Research Article

Journal of Environmental Nanotechnology

Investigation on Reinforced Concrete Beams with High-Strength FRP Composite

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Received: 12.04.2024 Accepted: 09.05.2024 Published: 30.06.2024
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ABSTRACT

This study examines an advanced material called High Strength Fiber Reinforced Polymer Composite (HSFRPC). The flexural characteristics of RC beams with dimensions of 2000 × 100 × 150 mm, strengthened with a HSFRPC overlay were investigated. The control RC beam was tested under four-point bending until failure. Two test RC beams were subjected to a preload of 70% of their ultimate load, while the third one was subjected to a preload of 65% of the ultimate load of the control beam. The preloaded RC beams were reinforced by applying a HSFRPC overlay to the lower surface. The overlay was applied across the whole width of one of 70% preloaded RC beams. The overlay was applied only in the area for the other 70% preloaded and the 65% preloaded RC beam, where the bending moment is constant. Strengthened beams underwent testing using a four point bending load. During the testing process, many factors like load, deflection, cracks and failure patterns were closely monitored. The experimental investigation revealed that beams with HSFRPC overlay showed enhanced load carrying capacity and ductility compared to conventional RC beams.

Keywords: High strength FRP; Reinforced concrete; Strengthening; Overlay; Retrofitting.

1. INTRODUCTION

Concrete constructions are widely utilized worldwide due to their numerous advantages, including their ease of manipulation, cost-effectiveness, and fire resistance. Reinforced concrete (RC) structures were introduced in the late 19th century to address the weakness of concrete in stress. Reinforcement is placed on the tension side of the concrete to counteract the tensile stresses that occur in specific areas of the concrete, which could potentially cause the structure to fail (Vasudeva *et al.* 2016; Çelik *et al.* 2022). An RC structure, if designed flawlessly and executed in accordance with codal standards, will have a maximum specified life duration of 100 years. Reinforced concrete structures frequently require modifications and enhancements to their performance throughout their lifespan (Abbass *et al.* 2014). The primary elements that contribute to the deterioration of structures include changes in their usage, new design requirements, corrosion in steel caused by harsh environments, and accidental catastrophes such as earthquakes, floods, and cyclones. There are two potential approaches for enhancing an RC construction, namely full construction replacement and retrofitting. Retrofitting involves the insertion of more advanced technologies into an older structure in order to improve its durability and ability to support heavy loads. Given the current economic conditions, it is more favorable to retrofit and rehabilitate damaged concrete structures to meet the stricter limits on performance and strength set by current codes (Mistretta *et al.* 2023). Strengthening the existing concrete structures to support higher loads is a more appealing option than demolishing and rebuilding. There are multiple techniques for retrofitting that are often used worldwide to repair damaged structures, such as, the external cable method, bonding and jacketing, and overlaying. Among these three strategies, the overlaying method is receiving significant attention in the field of retrofitting (El Damatty *et al.* 2003; Sreekanth *et al.* 2022). Therefore, there has been an increase in research efforts in the field of overlay approaches in the past decade (Miruthun *et al.* 2020). Superimposition technique involves utilizing external materials that offer the required qualities to strengthen the weakest area of concrete structures through retrofitting in order to improve its ability to carry heavy loads, longevity, and visual appeal. The Carbon Fiber Reinforced Polymer (CFRP), Engineering Cementitious Composite (ECC), and Ultra High Performance Fiber Reinforced Cementitious Composite (UHPFRCC) have been the most often utilized materials (Mini *et al.* 2014; Upendra

Mahendra *et al.* 2018; Saribiyik *et al.* 2021). The weaker portion is determined based on its fracture width and the degree of exposure of the concrete surface to severe environmental conditions. In this regard, Advanced Fiber-Reinforced Polymer (FRP) Composites with Exceptional Strength were studied (Naser *et al.* 2019). A novel composite material known as cementitious composite has been developed to address the limitations associated with strengthening fiber RC. In the past decade, significant endeavors to enhance the performance of cementitious materials through the integration of fibers have resulted in the development of High Strength Fiber Reinforced Polymer composites (HSFRPC). To achieve high strength in FRP composite, glass fiber was implemented. The yield force of HSFRP composite laminates was measured at 1350.27 N, and the yield elongation was measured at 7.27 mm. These are the mechanical parameters that were observed (Kim *et al.* 2011; Naser *et al.* 2019). In order to demonstrate that a laminate is capable of withstanding loads that are given to it, the yield force is the maximum significant force that it is able to withstand before it undergoes plastic deformation. The ductility of the material and the yield elongation reveal the extent of the deformation (Mariappan *et al.* 2012; Ronagh *et al.* 2013; Aravind *et al.* 2015). After careful analysis, the values for the break force and break elongation were found to be 1455.3 N and 8.32 mm, respectively. The qualities of HSFRPC are a direct consequence of the enhanced microstructural properties of the mineral matrix and the regulated bonding between the matrix and fiber. These revolutionary building materials offer structural engineers a distinctive combination of exceptionally low permeability, which inhibits the entry of harmful chemicals like water and chlorides.

