Flexural Behavior of Rubber-Filled Reinforced Concrete Beams Strengthening with CFRP Sheets

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Abstract. Although there are many advantages to using rubber to produce reinforced concrete substrates, there are still few applications for rubberized concrete substrates like beams, where the mechanical properties of rubber-infused concrete, such as flexural strength, begin to decline. On the other hand, flexural strengthening constitutes a sizeable portion of the structural uses for externally carbon fiber reinforced polymer (CFRP) sheets when used to strengthen reinforced concrete beams. For this study's rubberized concrete beams, the externally adhered (CFRP) sheets were used as a substitute for the loss of flexural strength. The study's reinforced concrete beams were split into two groups, each consisting of three beams. The first group's concrete mixture was included as a filler (5) % of the cement weight in the form of waste tire rubber with a size not more than (0.075) mm. Any group of concrete beams always had a first beam without any external reinforcement, a second beam with one layer, and a third beam with two layers of (CFRP) sheet. The results indicate that the load at the first crack increases to be equal to that of the un-rubberized beam when the rubberized reinforced concrete beam is strengthened with one layer of (CFRP) sheets, and it increases by (20%) when reinforced with two layers of (CFRP) sheets. When reinforced with one or two layers, the load at failure rises by 23.58 and 42.75 percent, respectively. The first crack deflection rises by 88.11 and 120.24 percent, while the failure deflection falls by 2.97 and 6.01 percent, respectively. On the (load-deflection) curve, the deflection decreases at symmetrical loads.

Keywords: CFRP sheets; beam strengthening; rubberized concrete; flexural behavior.

1. INTRODUCTION

Numerous studies have been conducted, with various degrees of success, to determine how to deal with the loss of mechanical properties, such as reinforced concrete substrates' flexural strength, due to the substitution or addition of waste tire rubber in the process of constructing these substrates. This study aims to reinforce flexural strength-reinforced rubberized concrete beams using externally adhered (CFRP) sheets on beam soffits, which is very efficient at strengthening structural members, including beams.

Since it requires fewer natural resources to produce concrete and eliminates used tires, using scrap tire rubber in concrete has been an interesting topic [1] since 2003, and more research has been done on recycling used tire rubber for incorporation into concrete. The effectiveness of incorporating or removing coarse or/and fine aggregate in concrete using different rubber ratios has been investigated in several studies [2, 3, 4]. Waste tire rubber can improve concrete's structural properties, such as its capacity to withstand repeated freezing and thawing, energy dissipation, deformability, and impact resistance. Rubberized concrete showed a lower unit weight and proper workability than normal concrete. But as the rubber content increases, the concrete's flexural, compressive, and tensile strength and its elastic modulus may also be reduced [5, 6]. When rubber was used as aggregate, the engineering properties of concrete decreased as rubber content rose. The flexural stiffness and load at failure decreased as waste tire rubber content rose, and toughness, deformability, and ductility indices followed similarly. The failure mode of the tested beams shifts from brittle to ductile with the addition of microsteel and rubber fibers [7]. The amount of replacement and rubber grain size impacted the concrete's compressive strength. Concrete's elastic modulus decreased when rubber was substituted for cement or aggregate, along with its flexural, compressive, and tensile strength [8].

The compressive strength of the mixed composites is marginally increased, according to experimental results of the use of recycled CFRP fibers and crumb rubbers in the creation of concrete. The ability to absorb energy, resistance to impacts, ductility, and flexural toughness has significantly improved. The evaluation results also demonstrate that recycled (CFRP) fiber-reinforced rubberized concrete used in the construction industry was highly beneficial to the environment regarding CO_2 emissions and long-term environmental sustainability [9]. Because of rubber's low elastic modulus, cement matrix adhesion, and hydrophobicity, poor adhesion and stress concentration occur. Treatment of rubber surfaces using chemical or physical methods improves rubberized concrete's mechanical properties and durability, strengthening the bond between the cement and rubber interface [10]. The mechanical properties of concrete can usually be decreased by adding rubber; this tendency worsens as rubber particle size and content increase. The ruts contained an interfacial transition zone because rubber and cement paste don't adhere well to one another. Compared to compressive strength, flexural and tensile strength decreased less [11].

