INVESTIGATION ON SINGLE FIBER PULLOUT AND INTERFACIAL DEBONDING MECHANISMS WITH ACOUSTIC EMISSION TECHNIQUES

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Keywords: steel fiber, pullout, acoustic emission, interfacial bonding, Hilbert transform.

Summary: Fiber pullout behaviour is of great significance in post-crack performance of steel fiber reinforced concrete. Firstly, in order to understand the debonding behaviour of the fiber/matrix interface during the pullout process, single fiber pullout tests are carried out in this study. Both hooked-end fibers and straight fibers with the same embedded length of 30mm are considered. Load versus relative displacement curves of different fiber type are studied. Secondly, to investigate the debonding behaviour along the interfacial zone, acoustic sensors are also applied. Based on the acoustic signal detected by the sensors attached on the concrete specimen, debonding mechanism is identified with parameter based AE signal analysis. Moreover, frequency and energy spectrum with regard to fracture behaviour of interfacial zone are further analyzed.

1 INTRODUCTION

Due to remarkable advantages over normal concrete in post crack performance, fiber reinforced concrete (FRC) has been applied in many real projects. The failure mode of fiber reinforced concrete are fibers pulled out for normal strength concrete, while for high performance concrete, when the bonding strength is even higher than fiber tensile strength, the fibers will be ruptured before it is pulled out. Due to the fiber pullout behaviour, FRC can absorb much more energy than the unreinforced concrete in the post cracking phase. Therefore it is of great significance to know how the fiber bridges and arrests the crack opening and how the fiber/matrix debonding behaviour is involved in the pullout process.

During the pullout, the transfer of forces between the fibers and the concrete matrix is achieved through interfacial bond defined as the shearing stress at the interface between the fiber and the concrete matrix. The bonding behaviour has a complex nature due to the presence and the combined action of several bond components, which at least include three items: 1) physical and chemical adhesion between fiber and matrix, 2) the mechanical component of bond such as hooked-end, crimped and other deformed fibers, 3) interfacial friction. Fiber pullout in cementitious composites has been investigated by numerous researchers, and lots of fiber pullout test were conducted to characterize the fiber matrix interfacial bond properties in the past three decades. Nilson [1] and Jiang [2] believed that the shear stress slip relationship is not unique but dependent on the location. By contrast, Edwards and Yannopoulos [3] stated that the maximum bond stress value would not vary whether it was from a loaded end or a crack face in the concrete member. Mirza and Houde [4] reported similar findings. Nammur and Naaman [5] investigated different factors affecting the bond in fiber reinforced concrete by a series of pullout tests, they observed that hooked-end fibers and
deformed fibers have higher resistance to pullout than smooth fibers because of the mechanical contribution. They also observed that the bond strength increases as the strength of the matrix increases. Cunha and Barros [6] carried out a series of single fiber pullout tests in self-compacting concrete to study the local bond stress-slip relationship, and an analytical model was proposed to describe both the adherence and mechanical bond. Xu and Ju [7] developed a micromechanical model to simulate the fracture energy dissipated in the pullout process, and it shows good agreement with the experimental results. Based on the improved pullout test of fully embedded single fiber by Mumm and Faber [8], Shah [9] proposed an analytical model to study the fracture process of steel fiber and cementitious matrix. It was found that differences in the debonding energy and interfacial sliding friction are linked to changes in the interfacial microstructure. Banthia and Trottier [15] investigated micromechanics of steel fiber pullout with different loading rates and temperatures, a higher pullout load was found under impact loading than under static loading for deformed fibers.

