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PULLOUT BEHAVIOR OF SHORT FIBERS UNDER MONOTONIC AND CYCLIC LOADINGS

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Abstract: Fiber Reinforced Concrete (FRC) is gaining popularity in the construction industry because of its ability to prevent crack formation and thus enhance the mechanical performance of concrete. The residual tensile strength in FRC depends on a single pullout response of the fiber and the number of fibers across the cracks. Given the widespread recognition of hooked-end steel fibers as the most suitable fiber type for structural applications, it is important to accurately predict the pull-out response of these fibers. This paper presents the single-fiber pullout behavior of hooked-end steel fiber subjected to monotonic and cyclic loadings, with an embedment length of 15 mm. Furthermore, a comparative pullout performance analysis was conducted for polypropylene (PP) fiber, straight steel fiber, and hooked-end steel fiber. The experimental results suggest that cyclic loading has no significant effect on the pullout performance of the hooked-end steel fibers whereas, cyclic loading decreases the pullout resistance of the specimen with PP fiber.

1 INTRODUCTION

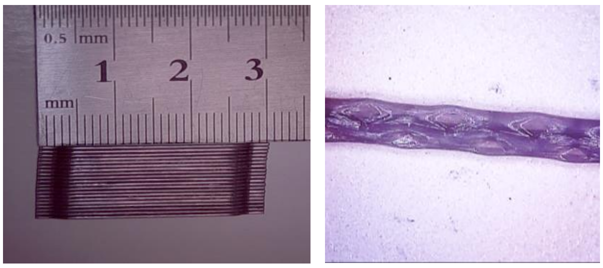
The addition of fibers into a cementitious matrix can improve ductility, inhibition of crack growth, and fracture properties of concrete [1–5]. The main contribution of fibers in concrete is typically observed during the initiation of cracking, as it often leads to improved post-cracking performance due to the enhanced stress transfer by fiber bridging across the cracked sections. This bridging action provided by the fibers greatly depends on the pull-out mechanism [6]. The fiber-matrix bond is the crucial factor in determining the fibers' efficiency to transfer the stresses in concrete. Hence the knowledge of bond mechanism in fibers is very important to understand the behavior of FRC. The fiber-matrix bond mechanism is assessed by using single-fiber pullout tests [7].

Numerous authors around the globe have conducted experimental, theoretical, and numerical investigations on the bond-slip relation of the fiber-concrete interface. However, there has been insufficient research on the pull-out behavior of hooked-end steel fibers due to their complex shape. To the best of the author's knowledge, no study has been conducted to investigate the effect of cyclic loading on the single-fiber pullout behavior of short fibers, particularly hooked-end steel fibers.

2 EXPERIMENTAL PROGRAM

2.1 Characteristics of used Fibers

Hooked-end steel fibers used in this study are shown in Fig. 1(a). The length of the fiber was 30 mm, and the fiber has a hooked end having a length of about 5 mm. The straight steel fibers used in this study were obtained by trimming the hooked ends from the hooked end fibers. The properties of the fiber used are presented in Table 1. PP fibers used in this study are shown in Fig. 1(b). The surface of the fiber is indented.



a) Hooked end fibers b) Polypropylene fiber

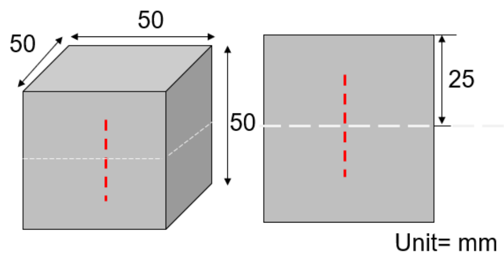
Figure 1 Short fibers.

