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RESEARCH **Open Access**

Experimental Study of the Shear Behavior of RC Beams Strengthened with High-Performance Fiber-Reinforced Concrete

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Abstract

In this study, the efficacy of strengthening of reinforced concrete (RC) beams in shear by utilizing high-performance fiber-reinforced concrete (HPFRC) was explored. The shear strengthening was achieved by epoxy bonding of prefabricated HPFRC strips or plates onto the beams. The beams were strengthened utilizing two different strengthening schemes: (i) plates side strengthening (ii) vertical strips applied at shear critical sections. The behavior of the two configurations was compared to the behavior of non-shear reinforced and shear-reinforced RC beams. The high-performance concrete (HPC) utilized contains 1.5% of steel fibers per volume of HPC mortar and is known as HPFRC. Parameters determined were the flexural strength and compressive strength of HPFRC mortar. The obtained results revealed that HPFRC realized a 28-day flexural strength of 20 MPa and a compressive strength of 108 MPa. Moreover, HPFRC strengthened RC beams experienced an increased in strength capacity of about 50% for plates and 36% for vertical strips compared to the RC beams with no stirrups. The results for HPFRC strengthened beams with plates were superior compared to those of the stirrup-reinforced beams, whereas the results of HPFRC strips strengthened beams were almost identical to the stirrup-reinforced beams. Also observed, was an improvement in the ductility of the beams with the best results achieved when employing HPFRC plates and strips.

Highlights

- Shear Strengthening of RC beams by HPFRC plates utilizing two methods.
- Precast HPFRC plates bonded by epoxy adhesive and anchored.
- Continuous shear strengthening resulted in high-capacity enhancement and ductility.

Keywords high-performance fiber-reinforced concrete, strengthening, rehabilitation, epoxy adhesive, shear strength

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1 Introduction

Existing concrete structures are frequently under-reinforced when it comes to shear design requirements. Shear failure is a brittle process; for this reason, existing concrete structures require special attention in strengthening to avoid sudden failure mode. Strengthening of concrete structures are common and widespread, mainly in vital structures, which are unfeasible and unreasonable to demolish except when the repairing and strengthening procedures have failed to achieve the required level of service. In this study, the strengthening of concrete structures is realized by adding an additional layer of HPFRC to the beam. HPFRC is relatively a new innovative material that could be utilized as a substitute to the conventional methods for strengthening concrete structures, specifically in shear. Strengthening of concrete structures has developed into a very essential and crucial method not only for the repair of deteriorating concrete structures, but also for the upgrading of new concrete structural members that were under-designed for their existing or future loading conditions.

Researchers have explored numerous types of materials and systems for the strengthening of RC structural members. One of the most commonly utilized method is the carbon fiber-reinforced polymer (CFRP) laminates wraps which have been widely accepted as a valid and reliable strengthening technique. The shear behavior of strengthened RC with CFRP has been investigated experimentally by Issa and Abou Jouadeh, 2004. Monti and Liotta, 2005 investigated both experimentally and analytically the shear strengthening of RC beams utilizing CFRP and the findings indicated that an encouraging shear enhancement capacity has been attained. A tremendous amount of research effort has been directed at the investigation of the efficacy of utilizing CFRP as a strengthening material. Nevertheless, strengthening with CFRP presented its own limitations. Not only is the long-term behavior of great concern, but also there is a performance issue in compression when exposed to cyclic loading and its performance is contingent upon the strength of the concrete substrate and the CFRP–concrete adhesion strength (Mohammed et al., 2016).