There are several ways to improve a reinforced concrete beam's flexural performance, and the most effective one depends on several factors. These factors include the cost of strengthening, an increase in size, the rate of load capacity improvement, and the availability of used materials. The shear and flexural strengths of composites made of externally adhered fiber-reinforced polymers (FRP) can be improved, and compression members may be confined and given ductility. Concrete structural members can be strengthened using carbon fiber reinforced polymers (CFRP), which have advantages like corrosion resistance, ease of installation, and superior specific strength [12]. Along with an increase in the (CFRP) sheet's layer number, the load-bearing capacity of reinforced concrete beams also increased. Beams that have been strengthened have significantly less ductility than beams that have not been strengthened [13]. With (CFRP) sheets added for reinforcement, all repaired beams typically regain approximately (80%) of their initial bearing capacity. The strengthened beam has an increased flexural strength of (30 to 40) %. Deflections are significantly decreased because the strengthened beams became stiffer. Some shear cracks are stopped from spreading by the existence of (CFRP) exterior strengthening, while others take longer to form [14]. Rupture only occurs when just one layer is used, whereas debonding occurs when two layers are used. Therefore, debonding is more likely to occur as the number of layers increases than rupture [15].

By using externally adhered (CFRP) sheets on beam soffits, which is very effective at strengthening structural members, including beams, this study aims to reinforce flexural strength-reinforced rubberized concrete beams to be used in construction projects and gain the benefits of rubberized concrete.

2. PROGRAM AND EXPERIMENTAL TOOLS

2.1 Specimens Configuration

There were two groups of reinforced concrete beams in total, and each group consisted of three beams with identical mixing parameters. The first group contained waste tire rubber with a size of no more than (0.075) mm, making up (5) % of the weight of the cement as a filler. The second group will be the reference group and use a concrete mix free of used tire rubber. Each beam measures (2.1) m in length, (0.2) m in width, and (0.3) m in height. It was developed using the ACI Code (318-19) [16]. Each of the two groups of beams is reinforced with the same proportion (ρ_{min}) of steel bars. The compression zone was strengthened using two steel rods with a diameter of (12) mm, similar to the tensile zone. A stirrup with a diameter of (12) mm was employed to resist shear stress every (200) mm c/c, as shown in Figure 1. The lower side of the (2.1×0.2) m beams will have the (CFRP) sheets adhered for external strengthening, and the beams in each group will be strengthened as follows: no external reinforcement for the first beam, the second gets one layer of reinforcement, and the third gets two layers, as shown in Figure 2.

Additionally, each beam will contain the same amount of silica fume, superplasticizer admixture, and water in cement ratio. Japanese-made (TML) strain gauge type (FLAB-6-11-3LJC-F), 6 mm long, was fixed in the middle of each beam's tensile reinforcement. Additionally, as seen in Figures 3 and 4, two strain gauge types (BFLAB-5-3-3LJC-F), 5 mm long, were to be connected in the middle of each (CFRP) layer.

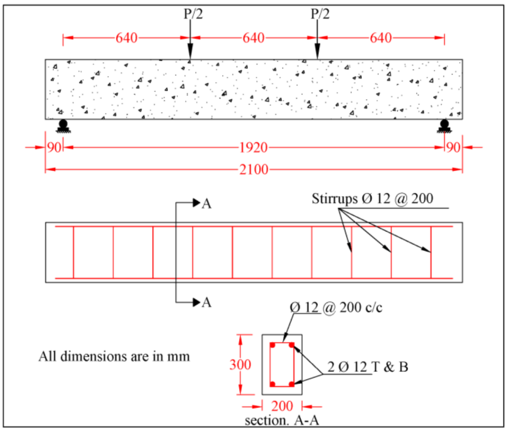

Figure 1: Dimensions and reinforcement specifications for the beam.

Figure 2: Adhering (CFRP) sheets.

Figure 3: Strain gauges installed on the tensile reinforcement.

Figure 4: Strain gauges installed on (CFRP) sheets

2.2 Reference Mix Design

The following ingredients were used to create a reference mixture: coarse aggregate, fine aggregate, water, cement, superplasticizer (Sika ViscoCreate®-5930L), and silica fume (MegaAdd MS (D). This mixture was required to have a compression strength at 28 days of at least (45) MPa. The mix's composition is thoroughly outlined in Table 1.

