Multi-scale Pull-Out Resistance of Steel Reinforcing Bar embedded in Hybrid Fiber Reinforced Concrete (HyFRC)

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Abstract. This paper investigates the pull-out resistance of a steel reinforcing bar embedded in a strain hardening hybrid fiber reinforced concrete that utilizes both polyvinyl alcohol (PVA) microfibers and hooked-end steel macrofibers. Both unconfined and specimens confined with transverse steel spiral reinforcements were investigated. Pull-out tests on rebars embedded in unconfined concrete revealed brittle splitting failure whereas rebars embedded in unconfined HyFRC exhibited ductile frictional pull-out behavior. The high early rebar pull-out resistance in HyFRC is linked to an improved pull-out resistance of the steel macrofibers due to the micro/macrofiber synergy. Steel macrofiber pull-out tests revealed that the PVA microfibers are very effective in enhancing the pull-out resistance of the steel macrofibers which then lead to an overall performance enhancement of the rebar pull-out resistance.

1. Introduction

A Hybrid Fiber Reinforced Concrete (HyFRC) was developed combining polyvinyl alcohol (PVA) microfibers and hooked-end steel macrofibers to obtain strain hardening behavior at relatively low fiber volume fraction [1]. When damage is induced in HyFRC, the PVA microfibers and steel macrofibers are effective in bridging the micro and macrocracks respectively. By providing such multi-scale crack resistance, the HyFRC can achieve both a strain hardening and deflection hardening behavior despite a fiber content as low as 1.5\% [1]. The superior mechanical properties and improved workability due to the low fiber content make HyFRC a practical material to enhance the performance of reinforced concrete structures.

This paper aims to investigate the pull-out resistance of a steel reinforcing bar embedded in a HyFRC matrix. The pull-out resistance is a function of the rebar/matrix bond which strongly affects the performance of reinforced concrete members. When the HyFRC is combined with longitudinal steel reinforcing bars and tested in uniaxial tension, significant tension stiffening was observed due to the rebar/matrix bond enhancement and the continuous load carrying capacity of the matrix [2].

This paper reports on results obtained from rebar pull-out tests that were conducted to provide insights into the mechanisms responsible for the bond enhancement. Pull-out tests have been performed on rebars embedded in high performance fiber reinforced composites that utilize one single type of fiber [3] but not
yet in a HyFRC matrix. In addition, hooked-end steel macrofibers are being pulled out of mortar matrices reinforced with PVA microfibers to investigate the macro/microfiber synergy and its effect on the pull-out performance of rebars embedded in a HyFRC matrix.

2. Experimental program

2.1. Rebar pull-out test

2.1.1. Materials. Rebar pull-out tests were performed with specimens that either utilize a HyFRC or a concrete control matrix without fibers (denoted here as CC). The HyFRC mix design is given in table 1. Coarse aggregates with maximum size of 3/8 inch (9.52 mm) and Vulcan sand with 2.9 fineness modulus were used for both the HyFRC and concrete control specimens. Three types of fibers were utilized in HyFRC: PVA microfibers and two types of hooked-end steel macrofibers, SF-1 (DRAMIX RC-80/60-BN fiber) and SF-2 (DRAMIX ZP305 (Bekaert) fiber). The dimensions and mechanical properties of the fibers are given in table 2.

Table 1. HyFRC mix design (per m$^3$)

| Mixture | Cement (kg) | Fine aggregate (kg) | Coarse Aggregate (kg) | Water (kg) | SF-1 (% vol.) | SF-2 (% vol.) | PVA (% vol.) | Water-to-cement ratio |
|---------|-------------|---------------------|-----------------------|------------|---------------|---------------|--------------|-----------------------|
| HyFRC   | 423         | 852                 | 774                   | 228        | 0.8           | 0.5           | 0.2          | 0.54                  |

Table 2. Fiber dimensions and mechanical properties

| Fiber  | Material             | Length (mm) | Diameter (mm) | Strength (MPa) | Stiffness (GPa) |
|--------|----------------------|-------------|---------------|----------------|-----------------|
| SF-1   | Steel, hook end      | 60          | 0.75          | 1225           | 210             |
| SF-2   | Steel, hook end      | 30          | 0.55          | 1350           | 210             |
| PVA    | Polyvinyl alcohol    | 8           | 0.038         | 1600           | 40              |