2. EXPERIMENTAL INVESTIGATION

The flexural performance of control RC beams and strengthened beams was investigated using the experimental program devised by (Attari *et al.* 2012; Nasr, 2019). Rectangular steel molds were utilized in the casting process for the control beams. Steel rods with a diameter of 8 mm were used to construct the steel cage, which has a yield stress of 415 MPa (Song *et al.* 2021; Sivamani *et al.* 2023). Shear reinforcement was given in the form of stirrups with a diameter of 6 mm and a center-to-center spacing of 150 mm. The stirrups were attached to the main bars using steel wires. To create the rectangular mold, the steel cage was lowered into the mold. As indicated in Fig. 1 (Navaneethan *et al.* 2021), the space between the reinforcement cage and the mold was kept at 15 mm in both the top and bottom of the mold, as well as 15 mm on each side of the mold during the manufacturing process (Jagan *et al.* 2023).

The mix-weight proportions of the concrete substance were obtained using the formulae provided in Appendix 1 of IS 456:2000 and IS 10262:2009. The mix proportion was determined to be 0.45:1:1.669:1.856 (water: Portland cement: fine aggregate: coarse aggregate). The coarse aggregate has a maximum particle size of 12 mm (Aidoo *et al.* 2004; Patil *et al.* 2023). A total of four beams were cast using the same mixture. The mixture was poured and subjected to vibration using a vibrator to ensure thorough compaction. After a period of 24 hours, the specimens were removed from the moulds and placed in the curing tank. The mix proportion achieved a maximum compressive strength of 20 MPa after 28 days. Fig. 2 displays the control RC beam specimen (Franklin *et al.* 2016).

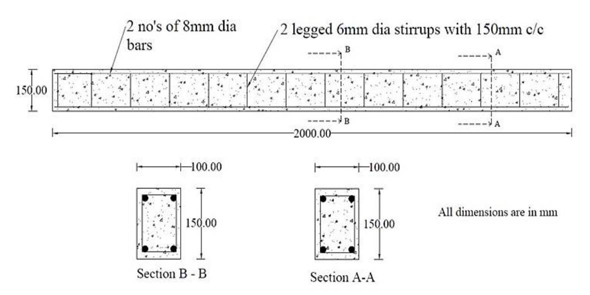

Fig. 1: Reinforcement detailing of control beam

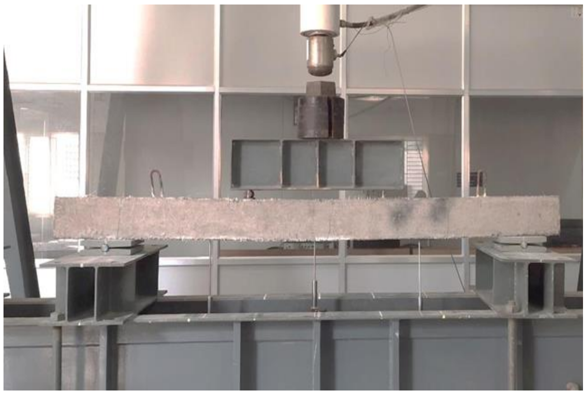

Fig. 2: RC control beam

2.1 Preparation of HSFRPC Overlay

A wide range water reducer, quartz sand, silica fume, quartz powder, and a small quantity of steel fibers make up the HSFRPC overlay (Tiadi *et al.* 2018). Removing coarse aggregate improves the microstructure of the materials. The use of steel fibers enhances the strength and ductility of composite materials. In addition to bearing flexural and tensile stresses, the material can also be deformed. Because of the controlled bonding within the matrix and fiber, as well as the improved microstructural characteristics of the mineral matrix, HSFRPC has desirable properties (Hadi *et al.* 2003; Meikandaan *et al.* 2017a). A combination of one part cement, twenty-five parts silica fume, one and a half parts quartz sand, and forty-four parts quartz powder was used to make the mixture (Aravind *et al.* 2013). The dry binders contained 1% steel fiber. The workability of the mixture was improved by using a super-plasticizer at a concentration of up to 3.5%. The density of the mixture was improved by reducing the water-cement ratio to 0.23. A Hobart mixer with a 15 kg capacity was used to mix the dry binders completely. The next step was to add water and high-range water reducer (Sundarraja *et al.* 2009). After the ingredients were thoroughly mixed to form a thick paste, the steel fibers were incorporated. About 10 mm was the thickness maintained for the HSFRPC layer. Fig. 3 shows an example of a typical HSFRPC overlay.

