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PREDICTION OF SHEAR STRENGTH OF CFRP-STRENGTHENED REINFORCED RECYCLED AGGREGATE CONCRETE BEAMS USING VARIOUS STRENGTHENING METHODS

Key words: strengthening, carbon fibre reinforced polymer, recycled concrete aggregates, reinforced concrete, stiffness, ductility

Introduction

The environmental problem of concrete can be traced to both existing buildings and structural waste whose useful lives have expired, meaning that they must be recycled or repurposed in significant quantities (Fahmy & Idriss, 2019). Thousands of concrete cubes, cylinders, and prisms are generated every day for laboratory testing or the construction of new buildings (Mussa, Abdulhadi, Abbood, Mutalib & Yaseen, 2020), all of which can also be considered waste material. Numerous researchers have consequently undertaken various studies to determine the practicality of employing recycled aggregate concrete (RAC) manufactured from waste concrete in new construction projects. Utilizing RCA is crucial for conserving and safeguarding natural aggregate (NA). Numerous researchers have examined the impact of RCA concentrations on concrete compositions. In addition, a number of laboratories (Danraka, Mahmod, Oluwatosin & Student, 2017; Zhang et al., 2020; Mater, Elansary & Abdalla, 2022) have examined the behaviour of normal and high strength RAC relative to NA under various flexural and shear loading conditions. Obviously the durability of ordinary concrete differs from that of reprocessed concrete.

Many infrastructures, including buildings and bridges in war-torn nations like Iraq, have been devastated by the effects of war, terrorist attacks, explosives, progressive collapse, and other unforeseen events. The majority of the damaged structural components,

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such as beams, columns, and slabs, have not collapsed completely and remain repairable. Today, carbon fibre reinforced polymer (CFRP) is commonly utilized to reinforce and retrofit structural members (Al-Saawani, El-Sayed & Al-Negheimish, 2020; Saadoon, Mashrei & Al Qumari, 2022). Carbon fibre reinforced polymer can repair the load-bearing capability of damaged structural members, to make them usable once more.

This work involves an experimental investigation to study the effect of using CFRP to strengthen a beam cast with various replacement elements of RCA in a concrete mix, as a continuous part of an experimental investigation conducted by the author (Sahib & Al-Asadi, in press).

Research significance

The aim of the work is to study the shear strength of beams consisting of RAC, reinforced with CFRP when FRP strengthening is a possible option when the load carrying capacity of a structure must be increased due to design, damage or construction issues.

Materials and methods

Six reinforced concrete (RC) beams were cast, measuring 1,200 mm in length with a cross-section of 120 × 200 mm, with NA and RAC. The test was conducted using four-point loading. The geometry of the beams being tested is depicted in Figure 1. The reinforcing bars were made of 12 mm diameter steel, with three bars in tension, two in compression, and four stirrups being utilized to secure the longitudinal rebar (Fig. 2).

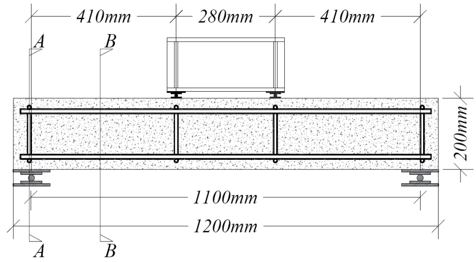

FIGURE 1. Geometry of the tested beams

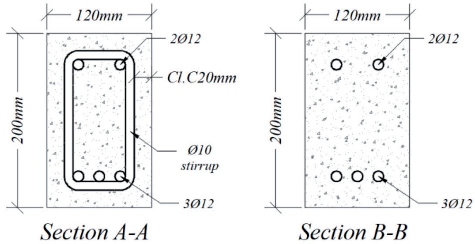

FIGURE 2. Reinforcement details of the tested beams

The experimented beams were divided into two groups according to the strengthening forms, inclination strips (IS) and continue strips (CS). Each group comprised three beams, with a replacement ratio of RCA 0%, 50% and 100%. Table 1 and Figures 3 and 4 show the data on the tested beams.