Acoustic emission (AE) techniques have been studied in concrete engineering for decades. Due to the large maintaining and retrofitting demand for aging structures, AE techniques have been used in real projects as non-destructive damage detection method. Some literature can be found on the parameter based analysis of AE signals due to microcracking behaviour in concrete, literature on signal based analysis on concrete structures are limited. Kim and Weiss [10] used AE techniques to monitor early age cracking in restrained fiber reinforced mortars; it was found that as the concrete neared the age of visible cracking, the acoustic waves generated in the restrained specimens had a greater amplitude and duration. Soulioti etc. [11] investigated the acoustic activity involved in a steel fiber reinforced concrete beam under four point bending with AE techniques. The fracture mode was analyzed as well by calculating the RA (Rise time/Amplitude) value and average frequency. It was found that the fracture mode is changing from tensile crack to shear crack as the fiber content increases. Reinhardt and Grosse [12] performed a single fiber pullout test with AE techniques, based on the signal detected by the acoustic sensors. Moment tensor inversion method combined with spectrum analysis were conducted to determinate the fracture type. Lu and Li [13] evaluated the fracture process of mortar specimens under various types of loading using signal based acoustic emission monitoring techniques, it was found that 3D localization of AE events are helpful to explain the microcrack generation and propagation, and signal based AE energy index was introduced to evaluate the fracture energy.

The main scope of this study is to investigate the debonding behaviour of single fiber pulled out from concrete matrix. Based on results of pullout tests, the relationship between pullout force and pullout displacement are studied. Results of straight fiber and hooked-end fiber are compared with each other to further study the different bonding mechanisms contributing to the pullout strength. With acoustic emission techniques, microcracking behaviour involved in the debonding behaviour during the pullout process are also investigated. Parameter based analysis of AE signals are performed to evaluate the microcracking properties.

2 EXPERIMENTAL PROGRAM

The pullout tests can be divided into 2 main groups according to the different fiber types used in the test: hooked-end fibers and straight fibers. There are 3 specimens tested for each fiber type, so 6 pullout tests were carried out in total. The fibers used in these tests are specially made by Bekaert, they were fabricated at 160mm in length, with one end hooked which is the same as DRAMIX RC-65/60-BN, and the other end is straight. They were cut into two pieces with the same length of 80mm before embedding in the concrete specimen. The embedded length for all the fibers is 30mm.

2.1 Specimen preparation

The concrete used in the pullout tests is normal strength concrete. Cement type is CEM I 42.5R, the water cement ratio (w:c) is 0.5. According to the sieving test, the particle size of aggregates is 0-4mm for sand and 5-14mm for gravel. The adopted fiber has a length of 80mm, a 0.9mm diameter,
and a yield stress of 1100MPa. The concrete mix used is shown in table 1. The fresh concrete has a slump of 140mm.

Table 1 : Concrete mixture composition

<table>
<thead>
<tr>
<th>Items</th>
<th>Weight (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement I 42.5R</td>
<td>350</td>
</tr>
<tr>
<td>Water</td>
<td>175</td>
</tr>
<tr>
<td>Sand (0~4mm)</td>
<td>856</td>
</tr>
<tr>
<td>Gravel (5~14)</td>
<td>175</td>
</tr>
<tr>
<td>Superplasticiser G51</td>
<td>26g (0.3%)</td>
</tr>
</tbody>
</table>

The specimen is a cylinder with dimension of 100mm in diameter and 50mm in depth. In order to embed the fiber into the concrete specimen, a special plastic mould was made, which is shown in figure 1. There are two holes drilled at the bottom of the mould, the one in the middle with diameter of 1mm is made for embedding the fiber, the other one with diameter of 5mm is made for demoulding using air pressure. Before concrete was casted, the fiber was put in the middle hole of the mould, and then the hole was sealed with a tape to make sure there is no leak of fresh concrete during the casting. The concrete was casted very carefully on a small vibration table. In this way the fiber will keep straight during the casting. The vibration takes around 1min to get the fresh concrete settle in the mould. When the casting is completed, the specimen is put in the curing chamber with constant temperature of 20°C and humidity of 90% for 7 days before the pullout test. Specimen dimension and casted specimens are shown in figures 2 and 3.
In order to know the physical and mechanical properties of this concrete composition, 6 additional cubes are casted at the same time. Since the pullout tests were performed after 7 days curing, three of them are tested to measure the 7-days compressive strength. The rest three cubes are tested to measure the 28-days compressive strength. The results of compressive strength are shown in Table 2.

