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RETROFITTING SFRC BEAMS BY USING CFRP

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Abstract: The use of structural members made of steel fiber reinforced concrete (SFRC) has been increasing since it has been shown through numerous researches that steel fibers promotes the mechanical properties of concrete beyond cracking and improve the crack control characteristics of concrete significantly. A particular use of steel fibers aims to enhance the behavior of reinforced concrete (RC) beams without web reinforcement. Even though there have been numerous researches focused on the contribution of steel fibers to the behavior of reinforced concrete (RC) beams without web reinforcement, the studies on retrofitting of SFRC beams is very limited. An advantageous retrofitting method is to use carbon fiber reinforced polymers (CFRP) due to the fact that it has relatively high tensile strength and low weight, and it can be applied easily and rapidly. In this study, RC beams with a shear span-to-effective depth ratio of 4.5 were loaded up to their load-carrying capacities and then tested again after retrofitting with CFRP. The experimental results were examined in the context of strength, stiffness and ductility.

Keywords: Reinforced concrete, beam, steel fiber, carbon fiber reinforced polymer

Introduction

The use of steel fiber reinforced concrete (SFRC) in structural members has been increasing recently. The addition of steel fibers improves the mechanical properties -especially beyond cracking- and the crack control characteristics of concrete significantly (Susetyo, Gauvreau, & Vecchio, 2011). A particular use of steel fibers is to improve the shear behavior of reinforced concrete (RC) beams without web reinforcement. Various researchers (Swamy & Bahia, 1985; Kadir & Saeed, 1986; Mansur, Ong & Paramasivam, 1986; Lim, Paramasivam & Lee, 1987; Narayanan & Darwish, 1987; Li, Ward & Hamza, 1992; Kwak, Eberhard, Kim & Kim, 2002; Yazici, Inan & Tabak, 2007; Dinh, Parra-Montesinos & Wight, 2010; Aoude, Belghiti, Cook & Mitchell, 2012; Minelli & Plizzari, 2013; Minelli, Conforti, Cuenca & Plizzari, 2014; Jain & Singh, 2014; Shoaib, Lubell & Bindiganavile, 2014; Sahoo & Sharma, 2014; Ahmed, Legeron & Ouahla, 2015; Sahoo, Maran & Kumar, 2015; Shao, Bhagat & Reddy, 2016; Biolzi & Cattaneo, 2017) have carried out experimental studies to demonstrate the improvements in the shear strength and ductility of RC beams due to the post-cracking characteristics enhanced by the addition of steel fibers. On the other hand, the studies on retrofitting of SFRC beams is very limited.

Among various retrofitting methods, the use of fiber reinforced polymers (FRP) has many advantages such as relatively high tensile strength and low weight, easy and rapid application, etc. The improvements in the strength, stiffness and ductility of RC structural members due to the use of FRP have been demonstrated by various researchers. Triantafillou (1998) tested RC beams strengthened with carbon FRP (CFRP) and observed up to 95% increase in the strength. Khalifa and Nanni (2000) used various configurations of CFRP sheets to strengthen T-section beams and observed up to 145% increase in the strength. Alzate, Arteaga, de Diego & Perera (2009) observed significant improvements in the shear strength of RC beams with insufficient shear

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reinforcement strengthened with CFRP, but did not in the stiffness. Similarly, Bukhari, Vollum, Ahmad and Sagaseta (2010) observed significant improvements in the shear strength but slight increases in the stiffness in their experiments.

Any experimental study on strengthening SFRC beams with CFRP is not available in the literature to the authors' knowledge, except the authors' own study in which a series of beams with a shear span-to-effective depth ratio (a/d) of 2.5 was tested and it was found that the strength and ductility of SFRC beams can be improved by CFRP strengthening but it does not have a significant effect on the stiffness (Keskin, Arslan and Sengun, 2017). In this paper, the experimental results of beams with a shear span-to-effective depth ratio of 4.5 are presented and examined in the context of strength, stiffness and ductility.

Experimental Program

Test Specimens

A combination of letters and numbers is used for specimen labels. "A" followed by the shear span-to-effective depth ratio to indicate all test specimens in this research; "D" to indicate that it is damaged prior to CFRP application; "F" to present the volume fraction of steel fibers; "C" to present the width and spacing of CFRP strips; TII to present the existence of two layers of CFRP sheets on the tension face of the beam.