Table 1: The reference concrete mix's design properties.

Cement (kg/m^3)	**Silica fume (kg/m^3)**	**Superplasticizer ($Liter/m^3$)**	**Fine aggregate (kg/m^3)**	**Coarse aggregate (kg/m^3)**	**W/C ratio**
500	25	3	680	1020	0.37

2.3 Materials Quantities Employed in Research

Table 2 below shows the amounts of raw materials, waste tire rubber, and additives used in the concrete beam mixtures.

Table 2: Quantities of materials used to execute a concrete beam.

Group No.	**Group symbol**	**Rubber content (%) of Cement weight**	**Beam symbol**	**Water (Liter)**	**Cement (kg)**	**Coarse aggregate (Kg)**	**Fine aggregate (kg)**	**Filler tire rubber (kg)**	**Silica fume (kg)**	**Superplasticizer (Liter)**	**CFRP layers (No.)**	**Strain gauges (No.)**
Group 1	B1	5 %	B1-0	27.13	73.33	149.6	99.75	3.67	3.67	0.38	0	2
			B1-1	27.13	73.33	149.6	99.75	3.67	3.67	0.38	1	4
			B1-2	27.13	73.33	149.6	99.75	3.67	3.67	0.38	2	6
Group 2	BR	0 %	BR-0	27.13	73.33	149.6	99.75	–	3.67	0.38	0	2
			BR-1	27.13	73.33	149.6	99.75	–	3.67	0.38	1	4
			BR-2	27.13	73.33	149.6	99.75	–	3.67	0.38	2	6

2.4 (CFRP) Sheets for External Strengthening

Using unidirectional (CFRP) sheets improved concrete beams' flexural qualities. The (CFRP) sheets' specific demands are given in Table 3 below through laboratory examination confirmation, including authorized specifications opposite to each experimental result.

Table 3: Specifications of the used (CFRP) sheets.

Item	**Test result**	**Limitation**	**Specification**
Dry fiber density (g/cm^3)	1.82	–	–
Area density (g/m^2)	304 ± 10	–	–
Laminate nominal thickness (mm)	0.167	–	–
Laminate nominal cross-section ($mm^2/m.l$)	167	–	–
Laminates tensile strength (N/mm^2)	3500	3200	ASTM D 3039-2000 [17]
Laminates elasticity modulus (KN/mm^2)	220	210	
laminates elongation at break in tension (%)	1.59	–	
Tensile resistance (N/mm)	585	534	

2.5 Steel Reinforcement

The laboratory program involved producing reinforced rubberized concrete with longitudinal reinforcement (compression and tensile zones) and shear reinforcement (stirrups) using steel bars with a diameter of (12) mm. Table 4 shows the steel bar test results according to ASTM A615/A615M-2020 [18].

Table 4: Test results for the used steel bars.

Item	Spe. No.1	Spe. No.2	Spe. No.3	Limitation
Specimen length (mm)	200	200	200	
Circumference (mm)	38	38	38	
Area (mm^2)	113	113	113	
Diameter (mm)	12	12	12	
Mass (kg/m)	0.96	0.96	0.96	Min. 0.95
Yield strength (MPa)	451	433	442	Min. 420
Tensile strength (MPa)	593	575	584	Min. 550
Elongation (%)	9	9	10	Min. 9
Curvature	Matching	Matching	Matching	Matching

3. TESTING PROGRAM

3.1 Tests on Fresh Concrete

The workability of each group mix was evaluated using the slump test, which was carried out in accordance with the guidelines in ASTM C143-01a [19]. It was (110 ± 5) mm for each group mix.

3.2 Tests on Hardened Concrete

A beam with a clear span of (1.92) m underwent a two-point monotonic loading test, as shown in Figure 5 to determine its flexural response. Compression strength testing (f_{cu}) of concrete was performed according to BS (1881 - part 116:2000) [20] at (28) days of age and the beam test age. To verify the rupture modulus (f_r), flexural testing was carried out in accordance with ASTM C78-02 [21]. The ASTM C496-04 [22] specifications for beam test specimens were used to calculate the splitting tensile strength (f_t) at the testing age. ASTM C469-02 [23] calculated concrete's static elasticity modulus (Ec).

