ISSN 2303-4521
Periodicals of Engineering and Natural Sciences *Original Research*
Vol. 155, No. 3, May 2023, pp.155-175

Flexural behavior of CFRP-strengthened reinforced concrete beams rubberized with finely minced rubber tire

Adnan Abdullah Adday[1] *, Ahmed Sultan Ali [2]
[1,2] College of Engineering, University of Al-Nahrain, Baghdad, Iraq

ABSTRACT

Although using rubber to create reinforced concrete substrates has many benefits, using rubberized concrete substrates, such as beams, is still limited. Where concrete with rubber included in it starts to lose a percentage of its mechanical qualities, such as flexural strength. Conversely, a significant portion of structural uses for strengthening reinforced concrete beams using exterior carbon fiber reinforced polymer (CFRP) sheets are for flexural strengthening. This study used externally bonded carbon fiber-reinforced polymer (CFRP) sheets to compensate for the reduction in flexural strength when creating rubberized concrete beams. The reinforced concrete beams used in this study were divided into three groups, each with three beams. Waste tire rubber was replaced (5%) of the fine aggregate volume in the first group and replaced (10%) in the second group. The reference group consists of the third set of beams. The first concrete beam in any group was always devoid of external strengthening, the second beam had one layer and the third beam had two layers of (CFRP) sheet. The third layer of strengthening was numerically represented using ABAQUS, a finite element analysis program. The results indicate that for two-volume replacement rates of fine aggregate (5 and 10) %, a decrease in ductility will have been accompanied by an improvement in the flexural strength of the rubberized concrete beam when externally strengthening with one, two, and three layers of (CFRP) sheets.

Keywords: Beam strengthening, CFRP sheets, Flexural behavior, Rubberized concrete, Waste tire rubber

Corresponding Author:

Adnan Abdullah Adday
College of Engineering
University of Al-Nahrain, Baghdad, Iraq
E-mail: adnanalqaisy72@gmail.com

1. Introduction

With varying degrees of success, many studies have been done on how to handle the loss of mechanical properties, like the flexural strength of reinforced concrete substrates, because of the addition or replacement of waste tire rubber in the production of these substrates. This research's objective will be to utilize externally adhered (CFRP) sheets on beam soffits to strengthen the flexural strength-reinforced rubberized concrete beams, which have proven to be very effective at strengthening structural members, including beams.