Table 1. Mix proportions of concrete

| Material | Proportions (kg/m ³) |
|-------------------------|-------------------------------------|
| 0-5 mm crushed sand | 1150 |
| 5-12 mm crushed stone | 310 |
| Fly ash (40% of binder) | 90 |
| Cement CEMI 42.5R | 220 |
| Water/Binder | 0.55 |
| Superplasticizer | 3.10 |

The concrete mix proportions for all beams are given in Table 1. The properties of test specimens are given in Table 2, where ρ is the tensile reinforcement ratio, f_c is the concrete compressive strength, V_f is the volume fraction of steel fibers, w_f and s_f are the width and spacing of CFRP strips wrapped around the beams, respectively. All beams were reinforced with two 16 mm diameter longitudinal bars whose yield and ultimate strengths are 420 MPa and 550 MPa, respectively. Hooked-end steel fibers with a length (L_f) of 30 mm and a nominal diameter (D_f) of 0.55 mm, resulting in an aspect ratio of 54.5, were used as the only shear reinforcement. The ultimate strength of steel fibers is reported by the manufacturer as 1156 MPa. Before casting the specimens, concrete was poured into a container in which steel fibers were mixed into concrete matrix by using a paddle mixer in order to overcome the reduced workability due to the relatively high volume fractions of steel fibers and obtain a properly mixed concrete. CFRP sheets with an elasticity modulus of 230 GPa, a tensile strength of 4900 MPa, a maximum elongation of 2.1% and a thickness of 0.166 mm (as reported by the manufacturer) were used for retrofitting the test specimens.

Table 2. Properties of test specimens

| Beam | a/d | ρ (%) | f_c (MPa) | V_f (%) | w_f (cm) | s_f (cm) |
|--------------------|-------|------------|-------------|-----------|------------|------------|
| A4.5F2.0 | 4.5 | 1.34 | 21.43 | 2.0 | 10 | 10 |
| A4.5F3.0 | 4.5 | 1.34 | 27.91 | 3.0 | 10 | 10 |
| DA4.5F2.0C10/10TII | 4.5 | 1.34 | 21.43 | 2.0 | 10 | 10 |
| DA4.5F3.0C10/10TII | 4.5 | 1.34 | 27.91 | 3.0 | 10 | 10 |

The beams A4.5F2.0 and A4.5F3.0 were loaded up to the maximum loads that they could resist. Then the cracks were repaired by using an epoxy-based mortar. After the corners of the beams were rounded with 30 mm radius and surface preparations were made, the damaged beams were retrofitted by wrapping CFRP strips around the beams on all four sides in two layers and covering the tension faces of the beams with two layers of CFRP sheets in such a way that fibers are parallel to the beam axis. The retrofitted beams were labeled as DA4.5F2.0C10/10TII and DA4.5F3.0C10/10TII. The beams are 150 mm x 230 mm x 2200 mm with an effective depth of 200 mm and a cover of 22 mm. The geometry, the longitudinal reinforcement arrangement and the layout of CFRP retrofitting are shown in Figure 1.

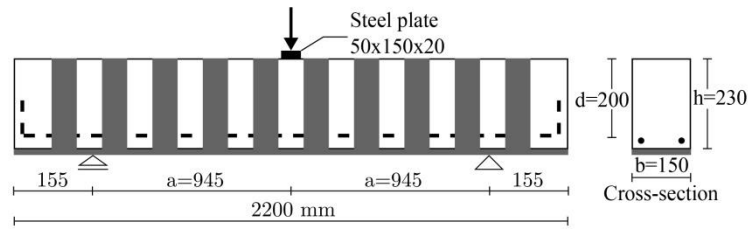


Figure 1. Geometry, longitudinal reinforcement arrangement and layout of CFRP retrofitting

Testing and Instrumentation

The beams were tested under a static rate of concentrated loading at mid-span using a displacement-controlled loading machine (Figure 2). A computer-aided data acquisition system was used for monitoring the applied load and the deflections at various locations at pre-determined time intervals. The net deflections of the beams were recorded by using potentiometric displacement transducers. Electrical strain gauges were installed on the CFRP strips wrapped around the beams and on the CFRP sheets covering the tension faces of the beams along the fiber direction in order to monitor the development of strains in the CFRP with progressive loading.



Figure 2. Test setup

Results and Findings

All beams in this study exhibited flexural failures. The crack patterns are shown in Figure 3-7. As expected, fine vertical cracks appeared around the mid-span of all beams during early stages of loading. New flexural cracks were formed away from the mid-span area with increasing load. Vertical flexural cracks in the vicinity of mid-span started to extend towards the point at which the load was applied. In each of the retrofitted beams, CFRP sheets on the tension face ruptured in the vicinity of mid-span at some point and a sudden drop was observed in the load, as can be observed from the load-deflection curves plotted in Figure 8. Neither the slipping failure of longitudinal reinforcement nor the debonding of CFRP strips was observed.