Ultra-high-performance fiber-reinforced concrete (UHPFRC) is relatively a newly developed material that could be deployed for the rehabilitation and the strengthening of RC structures with research effort performed on the durability and structural behavior indicating the effectiveness of UHPFRC (Ahlborn et al., 2012; Graybeal, 2006, 2011; Rahman et al., 2005; Tai et al., 2011). A comprehensive review of the mechanical properties of the UHPFRC has revealed the versatility and applicability of the material which possesses a high compressive strength and modulus of elasticity (Russell et al., 2013). Published results indicated that the compressive strength and flexural strength of ultra-high-performance concrete (UHPC) could be double or triple that of high-performance concrete (HPC) (Lubbers, 2003). A study on UHPFRC shear capacity compared to normal strength beams revealed that their performance improved in shear and flexural (Hussein & Amleh, 2015). The structural behavior of full-scale RC beams cast with UHPFRC layer inflexure conducted by Habel et al., 2007 resulted in a considerably enhancement of the structural capacity of the beams. An experimental and numerical investigation conducted by Martinola et al., 2010 exploring the efficacy of fiber-reinforced concrete (FRC) in the rehabilitation and strengthening of full-scale beams revealed the efficacy of the recommended procedure in improving the ultimate strength and serviceability function. A study by Lampropoulos et al., 2016 concluded that strengthening the beam specimens with UHPFRC at different positions resulted in an improved behavior in the yielding strength and the ultimate moment capacity. An investigation by Prem et al., 2015 on the performance of damaged RC beams that were rehabilitated with UHPFRC overlay strips resulted in a substantial improvement in load carrying capacity of the repaired beams. Noshiravani and Brühwiler, 2013 investigated the flexural and shear capacity of RC beams strengthened with UHPFRC (referred to R-UHPFRC) applied to a cantilever span with stirrup spacing and area of reinforcement in the UHPFRC layer as design variables resulting in the strengthened beams, showing enhanced capacity in the tensile and bending stresses. In an experimental study performed by Mohammed et al., 2016) in which RC beams having no shear reinforcement and strengthened with UHPFRC, by means of three different strengthening configurations, resulted in a substantial increase in the torsional strength with the specimen that was strengthened on all four sides displaying the highest increase. Gerges et al., 2020 explored the patch repair of severely damaged RC beams confirming that the recommended repair procedure can restore the load carrying capability of the damaged beams.

Regardless of these valuable research studies concerning the utilization of UHPFRC in rehabilitating and strengthening of RC beams, it can be construed that none of these studies explore the specific influence of HPFRC on the shear capacity of the RC beams. In addition, citations regarding a comparison of the numerous procedures for which HPFRC can be used for shear strengthened beams is scarce in the published body of knowledge. Thus, the main purpose of this study is to investigate the effect of HPFRC strengthening on the shear capacity of beams. Epoxy coating technique was used to bond the HPFRC strips onto the beams anchored with steel bars on each corner of the strips to insure adequate bonding and prevent slipping. Two configurations of HPFRC reinforcement were considered: a continuous strip of HPFRC and discontinuous strips of HPFRC at shear critical spacing. The behavior of the two configurations was compared to the behavior of both non-shear-reinforced and conventional stirrup-reinforced RC beams.

2 Experimental Program

Experimental studies involving the material and shear strength tests were performed. The material strength tests were performed to establish the compressive and splitting tensile strength of the normal strength concrete (NSC), along with the flexural and the compressive strength of the HPFRC prisms.

2.1 Specimen Preparation

Six beams of 750 mm length and square sections of 150 mm were cast. Four RC beams were cast with only two 14 mm bars at the bottom and without any stirrups as shown in Fig. 1. Two RC beams were reinforced with two 10 mm diameter bars at the top, two 14 mm bars at the bottom, and 8 mm diameter stirrups spaced at 100 mm center to center as displayed in Fig. 2.

2.2 Material Properties

2.2.1 Steel Reinforcing Bars and Concrete

The reinforcing steel bars were of Grade 420 deformed bars having a yield stress of 420 MPa, an ultimate tensile strength of 470 MPa, and a modulus of elasticity of 200 GPa according to ASTM A615, 2022.

Normal concrete was realized from utilizing a mix design of cement 325 kg/m^3, water 180 kg/m^3, fine aggregates 810 kg/m^3, medium aggregates 520 kg/m^3, and coarse aggregates 510 kg/m^3. Thus, the water to cement ratio was 0.55. The compressive strength and splitting tensile strength tests were conducted on a 100 mm by 200 mm cylinders conforming to ASTM C39, 2021 and ASTM C496, 2018a. The 28-day average cylinder compressive strength was 35 MPa and splitting tensile strength was 4.93 MPa. The reference beams were designed to fail at ultimate load capacity in the four-point loading of 103.92 kN according to ASTM C78, 2022. The shear-reinforced RC beams provided an ultimate shear capacity of 30.32 kN corresponding to a load of 60.64 kN load prior to any strengthening using HPFRC, whereas the non-shear-reinforced beam had a negligible shear strength.

