An experimental study on the behavior of fiber-reinforced concrete flexural members under cyclic loading

H R Gatabi1, M Celikag*1, H A Bengar2

1Department of Civil Engineering, Faculty of Engineering, Eastern Mediterranean University, Famagusta, North Cyprus, via Mersin 10 Turkey
2Department of Civil Engineering, University of Mazandaran, Babolsar, Iran

*Email: murude.celikag@emu.edu.tr

Abstract. An experimental work was performed to address the cyclic performance of reinforced concrete flexural members containing steel, PVA, and Forta-Ferro fibers. Four full-scale reinforced concrete flexural members having the same geometry were subjected to a one-point bending test with slow cyclic loading. One of the four specimens was a control specimen with 0% fiber volume fraction ($V_f$), and the other three contained 1.5, 0.6, and 1.5% $V_f$ of steel, Forta-Ferro, and PVA fibers, respectively. The ultimate resistance, ductility, stiffness, dissipation of energy was studied, and the influence that different fibers had on the cyclic performance was evaluated. In general, the cyclic performance of the reinforced concrete flexural members improved by adding fibers, leading to higher ultimate displacement and maximum strength value.

1. Introduction

One can trace back the procedure of adding fibers to materials with brittle behavior to improve their ductility to ancient times [1]; for example, Egyptians added to straws to mud bricks [2]. The fiber types utilized nowadays across different industries have increased significantly; for instance, the fiber types used most commonly in concrete structures are steel, polymeric, and carbon fibers.

Extensive research has been focused on steel fiber-reinforced concrete (SFRC) [3-9]. The performance of beams reinforced with steel fibers was investigated by [10]. They tested the beams under uniaxial tension to obtain the post-cracking behavior, whereby they defined characteristic stress vs. crack opening. Fibers can change the post-cracking softening behavior seen in concrete to a post-cracking hardening behavior, which allows the formation of extensive cracking prior to failure; however, in post-cracking softening, a strength reduction occurs after initial cracking, which prevents the formation of further cracks.

Furthermore, reinforcing cementitious materials with PVA fibers is also advantageous in terms of durability criterion when subjected to freeze-thaw or wet-dry cycles compared to plain concrete, with the crack width being limited to 100 μm [11, 12]. Short cut PVA (polyvinyl alcohol) fibers show good performance in improving the flexural and tensile behavior since they possess high strain and tensile strength capacities.
together with unique strain hardening property, which limits the crack width and allows for multiple fine cracks [13].

Forta-Ferro fibers are a type of synthetic fibers composed of 100 percent virgin copolymer/polypropylene. They are in the form of a twisted bundle of non-fibrillated monofilaments, as well as some fibrillated network fibers. Through their use, high quality and efficiency are achieved for reinforced concrete. Using this fiber type leads to less shrinkage in fresh and hardened concrete and improves the impact resistance, fatigue resistance, and stiffness of hardened concrete. By incorporating an integrated network of these fibers in concrete, the long-term durability and structural properties are improved, and secondary or thermal cracking in concrete is controlled. Other properties of Forta-Ferro fibers include their noncorrosive nature and 100 percent resistance in alkaline environments [14].

The present work aimed at investigating the performance of reinforced concrete beams containing fibers throughout the concrete mix under cyclic loading through an experimental program. This study focused on the performance of flexural concrete members reinforced with longitudinal and transverse steel bars built-in full scale under cyclic loading. Here, four beam specimens comprising of one fibreless, one with 1.5% steel fibers, one with 0.6 Forta-Ferro fibers, and one with 1.5% PVA fibers were manufactured in full scale and exposed to the slow cyclic one-point bending loading. To be able to study the effect of fibers on the cyclic performance of the specimens, their capacity curve, cyclic response, ductility, ultimate deflection, and loading and unloading stiffness, as well as damage propagation and energy absorption and dissipation were evaluated as some of the important parameters.

2. Experimental procedure

The following sections give more information regarding the specimens and their constituents, test set-up, and applied loading history.