1.1 Rubberized concrete

Using recycled tire rubber in concrete is an intriguing topic because it uses fewer natural resources to make concrete and dispose of used tires [1]. The study of recycling waste tire rubber for use in concrete has increased since 2003. Numerous studies have examined the effectiveness of adding or replacing fine and/or coarse aggregate in concrete in various rubber ratios [2]. Utilizing waste tire rubber will enhance concrete's structural characteristics, such as its resistance to repeated freezing and thawing, deformation capacity, damping capacity (impact resistance), and energy dissipation. Compared to normal concrete, rubberized concrete reported reduced unit weight and appropriate workability. But the tensile, compressive, and flexural strengths as well as the elastic modulus of the concrete may also be lowered as the rubber content increases [3, 4]. When rubber was employed as aggregates, concrete engineering characteristics decreased with increasing rubber content, whereas when rubber was used as filler materials, these properties increased. For all tested beams, the amount of wasted tire rubber reduced load at failure and flexural stiffness. The findings showed that the ductility, toughness, and deformability indices increased as rubber content increased. By incorporating rubber fibers and micro steel fibers, the tested beams' failure mode changes from brittle to ductile [5]. The compressive strength of the concrete was affected by the amount of addition and rubber replacement grain size. When rubber was used instead of cement or aggregate, concrete's compressive, tensile, and flexural strength, besides elastic modulus, dropped for both cases [6]. The larger rubber particles exhibit high workability to other finer ones when preparing concrete specimens. Compared to concrete with larger particles, the water permeability and strength of concrete with smaller rubber particles are better. Continuously graded rubber aggregates of various sizes provide higher water permeability resistance and workability when compared to rubber particles of a single size [7]. The experimental findings of using crumb rubbers and recycled CFRP fibers in concrete production indicate that the mixed composites' compressive strength is slightly enhanced. while the energy absorption capacity, impact resistance, flexural toughness, and ductility are significantly improved. Additionally, the evaluation's findings show that using recycled (CFRP) fiber-reinforced rubberized concrete in the construction industry has a significant positive impact on the environment in terms of both CO_2 emissions and environmental sustainability [8]. As the crumb rubber proportion in the concrete increased, the flexural strength values gradually decreased compared to the control mix [9]. It has been found that rubber aggregates have a lower bulk density and specific gravity than natural coarse aggregates. More rubber aggregates cause concrete to lose density, which helps to lighten the structure by making it more lightweight. On the other hand, the concrete's toughness increases while its compressive strength decreases as the proportion of rubber aggregate increases. Research suggests the ideal replacement rate could replace up to 15% of rubber aggregates [10]. Rubber aggregate in concrete provides better mass loss resistance because its hydrophobic properties prevent acidic solutions from instantly penetrating the concrete matrix right away. The rubber aggregate also made the concrete more resistant to chloride ion diffusion [11]. Poor adhesion and stress concentration are caused by rubber's low elastic modulus, hydrophobicity, and cement matrix adhesion. Rubberized concrete's durability and mechanical properties are enhanced by rubber surface treatment using physical or chemical techniques, which strengthens the bond between both the cement and rubber interface. [12]. Concrete's mechanical properties can typically be decreased by adding rubber, if rubber content and particle size increase, this tendency worsens. Since rubber and cement paste doesn't adhere well to one another, the ruts had an interfacial transition zone. Tensile and flexural strength dropped less than compressive strength [13]. Despite having a substitute ratio of (25%) and a rubber size limit of (12) mm, it was still able to create a flowable mixture including a controlled loss in compression strength, which is a result of the effects of particle packing caused by using rubber aggregates of a high grade, which improved the properties of the concrete. Unlike conventional concrete strengthened with steel fibers, the rubber aggregate mix under study provided better ductility. Concrete is typically reinforced with steel fibers. Compared to conventional concrete, the damping ratio increased by almost (90%) when using well-graded rubber particles in place of (25%) of the aggregates. This concrete can perform better when used in areas with high dynamic loads, including buildings vulnerable to earthquakes. Rubber aggregates changed concrete's brittle failure behavior towards a ductile failure pattern [14]. The crumb rubber concrete frame's maximum seismic response acceleration was (20.40%) which is lower than the conventional concrete frame, demonstrating that during the earthquake, the seismic forces placed on the crumbly rubber concrete frame will indeed be lower than those placed on a conventional concrete frame [15].

1.2 Strengthening of reinforced concrete structures with (CFRP) sheet

There are multiple ways to enhance the flexural performance of a reinforced concrete beam, and one or many factors affect which method is best. These factors comprise the cost of strengthening, an increment in dimensions, the rate of improved load capacity, and the obtainability of used materials. Composites that are externally bonded fiber-reinforced polymers (FRP) can enhance shear and flexural strengths and confine and give ductility to compression members. Carbon fiber reinforced polymers (CFRP), with positive characteristics like corrosion resistance, simple installation, and excellent specific strength, can strengthen concrete structural members [16]. The load-bearing capacity of the reinforced concrete beams increased along with the layer number of the (CFRP) sheet. Compared to un-strengthened beams, strengthened beams have a significantly lower ductility [17]. Increasing the flexure and shear strength by integrating longitudinal (CFRP) sheets with U-side strips. Utilize U-side (CFRP) strips and mechanical anchors to increase the beam's shear strength and longitudinal (CFRP) bond strength. To avoid debonding failure between both the beam soffit and the (CFRP) sheets, U-side strips made of (CFRP) could also be used [18]. With a lower proportion of steel reinforcement