TABLE 1. Details of tested beams

Group	Replacement ratio [%]	Beam	Design
G1 IS form	0	B1	R0-IS
	50	B2	R50-IS
	100	B3	R100-IS
G2 CS form	0	B4	R0-CS
	50	B5	R50-CS
	100	B6	R100-CS

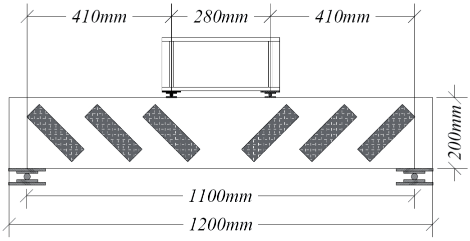

FIGURE 3. CFRP distribution for IS type beams

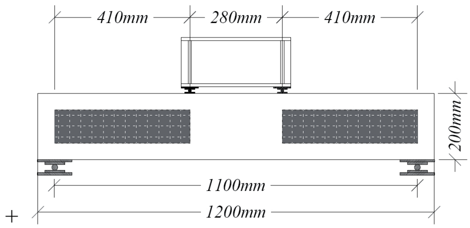

FIGURE 4. CFRP distribution for CS type beams

Materials

Cement

Ordinary Portland cement was used in this study. Both the physical and chemical results of the cement met the ASTM C150-15 requirements (ASTM International, 2015).

Sand

Prior to its use, the fine aggregate was tested according to the ASTM C136/C136M standard (ASTM International, 2006).

Natural and recycled concrete aggregate

It was decided to use crushed gravel with a maximum aggregate size of 19 mm as a natural aggregate (NA), while recycled concrete cubes that had been crushed were used as a recycled concrete aggregate (RCA), the grading satisfying the requirements of the ASTM C33/C33M-13 standard (ASTM International, 2013) for both materials (No 7).

Water

Potable water was used for all mixtures.

Steel reinforcement

The tensile test was used to determine the mechanical characteristics of the steel rebar. The results are summarized in Table 2. The results comply with the ASTM A615M--06b standard (ASTM International, 2004) (Grade 60).

Carbon fibre reinforced polymer (CFRP) and Sikadur®-330

A SikaWarp® Hex-300C unidirectional carbon fibre reinforced polymer strip was used to reinforce the concrete beam. Sikadur®-330 epoxy adhesive was used, comprising a primary base resin and hardener. Table 3 contains the manufacturer--supplied technical parameters of SikaWarp® Hex-300C strip and Sikadur®-330.

TABLE 2. Reinforcing steel test

Parameter	Steel sample		ASTM 615 limits
	Ø10 mm rebar	Ø12 mm rebar	
Yield stress [MPa]	573	560	≤ 420
Tensile strength [MPa]	672	635	≤ 620
Elongation [%]	16	15	≤ 9

TABLE 3. Properties of SikaWarp® Hex-300C sheets and Sikadur®-330

Material	Parameter	Result
Carbon fibre reinforced polymer	Tensile strength [MPa]	3 500
	Thickness [mm]	0.167
	Modulus of elasticity [GPa]	220
Epoxy	Elastic modulus [MPa]	4 500
	Tensile strength [MPa]	30
	Flexural modulus [MPa]	3 800

Tests

Mixing

Three different concrete mixes were utilized: natural aggregate concrete (M0-R0), 50% recycled concrete aggregate (M50-R50) and 100% recycled concrete aggregate (M100-R100). Each mixture was used to create reinforced beam specimens. The proportions of the concrete mix are shown in Table 4. Controlled use of the recycled and natural aggregate, as well as potable water, produced the desired compressive strength and workability (slump 6–8 cm).

Bonding of CFRP to concrete

The following steps were followed to bond the CFRP strip on each side of the concrete:
- increasing the surface roughness of the concrete with a steel brush;
- compressed air used to clean the concrete surface;
- use of a manual mixer to combine the two epoxy components;
- applying the epoxy paste to the surface of the CFRP strip;
- applying 2 mm of epoxy paste to the surface of the concrete;
- attaching the CFRP strip to the surface of the concrete;
- using a roller to release the air between the CFRP sheet and the epoxy.
- applying another layer of bonding material on top of the CFRP sheet, as shown in Figure 5.

Setup for the test

All specimens were tested using a hydraulically operated universal testing machine, “load controlled”, and were loaded to failure as shown in Figure 6. The deflections were

TABLE 4. Natural aggregate concrete and recycled aggregate concrete trial mix proportions

Mix content	Concrete		
	M0-R0	M50-R50	M100-R100
Cement [kg·m^{-3}]	430	430	430
Natural aggregate [kg·m^{-3}]	1 050	525	0
Recycled concrete aggregate [kg·m^{-3}]	0	525	1 050
Natural sand [kg·m^{-3}]	750	750	750
Water [kg·m^{-3}]	180	200	220
Slump [cm]	7.8	7.6	7.3

FIGURE 5. Sample with CFRP after bonding

FIGURE 6. Test equipment

measured during the tests using a linear variable displacement transducer (LVDT), while the load was measured using an electrical load cell.