2.1. Materials and specimens

In this work, four reinforced concrete flexural members were manufactured in the laboratory, among which one was fibreless and the other three each contained a specific volume fraction of a different fiber type including one with 1.5% steel fibers, one with 0.6% Forta-Ferro fibers, and one with 1.5% PVA fibers. Apart from the inclusion of fibers and their content, the three fiber-reinforced specimens had the same properties to eliminate the probability of the scattering of the results. Table 1 shows the mechanical properties of the fibers used in the specimens. The specimens had a length of 2440 mm and a cross-section of 270×270 mm. For the top and bottom longitudinal reinforcement, 4Φ14 deformed bars were used, and for transverse reinforcement, Φ8@56mm were used. The corresponding yield strength of the longitudinal and transverse rebar were 4560 and 3850 kg/cm², respectively. Fig. 1 gives some details about the specimens. The concrete cover thickness was 50 mm. Also, the concrete binder materials were Portland cement type II. For obtaining the compressive strength of the concrete, compression tests were conducted on three cubic 15×15×15 cm specimens of each mixture design after curing for 28 days. The specimens containing 1.5% steel fibers, 0.6% Forta-Ferro fibers, 1.5% PVA fibers and the one without fiber had compressive strength values of 29.4, 28.85, 29.7, and 30.8 MPa, respectively.
Table 1. Mechanical properties of fibers

| Fiber    | Density (gr/cm$^3$) | Tensile Strength (N/mm$^2$) | Length (mm) | Diameter (mm) | $V_f$ (%) |
|----------|---------------------|----------------------------|-------------|---------------|-----------|
| Steel    | 7.85                | 1100                       | 30          | 0.500         | 1.5       |
| Forta-Ferro | 0.91               | 660                        | 54          | -             | 0.6       |
| PVA      | 1.30                | 1300                       | 8           | 0.085         | 1.5       |

Fig. 1. Dimensions and reinforcement detail of specimens

2.2. Test setup and experiments

The simply-supported beam specimens were subjected to the one-point flexural testing under slow cyclic loading applied by a universal machine. The equipment and devices used in the test setup included a reaction frame, a load cell for measuring the load, and two Low Voltage Displacement Transducers (LVDTs) for measuring the mid-span deflection of the specimens. The experimental setup is schematically shown in Fig. 2.
2.3. Loading history

During the test, the specimens were subjected to cyclic loading in a displacement-controlled manner. Each cycle was repeated three times, with the first one initiated at ± 2 mm. In total, 14 drift ratios were applied to the specimens, which included 0.20, 0.25, 0.35, 0.50, 0.75, 1.00, 1.40, 1.75, 2.20, 2.75, 3.5, 4.5, 6.0, and 8.0%. Fig. 3 demonstrates the cyclic loading regime conducted compliant to the ACI Committee 374.1-05 [15].

![Fig. 2. Schematic view of the test setup](image_url)

![Fig. 3. Cyclic loading protocol](image_url)
3. Results and discussion

This section gives the results obtained from the experiments. In this work, the hysteresis behavior of specimens was investigated, and based on the obtained results, their peak and ultimate strength, capacity curve, ultimate displacement, and ductility, as well as energy dissipation, were investigated. A comparison was made among the results of different specimens, including fibreless and fiber-reinforced ones, to specify the influence of fibers on the cyclic performance of reinforced concrete flexural members.

3.1. Hysteresis behavior

The hysteresis behavior of the specimens is represented in the form of load vs. the mid-span displacement at the top and bottom surfaces of the steel beam. The cyclic performance and failure mechanism of the specimens are demonstrated in Fig. 4.

![Hysteretic behavior graphs](image)

**Fig. 4. Hysteretic behavior**

The failure of the flexural specimen without fibers was characterized by concrete crushing in the compressive zone as well as extensive cracking with branching. However, flexural specimens containing steel, Forta-Ferro, and PVA fibers failed through a major crack, commonly located in the middle region of the flexural members (Fig. 5). Fig. 4 shows that in the case of using fibers in the concrete mix, an increase
was seen in the ultimate displacement and maximum strength relative to the fibreless specimen. In addition, in the specimens without fibers, the damage was more extended, and cracks propagated more in the entire length compared to the fiber-containing specimens. In addition, in the specimens containing fibers, a major crack located in the middle region occurred.

The capacity curves derived from the hysteresis curves are compared in Fig. 6. According to the mean values, as well as the assessment of the specimen results, these curves were derived. Furthermore, Table 2 lists the ultimate displacement and maximum strength values in the positive and negative loading range for the tested specimens.