Table 1 Properties of fiber

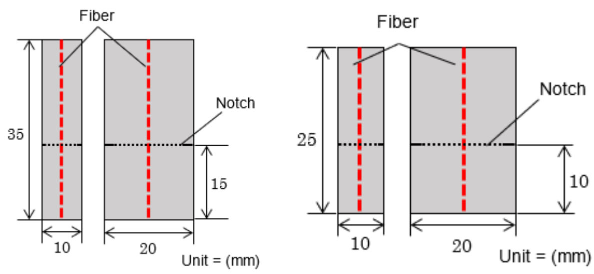
Fiber Type	L (mm)	D (mm)	Tensile Strength (Mpa)	Elastic modulus (Gpa)
Steel fiber	30	0.62	1270	210
PP fiber	48	0.70	530	10

2.2 Fabrication of test specimens

An overview of the specimens prepared for this study is illustrated in Figure 2. Mortar with a water-cement ratio of 50 % was used to prepare specimens. Mixing was done by using a Hobart-type mixer. For the steel fiber specimen, mortar was poured into molds in two layers, the first layer was poured into molds and then steel fiber was placed at the center with an embedment length of 15 mm. The second layer was poured after curing the first layer for 24 hours. A polyethylene sheet with a thickness of 0.1 mm was placed so that the cross-sectional area where cracking occurs after the first layer cured (24h of age) was 25 mm^2. The PP fiber specimens were prepared by placing the fibers in a mold and pouring a cement paste with a water-cement ratio of 50%. Specimens of a given size were then obtained by cutting them using a micro cutter. The fiber embedment length was adjusted by changing the position of the notch to specify the crack location. Notch depths were added on four sides of the specimen to achieve a cross-sectional area of cracks approximately equal to 100 mm^2. The specimens were demolded after 48 hours and cured for 28 days.



a) Specimen for hooked-end steel fiber



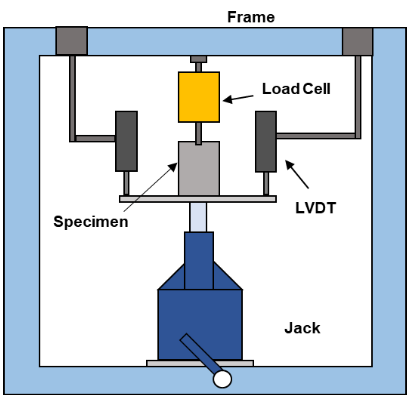
b) Specimen for PP fiber c) Specimen for straight steel fiber

Figure 2 Overview of fiber pullout specimens

2.3 Testing method

The apparatus shown in Fig.3 was used to apply cyclic loading to the fiber-embedded specimens. The specimen and testing machine were bonded using adhesives, and tensile and compressive forces were applied using a jack. The cyclic loading was produced by unloading the specimen in the compressive direction every time the maximum specified displacement in the tensile direction is reached and loading again in the tensile direction after unloading to zero. The loading rate was about 1 mm/min. Several series of experiments were conducted by changing the loading type and displacement intervals for each cycle. Table 2 shows the details of the series of specimens tested.

a) Pullout apparatus



b) Schematic diagram of pullout apparatus

Figure 3 Apparatus for Fiber pullout tests

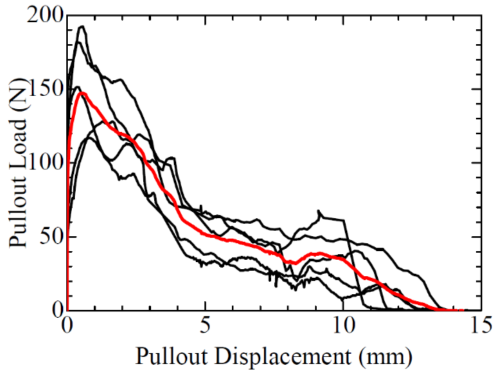
Table 2 Detail of tested specimens and loading protocol

Fiber Type	Embedment length (mm)	Loading Method	No. of Specimens
Hooked end steel fiber	15	Monotonic	5
	15	Cyclic at 0.5 mm interval	5
	15	Cyclic at 1 mm interval	5
	15	Cyclic at 2 mm interval	5
PP Fiber	15	Monotonic	3
	15	Cyclic at 1mm interval	3
Straight Steel Fiber	10	Monotonic	3
	10	Cyclic at 1mm interval	3