2.1.2. Test specimens. Pull-out tests were performed on unconfined and confined HyFRC and unconfined and confined concrete control specimens. All confined specimens were reinforced with transverse steel spiral reinforcements. The dimensions of the rebar pull-out specimens are shown in figure 1. The geometry of the specimens are similar to the ones described in [4]. All rebar pull-out specimens consist of a ribbed No. 8 steel rebar (with dimensions given in table 3) centrally embedded in a cylindrical concrete matrix (152.4 mm of diameter and 304.8 mm of height). The ratio between concrete cover thickness and rebar diameter (c/db) is 2.5. The rebar at the top and the bottom of the specimen was debonded by PVC (Polyvinyl Chloride) pipes which are shown as dashed lines in figure 1. The bond length (Lb) of the rebar was 3.5 times the rebar diameter (db) and included approximately 5 ribs. The confined specimens that contain transverse steel spiral reinforcements are shown in figure 2. The spiral wire is an ASTM A641, Zinc–Coated (Galvanized) Carbon Steel with a tensile strength of 483 MPa (70 ksi) and a diameter of 3.43mm. Transverse reinforcements of 0.75% and 1.5% were provided by 25.4mm and 12.7 mm of spiral spacing respectively. Information on all rebar pull-out specimens are given in table 4. Specimens that were not confined by spirals are denoted as NC. Specimens confined by spirals are denoted as C with the % of transverse reinforcement given in parenthesis. For example CC-C(1.5) indicates that the concrete control specimen is confined with 1.5% transverse spiral reinforcement.

An external vibrator was used during casting to achieve good compaction. After casting the specimens were moist cured for 28 days in their plastic molds with their top faces covered by wet fabrics and plastic sheets. Both cylindrical HyFRC and CC specimens (102x203mm) were cast and tested in compression to determine their compressive strength.
Table 3. Rebar characteristics

| Rebar size | Diameter (mm) | Height of rib (mm) | Rib spacing (mm) | Rib height/rib spacing |
|------------|---------------|--------------------|------------------|------------------------|
| No. 8      | 25.4          | 2.845              | 18.29            | 0.156                  |

Figure 1. Dimensions for rebar pull-out specimens

Figure 2. Spiral configuration for rebar pull-out specimens

Table 4. Rebar pull-out Specimens

| Specimen name | Presence of spiral | Spiral Reinforcement | Spiral spacing (mm) | Number of specimens |
|---------------|--------------------|----------------------|---------------------|---------------------|
| CC-NC         | No                 | 0                    | -                   | 3                   |
| CC-C(0.75)    | Yes                | 0.75%                | 25.4                | 3                   |
| CC-C(1.5)     | Yes                | 1.5%                 | 12.7                | 3                   |
| HyFRC-NC      | No                 | 0                    | -                   | 3                   |
| HyFRC-C(0.75) | Yes                | 0.75%                | 25.4                | 3                   |

2.1.3. Test set-up and procedure. Monotonic rebar pull-out tests were conducted on a 534 kN (120 kip) capacity universal testing machine. The test set-up is shown in figure 3. The matrix surrounding the rebar was supported by a bearing plate on the upper machine head and the rebar was gripped by the lower machine head. The pull-out experiment was performed by moving the upper head upwards at a rate of 2.54 mm/min. The debonded region of the rebar at the bottom of the specimen kept the bond region away from the bearing plate to prevent local confinement. The load applied to the rebar was recorded by a load cell and the slippage of the rebar was measured with potentiometer 1 shown in figure 3.
2.2. **Fiber pull-out test**

2.2.1. **Materials.** Mortar mixtures for the hooked-end steel macrofiber pull-out tests are given in table 5. These mortar mixtures contain the same fine aggregates and PVA microfibers as the rebar pull-out specimens. The mortar mixture of the fiber pull-out specimens was designed to be identical to the mortar proportions of the HyFRC mixture. Hence, the 0.29vol% of PVA microfibers used in the mortar matrix corresponds to the 0.2 vol% of PVA microfibers in the HyFRC specimens.

| Table 5. Mixtures for fiber pull-out specimens (per m³) |
|-----------------------------------------------|------------------|------------------|------------------|------------------|
| Mixture name   | Cement (kg) | Fine aggregate (kg) | Water (kg) | PVA fiber (Vol. %) | W/C ratio |
| M-0%PVA        | 611.4       | 1232.9             | 330.2     | 0                 | 0.54       |
| M-0.29%PVA     | 609.6       | 1229.3             | 329.2     | 0.29              | 0.54       |

2.2.2. **Specimens and testing.** Figure 4 shows the dimensions of the fiber pull-out specimens. The steel macrofiber SF-1 (see table 2 for dimensions) is centrally embedded in a cylindrical mortar specimen of 38 mm in height and 38 mm in diameter. The embedment length of the steel fiber was kept constant for all specimens. All mortar specimens were vibrated by a table vibrator during casting to achieve good compaction and cured in a fog room for 28 days.