(1%), externally adhered strengthening systems like carbon fiber reinforced polymers (CFRP) are used to strengthen beams. The load growth rate ranges from (26%) to (50%). But with the highest percentage of reinforcement (1.5%) the rate of load growth is around (17%) to (33%). The ductility has decreased due to the brittle failure brought on by the occurrence of end debonding of the (CFRP) strengthening [19]. By applying a second layer of (FRP) composite material to reinforced concrete beams, they can be significantly strengthened; samples of strengthened beams show an increase in strength capacity of (114%) [20]. Soffit-mounted, side-extending (CFRP)-wrapped reinforced concrete beams, together including and not including end anchors, improved the structural performance of the beams' ductility, load-carrying ability, and stiffness [21]. All repaired beams usually regain close to (80%) of their original bearing capacity when reinforced with (CFRP) sheets. The strengthened beam now has an additional (30 to 40) % flexural strength. Since the strengthened beams stiffened, the deflections are significantly reduced. The presence of (CFRP) exterior strengthening prevents some shear cracks from spreading and delays the formation of others [22]. Only when a single layer is used, rupture takes place, whereas de-bonding happens when dual layers are applied. Debonding therefore has a higher probability than rupture as the number of layers rises [23].

1.3 Research significance

The study's main objective is to increase the flexural strength of rubberized reinforced concrete beams so they can be used in construction projects and gain the full benefits of rubberized concrete.

2. Program and equipment for experiments

2.1 Specimens configuration

There were, in total, three reinforced concrete beam groups, each containing three beams with exactly similar mixing parameters. In both the first and second groups, well-graded waste tire rubber will replace (5%) and (10%) of the volume of fine aggregates. The third reference group will utilize a concrete mixture previously intended to be free of used tire rubber. Each beam has the following dimensions: (2.1 m in length ×0.2 m in width ×0.3 m in height). The ACI Code (318-19) [24] was followed in its creation. The same ratio (ρ_{min}) of steel bars is used to reinforce the beams in each of the three groups. As with the tensile zone, two rods with a diameter of (12) mm were used to reinforce the compression zone, and every (200) mm c/c, a stirrup with (12) mm in diameter was used to resist shear stress, as illustrated in Figure 1. The (CFRP) sheets will have adhered to reinforce the lower side of the beams externally with dimensions (2.1×0.2) m, and each group's beams will receive the following strengthening: the first beam is left un-strengthened, the second is given a single layer of reinforcement, and the third is given two layers of reinforcement as depicted in Figures 2 and 3. The third reinforcing layer will be numerically represented using the finite element analysis program ABAQUS. Furthermore, the proportion of water to cement and the quantity of silica fume admixture in each beam will be the same. But to keep the slump at (110 ± 5) mm, the superplasticizer was adjusted. The strain gauges were TML Japanese-made, fixed in the mid of each beam tensile reinforcement. In addition, two strain gauges would be attached in the center of each (CFRP) layer, as shown in Figures 4 and 5.