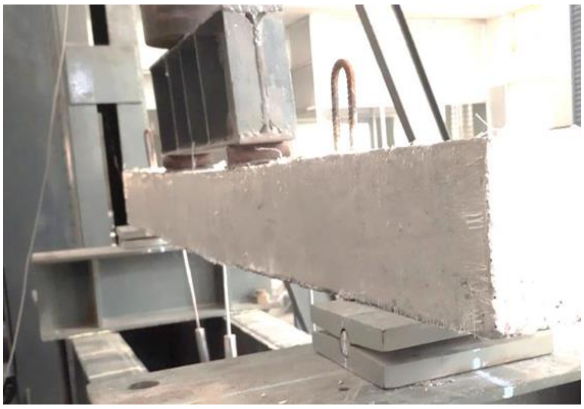

Fig. 3: A typical HSFRPC overlay

3. RESULTS AND DISCUSSION

3.1. Testing Procedure and Observations on Control RC Beam

An online data collecting system and a servo hydraulic actuator with a 1000 kN capacity make up the experimental setup. A displacement control testing machine was used to test the control beam (Nayak *et al.* 2018). The loading rate was kept at 0.5 mm/min, and data was captured using a sampling rate of 50 Hz. A control beam measuring 2000 mm × 100 mm × 150 mm was subjected to a four-point bending test. The effective span of the beam was maintained at 1800 mm (Dong *et al.* 2013; Danraka *et al.* 2017). Linear Voltage Displacement Transducers [LVDTs] were utilized as monitoring devices to ascertain the strains and deflections of the specimens. Cracks first appeared with a load of 14 kN. Specifically, the zone of constant bending moment was the most cracked (Triantafillou *et al.* 1998; Nasr *et al.* 2019). Fig. 4 shows a load-displacement graph that indicates the steel yielded at a load of 16 kN.

Following crack propagation in the flexural zone reaching nearly three quarters of the beam's depth, concrete crushing happened on the compression face of the beam. The beam's ultimate load measurement was 20 kN. Flexure was the mode of failure. There were no signs of deboning or shear cracks in the beam.

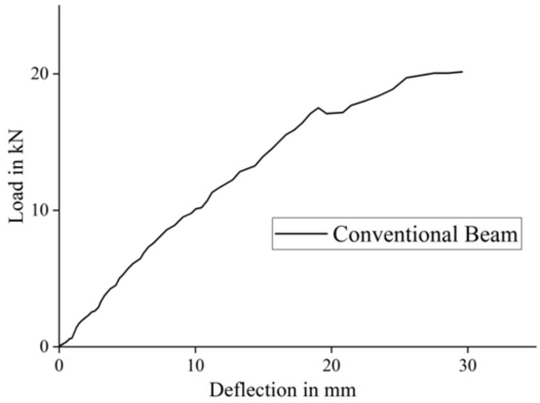

Fig. 4: Load deflection of conventional RC beam

3.2 Strengthening of Beams using HSFRP Laminates

The control beam was subjected to a preloading of 65% of the ultimate load (25 kN), using the same testing procedure as conventional RC beam, and thereafter removed from the system. The weakened control beam was reinforced by applying a 5 mm thick overlay composed of HSFRPC as shown in Fig. 5 (Navaneethan *et al.* 2021; Navaneethan *et al.* 2023). The overlay was affixed using a 5 mm thick glue made of epoxy resins.