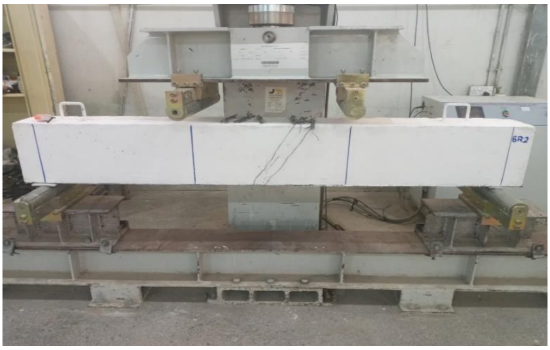

Figure 5: Flexural testing machine.

4. LAYOUT OF EXPERIMENTAL STUDY

4.1 Concrete Properties

Rubber from waste tires behaves in a way that needs to be understood in terms of its mechanical characteristics when added to concrete by the weight of the cement. Table 5 displays the values for the hardened rubberized concrete's properties. The mechanical properties of rubber concrete were compared to those of reference concrete at age (28) days, including splitting tensile strength, elastic modulus, compressive strength, density, and rupture modulus, which decreased by (28.91, 13.26, 25.29, 0.04, and 19.37) % respectively.

Table 5: Results of rubberized concrete's properties.

Group No.	Beam Groups		Ave. Density (kg/m^3)	Ave. (f_{cu}) (28) days (MPa)	Ave. (f_r) (28) days (MPa)	Ave. (f_t) (28) days (MPa)	Ave. (E_c) (28) days (MPa)
	Symbol	Beams included					
Group 1	B1	B1-0, B1-1 & B1-2	2336	34.185	3.322	2.724	24988
Group 2	BR	BR-0, BR-1 & BR-2	2337	45.759	4.120	3.832	28808

4.2 Flexural Test Results and Discussion

Table 6 displays the experimental findings (first crack load and deflection with failure load and deflection), which depict the flexural reaction to the two-point monotonic loading applied to these two groups of concrete beams when waste tire rubber with a size of no more than (0.075) mm makes up (5) % of the weight of the cement in the concrete mixture as a filler, this shows a reduction in load at the first crack and failure occurs.

Table 6: Results of beams' flexural tests.

Group No.	Beams		Load at the first crack (KN)	Deflection at the first crack (mm)	Load at failure (KN)	Deflection at failure (mm)
	Group symbol	Beam symbol				
Group 1	B1	B1-0	27	1.598	142.4	30.449
		B1-1	35	1.915	185	21.544
		B1-2	42	2.242	213.7	21.991
Group 2	BR	BR-0	35	1.018	149.7	23.397
		BR-1	47	1.647	172.3	16.565
		BR-2	49	1.902	218.7	16.834

4.2.1 The Load at the First Crack

The load at the first crack for the beams in group (B1), which were externally reinforced with single and double layers of (CFRP) sheets, correspondingly ascended by (29.63) and (55.56) %. The strengthening of the beam with one layer of (CFRP) sheet for beam (B1-1) equalized the load at the first crack for beam (BR-0) but increased it with two layers of (CFRP) sheets for beam (B1-2) by (20.0) %. The addition of waste tire rubber decreased the load at the first crack for beam (B1-0) by (22.86) %. In addition, the first crack load decreased at various rates (22.86, 25.53, and 6.67) % when the beams in the (B1) group were contrasted with the equivalent beams in the reference group (BR). The inclusion of waste tire rubber was the cause of this, although the beams (B1-1) and (B1-2) were externally reinforced with (CFRP) sheets.