Fig. 6 shows that using fibers leads to increased maximum strength and ultimate displacement in the negative and positive loading ranges. In order to better compare the capacity curves of the specimens, it is easier to use idealized form of the tri-linear force-displacement diagrams of the specimens considering a considerable stiffness change for defining the elastic stiffness and yielding displacement (γ) as well as a strength reduction of 20% from the highest obtained ultimate strength (Table 2). In general, when fibers were used, it was observed that the maximum strength, ultimate strength, and maximum displacement were all increased.
Table 2. Characteristic values of capacity curves of specimens

| Specimen | Peak load (kN) | Average peak load (kN) | Displacement at yielding point (mm) | Displacement at 20% drop in peak load (mm) | Ductility factor |
|----------|----------------|------------------------|-------------------------------------|--------------------------------------------|-----------------|
|          | Pull (+)       | Push (-)               | Pull (+)                            | Push (-)                                   |                 |
| RC       | 112.00         | 129.35                 | 120.67                              | 58.83                                      | 5.34            |
|          | 163.4          | 176.49                 | 161.54                              | 78.1                                       | 8.22            |
| SFRC     | 159.2          | 207.61                 | 183.4                               | 47.7                                       | 4.86            |
| FFRC     | 146.6          | 176.49                 | 161.54                              | 78.1                                       | 8.22            |
| PFRC     | 137.61         | 156.71                 | 147.16                              | 71.2                                       | 7.73            |

3.2. Stiffness degradation

Fig. 7 shows the slope of a line connecting peak points in each cycle approximates the cyclic stiffness of the flexural member. Eq. (1) was used to calculate the cyclic stiffness at different cycles (Fig. 7), and for this purpose, only the first reversal cycle was considered.

$$K_i = \frac{F_i^+ - F_i^-}{d_i^+ - d_i^-}$$  \hspace{1cm} (1)
Fig. 8 shows a degradation for the peak-to-peak secant stiffness (slope) of all the specimens that sees a degradation. This is believed to have been a result of the nonlinear concrete deformations, flexural and shear cracking, cover fracture, and the reinforcement slippage.

According to Fig. 8, the steel fiber reinforcement (SFRC), Forta-Ferro fiber reinforcement (FFRC), and PVA fiber reinforcement (PFRC) specimens showed initial stiffness values of 25.98, 22.18, 20.02, respectively and these are 57.16, 34.18, and 21.11% greater than that of the specimen without fiber, respectively. This difference became even higher at a drift of 0.75%, such that the secant stiffness of the SFRC, FFRC, and PFRC specimens were around 62.75, 42.78, and 50.5% higher than that of the fibreless specimen, respectively. On the other hand, the initial stiffness of the FRC specimens is more stable in a way that the initial cyclic stiffness of these specimens has a lower decline compared to that of the specimen without fibers. In addition, four specimens had closely spaced stiffness values at large displacements, namely drifts of above 4.5%.

3.3. Energy absorption and dissipation

The resistance of a structure to seismic loads is dependent on the ability of the structure to absorb and dissipate the energy of an earthquake. The area inside the hysteresis loop specifies the energy dissipation, and as this area increases, more seismic energy is absorbed and transformed into the hysteresis energy. In Fig. 9, the hysteresis energy and displacement curves of different beams are compared. In general, at small displacements, there is no considerable difference among hysteresis energy values; however, at large displacements, this difference among hysteresis energy values was increased. This is attributed to the addition of fibers. The specimens containing steel, Forta-Ferro, and PVA fibers showed around 7.21, 50.51, and 37.12% increase in energy dissipation relative to the specimen with 0% fiber volume fraction ($V_f$). Up to 8% drift, the cumulative dissipated energy of the specimens RC, SFRC, FFRC, and PFRC were 96866, 103853, 145793, and 132821 kN.mm, respectively.
3.4. Discussions

Based on test findings, all the beams experienced the flexural failure mode. Nevertheless, when the fibers were present in the concrete, damage in the specimens was concentrated to the maximum displacement area, while cracks propagated along the entire length of the flexural member in the fiberless beam, with the final failure occurring at the location of load application. The steel, Forta-Ferro, and PVA fibers bridge across the two faces of micro-cracks, preventing their further widening. As the displacement increased, all of the fibers crossing the mouth of the crack at the mid-span started to elongate, then yielded, and eventually ruptured at the ultimate state of the flexural members. This phenomenon led to increased, ultimate loading capacity. Including fibers in the concrete matrix that were considerably affected the stiffness and stability of the specimens at loading and unloading increments. When the fibers were added to the mixes, more energy was absorbed and dissipated, as expected.