### Table 2: Hardened concrete matrix property

<table>
<thead>
<tr>
<th>Ages</th>
<th>Average Density (g/cm³)</th>
<th>Average Strength (MPa)</th>
<th>S.D (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 days</td>
<td>2.31</td>
<td>38.9</td>
<td>1.17</td>
</tr>
<tr>
<td>28 days</td>
<td>2.31</td>
<td>45.1</td>
<td>0.84</td>
</tr>
</tbody>
</table>

#### 2.2 Pullout test setup

The pullout tests are performed in a servohydraulic loading machine with capacity of 100kN. The specimen is placed in a steel supporting system, as shown in Figure 4. The whole system was clamped firmly at the bottom on the testing machine. The specimen is hold by the upper steel ring which is fixed in the supporting system during the pullout process. A special steel grip is made to clench the steel fiber to make sure no slip can occur during the pullout process. The clamp is connected with the testing machine by a screw bar and a load cell. The schematic view of the pullout test setup is shown in Figure 4.

A load cell with capacity of 5kN is used to measure the pullout load, as is shown in figure 4. Three LVDTs are mounted on the steel grip to measure the pullout displacement. The actual pullout displacement is the average value of the three LVDTs. The displacement control is adopted during the pullout loading. In the beginning, the loading rate is 0.6mm/min, and then it is increased to 1mm/min when the pullout displacement reaches 6mm, and it was gradually increased to 5mm/min after the
pullout displacement reaches 10mm.

### 2.3 Acoustic sensor setup

In order to detect the microcracking behaviour at the interface between steel fiber and concrete matrix, acoustic sensors are used during the pullout process. Four piezoelectric sensors are used in order to perform the 3D localization of the acoustic events, three of them are attached on the top surface of the specimen to localize the x and y coordinates, and another one is attached on the cylinder surface out of the x and y plane with a rubber band to localize the z coordinates. The cylinder surface is flattened before the test so the sensor can be attached easily. The acoustic sensors used in this test are of type Vallen VS150-M with resonance frequency of 150 kHz. The sensors are firstly connected with 4 preamplifiers respectively, and then connected with the data acquisition box. The detection results can be visualized on the computer during the pullout test. The acoustic sensors setup and the data acquisition system (Vallen AMSY-5) are shown in figures 5, 6 and 7 respectively.

![Acoustic sensors setup](image-url)

**Figure 5 and 6: Acoustic sensors setup**

![Data acquisition system](image-url)

**Figure 7: Data acquisition system**

The signal threshold for acoustic events was preset at 35dB, which means any acoustic signal with amplitude less than 35dB will be considered as environmental noise, and will not be recorded by the computer. Before performing the 3D localization, the wave travelling speed in the concrete specimen was determined by calibration. And the coordinates of the four sensors were also preset. Since the
acoustic sensors are highly sensitive, the surroundings were kept as quiet as possible during the pullout test in order to reduce the environmental noise to the minimum level.