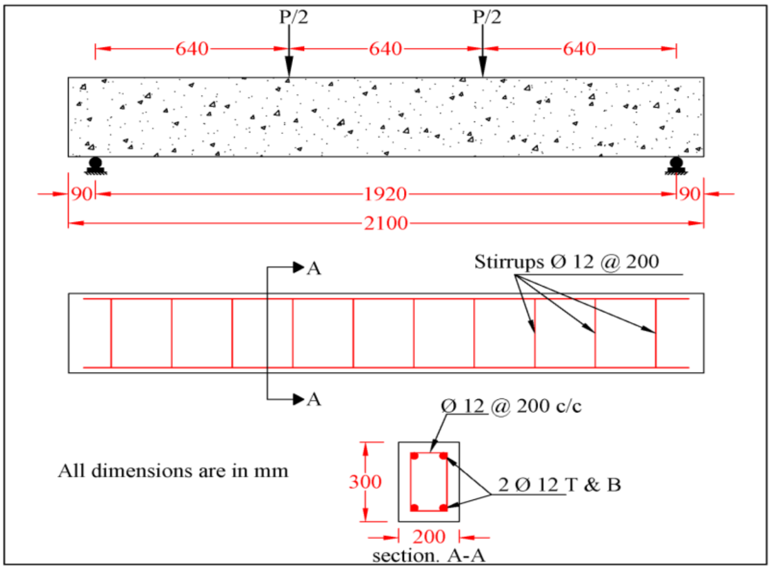

Figure 1. Dimensions and reinforcement specifications for the beam

Figure 2. Beam soffit preparation before CFRP sheets installing

Figure 3. Adhering (CFRP) sheets

Figure 4. Strain gauges installed on the tensile reinforcement

Figure 5. Strain gauges installed on (CFRP) sheets

2.2 Reference mix design

To produce a reference mixture of a compression strength at 28 days of at least (45) MPa, a typical concrete mixture was made using the following ingredients: water, cement, fine aggregate, coarse aggregate, silica fume (MegaAdd MS(D), and superplasticizer (Sika ViscoCreate®-5930L). Table 1 describes the mix's composition in detail.

Table 1. The reference concrete mix's design properties

Cement (kg/m^3)	Silica fume (kg/m^3)	Super plasticizer (Liter/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	W/C ratio
500	25	1.5 – 2.5	680	1020	0.37

According to the technical report for this product, the percentage of the superplasticizer admixtures to cement weight varied in each group's casting process from (0.3 to 0.5%).

2.3 Rubber sizes are utilized as a substitute for fine aggregates

The sizes of used waste tire rubber, as a percent of fine aggregates, are shown in Table 2.

2.4 Materials Quantities Employed in Research

The quantities of raw materials, waste tire rubber, and additives utilized in the concrete beam mixtures are broken down in Table 3 below.

2.5 (CFRP) sheets for external strengthening

The flexural properties of concrete beams were enhanced using unidirectional (CFRP) sheets. The (CFRP) sheets' detailed requirements are listed in Table 4 below through lab test verification, which includes authorized specifications next to each experimental result.

Table 2. Sieve analysis of rubber employed as a fine aggregate according to IQS No. 45/1984 (zone 2) [25]

Sieve size (mm)	Passing (%)	Limits
4.75	95	90 – 100
2.36	88	75 – 100
1.18	73	55 – 90
0.6	48	35 – 59
0.3	19	8 – 30
0.15	5	0 – 10

Table 3. Quantities of materials used to execute a concrete beam

Group No.	Group symbol	volumetric replacement	Beam symbol	Water (Liter)	Cement (Kg)	Coarse aggregate (Kg)	Fine aggregate (Kg)	Fine 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	94.75	1.99	3.67	0.4	0	2
			B1-1	27.13	73.33	149.6	94.75	1.99	3.67	0.4	1	4
			B1-2	27.13	73.33	149.6	94.75	1.99	3.67	0.4	2	6
Group 2	**B2**	10 %	B2-0	27.13	73.33	149.6	89.76	3.99	3.67	0.35	0	2
			B2-1	27.13	73.33	149.6	89.76	3.99	3.67	0.35	1	4
			B2-2	27.13	73.33	149.6	89.76	3.99	3.67	0.35	2	6
Group 3	**BR**	0 %	BR-0	27.13	73.33	149.6	99.75	–	3.67	0.4	0	2
			BR-1	27.13	73.33	149.6	99.75	–	3.67	0.4	1	4
			BR-2	27.13	73.33	149.6	99.75	–	3.67	0.4	2	6

Table 4. 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 [26]
Laminates elasticity modulus (KN/mm^2)	220	210	
laminates elongation at break in tension (%)	1.59	–	
Tensile resistance (N/mm)	585	534	

3. Testing program

3.1 Tests on fresh concrete

The slump test, which was conducted in accordance with the recommendations in ASTM C143-01a [27], was used to assess the workability of every group mix. For each group mix, the superplasticizer was changed to maintain a slump of (110 ± 5) mm.

3.2 Tests on hardened concrete

Two-point monotonic loading was used to test the flexural response of a beam with an effective span of (1.92) m, as shown in Figure 6.

