The repair of recycled crushed brick aggregate RC beams with shear deficiencies with CFRP

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Abstract: Repairing reinforced concrete (RC) beams using externally bonded carbon fibre reinforced polymer (CFRP) laminate has become one of the main rehabilitation techniques utilised to promote sustainability in construction. The aim of this study was thus to investigate the repair of rectangular simply supported reinforced crushed brick aggregate concrete beams with shear deficiencies in their design. The experimental work consisted of testing twelve full-scale beams (1400 × 200 × 150 mm) under two points load. The specimens were made of normal, and lightweight course aggregate concrete, four beam specimens were used as references, being tested until failure in shear to obtain the ultimate load carrying capacity, while the other specimens were loaded up to 60%-89.4% of the total load at failure, then repaired by wrapping in a layer of CFRP strips in two orientations (90°) and (45°). The variables investigated in this study were therefore the concrete type (normal and lightweight), shear span-to-effective depth ratio (a/d) with two variables (a/d=2.5) and (a/d=3), and the orientation of the CFRP. The results showed that a significant contribution was made by externally bonded CFRP in terms of repairing the beams, which not only refreshes initial shear capacity but also increases the ultimate capacity. The beams showed maximum reliability when the CFRP was oriented at 90° at a ratio of 72%.

Keywords: Crushed brick aggregate, CFRP repair, RC beams, Lightweight concrete

1. Introduction

Using structural lightweight aggregate concrete (SLWAC) has several benefits that substantially reduce project costs; lowering density allows for longer spans, reduced self-weight and a reduction in foundation size, in particular[1]

Many reinforced concrete structures are vulnerable to damage due to natural causes such as hurricanes or earthquakes, however, and other suffer from design flaws or the effects of rust and corrosion over time, which decrease the area of reinforcement, necessitating the rehabilitation of these structures. External bonding techniques using CFRP strips have become widely used in such repairs, and these are also believed to increase sustainability by increasing the resultant service load, restoring structural integrity, and improving ductility due to the resulting high tensile strength, resistance to corrosion, high durability, light weight, and ease of installation [2],[3].

Over the last few years, the use of composite fibre-reinforced polymer (FRP) materials has received a great deal of attention with respect to the rehabilitation of reinforced concrete beams and strengthening in flexure and shear. Uje [4] used eight RC shear deficient beams wrapped externally with CFRP laminates in research that showed that the use of CFRP laminates increased the load-carrying capacity of the strengthened specimens. Norris et al. [5] performed experimental and analytical studies, using various orientations of carbon fibre reinforced polymers (CFRP) sheets to
repair damaged concrete beams. Their study results showed that the different orientations of fibre contributed to increases in stiffness as well as in strength. Triantafillou [6] tested eleven RC beam specimens with shear deficiencies to study the effect of using composite CFRP strips adjacent to the vertical sides of specimens for repair. The results revealed an increase in the shear capacity in the range from 65 to 95%. Li and Leung [7] studied the effect of changing of the shear span-to-effective depth ratio (a/d) on the behaviours of fully-wrapped RC beams with FRP strips. Twelve RC beams were tested, with six strengthen beams and six normal beams. The a/d ratio ranged from 1.0 to 3.5, and the results showed that with increases in the a/d ratio, the FRP shear contribution also increased until the ratio exceeded 2.5, when the FRP shear contribution decreased. The study also revealed that the FRP strain was distributed along the critical shear crack in different manners for different a/d ratios. An experimental study carried out by Meikandaan [8] was based on testing two sets of beams, the control beams without CFRP laminates and those damaged then repaired with bonding using CFRP composite laminates. The parameters used in the study were the degree of damage and the CFRP laminate width; the simply supported condition was used in the investigation. The results showed that the ultimate load carrying capacity of the control beams was 17% less than that of the strengthened beams. FRP laminates used in reinforced beams improve load carrying capacity, delay crack formation, and increase energy absorption capability.

The literature review on composite fibre-reinforced polymer (FRP) materials for rehabilitation and strengthening various structural elements did not identify any existing research on the rehabilitation of shear-deficient RC lightweight concrete beams, however, and the main significance of the current study is an examination of the contribution of external CFRP reinforcement in two orientations (vertical/inclined) on the shear strength based on the shear span-to-effective depth ratio (a/d) of shear deficient RC lightweight concrete beams, with the relevant structural lightweight aggregate concrete produce from a crushed clay brick lightweight aggregate.