4.2.2 The Load at Failure

The load at failure of beams with a single and a pair of layers of externally glued (CFRP) sheets, correspondingly, raised in ascending order by (29.92 and 50.07) % from the un-strengthened beam (B1-0), and the beam with no externally adhered (CFRP) sheets. (CFRP) sheets used as external reinforcement allowed for this development. When the failure loads of the group (B1) beams were contrasted with that of the reference beam lacking strengthening (BR-0), the load at failure was increased ascendingly by (23.58 and 42.75) % for the beams (B1-1) and (B1-2) because of the reinforcement with (CFRP) sheet and decreased by (4.88) % for the beam (B1-0) attributed to the addition of waste tire rubber. Additionally, the load at failure for beams (B1-0) and (B1-2) were lower (4.88 and 2.29) % and higher (7.37) % than those for the equivalent beams in the reference group (BR), respectively.

4.2.3 The Deflection at the First Crack

The deflection at the first crack of the beams in the group (B1) with a single and a pair layer of strengthened (CFRP) sheets, correspondingly, increased in ascending order by (19.84 and 40.30) % as compared to the un-strengthened beam (B1-0). As a result of external strengthening, the first crack load has increased, which accounts for this. Furthermore, the addition of used tire rubber to the (B1) group beams increased the first crack deflection by an increasing percentage (56.97, 88.11, and 120.24) % in comparison to the reference beam (BR-0) that had not been strengthened. The deflection at the first crack increased in various proportions (56.97, 16.27, and 17.88) % if compared to the matching beams in the reference group (BR) despite the strengthening provided by the (CFRP) sheets for the beams (B1-1) and (B1-2) and the inclusion of waste tire rubber.

4.2.4 The Deflection at Failure

When compared to the UN externally reinforced beam (B1-0), the failure deflection of beams (B1-1) and (B1-2) with one and two layers of (CFRP) sheets, correspondingly, declined in a downward ratio by (29.25 and 27.78) %. When contrasted to the reference beam lacking external reinforcement (BR-0), the failure deflection of the (B1) group beams raised by (30.14) % due to the inclusion of rubber but decreased in declining rates by (7.92 and 6.01) % because of the strengthening employing one and two layers of (CFRP) sheets, respectively. Even with external reinforcement, the inclusion of waste tire rubber increased the group (B1)'s failure deflection by (30.14, 30.06, and 30.63) % over the reference group's (BR) corresponding beams.

4.2.5 Load-Deflection Relationship

1- A decline in deflection at similar load ranges and a greater failure load for beams with an equivalent decrease in deflection are shown in Figure 6 for a beam with one layer of (CFRP) adhered to it (BR-1) and a beam with two layers adhered to it (BR-2). This contrasts with a beam that is not reinforced (BR-0). Figure 7 shows how strengthening the beams (B1-1) and (B1-2) with one and two layers of (CFRP) sheets, correspondingly, results in increased flexural strength for the (B1) group of beams in comparison to the un-strengthened beam (B1-0), greater failure loads, and smaller failure deflection for the beams, and the deflection declines at similar load levels.

2- The beam (B1-0) fails with a lower failure load and a higher failure deflection than (BR-0) when waste tire rubber is present, as shown in Figure 8. Additionally, it deflects more under symmetrical loads in a significant portion of the curve with convergence. As shown in Figure 9, the beam (B1-1) that had been strengthened with one layer of (CFRP) sheets demonstrated higher failure loads and deflection and also higher deflection at similar loading points than the beam (BR-1). According to Figure 10, the beam (B1-2) has a higher deflection at failure than the beam (BR-2), a lower failure load, and a lower deflection at similar load levels.

3- At symmetrical load levels, the deflection of the externally reinforced beams of the group (B1) is significantly less than that of the reference beam (BR-0). Higher failure loads result in less failure deflection, as shown in Figure 11.

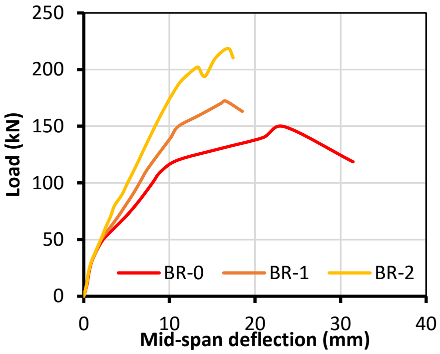

Figure 6: Load-deflection diagram of group (BR) beams.