Figure 6. Flexural testing machine

Concrete was subjected to compression strength testing (f_{cu}) at (28) days of age and the beam test age in accordance with BS (1881 - part 116:2000) [28]. Flexural testing was done in accordance with ASTM C78-02 [29] to confirm the rupture modulus (f_r). For beam test specimens, the splitting tensile strength (f_t) at the testing age was measured using the ASTM C496-04 [30] specifications. The static elasticity modulus (E_c) of concrete was calculated in accordance with ASTM C469-02 [31]

4. Layout of experimental study

4.1 Concrete properties

When used in place of a specific percentage of fine aggregate in concrete beams, waste tire rubber exhibits behavior that must be identified in terms of its mechanical properties. Due to the volumetric replacement of waste tire rubber, compared to the properties of reference concrete from Group (BR), the values for hardened rubberized concrete are shown in Table 5. At age (28) days, rubber concrete's mechanical characteristics (elastic modulus, splitting tensile strength, rupture modulus, compressive strength, and density) were compared to those of reference concrete, if the fine aggregate replacement rate is (5%), the quantities will decrease by (6.18, 19.57, 10.95, 14.21, and 1.41) %, and by (11.44, 28.03, 16.8, 22.32, and 2.18) %, respectively, if the replacement rate for fine aggregates is (10%).

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)
	Group symbol	Beams included					
Group 1	B1	B1-0, B1-1 & B1-2	2304	39.257	3.669	3.082	27027
Group 2	B2	B2-0, B2-1 & B2-2	2286	35.544	3.428	2.758	25513
Group 3	BR	BR-0, BR-1 & BR-2	2337	45.759	4.120	3.832	28808

4.2 Flexural test results and discussion

Table 6 lists the experimental results, load, and deflection at the first crack with load and deflection at the failure, which represents the flexural response to two-point monotonic loading carried out on these three groups of concrete beams, this demonstrates a reduction in load at the first crack, and failure happens when volumetric replacement of fine aggregates with well-graded waste tire rubber by (5 and 10) %.

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	30	1.457	146.3	30.516
		B1-1	39	1.829	189.2	18.911
		B1-2	47	2.188	227.7	23.897
Group 2	B2	B2-0	27	1.014	143.5	33.621
		B2-1	39	1.641	168.3	18.064
		B2-2	41	1.698	222	24.382
Group 3	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

1- Table 7 includes a comparison of the group (B1) beams that are rubberized by a (5%) volumetric replacement of fine aggregates according to the information below:
   a) Comparison of un-strengthened beams (B1-0) with (BR-0): Crack and failure load decreased by (14.29 and 2.27) % respectively, accompanied with increasing of the crack and failure deflection by (43.12 and 30.43) % correspondingly.
   b) Comparison of strengthened beams (B1-1) and (B1-2):
      - Compared to the (B1-0), un-externally strengthened beam within the same group: the first crack load increased by (30 and 56.67) %, the failure load increased by (29.32 and 55.74) %, the first crack deflection increased by (12.63 and 16.54) %, and the failure deflection decreased by (21.69 and 38.03) %, respectively.
      - Compared to the (BR-0), un-externally strengthened beam within the reference group: the first crack load increased by (11.43 and 34.29) %, the failure load increased by (26.39 and 52.10) %, the deflection at the first crack increased by (79.67 and 114.93) %, and the deflection at failure decreased by (19.17 %) and increased by (2.14) %, respectively.
      - Compared to the symmetrical beams in the reference group: the first crack load increased by (17.02 and 4.08) %, the failure load increased by (9.81 and 4.12) %, the first crack deflection increased by (11.05 and 15.04) %, and the deflection at failure increased by (14.16 and 41.96) %, respectively.