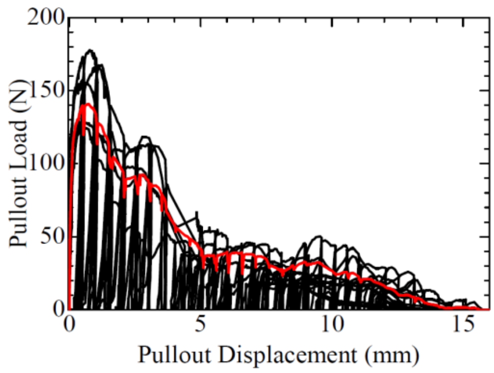
3 RESULTS AND DISCUSSION

3.1 Pullout behavior of hooked end fibers

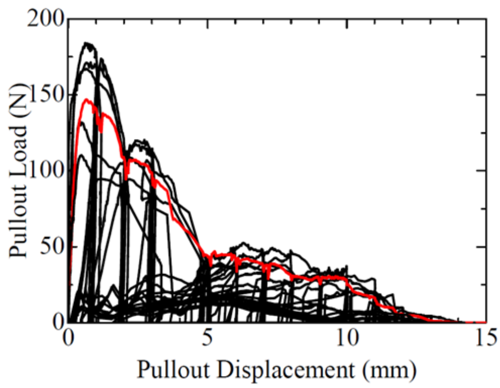
The pull-out load versus pullout displacement curves obtained from the specimens with hooked-end steel fiber are shown in Figure 4. The bond behavior in hooked end fibers is mainly determined by adhesion, mechanical anchorage effect, and frictional resistance. It can be observed from Fig.4 that the curve starts to rise steeply until it reaches peak load and then decreases until the fiber is completely pulled out from the matrix. Moreover, the post-peak decay is not abrupt, since with an increase of pullout displacement mechanical anchorage of hooked end fiber started to mobilize progressively. When the pullout displacement reaches approximately 5 mm, which is the length of the straightened hook, the pullout process occurs under frictional resistance, similar to that of straight fibers.



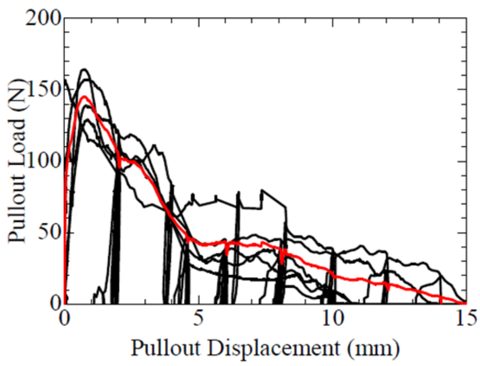
(a) Monotonic loading



(b) Cyclic loading at 0.5mm displacement interval



(c) Cyclic loading at 1 mm displacement interval



(d) Cyclic loading at a 2 mm displacement interval

Figure 4 Pull-out versus displacement curves of hooked-end steel fibers

3.2 Effect of cyclic loading intervals on pullout resistance of Hooked end Steel fiber

The pullout load versus pullout displacement relationship after averaging is shown in Fig.5. To evaluate the effect of cyclic loading on the pullout resistance, the pullout load versus displacement relationships obtained for each tested series were averaged and only the envelope curves are shown in the graph. Eventually, there was no effect of interval in cyclic loading until the peak load. The result shows that after peak load the pullout resistance decreased with a decrease of interval in cyclic loading. However, the difference was not significant. This indicates that the cyclic loading has no significant effect on the pull-out resistance of the hooked end fibers. Figure 6 shows the normalized pull-out energy for average pullout displacement curves for each tested series. The pullout energy decreases with an increase in the number of cycles by changing the displacement interval of each cycle from 2 mm to 0.5mm. The pull-out energy of samples tested at 0.5 mm intervals of cyclic loading has 11.0 % lower than that of the monotonic loading case. Similarly, the samples tested at 1 mm and 2mm intervals of cyclic loading have 8.8 % and 7.2 % lower pullout energy than that of the monotonic loading case, respectively.

3.3 Effect of cyclic loading on pullout resistance of PP fiber

Regarding PP fiber, the pullout load-displacement relationship after averaging is shown in Fig.7. It can be observed that cyclic loading had no effect on the specimen until the maximum load was reached. After the peak load, the specimen subjected to cyclic loading had lower pullout resistance than the monotonically loaded specimen. This may be due to the rupturing of the PP fiber with an increase in the number of cycles.