Test results

Hardened concrete tests

Concrete compressive strength was determined after both 7 and 28 days of curing in water at 20°C, using 150 × 150 × 150 mm cubes. Three cubic specimens were used in each part of the experiment. The test results of the concrete compressive strength are shown in Table 5.

Table 5 demonstrates that the compressive strength of the concrete cubes decreases as the replacement ratio of RCA increases. Clearly, the compressive strength of RAC with 50% and 100% substitution fell by 9.5% and 13.4%, respectively, compared to the compressive strength of the natural aggregate concrete.

Fracture pattern and failure mechanisms

Figures 7–12 show the representative cracking pattern. The initial flexural crack on the beam began at the centre of the beam within the pure moment region at 22–28 kN or 25–32 kN, for strengthened beams with IS and CS forms respectively. In excess of this load, the cracks expanded toward the top fibre and more flexural cracks occurred along the length of the beam. At 35–50 kN, a shear angle fracture developed independently of the existing flexural cracks in the shear span zone. With a further load increase, the cracks

TABLE 5. Test results of concrete compressive strength (Sahib & Al-Asadi, in press)

Mix replacement ratio	Average compressive strength (28-day curing) [MPa]	Compressive strength [%]	Density [kg·m^{-3}]
R 0%	35.00	–	2 314.17
R 50%	31.67	–9.5	2 291.33
R 100%	30.31	–13.4	2 278.24

extended both towards the support and the load point, leading to a sudden, brittle shear failure and CFRP debonding, as shown in Figures 7–12 and Table 6.

FIGURE 7. Modes of failure of beam BM-R0-IS

FIGURE 8. Modes of failure of beam BM-R0-CS

FIGURE 9. Modes of failure of beam BM-R50-IS

FIGURE 10. Modes of failure of beam BM-R50-CS

FIGURE 11. Modes of failure of beam BM-R100-IS

FIGURE 12. Modes of failure of beam BM-R100-CS

Types of failure

According to Table 6, strengthening beams with CFRP in the form of VS (Sahib & Al-Asadi, in press), at the replacement ratios

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TABLE 6. Summary of beam test results

Group	Specimen	Ultimate load [kN]	Increase/decrease in load capacity [%]	Ultimate deflection [mm]	Yield load [kN]	Mode of failure
G1a*	B1-R0%	65.12	–	5.57	52	shear failure
	B2-R50%	62.00	–	5.47	56	shear failure
	B3-R100%	53.85	–	5.80	47	shear failure
G2a*	B4-R0%-VS	71.34	9.50	6.14	50	CFRP debonding
	B5-R50%-VS	68.37	10.27	6.20	47	CFRP debonding
	B6-R100%-VS	61.66	14.50	6.18	50	CFRP debonding
G1b	B7-R0%-IS	76.27	17.10	6.25	60	CFRP debonding
	B8-R50%-IS	73.16	18.00	6.35	53	CFRP debonding
	B9-R100%-IS	64.18	19.18	6.48	50	CFRP debonding
G2b	B10-R0%-CS	88.55	35.90	5.69	71	CFRP debonding
	B11-R50%-CS	85.69	38.21	6.51	67	CFRP debonding
	B12-R100%-CS	75.39	40.00	6.00	60	CFRP debonding

*Results of G1a and G2a are taken from an article by Sahib and Al-Asadi (in press).

of RCA 0%, 50% and 100%, raised the ultimate load by 9.5–14.5%. Additionally, when strengthening beams with CFRP in the form of IS, the ultimate load increased by 14.5–40% at the replacement ratios of RCA 0%, 50% and 100%. The maximum load of beams strengthened in the CS form was 35.9–40% of the un-strengthened beam forms. These results show that strengthening using CFRP in the form of CS is particularly effective at improving the shear capacity of beams.