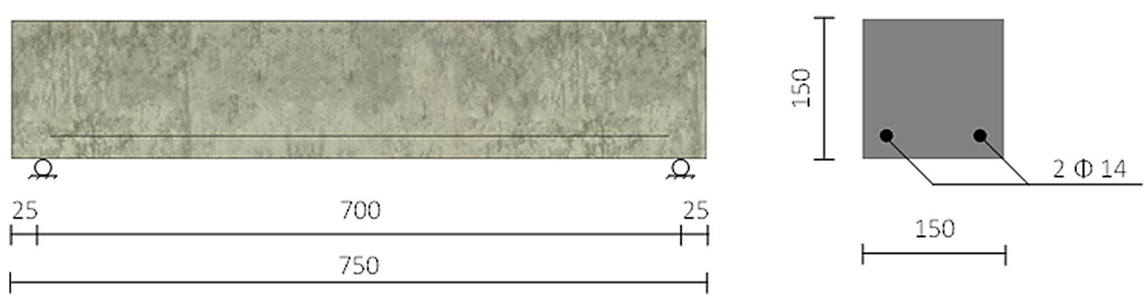

Fig. 1 RC beam without stirrups (All dimensions in mm)

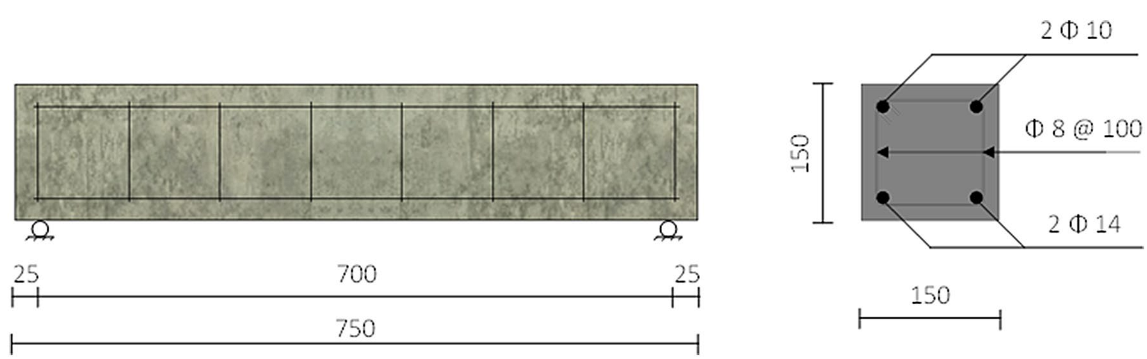

Fig. 2 RC beam with stirrups (All dimensions in mm)

2.2.2 HPFRC

In this study, the component materials utilized to realize the HPFRC included Type I Portland cement 712 kg/m^3, fine sand 1020 kg/m^3, silica fume 231 kg/m^3, ground quartz 211 kg/m^3, steel fibers 117 kg/m^3, and water 109 kg/m^3. The steel fiber are classified as unreformed cylindrical steel microfibers having length of 13 mm and diameter of 0.18 mm with tensile strength of the drawn wire varied from 2400 to 2900 MPa. The steel fibers were added as 1.5% by volume of the HPC and a water to binder ratio of 0.35 was used. These proportions provided good workability and prevented segregation and conforms to ASTM C157, 2017. For the strengthening process, the HPFRC was cast in the form of plates to be epoxy bonded onto the RC beams. Three types of plates with the same thickness of 12 mm and length of 150 mm but with widths of 100 mm, 150 mm, 300 mm were cast.

The flexural strength of the HPFRC was performed according to ASTM C348, 2021 by testing 40 mm × 40 mm × 160 mm simply supported prisms under 3 point-bending at a rate of 0.05 kN/m^2. The axial compressive strength was performed on 40 mm cubes sections of prisms broken in flexure according to ASTM, 2018b at a rate of 2.5 kN/m^2. Three specimens were tested at each time interval of 5, 8, and 28 days. Fig. 3 displays the average values resulting in an enhancement of the flexural strength with time attaining a maximum value of 20.01 MPa at 28 days.

As for the compressive strength of the HPFRC, six specimens were tested at each time interval. Fig. 4 displays the average values of the compressive strength with time. Thus, HPFRC clearly generates high strength as early as 5 days equal to 68.43 MPa. The compressive strength kept on increasing and reached 108.09 MPa at 28 days.

2.3 Strengthening Schemes

Two shear strengthening schemes were deployed. Fig. 5 displays the beam with continuous HPFRC shear reinforcement and Fig. 6 displays the beam with discontinuous HPFRC shear reinforcement. The prefabricated HPFRC strips were bonded onto the beams utilizing epoxy adhesive with properties, as indicated in Table 1. The first beam was strengthened with HPFRC plates within L/3 away from the support, as shown in Fig. 7. The second beam was strengthened with vertical HPFRC strips within L/3 away from the support, as shown in Fig. 8. The sides of the beams as well as the backside of the HPFRC plates were roughened using a hard laser bladed hand grinder before bonding to achieve a high bond strength at the concrete–HPFRC interface. The HPFRC plates were bonded onto the sides of the beams using a 5 mm thick layer of a bi-component high strength epoxy adhesive possessing the mechanical properties provided in Table 1. Steel bars of 12 mm in diameter were inserted into the HPFRC plates and embedded 50 mm