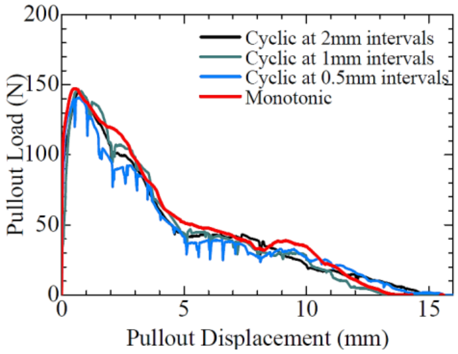


Figure 5 Average pullout load versus displacement curves of hooked end steel fiber

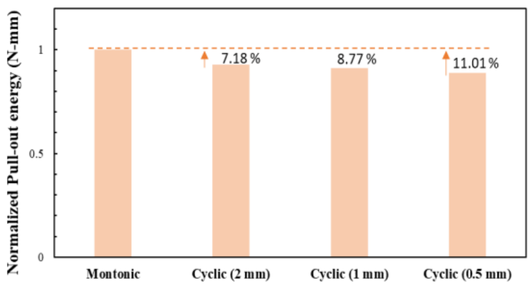


Figure 6 Normalized Pull-out energy (N-mm)

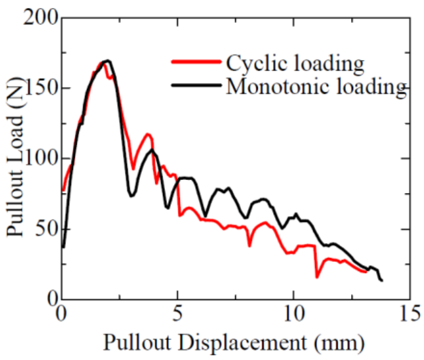


Figure 7 Average pullout load-displacement curves of PP fiber

3.4 Hook-end Efficiency: A Comparative Analysis of Straight and Hooked-End Steel Fibers

Figure 8 shows the pullout response of the straight steel fiber subjected to cyclic loading. It can be observed that the straight steel fiber pullout behavior is characterized by a rapid, linear increase in load up to a peak load, followed by a sudden drop in load. This indicates that fiber debonding occurs rapidly. Afterward, with an increase in pullout displacement, the load continues to decrease. However, in the case of hooked-end fibers, the peak pullout load is significantly higher (approximately 10 times higher than straight steel fibers), which can be attributed to the mechanical anchorage provided by the hook ends, which effectively resist slippage. Moreover, the pullout load decreases more gradually from the peak value to the residual value due to the more complex interface bond mechanism.

Figure 9 illustrates the pullout response of both straight and hooked-end steel fibers subjected to cyclic loading with a cyclic interval of 1 mm displacement. The experimental observations have shown that the pull-out behavior of hooked-end steel fiber is quite similar to straight fiber until the fiber debonding occurs. After that, the main contributing factor was the mechanical anchorage provided by the hook section, which enhanced the hook end fibers' efficiency. At an approximate pull-out displacement of 5 mm, which corresponds to the straightened hook length (shown in Fig. 10), the pullout process occurs primarily due to frictional resistance, similar to that observed in straight fibers.

Figure 10 shows the microscopic photo of the internal section of the specimen after being subjected to the pullout load at 5 mm displacement. It can be observed from the picture that the hook end fiber was straightened.

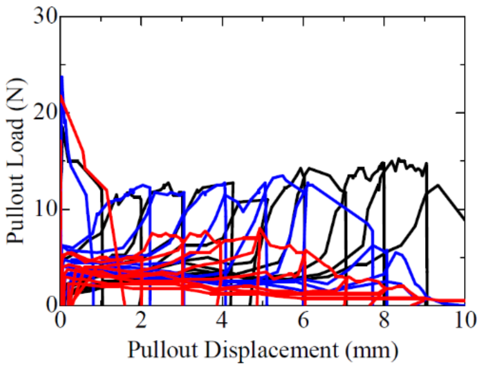


Figure 8 Pullout curves for straight steel fibers

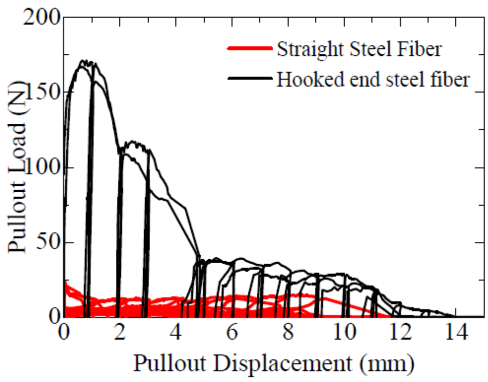


Figure 9 Pull-out load versus pull-out displacement curves for straight and hook-end fiber

