obtained even after peak load.

5. CONCLUSIONS

The very short anchor length achievable when conventional passive rebars are embedded in UHPFRC has been experimentally confirmed (ideally 3.2 to generally less than 4 times the

diameter of the bar) even with a reduced cover thickness, provided placement of the cover UHPFRC has ensured satisfactory distribution of the fibres in the thinnest part of this zone. Simple or advanced models can be validated using direct reinforcement strain measurements through fibre optic sensors to describe the results obtained, opening the way to extension of valuable design and detailing provisions for reinforced UHPFRC, especially if a strain-hardening behaviour of the material can be ensured up to strains higher than about 3 %. This result is still valid for repeated loading cycles. Ongoing work will address alternate loading cycles and application to realistic situations of seismic design.

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