The fiber pull-out tests were conducted on a 267 kN (60 kip) capacity universal testing machine and the test set-up is shown in figure 5. The specimens were glued to the bottom plates by epoxy to induce a matrix stress field similar to the stress field around a fiber when the fiber is bridging a crack [5]. The grip with a set-screw clamps onto the fiber and the fiber is being pulled out with the upward movement of the upper machine head. The applied axial load and the fiber displacement were measured by a load cell and a potentiometer, respectively.
3. Test results

3.1. Rebar pull-out test

From the test results, the averaged bond stress along the bond length is calculated by the following equation:

\[ \tau = \frac{F}{\pi d_b l_c} \]  

where \( \tau \) is the bond stress, \( F \) the axially applied load, \( d_b \) the rebar diameter, and \( l_c \) the bond length. In equation (2) the bond stresses are normalized according to [4] to allow for direct comparison independent of \( f_c' \).

\[ \tau_{\text{normalized}} = \tau \left( \frac{36.8}{f_c'} \right)^{1/2} \]

where \( \tau_{\text{normalized}} \) is the normalized bond stress, \( \tau \) the experimentally determined bond stress determined from equation (1), and \( f_c' \) the measured concrete compressive strength. The normalized bond stresses provide information on the rebar pull-out resistance. The results of the rebar pull-out tests are given in table 6. The normalized bond stresses are plotted against rebar slippage in figure 6. Figure 6a represents the total slippage of the rebar and figure 6b highlights the initial slippage of the rebar up to peak stress.

As shown in figure 6 the unconfined CC not only exhibits the lowest peak stress but also reveals abrupt failure after reaching the peak stress. Only confinement provided by transverse spiral reinforcements could prevent such brittle failure in CC specimens. On the other hand, the rebar embedded in HyFRC exhibits not only a higher peak bond stress but also a gradual post-peak softening behavior even without transverse confinement. In addition, only specimens with HyFRC matrices exhibit significant increase in pull-out resistance in the ascending branch prior to reaching the peak bond stress as evident from figure 6b.
Table 6. Results for rebar pull-out test program

| Rebar pull-out specimen name | Averaged compressive strength (MPa) | Peak of normalized bond stress (MPa) | Slip at peak bond stress (mm) | Failure mode |
|-----------------------------|-------------------------------------|-------------------------------------|-------------------------------|-------------|
|                            | Individual value | Average | Individual value | Average |                       |
| CC-NC-1                    | 41.93                | 14.74  | 15.16           | 0.965     | 0.851     | Splitting failure     |
| CC-NC-2                    | 15.64                | 0.856  |                  |           |           |                       |
| CC-NC-3                    | 14.95                | 0.729  |                  |           |           |                       |
| CC-C(0.75)-1               | 16.26                | 15.64  | 1.483            | 1.077     | Frictional pull-out   |
| CC-C(0.75)-2               | 15.43                | 1.059  |                  |           |           |                       |
| CC-C(0.75)-3               | 15.23                | 0.691  |                  |           |           |                       |
| CC-C(1.5)-1                | 36.50                | 18.53  | 18.05           | 1.361     | 1.674     | Frictional pull-out   |
| CC-C(1.5)-2                | 17.78                | 2.189  |                  |           |           |                       |
| CC-C(1.5)-3                | 17.91                | 1.468  |                  |           |           |                       |
| HyFRC-NC-1                 | 40.04                | 20.19  | 20.39           | 0.808     | 1.021     | Frictional pull-out   |
| HyFRC-NC-2                 | 20.33                | 1.349  |                  |           |           |                       |
| HyFRC-NC-3                 | 20.60                | 0.907  |                  |           |           |                       |
| HyFRC-C(0.75)-1            | 25.70                | 23.98  | 1.808           | 1.783     | Frictional pull-out   |
| HyFRC-C(0.75)-2            | 22.67                | 1.544  |                  |           |           |                       |
| HyFRC-C(0.75)-3            | 23.49                | 1.999  |                  |           |           |                       |

Figure 6. Rebar pull-out responses; (a) total slippage of rebar; (b) slippage of the rebar in the ascending portion up to the peak bond stress.