4. Conclusion

This experimental study attempted to investigate the influence that steel, Forta-Ferro, and PVA fibers have on the cyclic performance of reinforced concrete flexural members. The main conclusions obtained are given as follows:

1. In general, the maximum strength and displacement increased by the addition of fibers.
2. When the various fibers were present to the concrete mix, the cracking was limited to the main crack localized at the mid-span of the flexural members, and also, cracks were fewer compared to the case of the fiberless specimen.
3. Adding fibers, in general, led to a higher secant stiffness during cycles of loading and unloading. This means that via the addition of steel, Forta-Ferro, and PVA fibers in the concrete mixes, damage to the specimens decreased, and the stability of the cyclic behavior increased relative to the specimens without fibers.
4. At smaller displacements, no considerable difference was seen among the hysteresis energy values of the beams; however, at greater displacements, this discrepancy became significant.

Fig. 9. Cumulative energy of the specimens compared with each other
References

[1] Felekoğlu, B., Türkel, S., & Altuntaş, Y. (2007). Effects of steel fiber reinforcement on surface wear resistance of self-compacting repair mortars. Cement and Concrete Composites, 29(5), 391-396.
[2] Ranjbaran, F., Rezayifar, O., & Mirzababai, R. (2018). Experimental investigation of steel fiber-reinforced concrete beams under cyclic loading. International Journal of Advanced Structural Engineering, 10(1), 49-60.
[3] Sahoo, D. R., Bhagat, S., & Reddy, T. C. V. (2016). Experimental study on shear-span to effective-depth ratio of steel fiber reinforced concrete T-beams. Materials and Structures, 49(9), 3815-3830.
[4] Sahoo, D. R., Maran, K., & Kumar, A. (2015). Effect of steel and synthetic fibers on shear strength of RC beams without shear stirrups. Construction and Building Materials, 83, 150-158.
[5] Sahoo, D. R., Solanki, A., & Kumar, A. (2014). Influence of steel and polypropylene fibers on flexural behavior of RC beams. Journal of Materials in Civil Engineering, 27(8), 04014232.
[6] Özcan, D. M., Bayraktar, A., Şahin, A., Haktanir, T., & Türker, T. (2009). Experimental and finite element analysis on the steel fiber-reinforced concrete (SFRC) beams ultimate behavior. Construction and Building Materials, 23(2), 1064-1077.
[7] Nataraja, M. C., Dhang, N., & Gupta, A. P. (1999). Stress–strain curves for steel-fiber reinforced concrete under compression. Cement and concrete composites, 21(5-6), 383-390.
[8] Vandewalle L et al (2003) Final recommendation of RILEM TC 162-TDF: Test and design methods for steel fiber reinforced concrete sigma-epsilon-design method. Materials and Structures 36:560–567
[9] Ganesan, N., Indira, P. V., & Abraham, R. (2007). Steel fiber reinforced high performance concrete beam-column joints subjected to cyclic loading. ISET Journal of Earthquake Technology, 44(3-4), 445-456.
[10] Casanova, P., & Rossi, P. (1997). Analysis and design of steel fiber reinforced concrete beams. Structural Journal, 94(5), 595-602.
[11] Yu, J. H., Chen, W., Yu, M. X., & Hua, Y. E. (2010). The microstructure of self-healed PVA ECC under wet and dry cycles. Materials Research, 13(2), 225-231.
[12] Şahmaran, M., Lachemi, M., & Li, V. (2010). Assessing the durability of engineered cementitious composites under freezing and thawing cycles. In Recent Advancement in Concrete Freezing-Thawing (FT) Durability. ASTM International.
[13] Li, V. C., & Kanda, T. (1998). Innovations forum: engineered cementitious composites for structural applications. Journal of Materials in Civil Engineering, 10(2), 66-69.
[14] Arafa, M., Arafa, M., Alqedra, M., & Almassri, H. G. (2013). Effect of forta-ferro fibers on fresh and mechanical properties of ultra-high performance self-compacting concrete. Effect of forta-ferro fibers on fresh and mechanical properties of ultra-high performance self-compacting concrete, 1.
[15] ACI Committee 374.1-05. Acceptance criteria for moment frames based on structural testing and commentary. Farmington Hills, Michigan, USA: American Concrete Institute; 2005.