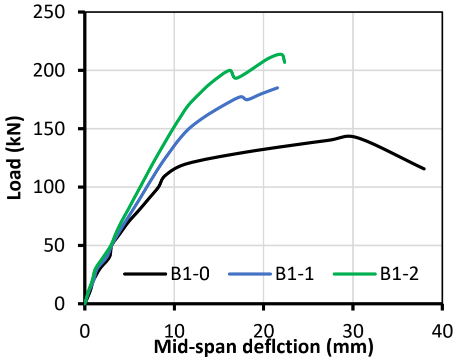

Figure 7: Load-deflection diagram of group (B1) beams.

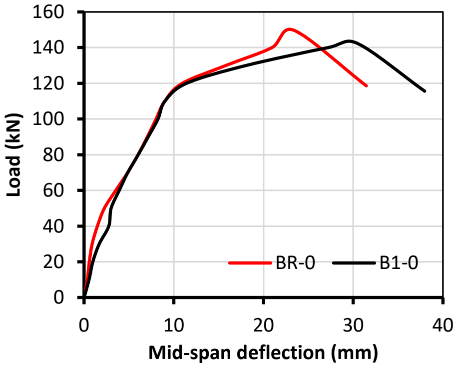

Figure 8: Load-deflection diagram of the beam (BR-0) and (B1-0).

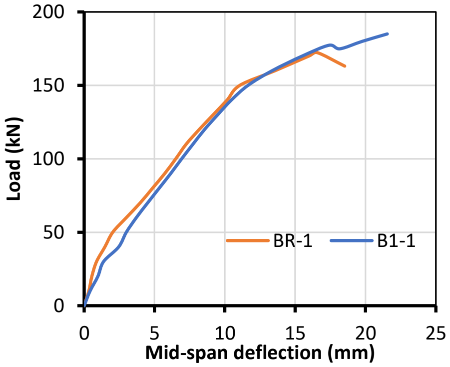

Figure 9: Load-deflection diagram of the beam (BR-1) and (B1-1).

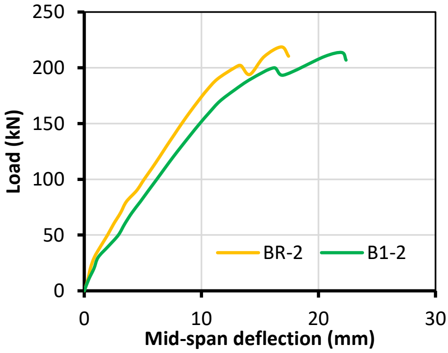

Figure 10: Load-deflection diagram of the beam (BR-2) and (B1-2).

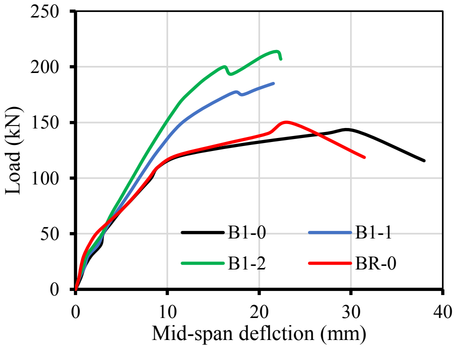

Figure 11: Load-deflection diagram of group (B1) beams and (BR-0).

4.2.6 Main Steel Reinforcement and (CFRP) Sheet Strains

Considering that the addition of waste tire rubber causes more deformation:

1- In Figure 12, it is evident that the tensile steel reinforcement of the beam (B1-0) experiences more significant strain than the reference beam (BR-0) when subjected to symmetrical loads .
2- Under symmetrical loads, the beam (B1-1) experienced more significant strain for the steel reinforcement and (CFRP) strengthening sheet than the reference beam (BR-1) as shown in Figure 13.
3- Similar regulations apply to the steel reinforcement and the two layers of (CFRP) sheets used as reinforcement of the beam (B1-2), as shown in Figure 14. Under symmetrical loads than that of the reference beam (BR-2) .

This is in line with how loading-deflection diagrams depict flexural behavior.