Two to four fully developed splitting cracks formed in the unconfined CC specimens at the peak bond stress. These splitting cracks then propagate in an unstable manner and lead to the observed brittle splitting failure shown in figure 7. On the other hand, by either adding transverse spiral reinforcements to the CC matrix or replacing the CC matrix with HyFRC the crack pattern changes and the brittle splitting failure can be prevented. Instead of a few dominant splitting cracks a crack pattern with multiple hair-line splitting cracks develops in the radial direction. In figure 8 which represents a typical saw-cut cross section of unconfined HyFRC specimens these multiple fine splitting cracks are indicated by dashed lines.
In both unconfined HyFRC specimens and confined CC specimens, frictional pull-out failure was observed instead of the brittle splitting failure which dominated the CC specimens.

![Figure 7. Splitting failure for unconfined CC specimens](image)

![Figure 8. Saw-cut cross section for HyFRC-NC after frictional pull-out failure. The dashed lines represent the multiple fine splitting cracks](image)

### 3.2. Fiber pull-out test

The results of the steel fiber pull-out test conducted with unreinforced and PVA microfiber reinforced mortar matrices are given in table 7. The fiber displacement includes both the elastic elongation and the slippage of the fiber.

| Fiber pull-out specimen name | Peak load (N) | Fiber displacement at peak load (mm) |
|-----------------------------|---------------|-------------------------------------|
|                             | Average       | Individual value | Average | Individual value |
| M-0%PVA-1                   | 330.3         | 334.6               | 0.89     | 0.89               |
| M-0%PVA-2                   | 340.2         | 0.86                 |          |                    |
| M-0%PVA-3                   | 338.4         | 0.95                 |          |                    |
| M-0%PVA-4                   | 331.9         | 0.83                 |          |                    |
| M-0%PVA-5                   | 325.5         | 0.88                 |          |                    |
| M-0%PVA-6                   | 341.5         | 0.91                 |          |                    |
| M-0.29%PVA-1                | 329.5         | 339.2               | 0.79     | 0.87               |
| M-0.29%PVA-2                | 324.3         | 0.87                 |          |                    |
| M-0.29%PVA-3                | 325.4         | 0.89                 |          |                    |
| M-0.29%PVA-4                | 380.1         | 0.97                 |          |                    |
| M-0.29%PVA-5                | 333.5         | 0.84                 |          |                    |
| M-0.29%PVA-6                | 342.7         | 0.84                 |          |                    |

The average load-fiber displacement curve for each type of mortar is plotted in figure 9 with the total displacement of the fibers given in figure 9a and the ascending portion up to peak load highlighted in figure 9b. The pull-out response of the steel macrofiber embedded in either the unreinforced or PVA
microfiber reinforced mortar matrices are similar in shape exhibiting two peaks, P1 and P2, as shown in figure 9a. These peaks are associated with the plastic deformation of the hooked ends of the steel fiber at two locations [5] indicated in figure 4 by bend 1 and bend 2.

(a)                       (b)

Figure 9. Averaged fiber pull-out responses in (a) high displacement range (b) low displacement range

The difference in fiber pull-out behavior between unreinforced and PVA fiber reinforced mortars is more apparent in the ascending portion of the curves as shown in figure 9b. The curves exhibit a linear ascending branch followed by a plateau like region. The linear portion of the curve is being extended from 82.8N in unreinforced to 139.1N in PVA microfiber reinforced mortar specimens. The linear ascending branches in figure 9b are due to the elastic elongations of the steel fibers. After the plateau region fiber slippage becomes the dominant mechanism.