Load–displacement curve

Figures 13–16 depict the load–deflection curves of the 12 beam tests (6 beams from previous work and the other 6 from this work). All the beam specimens exhibited a comparable linear load–deflection response until the onset of the first flexural fracture, indicating the effect of gross section stiffness and the fact that the concrete contributed to the majority of the flexural resistance. Figure 13 compares the behaviour of beam specimens with varied RCA ratios, and without strengthening. Figures 14–16 show the load deflection for three groups with strengthened beams (VS, IS and CS) and compare them with unstrengthened beams, where it is evident that the strengthened beams exhibited more ductile behaviour compared to the other beams. The CS form is very effective at improving the ultimate load of beams, as it uses the same amount of CFRP as the VS form and provides a high ultimate load and low deflection.

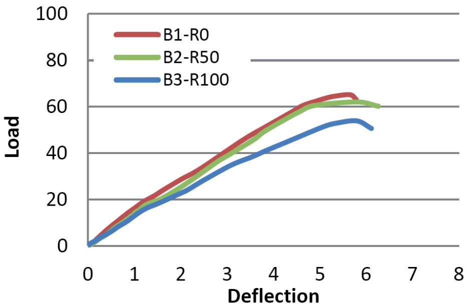

FIGURE 13. Load–deflection curve of un-strengthened beams (Sahib & Al-Asadi, in press)

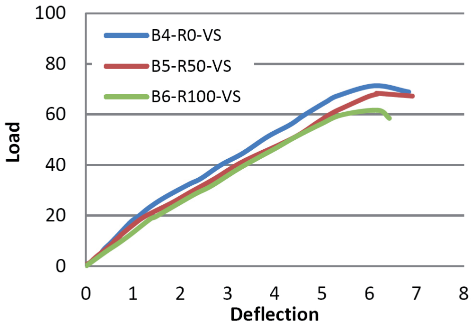

FIGURE 14. Load–deflection curve of beams strengthened with VS (Sahib & Al-Asadi, in press)

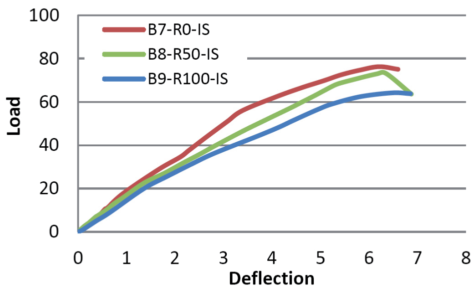

FIGURE 15. Load–deflection curve of beams strengthened with the IS form

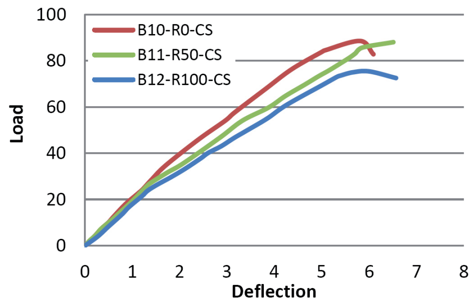

FIGURE 16. Load–deflection curve of beams strengthened with the CS form

First crack

Cracks were noticeable in the middle third after the applied force was shed, the first crack load being 18–32 kN for all beams. The visual first crack loads for the various beams are summarized in Table 7.

The beam results showed that the first crack loads increased by 16.67–39.13% when CFRP sheets were added to the beams, compared to the same beam without strengthening. The initial crack load increased as a result of strengthening the beams because CFRP had a role in confining the concrete and delaying the formation of cracks in the stress zone.

Stiffness test

The load versus deflection graphs in Figures 13–16, shows how different strengthening methods affect the flexural stiffness of the beams. The stiffness of the beams was defined as the slope of the line connecting the origin point and a point before the crack's location in order to compare the results quantitatively. This means that the beam stiffness was defined as the slope of the load versus deflection curve when the beams were in the linear stage. The stiffness results for each beam are listed in Table 7. Compared to the control beams (B1, B2, B3), the stiffness of all the strengthened specimens increased. The average increases for groups two, three and four were 13.88%, 21.06% and 37.31% over the control beams, respectively. On the other hand, the stiffness of beams with a replacement ratio of 50% and 100% of the RCA decreased by 17.7% and 23.07% respectively. It can be concluded from the results that the stiffness value was affected by the percentage of recycled aggregate and the strengthening beam with CFRP, where it was decreased and increased by these effects respectively.

Ductility test

Ductility is defined as the ability of a member to withstand a load after failure (Anwar & Najam, 2016), and in the current study it was measured from the load deflection curve of the beam at mid span. This index was calculated using Eq. (1), as suggested in the literature (Pan, Kwan & Islam, 2001).

$$\mu = \frac{\Delta u}{\Delta y}, \tag{1}$$

where:
μ – ductility index of the beams,
Δu – ultimate deflection,
Δy – yield deflection.