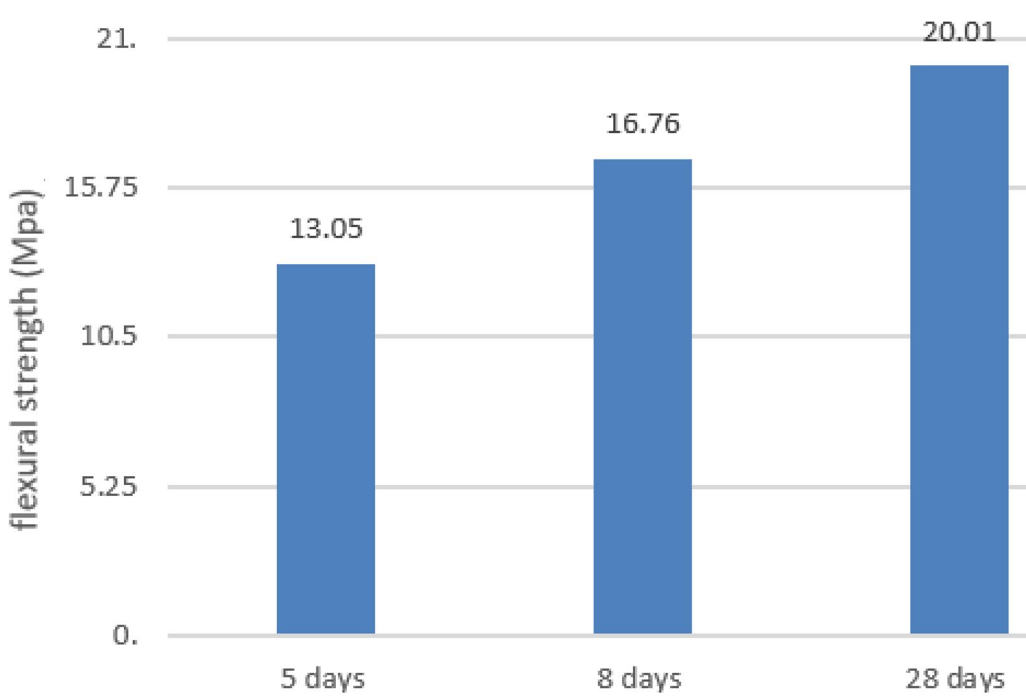

Fig. 3 Flexural strength of HPFRC prisms

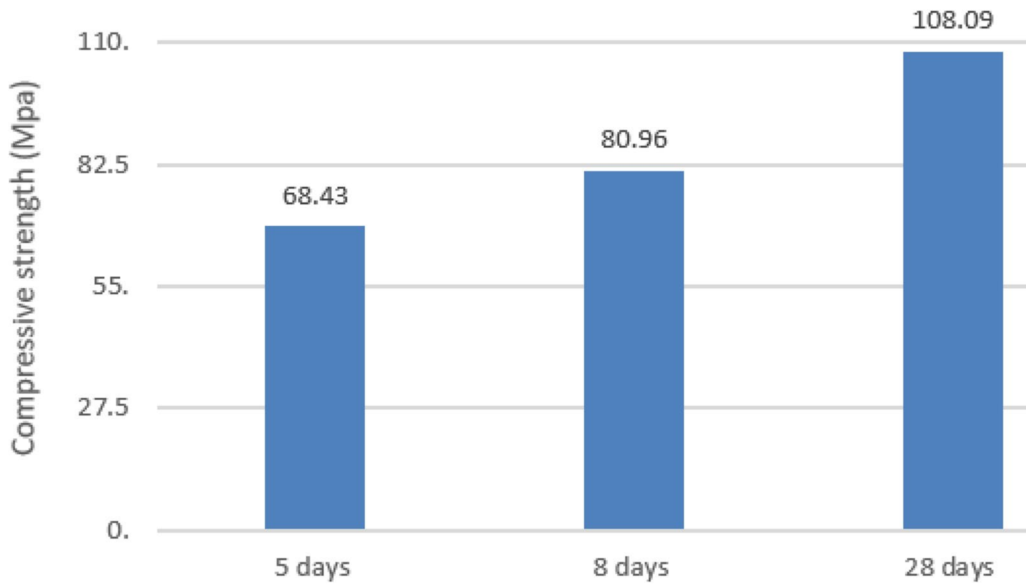

Fig. 4 Compressive strength of HPFRC prisms

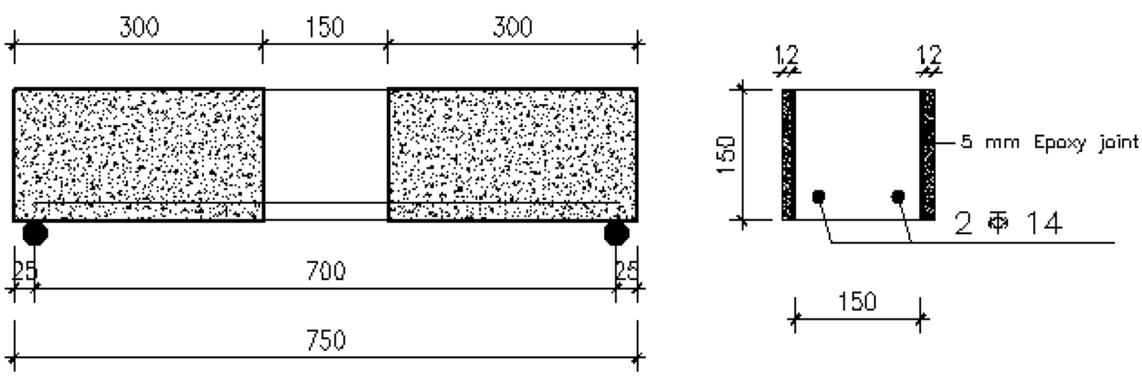

Fig. 5 RC beam strengthened with continuous HPFRC plates (All dimensions in mm)

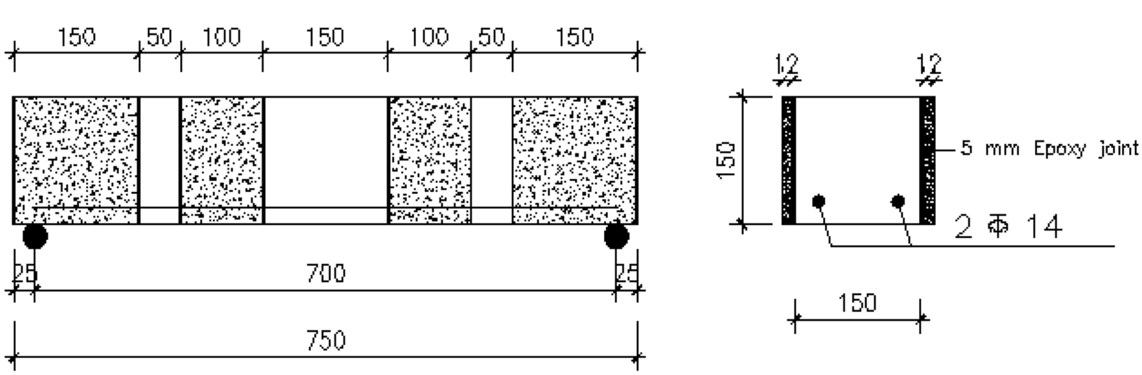

Fig. 6 Beam strengthened with vertical HPFRC strips (all dimensions in mm)

Table 1 Epoxy adhesive properties

Compressive strength at 3 days	47 MPa
Modulus of elasticity in compression at 14 days	2300 MPa
Tensile strength in flexure at 3 days	25 MPa
Tensile strength	12 MPa
Modulus of elasticity in tension at 14 days	3000 MPa

into the concrete stratum to insure an adequate bonding and prevent slipping.

2.4 Repairing Scheme

The RC beam with shear reinforcement was repaired after failure by patching with NSC and strengthening with HPFRC plates per the scheme presented previously.

Fig. 7 Strengthening scheme with HPFRC plates

Fig. 8 Strengthening scheme with HPFRC strips

3 Testing Procedure

The test setup for the four beams is manifested by a four-point loading, as shown in Fig. 9. An LVDT was mounted at the mid-span region to measure the displacements.

Five RC beams were tested for the shear strength with the reference RC beam being without shear reinforcement, the beam reinforced with HPFRC plates, the beam reinforced with vertical HPFRC strips, the beam reinforced with stirrups, and the beam reinforced with both stirrups and HPFRC plates.