2. Experimental program
2.1 Description of the tested specimens and materials
A total of 12 specimens were tested, with four non-repaired and eight repaired simply supported beam specimens with clear spans of 1,400 mm, 150 mm width, and 200 mm depth tested under two-points loading. The specimens were grouped into two series, designated N for those with normal weight course aggregate, and B for those with lightweight crushed brick course aggregate. Four beams were used for each type of concrete, and a further four beams were used as reference beams (RN-3, RN-2.5, RB-3, RB2.5) to obtain the ultimate load carrying capacity in each case. All of the specimen details and dimensions are illustrated in figures 1 to 3.

To produce lightweight concrete, crushed bricks were used as coarse lightweight aggregate [9], with the brick samples crushed into smaller sizes using a hand hammer to create a final product of nearly 4.75 to 19 mm aggregate size. Figure 4 shows the crushed bricks used throughout this work, which were saturated surface dry. The cement used conformed to Iraqi specifications [10], and a natural sand (fine aggregate) with 0 to 4.75 mm particle size was used. To obtain good workability for the fresh concrete mixture, a high-performance super plasticizer (Sika ViscoCrete® -5930) was used.

The specimens were tested under load percentages of 60 to 89% of the ultimate load carrying capacity, then repaired by bonding with one layer of carbon fibre with the use of epoxy resin. Stirrups of 6 mm diameter and 228 mm spacing were used as shear reinforcement to ensure that the shear deficiency emerged, and all beam specimens failed in shear. Each specimen had steel bars (12 mm diameter) on the tensile side and steel bars (10 mm diameter) on the compressive side.
All the details of the materials are described in Table 1, and the ACI 318-14[11] formula was used to find the elastic modulus of concrete.

\[ Ec = Wc^{1.5} * 0.043*(f_c^{'})^{1/2} \] .......................... (1)

where

\( Ec \) = Modulus of elasticity, MPa

\( Wc \) = Equilibrium density of lightweight concrete between 1,440 and 2,560 kg/m³

\( f_c^{'} \) = Cylinder compressive strength, MPa

| Material | Specifications | Compressive strength (MPa) | Yield point (MPa) | Ultimate tensile strength (MPa) | Modulus of elasticity (GPa) |
|----------|----------------|---------------------------|-------------------|-------------------------------|---------------------------|
| Concrete | N              | 39.9                      | -                 | -                             | 31.179                    |
|          | B              | 30.3                      | -                 | -                             | 19.757                    |
| Steel    | D=12 mm        | -                         | 604.9             | 689.6                         | -                         |
|          | D=10 mm        | -                         | 581.4             | 661.8                         | -                         |
|          | D=6 mm         | -                         | 489.1             | 508.2                         | -                         |
| CFRP     | T=0.165        | -                         | -                 | 4900                          | >230                      |

*Thickness of the CFRP

**Figure 1.** Longitudinal section of the beam with a/d = 2.5.
Figure 2. Longitudinal section of the beam with a/d = 3.

Figure 3. Cross section of the beam.

Figure 4. Crushed brick coarse aggregate.

2.2 Concrete Mixing Design and Procedure

SLWAC refers to a concrete with an oven dry density of less than 2,000 kg/m$^3$ and a cylinder compressive strength of more than 17 MPa at 28 days curing [12]. Several trial mix were prepared according to ACI committee 211.2-98 guidelines [13], with the preferred mix proportions then used in this study for both mixes (normal coarse aggregate and crushed brick coarse aggregate)[14]. The selected mix proportions were 1:1.2:2. by weight of cement; while both mixes had the same dry proportions, the w/c ratio was changed to achieve approximate workability. Table 2 shows the details of the concrete mixes used throughout this investigation.

| Mix                  | Cement Kg/m$^3$ | Dry fine aggregate Kg/m$^3$ | Dry course aggregate Kg/m$^3$ | W/C% | Plasticizer % | Slump cm | Cube compressive strength MPa | Oven Dry Density Kg/m$^3$ |
|----------------------|-----------------|----------------------------|-------------------------------|------|---------------|----------|------------------------------|--------------------------|
| Crushed bricks aggregate | 365             | 769                        | 408                           | 0.4  | 0.5           | 8        | 30.3                         | 1910                     |
| Normal weight aggregate | 365             | 769                        | 408                           | 0.36 | 0.5           | 10       | 39.9                         | 2362                     |
2.3 Supporting and loading system

Simply supported conditions with two supporters (hinge, roller) were used as supporting systems positioned at the top face of the testing machine base. The simply supported condition of the beam was achieved by using a steel bar of 30 mm diameter, movable on one side of the support, that was welded on the upper face of the other support. These supports were positioned 100 mm from the beam ends. The testing machine and loading setup is shown in figure 5.