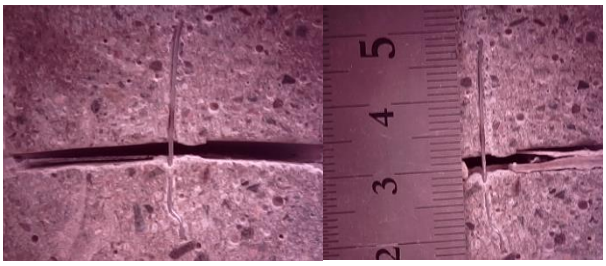
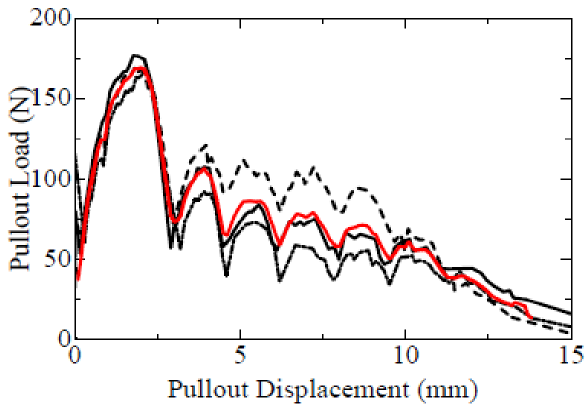


Figure 10 Microscopic image showing the internal section of the specimen after undergoing pullout testing at 5 mm displacement.

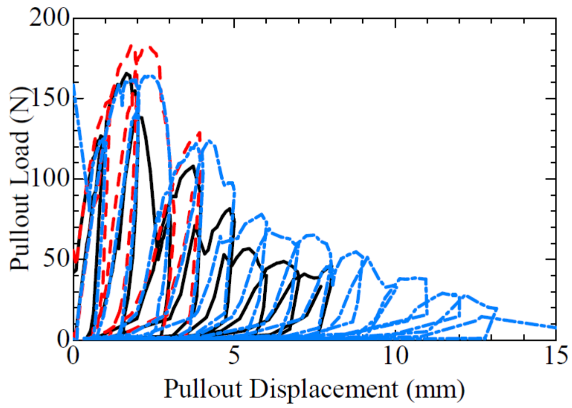
3.5 Performance Comparison: PP fibers vs. Hooked-End Steel Fibers

The pullout behavior of PP fibers subjected to monotonic and cyclic loading at intervals of 1 mm displacement, is shown in Fig.11. It is evident from Fig.11 and Fig. 12 that the PP fiber ruptured after several cycles of pullout loading in two specimens. One specimen ruptured after eight cycles, while the other specimen ruptured after four cycles. Figure 13 shows a microscopic photo of the hooked-end steel fiber taken after the test. No fiber rupture was observed for hooked-end steel fiber specimens- a testament to their higher stiffness.

The differences in pullout response of the PP fiber and hooked-end steel fiber subjected to monotonic and cyclic loading are shown in Fig.14 and 15, respectively. It can be seen that the pullout load initially increases linearly with pullout displacement, but then the pullout load-displacement curve shows a hardening behavior due to the increase in frictional shear stress as the PP fiber slips. The abrasion of the PP fiber's outer surface during the pullout test might be responsible for the hardening behavior of the pullout curve. After reaching peak load there was a sudden drop in load for PP fiber specimens, whereas hooked-end steel fibers have gradual post-peak load decay. The peak load of PP fiber specimens was observed at a pullout displacement of approximately 2 mm, whereas for the hooked-end steel fiber, the peak load was observed at a pullout displacement of 0.5 to 1 mm. The experimental observation suggests that the hooked-end steel fiber demonstrates better performance in controlling cracks due to the mechanical anchorage effect.