The ductility index (μ) of the tested beams was calculated and is listed in Table 7. The yield deflection (Δy) is also presented in Table 7.

Beams strengthened with CFRP performed better in terms of ductility than un-strengthened beams, which can be attributed to the type of failure. It can be seen that the failure type of all the beams was a shear failure, which is defined as a brittle failure, thus by strengthening the shear capacity of the beam, the failure was pushed more to flexural failure, which could be noticed from the strain values and crack pattern of the beam. The flexural failure is known to be a more ductile failure, hence the increase in the ductility value can be seen for the beam when the shear strength of the beam increases. The only exception was for beams with CFRP in the shape of CS, where the ductility decreased slightly from that of other strengthened beams, which might be due to the contribution of the CFRP in the flexural stiffness of the beam.

Conclusions

1. Strengthening the beams with CFRB increased the ultimate load carrying capacity.
2. Using CFRP increased the load capacity by an average of 11.42%, 18.09% and 38.04% for beams strengthened with VS, IS and CS forms respectively.
3. The use of the CS configuration was more effective than an IS scheme for beams strengthened with CFRP, where

TABLE 7. Ultimate deflection, yield deflection, stiffness, ductility and first crack load of tested beams

Group	Specimen	Ultimate deflection (Δu) [mm]	Yield deflection (Δy) [mm]	Stiffness (K_T) [%]	Ductility index (μ) [-]	First crack load (P_{cr}) [kN]
G1a	B1-R0%	5.57	3.85	16.90	1.45	23
	B2-R50%	5.47	4.47	13.91	1.22	20
	B3-R100%	5.80	4.12	13.00	1.41	18
G2a	B4-R0%-VS	6.14	3.79	18.74	1.62	29
	B5-R50%-VS	6.20	4.05	16.94	1.53	24
	B6-R100%-VS	6.18	4.37	14.17	1.41	26
G1b	B7-R0%-IS	6.25	3.87	19.65	1.61	28
	B8-R50%-IS	6.35	4.00	18.31	1.59	26
	B9-R100%-IS	6.48	4.29	14.99	1.51	22
G2b	B10-R0%-CS	5.69	3.81	21.79	1.49	32
	B11-R50%-CS	6.51	4.41	20.00	1.48	32
	B12-R100%-CS	6.00	4.18	18.10	1.44	25

the improvement in the ultimate load was 35.9–40% for a beam strengthened with the CS scheme, whereas the IS form increased the ultimate load by 17.1–19.18%, compared to un-strengthened beams.

4. The use of CFRP to strengthen beams was clear on the tangent stiffness value of the beams, where using VS forms increased the stiffness of the beam by 10.88%, 21.7% and 9% for an RCA replacement ratio of 0%, 50% and 100% respectively. In addition, the increase was 15.3–31.63% and 28.93–43.78% for IS and CS forms, respectively.
5. The ductility of beams strengthened with CFRP increased by an average of 8.48, 25.6 and 3.07 for beams strengthened with the VS, IS and CS forms respectively.

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Summary

Prediction of shear strength of CFRP-strengthened reinforced recycled aggregate concrete beams using various strengthening methods. Fibre reinforced polymer (FRP) strengthening is a possible option when the load carrying capacity of a structure needs to be increased for various reasons. On the other hand, the focus nowadays aims to save the environment by reducing the waste material. A suggestion was made to use waste concrete as an aggregate. If this new material was used more, it would be possible to use recycled concrete aggregate (RCA) and carbon fibre reinforced polymer (CFRP) to strengthen reinforced concrete (RC) structures and make them more environmentally friendly. An experimental investigation study on the shear behaviour of RC beams strengthened with CFRP strips was carried out. Tests were conducted on six reinforced concrete beams, with variations in the replacement ratio of RCA and strengthened by different configurations of CFRP under four-point loading. The results indicated that the load carrying capacity was increased, on average, by 18.09% and 35.04% for beams strengthened with CFRP with an inclined strip (IS) and continuous strip (CS) configurations respectively. The results also indicated that the increases in the stiffness were 21.08 and 37.31 for beams strengthened with CFRP in the IS and CS configurations, respectively. In addition the ductility of the beams increased after strengthening.