3 RESULTS AND DISCUSSION

The overall pullout behaviour is evaluated based on pullout load-displacement curves, peak pullout load and energy dissipated during the pullout process (pullout work). For each pullout test, load vs. displacement curve, peak load $P_{\text{peak}}$, displacement at peak $\Delta_{\text{peak}}$, and the energy dissipated in the whole pullout process $E_{\text{pullout}}$ are determined. The energy dissipated by the mechanical debonding $E_{\text{mech}}$ is also calculated by subtracting $E_{\text{pullout}}$ of straight fiber from $E_{\text{pullout}}$ of hooked-end fiber at pullout displacement of 5.5mm. The pullout load and pullout displacement curves for the tested fibers are shown in figure 9. A representative sample of the test results is shown in figure 8. For straight fibers, a sudden drop is observed after the peak load is obtained, which indicates that the bond at the interface between fiber and concrete matrix is damaged, and afterwards, friction resistance becomes the dominating mechanism of the pullout behaviour. For the hooked-end fibers, pullout curves have a distinct linear initial portion terminating at a point at which nonlinear behaviour is exhibited until the peak load is reached followed by fiber/matrix debonding and frictional sliding. Compared with straight fiber, the $\Delta_{\text{peak}}$ is much higher for hooked-end fiber due to the mechanical anchorage, and the postpeak load is decreasing not as abrupt as in straight fiber, at approximately 5.5mm slip (the length of hooked-end). After the hooked length is completely straightened, the pullout process occurs under frictional resistance similar with straight fibers. As illustrated in table 3, the peak load of straight fiber is 0.2kN, which is only the half of the peak load of hooked-end fiber.

Table 3: Peak load, pullout displacement and energy dissipation

<table>
<thead>
<tr>
<th>No.</th>
<th>Fiber type</th>
<th>Embedded length (mm)</th>
<th>$P_{\text{peak}}$ (kN)</th>
<th>$\Delta_{\text{peak}}$ (mm)</th>
<th>$E_{\text{pullout}}$ (kN.m)$\times10^{-3}$</th>
<th>$E_{\text{mech}}$(at $\Delta=5.5mm$) (kN.m)$\times10^{-3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>Straight</td>
<td>30</td>
<td>0.20</td>
<td>0.24</td>
<td>0.39</td>
<td>0</td>
</tr>
<tr>
<td>H1</td>
<td>Hooked</td>
<td>30</td>
<td>0.40</td>
<td>6.87</td>
<td>7.10</td>
<td>1.38</td>
</tr>
<tr>
<td>H2</td>
<td>Hooked</td>
<td>30</td>
<td>0.42</td>
<td>0.95</td>
<td>3.77</td>
<td>1.40</td>
</tr>
<tr>
<td>H3</td>
<td>Hooked</td>
<td>30</td>
<td>0.44</td>
<td>1.32</td>
<td>4.61</td>
<td>1.78</td>
</tr>
<tr>
<td>H4</td>
<td>Hooked</td>
<td>30</td>
<td>0.48</td>
<td>1.35</td>
<td>5.35</td>
<td>1.80</td>
</tr>
<tr>
<td>H5</td>
<td>Hooked</td>
<td>30</td>
<td>0.46</td>
<td>2.59</td>
<td>6.44</td>
<td>2.16</td>
</tr>
</tbody>
</table>

The pullout load displacement curves together with cumulative acoustic emission events detected by 4 channels are shown in figures 10 and 12. In order to consider the mechanical bonding contributed by the hooked-end, a clear physical comprehension of its straightening process is required. Correlations between fiber pullout and respective load-crack responses were provided by Pomo et al. [14] through video photography techniques. According to his research, four distinct regions are suggested for pullout response of inclined fibers: (1) elastic response followed by debonding; (2) fiber pullout and straightening processes; (3) frictional sliding within the straight matrix channel; (4) fiber removal from the matrix. Similar with the work of Pomo, only the first three regions (R1 R2 and R3) are distinguished by red dashed lines in figures 10 and 12. For the second region R2, it is subdivided into R2a and R2b according to the geometry dimensions of the hook. It is interesting to see from figure 8 and 9 that the pullout resistance by frictional sliding for hooked fiber is much higher than that for straight fiber. This is introduced by the snubbing effect because the hooked end is not completely straightened in the channel, which can also be observed from the pullout fiber after the test.