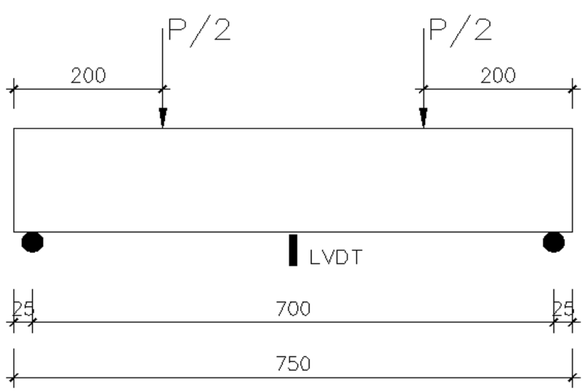

Fig. 9 Four point loading test setup

4 Results

The reference RC beam without shear reinforcement failed at an ultimate load of 51.48 kN. The RC beam shear strengthened with HPFRC plates failed at an ultimate load of 104.90 kN which is about twice the load achieved by the reference RC beam. The RC beam shear strengthened with vertical HPFRC strips failed at an ultimate load of 80.56 kN which corresponds to about 36% increase compared to the reference RC beam. The RC beam shear reinforced with stirrups failed at an ultimate load of 91.36 kN which corresponds to around 44% increase compared to the reference beam. The RC beam shear reinforced with stirrups and HPFRC plates failed at an ultimate load of 140.0kN which corresponds to around 63.22% increase compared to the reference RC beam.

Thus, the RC beams strengthened with HPFRC plates was the most efficient in improving the load carrying capacity of the beams. Comparing between the two types of HPFRC schemes, plates are more efficient than the vertical strips. In addition, stirrups do provide a better load carrying capacity than the vertical HPFRC strips in terms of strength.

Figs. 10, 11, 12, 13, 14 display the performance of the beams under the four-point loading strength test. Both the reference beam and the shear-reinforced beam did not show the customary flexural cracking pattern

Fig. 10 Reference RC beam without stirrups

Fig. 11 RC beam shear reinforced with stirrups

Fig. 12 RC beam without stirrups strengthened with vertical HPFRC strips

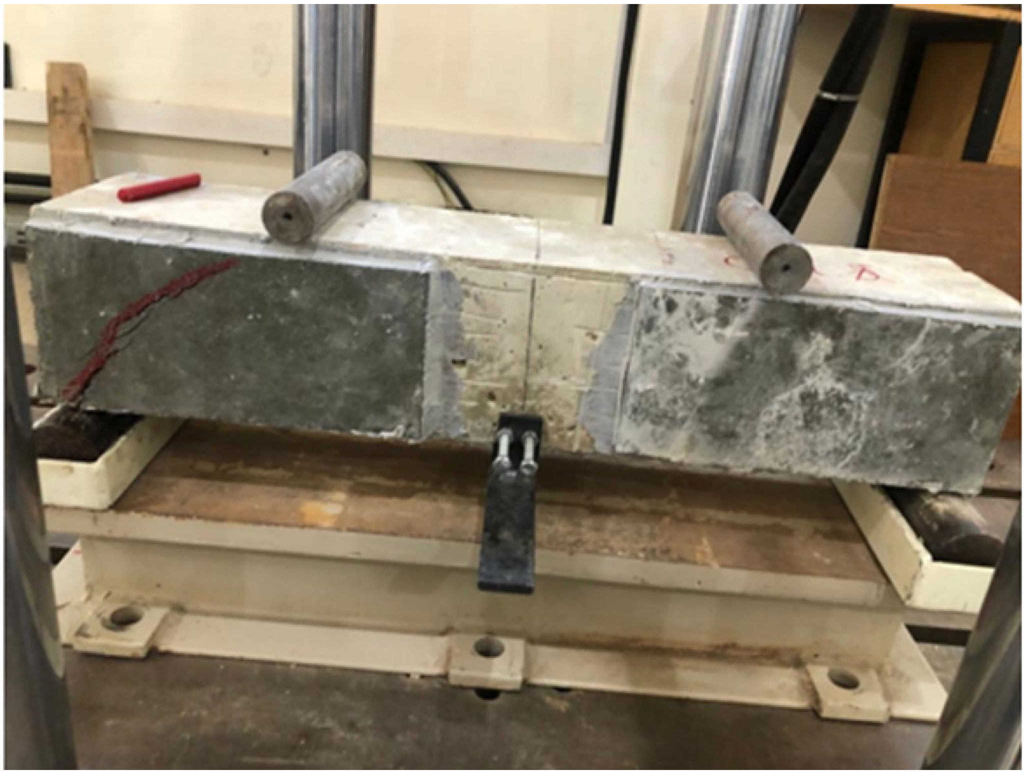

Fig. 13 RC beam without stirrups strengthened with HPFRC plates

Fig. 14 RC beam shear-reinforced and strengthened with HPFRC plates

described by vertical cracks initiated from the midspan and scattering outward toward the supports with an increase in load, as the beams were designed not to fail in flexure. However, at the approach of the failure load, inclined shear cracks began to develop at the furthest positions toward the supports, as shown in Figs. 10 and 11. The failure load sustained by the shear-reinforced beam was almost double that of the reference beam.