Figure 3. Crack pattern of A4.5F2.0



Figure 4. Crack pattern of A4.5F3.0

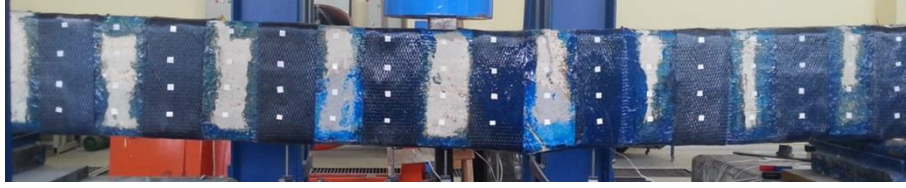


Figure 5. Crack pattern of DA4.5F2.0C10/10TII



Figure 6. Rupture of CFRP on the tension face



Figure 7. Crack pattern of DA4.5F3.0C10/10TII

The experimental results are summarized in Table 3, where P_{co} is the maximum load carried by a beam, δ_{co} is the mid-span deflection under the P_{co} and the dissipated energy is the area under the load-deflection curve up to the P_{co} . After retrofitting with CFRP, the beam with a fiber content of 2.0% by volume reached a maximum load 48% greater than the load it reached originally. Similarly, the beam having steel fibers of 3.0% by volume resisted a 33% greater load compared to the originally resisted load. Increasing the volume fraction of steel fibers from 2.0% to 3.0% improved the maximum load by 39% and 25% before and after retrofitting, respectively. It can be observed in Figure 8 that retrofitting with CFRP restored the initial stiffness of the beams satisfactorily. Moreover, the degradation in the stiffness of the beam with a fiber content of 2.0% by volume at relatively low load levels was not observed after retrofitting. All beams except DA4.5F3.0C10/10TII reached their load-carrying capacities approximately at the same mid-span deflection. It can be seen in Table 3 that the dissipated energies by the beams with fiber contents of 2.0% and 3.0% by volume increased 72% and 62%, respectively, after retrofitting. The retrofitted beams exhibited a ductile behavior until the rupture of CFRP sheets on the tension face, after which the load dropped suddenly. It is to be noted that the retrofitted beam with a fiber content of 3.0% by volume kept carrying a load approximately the same as the load carried originally for an additional mid-span displacement of 18 mm after the rupture of CFRP sheets on the tension face.

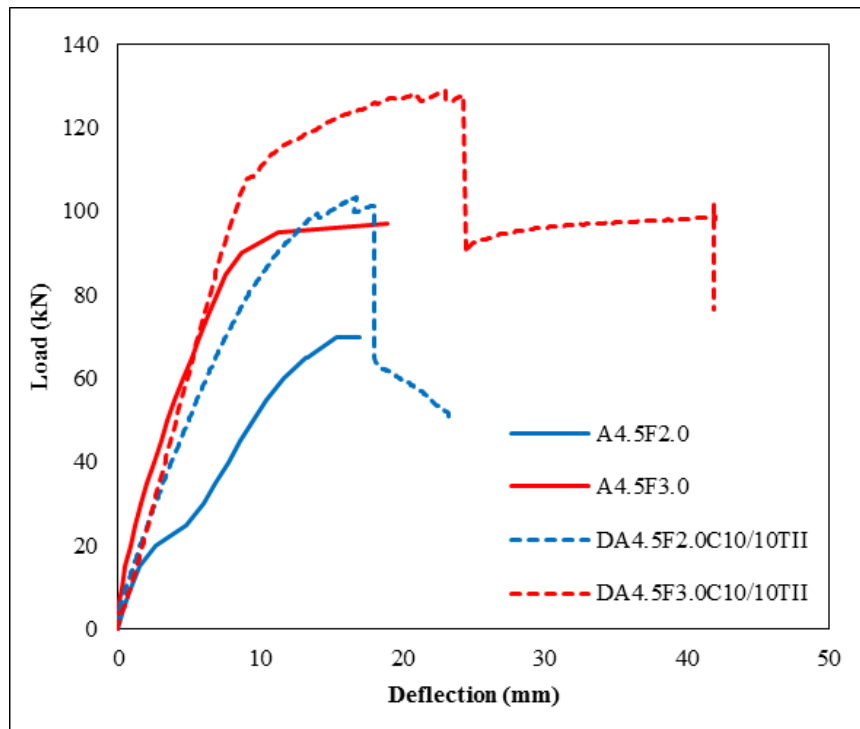


Figure 7. Load deflection curves

Table 3. Experimental results

| Beam | P_{co} (kN) | δ_{co} (mm) | Dissipated Energy (kNm) |
|--------------------|------------------|-----------------------|-------------------------------|
| A4.5F2.0 | 70.00 | 17.0 | 0.734 |
| A4.5F3.0 | 97.00 | 18.9 | 1.454 |
| DA4.5F2.0C10/10TII | 103.35 | 16.8 | 1.264 |
| DA4.5F3.0C10/10TII | 128.83 | 23.0 | 2.354 |

Conclusion

The following conclusions are drawn based on the experiments of SFRC beams before and after retrofitting with CFRP.

- The load-carrying capacities of SFRC beams were increased considerably by retrofitting with CFRP.
- Increasing the fiber content improved the load load-carrying capacities of beams both before and after retrofitting.
- The initial stiffness of the beams was restored by retrofitting with CFRP.
- Retrofitting with CFRP provided a ductile behavior until the CFRP sheets on the tension faces of the beams ruptured, after which the load dropped suddenly.

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