(a) Pullout under monotonic loading



(b) Pullout under cyclic loading

Figure 11 Pullout response of the PP fiber

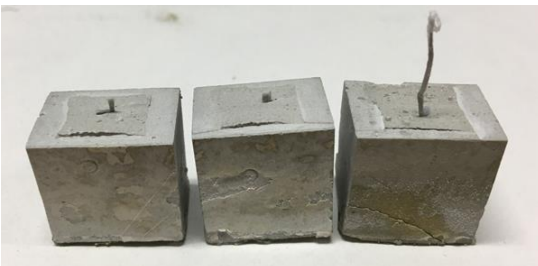


Figure 12 PP fiber specimens after test

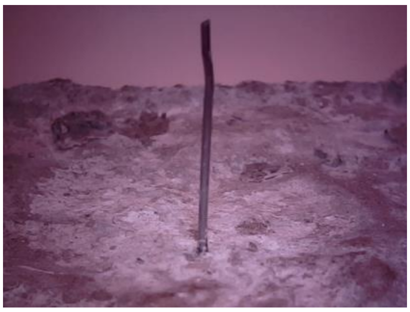


Figure 13 Hooked end steel fiber after test.

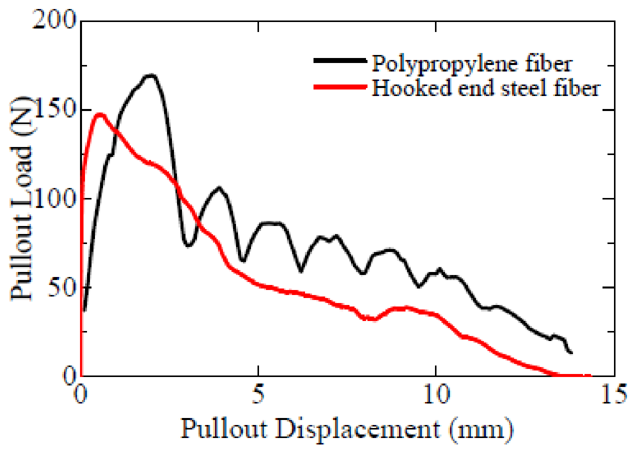


Figure 14 Average pullout response of the PP fiber and hooked end steel fiber subjected to monotonic loading.

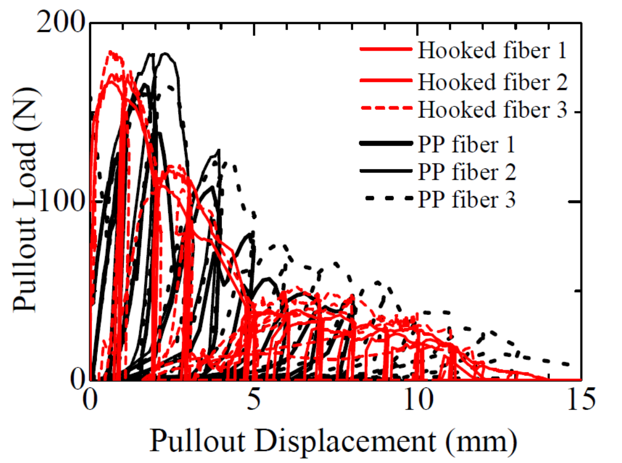


Figure 15 Pullout response of the PP fiber and Hooked end steel fiber subjected to cyclic loading.

4 CONCLUSIONS

This study demonstrated a cyclic pullout test to investigate the cyclic loading effect on the pullout behavior of steel fibers and PP fibers. The following conclusions were obtained:

1. Cyclic loading has no significant effect on the pullout resistance of the specimens with hooked-end steel fibers.
2. The pullout resistance of PP fiber specimens was not affected by cyclic loading until the

peak load. However, after the peak load, the pullout resistance was slightly decreased, which may be due to the damage of PP fibers during cyclic loading.

3. The peak pullout load for the hooked-end fiber was observed to be higher (approximately 10 times) than that of the straight steel fibers. This can be attributed to the mechanical anchorage provided by the hook.

5 ACKNOWLEDGEMENT

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