No debonding between the concrete substrate and the HPFRC plates occurred throughout the test, hence bonding the HPFRC plates onto the concrete substrate proved to be a successful alternative to the cast in place method.

Fig. 15 displays the load deflection curve for the six beams. It is observed that the reference beam showed the most brittle failure, while the other beams showed an improvement in ductility. In other words, fracture did not occur suddenly for the HPFRC-reinforced beams. The beam containing the HPFRC elements failed in a ductile manner, whereas the beams without any stirrups experienced less ductile failure mode. The beam strengthened with continuous HPFRC strips behaved better than the one strengthened with discontinuous ones.

5 Analysis of Results

The beams did not show the customary flexural cracking pattern categorized by vertical cracks beginning from the mid-span. Rather, the beam failed in pure shear displaying an inclined flexural–shear crack at the furthest positions toward the supports up to failure load (Fig. 10). No cracks were detected in the middle half of the beams. The HPFRC jackets did cause a delay crack propagation and provided added shear strength, thus increasing the flexural strength of the beam by resisting parts of the tensile flexural stresses prior to the activation of the

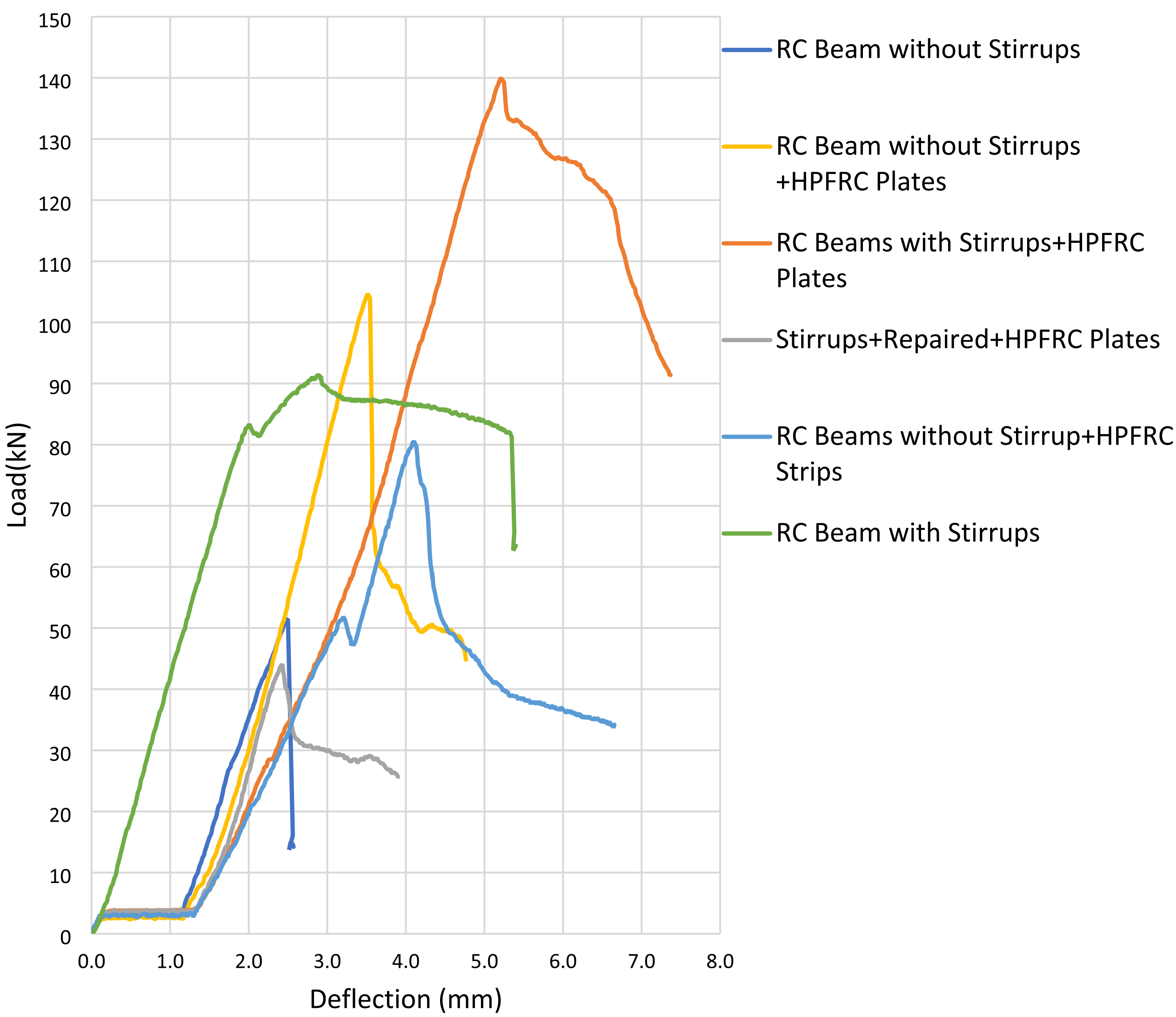

Fig. 15 Combined load deflection graph for all the cases

flexural reinforcing steel bars in tension. As a matter of fact, the HPFRC did cause the initial section of the load deflection curve to remain flat, thus absorbing the load and behaving in a ductile manner (Fig. 15). The reason is that the bonding of the epoxy of the HPFRC plates onto the concrete beams provided a high tensile strength, thus deferring the crack propagation through it, and the cracks became visible when failure occurred at the supports. Interestingly, the increase in the failure load for the shear-reinforced RC beam strengthened with HPFRC plates could probably be partially attributed to the effective area and moment of inertia due the added HPFRC plates bonded onto the sides surfaces of the beam.

It was detected that the two strengthening schemes enhanced the cracking load capacity of the beam and reduced the number and propagation of cracks over the span, thus resulting in a decrease in the developed crack width openings. In addition, the cracks that resulted from both flexure and shear and detected toward the supports in the case of the reference beam, were deterred, since the HPFRC plates enhanced the shear capacity of the beams. The load–deflection performance of the shear-reinforced RC beam with stirrups was the customary one; like the majority types of regular RC beams, it displayed an elastic behavior at the initial stage. The load carrying capacity improved linearly, with a minor decrease in stiffness at the initiation of cracking, prior to the yielding of the rebars at a load equal to 82 kN. Subsequently, it exhibited an unusual hardening behavior attributed to the consistency with the uniaxial tensile properties of the local steel and with significant decrease in the stiffness and substantial deformations up to failure, as shown in Fig. 15. Failure ultimately resulted from the failure of concrete at the supports. For RC beam without stirrups, the load increased quickly with more enhanced stiffness to the level of 51 kN, where a brittle failure occurred, as shown in Fig. 15. The RC beams without stirrups strengthened with HPFRC and despite showing similar behavior, showed a higher ultimate load and decreased stiffness, as displayed in Fig. 15. The failure behavior of the two cases can be categorized as ductile.