The maximum pullout stress of hooked fiber is also calculated as $\frac{P_{\text{peak}}}{\text{Area}} = 612\text{MPa}$, which is much less than the yielding stress of the fiber (1100MPa).
There were few acoustic events detected in the first region. However, due to the mechanical debonding, considerable acoustic events were detected in the region R2, it is also interesting to see from both figures, that the most acoustic events detected are from R2a where pullout load reaches the peak, only a few events from R2b where the pullout load gets flattened. When the fiber lost all its mechanical bonding, few acoustic events were detected in the region R3 as shown in figure 13, which means it is relatively “quiet” when the fiber slides in the channel and the pullout force is dominated only by the frictional resistance. For specimen H4, the hooked-end is not completely flatten, so there are still many acoustic events detected after 5.5mm in figure 11. If we look at the energy dissipation in table 3, it could be found that, for specimen H3 and H4, the energy dissipated in mechanical debonding $E_{mech}$ takes 39% and 34% of total energy respectively. The amplitude of the hits detected during the pullout process is shown in figures 11 and 13.
Figure 12 (Left): Pullout curve with cumulative hits of H3

Figure 13 (Right): Amplitude vs. Pullout displacement of H3

Figure 14 (Left) and 15 (Right): 2D and 3D localization of acoustic events of H3.

The 2D and 3D localization results of H3 and H4 are shown in figures 15 and 17. The figure on the left shows the position of acoustic events detected by three sensors on the top surface of specimen. X and Y coordinates on the 2D plane were determined in the figure together with surface photo of the specimen. The black rectangular spots represent the three sensors. The coloured round spots represent the localized acoustic events. The figure on the right is the 3D localization results; the Z coordinates were calculated by the other sensor attached on the cylinder surface. The rectangular spots represent the projections of these events on the x-y plane. It can be seen in figure 14 and 16, most of the acoustic events were successfully localized in the centre around the fiber on the 2D plane. However, in 3D space, only few events were successfully localized (some localization are out of the
specimen). The limited number of localized events in 3D is due to the limited number of available sensor, which is only just efficient to perform 3D localization.

Figure 16(Left) and 17(Right): 2D and 3D localization of acoustic events of H4

Figure 18: Signal waveform and frequency spectrum
It is also interesting to look at the frequency spectrum of signals from different pullout regions. Two representative signals are selected from region R2 and R3 respectively. The mechanisms in this two pullout regions are totally different. The acoustic signal generated in region R2 is mainly induced by matrix fracture (concrete local crushing), and signal generated in region R3 is mainly by frictional sliding. The acoustic signal waveform and corresponding spectrum are displayed in figure 18. The representative signal in the first line is selected in region R3, the other signal in the second line is selected in region R2a. The red dashed lines represent the signal threshold. First, it can be seen that the amplitude of acoustic signal induced by mechanical debonding is much higher than that detected in the frictional sliding, which is also in agreement with the energy dissipation results calculated in table 3 and the figure 13, that the pullout energy is mostly consumed by straightening of the hooked-end. Second, the signal frequency is also quite different for two pullout regions. It shows a single peak at 250kHz for the signal detected in the frictional sliding, however, the signal frequency concentrates at around 350kHz with a minor peak at around 230kHz in the mechanical debonding process.

The frequency spectrum was calculated by Hilbert transform with empirical mode decomposition (EMD) techniques. The algorithm is programmed in Matlab.

4 CONCLUDING REMARKS

The experimental results of single steel fiber pullout tests were presented and discussed. The debonding mechanism at the fiber/matrix interface was studied with acoustic emission techniques. The hooked-end fiber shows a higher pullout resistance due to the mechanical debonding compared with straight fiber. For hooked-end fiber, there were more acoustic events generated due to local concrete crushing when the hooked length was straightened. After the mechanical debonding, few acoustic events were detected when the fiber was sliding in the channel. The amplitude of signal detected in the mechanical debonding was higher than that in the frictional sliding. And in the frequency domain, the acoustic events induced by the local concrete crushing concentrated more on higher frequency around 350kHz, however, the acoustic signal induced by frictional sliding came up with lower narrow-banded frequency around 250kHz.

REFERENCES