![Figure 5. Testing machine and loading setup](image)

2.4 Test procedure

A universal testing machine with 2,000 kN capacity was used to test all specimens; this was located in the concrete laboratory of the Civil Engineering Department at Kerbala University, as shown in figure 6. An LVDT of 100 mm capacity was placed vertically at the centre point of the beam specimens to measure the deflection, and the applied load was fixed at 54 kN in the first stage of loading, taken relative to the reference non-strengthened beams to offer a ratio of 60 to 89.4% of the ultimate load of the control beam for the two groups, respectively.

![Figure 6. Beam testing arrangement](image)
2.5 Repair schemes

The reference beams were not repaired with CFRP; the other beam specimens were repaired by complete wrapping in one layer of CFRP strips. The width of each strip was 50 mm and the spacing was 100 mm centre to centre. The specimens were wrapped in one of two orientations (90° or 45° angle to the edge). The details of this are laid out in Table 3 and shown in figures 7 and 8. The bonding process started with the removal of dye from the beam surface, which was then cleaned of dust particles to ensure a good bond with the CFRP sheets. The primer was applied at the specific areas where the CFRP was to be wrapped and left to dry as shown in figure 9; then, when the concrete surface was dry, the resin was positioned as illustrated in figure 10. Finally, the CFRP strips were applied as shown in figure 11, and the repaired beams were loaded until failure, as illustrated in figure 12.

Table 3. Repaired schemes details

| Beam symbol | (a/d) ratio | No. of Layer | Orientation of CFRP sheets |
|-------------|-------------|--------------|----------------------------|
| N3-45       | 3           | One layer    | 90°                        |
| N3-90       | 3           | One layer    | 45°                        |
| N2.5-45     | 2.5         | One layer    | 90°                        |
| N2.5-90     | 2.5         | One layer    | 45°                        |
| B3-45       | 3           | One layer    | 90°                        |
| B3-90       | 3           | One layer    | 45°                        |
| B2.5-45     | 2.5         | One layer    | 90°                        |
| B2.5-90     | 2.5         | One layer    | 45°                        |

Figure 7. CFRP wrapping in the perpendicular direction (90°)

Figure 8. CFRP wrapping in the inclined direction (45°)
3. Experimental Results and Discussion

3.1 General behaviours

All the concrete beams were tested in two stages. In the first stage, the specimens were loaded to 54 KN, a percentage of 60 to 89.4\% of the ultimate load of the unrepaired beams, which have shear deficits. In the second stage, after repair with CFRP strips, the beams were loaded to failure. Cracks started to appear on the tension faces of the beams as the applied load increased, with additional and wider cracks appearing throughout and moving upwards. The results show an improvement in shear resistance, with CFRP materials offering good effectiveness in turning the failure into flexural failure by improving the shear capacity of the rehabilitated beams, with the most significantly affected parameter being the a/d ratio, which varied from 2.5 to 3, as shown in figures 13 to 20, and as illustrated in table 4.

| Beam symbol | a/d ratio | Orientation of CFRP strips | Loading stage % from the reference beams | Ultimate load kN | Failure mode | CFRP repairing effectiveness ratio (%) | Ductility DI.\(=\Delta u/\Delta y\) | Toughness s*** |
|-------------|-----------|-----------------------------|----------------------------------------|-----------------|-------------|----------------------------------------|-----------------|---------------|
| RN-2.5      | 2.5       | -                           | -                                      | 90              | Shear failure | -                                      | -               | -             |
| RN-3        | 3         | -                           | -                                      | 75              | Shear failure | -                                      | -               | -             |
| RB-2.5      | 2.5       | -                           | -                                      | 72.5            | Shear failure | -                                      | -               | -             |

Table 4. Results of tested after repair.
| Sample | Degree | Shear | Ultimate load | Shear failure | Effect | Shear | Ultimate load | Shear failure |
|--------|--------|-------|---------------|---------------|--------|-------|---------------|---------------|
| RB-3   | 3      | -     | 60.4          | -             | -      | -     | -             | -             |
| N3-45  | 3      | 45°   | 72            | 84.93         | Flexural failure | 50    | 4             | 2191          |
| N3-90  | 3      | 90°   | 72            | 82.25         | Flexural failure | 48    | 2.8          | 930           |
| N2.5-45| 2.5    | 45°   | 60            | 95.45         | Flexural failure | 71    | 3             | 1118          |
| N2.5-90| 2.5    | 90°   | 60            | 111.63        | Flexural failure | 97    | 2.5          | 1867          |
| B3-45  | 3      | 45°   | 89            | 82.63         | Flexural failure | 49    | 2.3          | 799           |
| B3-90  | 3      | 90°   | 89            | 87.62         | Flexural failure | 56    | 2.4          | 835           |
| B2.5-45| 2.5    | 45°   | 74.5          | 116.13        | Flexural failure | 108   | 2.5         | 1368.8        |
| B2.5-90| 2.5    | 90°   | 74.5          | 115.73        | Flexural failure | 105   | 2.4         | 1330          |