Fig. 5: Overlay beneath the tension face of the preloaded beam

3.3 Flexural behavior of RC-HSFRPC

The visible fissures in the overlaid material appeared accompanied by the dissipation of sound when a force of 16.5 kN was applied. The sound was caused by the fracturing of steel fibers in the overlay. The crack was observed at the area of the overlay where the bending moment was consistently applied, suggesting that the overlay material experiences failure due to flexural stress. Up to a force of 13.5 kN, the overlay material bore the entire load as no more cracks were observed spreading in the beam. Once the load reached 14 kN, cracks began to propagate in the beam towards the compression face. The fissures began to expand in the overlay material with the application of a load of 16.5 kN. The steel reinforcements began to deform under a stress of 15.5 kN. The concrete was crushed under a weight of 16.5 kN, as evidenced by the crushing of the top face of the concrete at the center of two loads. The flexure crack was more prevalent in the beam within the constant moment area. The test was halted when the concrete began to collapse. During the testing process, sound was detected, suggesting that the steel fibers were undergoing deformation. The test revealed the absence of any significant shear cracks or delamination between the overlay and the beam material. The Retro RC Beam-with HS-FRP 2 strengthens the damaged control beam by applying a 6 mm thick overlay composed of HSFRPC layer. The maximum allowable length for the overlay was 1800 mm. The overlay was affixed to the lateral surface of the RC beam using an adhesive. The experimental testing was used to examine the flexural behavior of Retro RC Beam-with HS-FRP 2. The fissures in the overlay material became obvious when a load of approximately 16 kN was applied at the center of the overlay. Diagonal cracks, known as shear cracks, were observed when a load of 19 kN was applied to the beam. Breaking of the fiber in the overlay occurred under a stress of 21 kN. Three prominent cracks were observed in the overlay developed in the constant bending zone, and they appeared to be expanding. The retrofitting was done to the entire surface area of the conventional beam, which was referred to as Retro RC Beam-with HS-FRP 3. The flexural behavior of Retro RC Beam-with HS-FRP 3 was superior when compared to other methods of retrofitting. The apparent fractures became evident when the stress reached around 18.5 kN in the covering material. The cracks in the beam began to expand in the affected sections after reaching a load of approximately 22.7 kN. At a load of approximately 23 kN, hairline cracks appeared longitudinally in the beam, suggesting the onset of debonding between the steel and concrete (Meikandaan *et al.* 2017b). The beam did not exhibit any shear cracks. The separation between the overlay material and the beam was not seen during or after the testing. The concrete experienced compression and deformation when subjected to a load of 26.5 kN, resulting in the top face of the concrete peeling at the center of the two loads.

Through the use of an LVDT positioned in the middle of the specimen at the base of the beam, the mid-span downward displacement was measured. The load-displacement statistics of both the control beam and the strengthened beams are presented in Fig. 6. The ultimate load and the corresponding displacement for all the beams are shown in Table 1. The table 1 provides an indication of the % increase in the load carrying capability of the strengthened beams. The table 1 compares the performance of different types of RC beams under ultimate load conditions. The first entry represents a conventional RC beam, which sustained a load of 20 kN before failure, resulting in a displacement of 29.5 mm. The next three entries detail retrofitted RC beams using HSFRP materials (Mini *et al.* 2014). The beam labeled "Retro RC Beam-with HS-FRP 1" endured a load of 16.5 kN, displacing 26.3 mm (Aravind *et al.* 2017). The "Retro RC Beam-with HS-FRP 2" supported a load of 21 kN with a displacement of 32.4 mm, showcasing a 105.2% increase in load-bearing capacity compared to the conventional beam. Finally, the "Retro RC Beam-with HS-FRP 3" exhibited the highest performance, withstanding a load of 26.5 kN and displacing 44.2 mm, marking a 125% increase in load capacity over the conventional beam. This data highlights the significant enhancement in load-bearing capabilities achieved through HS-FRP retrofitting in RC beams.

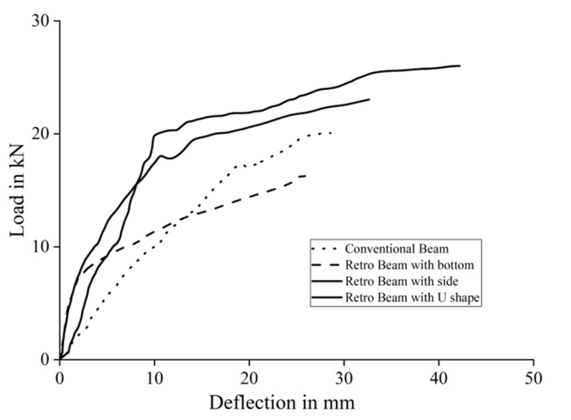

Fig. 6: Load vs Displacement plot

Table 1. Load deflection for tested RC beam

Beam type	Ultimate load, kN	Displacement at ultimate load, mm	% Increase in load
RC Beam-conventional	20	29.5	-
Retro RC Beam-with HS-FRP 1	16.5	26.3	-
Retro RC Beam-with HS-FRP 2	21	32.4	105.2 %
Retro RC Beam-with HS-FRP 3	26.5	44.2	125 %

4. CONCLUSION

The findings of the present work showed that the flexural behavior of retrofitted RC beams with HSFRPC layers demonstrated improved performance compared to conventional methods of retrofitting. Specifically, Retro RC Beam-with HS-FRP 3 showed superior flexural strength, with no shear cracks observed during testing. However, visible fractures appeared in the overlay material around 18.5 kN, and cracks expanded in affected sections at approximately 22.7 kN, indicating potential debonding between steel and concrete at 23 kN. For Retro RC Beam-with HS-FRP 2, cracks in the overlay material were noticeable at 16 kN, with shear cracks appearing at 19 kN, and significant failure observed at 21 kN. The retrofitting process significantly strengthened the damaged beams, evident from the load-displacement graphs and the absence of major shear cracks or delamination. In conclusion, the research highlights the effectiveness of HSFRPC retrofitting in improving the flexural behavior of RC beams, although attention should be paid to potential debonding issues at higher loads.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

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