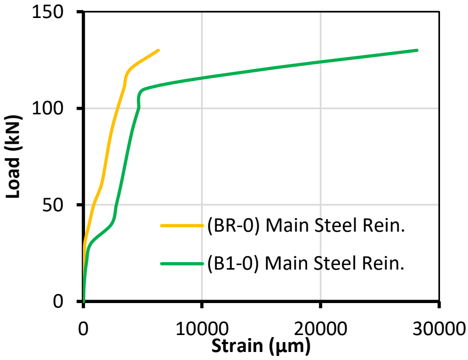

Figure 12: Main steel reinforcement load-strain diagram of the beams (BR-0) and (B1-0).

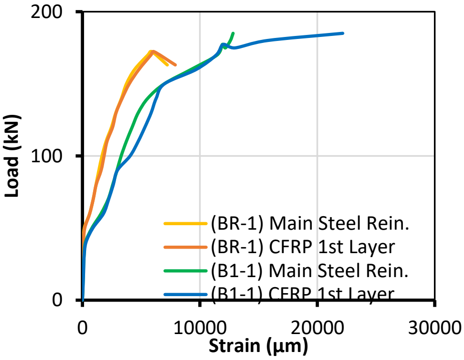

Figure 13: Main steel reinforcement and CFRP sheet load-strain diagram of the beams (BR-1) and (B1-1).

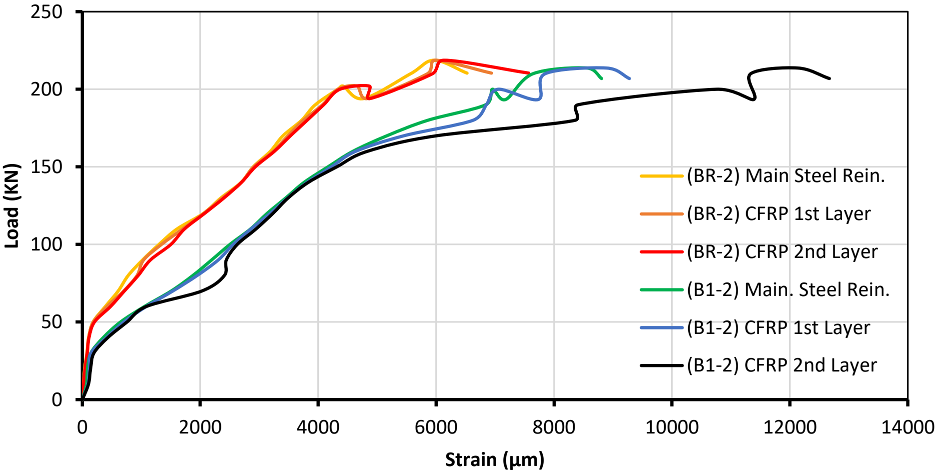

Figure 14: Main steel reinforcement and CFRP sheet load-strain diagram of the beams (BR-2) and (B1-2).

4.2.7 Mode of Failure

The failure mode of beams externally reinforced with a single layer of (CFRP) sheet, such as the Beams (BR-1) and (B1-1) was the rupture of (CFRP) sheet that occurs after the yielding of tension steel reinforcement, which happens when the tensile strain of (CFRP) sheets reaches its design rupture strain. However, in the beams (BR-2) and (B1-2) that were reinforced with a dual layer of (CFRP) sheet, there was a debonding of the (CFRP) sheet, which happens when the force in the (CFRP) sheets is too great to be transferred to the bonded concrete beam and can lead to the delamination of the concrete cover or the debonding of the CFRP sheets. Figure 15 shows the deformation patterns of all beams.