4. Discussion

4.1. Pull-out resistance between rebar and concrete matrix

The mechanical interlock between rebar ribs and the surrounding concrete matrix provides most of the pull-out resistance. When the rebar slips against the matrix, the radial components of the inclined bearing force between rebar ribs and the matrix induce a tensile stress field in the matrix as schematically shown in figure 10. The tensile stresses are responsible for the formation of splitting cracks. The brittle failure observed in the unconfined CC matrix was caused by the unstable propagation of such splitting cracks. In HyFRC on the other hand, the propagation of splitting cracks is resisted by both micro and macrofibers. The PVA microfibers are effective in bridging and arresting such cracks at onset while the steel macrofibers resist their widening and propagation. Both, the bridging of PVA microfibers and steel macrofibers induce intense crack closure stresses onto the crack surfaces as shown in figure 11. These crack closure stresses which result in normal stresses acting on the rebar enhance the rebar/matrix bond and increase the pull-out resistance of the rebar and ultimately change the failure mode to a more ductile frictional pull-out behavior.

While spiral reinforcements also induce normal stresses on the rebar during rebar pull-out the unconfined HyFRC provides higher pull-out resistance compared to the CC matrix reinforced with 0.75% spirals. At least 1.5% of spiral reinforcement was required to confine the CC matrix to achieve similar...
peak stress and post-peak behavior as unconfined HyFRC. Adding spiral reinforcement to HyFRC further increases the pull-out resistance due to the additional normal stresses acting on the rebar.

Besides the higher peak and post peak bond stress observed in unreinforced HyFRC compared to unreinforced and spiral reinforced CC the ascending curves (shown in figure 6b) are far steeper in unreinforced HyFRC. The steeper ascending curves reveal a rather significant slip stiffening behavior up to the peak stress, while the addition of spiral reinforcements in both CC and HyFRC had only a minimal effect on the ascending curve. These differences can be explained by the effectiveness of fibers and the lack of spiral reinforcement in resisting splitting crack formation at onset. The fibers are located close to the rebar and hence are able to bridge the splitting cracks and prevent their opening during the early crack initiation phase. On the other hand, the transverse spiral reinforcement was not mobilized until the splitting cracks have already reached a certain length and crack width. Hence, the minimal effect of the spiral reinforcement on slip stiffening can be explained by the lack of crack closure stresses acting on the splitting cracks during the crack initiation phase.

4.2. Micro/macro fiber synergy in a HyFRC-rebar system

When steel macrofibers bridge the splitting cracks that form during rebar pull-out, the fibers initially stretch elastically and then eventually start to pull out. Once fiber pull-out takes place both the crack closure stresses acting along the splitting cracks and the normal stress acting on the rebar are being reduced which changes the pull-out response of the rebar. However, in HyFRC the pull out of the steel macrofibers is delayed up to higher load levels due to the presence of the PVA microfibers. When hooked-end steel macrofibers pull out of the matrix, microcracks form around these steel fibers. These microcracks, if not bridged by PVA microfibers, weaken the bond between the matrix and the steel fibers which reduce the pull-out resistance of the steel fibers.

The observed increase in pull-out resistance of the rebar embedded in HyFRC can be explained by a process that occurs on multiple scales. On the smaller scale, the pull-out resistance of the steel fibers is enhanced by PVA microfibers bridging the microcracks around the steel fiber which enhances the fiber/matrix bond. On the larger scale, the pull-out resistance of the rebar is enhanced by the steel macrofibers bridging the splitting cracks and their ability to maintain higher closure stresses across the splitting crack surfaces due to the presence of PVA microfibers. The higher normal stresses acting on the
rebar due to the higher closure stresses enhance the rebar/matrix bond. This micro/macrofiber synergy provides the basis for the enhanced pull-out resistance of the rebar when pulled out from a HyFRC matrix.

5. Conclusion
A rebar embedded in a HyFRC matrix exhibits a far higher pull-out resistance compared to the same rebar being pulled out from a concrete matrix. In addition, even an unconfined HyFRC matrix is able to change the failure mode from a brittle splitting failure to a more ductile frictional pull-out behavior. Although transverse spiral reinforcements also provide a frictional pull-out failure in confined concrete control specimens, a spiral reinforcement as high as 1.5% is required to achieve peak/post-peak rebar pull-out resistance comparable to the resistance provided by unconfined HyFRC. While HyFRC enhances the pull-out resistance prior to the peak bond stress only a small enhancement could be observed with transverse spiral reinforcements. The experimental results reveal that this enhancement in HyFRC was partially due to a steel fiber bond enhancement induced by PVA microfibers. In a HyFRC member reinforced by a steel reinforcing bar, such multi-scale pull-out resistance can provide superior composite behavior between rebar and matrix.

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