6 Conclusions

Experimental studies of the shear performance of RC beams strengthened with HPFRC plates were conducted. Material testing was realized to establish the mechanical properties of the HPFRC and the NSC. Based on this study, the following conclusions may be drawn:

- Concrete specimens which are reinforced with HPFRC substrates and bonded with epoxy adhesive showed no indications of adhesion failures.
- A significant difference in the results was detected between the two schemes of strengthening, namely, HPFRC strips and plates with the latter displaying a higher increased load carrying capacity.
- HPFRC strengthening enhanced the ductility of the RC beams under loading conditions, which translated to an increase of deformations under applied loads in comparison with the reference beams.
- HPFRC strengthening resulted in an increase of the magnitude of the load at which cracking occurred, consequently, postponing the crack propagation and spread, in comparison with the reference beams. Similarly, this is realized in the improvement of the shear capacity with the utilization of HPFRC plates, as indicated by the diminished crack spread toward the support area.
- The strengthened beams exhibited monolithic performance which is evident due to the lack of debonding that was detected in both schemes of strengthening.
- Beam specimens strengthened with HPFRC plates displayed the highest strength improvement; however, beams strengthened with HPFRC strips displayed the least improvement for HPFRC strengthening schemes. Nevertheless, higher improvement lead to a substantial increase of beam ductility, realizing a more appropriate softening failure mode.
- No indication of any cracks resulting from the flexural behavior at mid-span was detected in any of the RC beams. A few of the flexural cracks in the shear-reinforced RC beams strengthened with HPFRC plates were damped out partially or totally. Basically, the shear capacity of the beam cross section improved due to the HPFRC plates bonded on the sides of the beam.

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Author contributions

NG and CI were the Principal Investigators on this Project. ES was the supervisor of the experimental work. MN and AK were the Graduate Students performing the experimental work. All authors read and approved the final manuscript.

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Availability of data and materials
All generated data are presented in the paper.

Declarations

Ethics approval and consent to participate
The authors are not misrepresenting research results and are maintaining the integrity of this research and its presentation. This manuscript is only submitted to this journal. The submitted work is original and have not been published elsewhere in any form or language.

Consent for publication
The authors are actively seeking the publication of their work to increase the body of knowledge.

Competing interests
The submitted paper by the authors whose names appear on the paper, certify that they have no affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

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