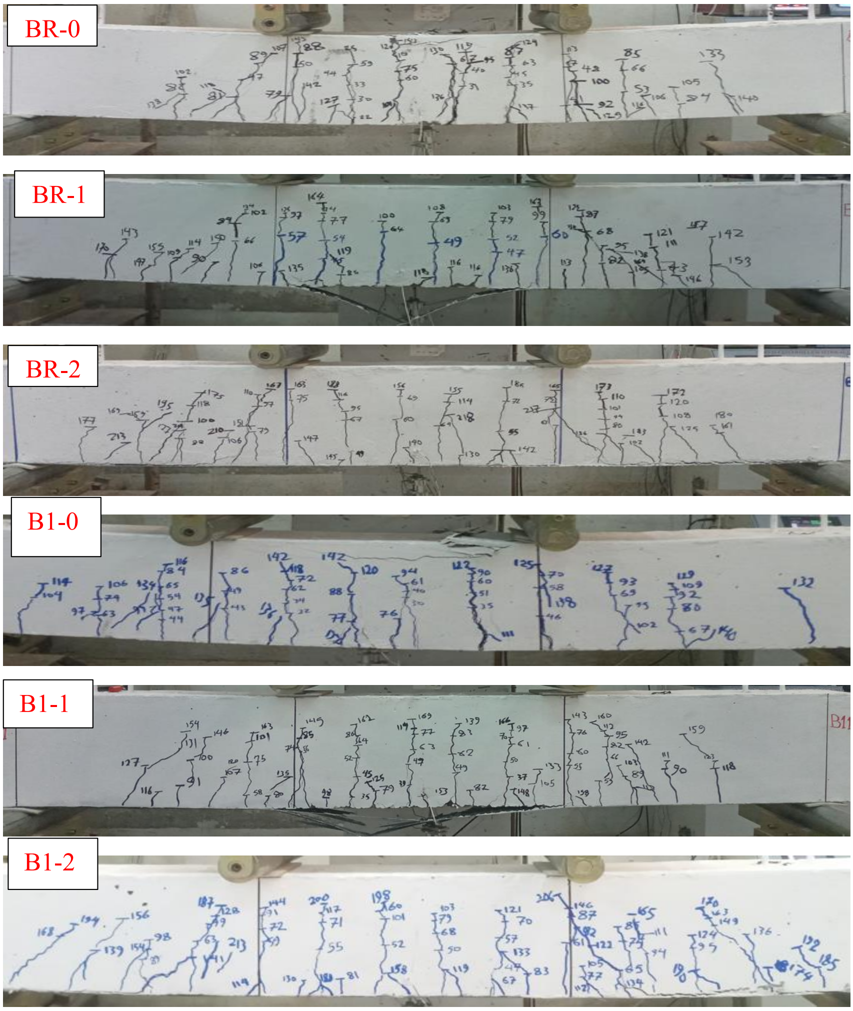

Figure 15: The group (BR) and (B1) beams deformation pattern.

5. CONCLUSIONS

This study's main purpose is to show that the flexural strength lost during the construction of rubberized reinforced concrete beams can be recovered. In light of this, the comparison that is most relevant to the research's objective will be between rubberized reinforced concrete beams that were strengthened by single and double layers of (CFRP) sheets, (B1-1) and (B1-2) and the control reinforced concrete beam (BR-1), which is not rubberized and not externally strengthened. All mechanical properties, such as splitting tensile strength, elastic modulus, compressive strength, density, and rupture modulus, decreased when waste tire rubber with a size of no more than (0.075) mm and comprising (5) % of the weight of the cement was added as a filler to the concrete mixture. Experimental results showed that adding one or two layers of (CFRP) sheets to the outside of reinforced concrete beams that had been rubberized by including waste tire rubber with a size less than (0.075) mm and making up (5) % of the cement weight increased the flexural strength in the following capacities:

- As a result of rubberizing, the first crack load with failure load decreased by 22.86 and 4.88 percent, respectively, and the first crack deflection with failure deflection increased by 56.97 and 30.14 percent, respectively.
- By using a single layer of (CFRP) sheet, It is possible to equalize the load at the first crack, increase the load at failure by (23.58) percent, increase the deflection at the first crack by (88.11) percent, and decrease the deflection at failure by (7.92) percent. The curve of load-deflection: reducing deflection at symmetrical loads and raising failure load with lowering failure deflection.

- By using a dual layer of (CFRP) sheet, The load at the first crack and failure is increased by (20.00 and 42.75) percent, the deflection at the first crack is increased by (120.24) percent, and the deflection at failure is reduced by (6.01) percent.
- The load-deflection curve: Increases in failure load are accompanied by decreases in failure deflection, and decreases in deflection are also seen at symmetrical loads.
- In future research, it is suggested to employ a different type of rubberized concrete for constructing concrete beams, with waste tire rubber added or substituted for fine and coarse aggregates, and demonstrate the impact of CFRP layer strengthening on the structural behavior of these beams.

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