*Deflection at ultimate load

**Deflection at yield load

***The area under the load deflection curve
3.2 Material effects

During the repair test results, the influence of the materials was observed; the rehabilitated beam specimens with crushed brick aggregate concrete developed the highest ultimate load, while the normal weight aggregate concrete beam specimens failed at a load 10.57% lighter, due to the high porosity of the crushed brick under saturated surface dry conditions. These acted as water tanks inside the concrete and worked to supply the concrete with water during hardening, extending the period of rehydration. Beam B2.5-45 had the highest ultimate load of 116.13kN, while beam N3-90 had the lowest ultimate load, 82.25kN; this latter failure was also shear, as illustrated in figure 26. The ductility decreased with increases in ultimate load, with crushed brick aggregate displaying a value of just 54.06% of the normal weight aggregate’s value of 6.02. The toughness values were very close, however, with the normal weight having a higher percentage of just 3.01% in beam No. N3-45 scored at 2,191 kN.mm², as shown in the load-deflection curves in figures 22 to 25.
Figure 22. Load-deflection curve for specimens with \(a/d=3\) and 45° strips

Figure 23. Load-deflection curve for specimens with \(a/d=2.5\) and 45° strips

Figure 24. Load-deflection curve for specimens with \(a/d=3\) and 90° strips

Figure 25. Load-deflection curve for specimens with \(a/d=2.5\) and 90° strips
3.3 a/d ratio effect

The difference of shear span to effective depth ratio (a/d) influences the behaviours of reinforced concrete beams. The use of crushed brick aggregate concrete and normal weight aggregate concrete showed that the ultimate load increased as the shear span/depth ratios (a/d) decreased in all cases, up to percentages of 36% for crushed brick aggregate concrete and 32% normal weight aggregate concrete. Ductility and toughness also increased with the decrease in shear span/depth ratios (a/d), with the ductility percentage increase being 6% for crushed brick aggregate concrete and 17% for normal weight aggregate concrete; in terms of toughness, the increase was 65% for crushed brick aggregate concrete and 102% for normal weight aggregate concrete, with constant CFRP orientation. Table 3 illustrates the effect of a/d ratios on ultimate load and mid-span vertical deflection for beams as shown in figures 27 to 30.

![Ultimate load chart](image)

**Figure 26.** Ultimate load for the beam specimens.

**Figure 27.** Load-deflection curve for crushed brick specimens tested with 45° CFRP orientation

**Figure 28.** Load-deflection curve for crushed brick specimens tested with 90° CFRP orientation
3.4 CFRP orientation effect

With regard to the orientation of the CFRP materials, the general trend of the beam specimens suggested that using a wrapping angle of 90° is more effective and gives better results than using an angle of 45°. The ultimate loads for beams with angles of 90° were at higher values, with rates of 2.8% and 1.5% for crushed brick and normal weight aggregate concrete, respectively. The influence of the CFRP orientation on ductility was variable, however, with the effect being large for crushed brick aggregate concrete; the contribution of the 90° angle was higher when the shear span/depth ratio (a/d) was 3, at 3.3%, while a/d = 2.5 gave a decrease in the ductility with a ratio of 1.6% as compared with the 45° angle, as shown in the load-deflection curves in figures 31 to 34.

Figure 29. Load-deflection curve for normal specimens tested with 45° CFRP orientation

Figure 30. Load-deflection curve for normal specimens tested with 90° CFRP orientation

Figure 31. Load-deflection curve for crushed brick aggregate specimens with a/d = 2.5

Figure 32. Load-deflection curve for crushed brick aggregate specimens with a/d = 3

Figure 33. Load-deflection curve for normal aggregate specimens with a/d = 2.5

Figure 34. Load-deflection curve for normal aggregate specimens with a/d = 3
4. Conclusions

The study leads to the following conclusions:

- The shear strength gained due to adding CFRP materials to lightweight crushed brick aggregate specimens is greater than that gained by adding them to normal weight concrete specimens.
- The repaired beams’ mechanical performance is highly increased by using CFRP materials. CFRP materials are thus deemed effective at restoring the mechanical performance of damaged or cracked beams.
- Shear span-to effective depth ratio (a/d) has a significant impact on the contribution of externally added CFRP materials to the shear capacity, which appeared to increase with the decrease in the a/d ratio at a percentage rate of 12%.
- Vertical CFRP strips were more effective in improving the shear-deficiency of beams than inclined CFRP strips with an angle of 45°.
- The behaviours of repaired RC beams wrapped with CFRP show that the integrity, longevity, and sustainability of existing structures can be improved using this rehabilitation process.

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