2- Table 8. includes a comparison of the group (B2) beams that rubberized by a (5%) volumetric replacement of fine aggregates according to the information below:
   a) Comparison of un-strengthened beams (B2-0) with (BR-0):
   Crack and failure load decreased by (22.86 and 4.14) % respectively, accompanied with decreasing in the crack deflection by (0.39 %) and increasing the failure deflection by (43.7 %).
   b) Comparison of strengthened beams (B2-1) and (B2-2):
      - Compared to the (B2-0), un-externally strengthened beam within the same group: the first crack load increased by (44.44 and 51.85) %, the failure load increased by (17.28 and 54.72) %, the first crack deflection increased by (61.83 and 67.46) %, and the failure deflection decreased by (46.27 and 27.48) %, respectively.
      - Compared to the (BR-0), un-externally strengthened beam within the reference group: the first crack load increased by (11.43 and 17.17) %, the failure load increased by (12.42 and 48.30) %, the deflection at the first crack increased by (61.20 and 66.8) %, and the deflection at failure decreased by (22.79 %) and increased by (4.21) %, respectively.
      - Compared to the symmetrical beams in the reference group: the first crack load decreased by (17.02 and 16.33) %, the failure load decreased by (2.32) % and increased by (1.51) %, the first crack deflection decreased by (0.36 and 10.73) %, and the deflection at failure increased by (9.05 and 44.84) %, respectively.

Table 7. Load with the deflection at the first crack and load with the deflection at failure comparison results of the group (BR) and (B1) beams

Load at the first crack (KN)				Comparative ratio to the beam (B1-0) (%)		Comparative ratio to the beam (BR-0) (%)		Comparative ratio to a similar reference beam (%)	
The reference group (BR)		Group (B1)							
Beam	Load	Beam	Load	Lower by	Greater by	Lower by	Greater by	Lower by	Greater by
BR-0	35	B1-0	30	–	–	14.29	–	14.29	–
BR-1	47	B1-1	39	–	30	–	11.43	17.02	–
BR-2	49	B1-2	47	–	56.67	–	34.29	4.08	–
Deflection at the first crack (mm)									
The reference group (BR)		Group (B1)							
Beam	Deflection	Beam	Deflection						
BR-0	1.018	B1-0	1.457	–	–	–	43.12	–	43.12
BR-1	1.647	B1-1	1.829	–	25.53	–	79.67	–	11.05
BR-2	1.902	B1-2	2.188	–	50.17	–	114.93	–	15.04
Load at failure (KN)									
The reference group (BR)		Group (B1)							
Beam	Load	Beam	Load						
BR-0	149.7	B1-0	146.3	–	–	2.27	–	2.27	–
BR-1	172.3	B1-1	189.2	–	29.32	–	26.39	–	9.81
BR-2	218.7	B1-2	227.7	–	55.64	–	52.10	–	4.12
Deflection at failure (mm)									
The reference group (BR)		Group (B1)							
Beam	Deflection	Beam	Deflection						
BR-0	23.397	B1-0	30.516	–	–	–	30.43	–	30.43
BR-1	16.565	B1-1	18.911	38.03	–	19.17	–	–	14.16
BR-2	16.834	B1-2	23.897	21.69	–	–	2.14	–	41.96

Table 8. Load with the deflection at the first crack and load with the deflection at failure comparison results of the group (BR) and (B2) beams

Load at the first crack (KN)				Comparative ratio to the beam (B2-0) (%)		Comparative ratio to the beam (BR-0) (%)		Comparative ratio to a similar reference beam (%)	
The reference group (BR)		Group (B1)							
Beam	Load	Beam	Load	Lower by	Greater by	Lower by	Greater by	Lower by	Greater by
BR-0	35	B2-0	27	–	–	22.86	–	22.86	–
BR-1	47	B2-1	39	–	44.44	–	11.43	17.02	–
BR-2	49	B2-2	41	–	51.85	–	17.14	16.33	–
Deflection at the first crack (mm)									
The reference group (BR)		Group (B1)							
Beam	Deflection	Beam	Deflection						
BR-0	1.018	B2-0	1.014	–	–	0.39	–	0.39	–
BR-1	1.647	B2-1	1.641	–	61.83	–	61.20	0.36	–
BR-2	1.902	B2-2	1.698	–	67.46	–	66.80	10.73	–
Load at failure (KN)									
The reference group (BR)		Group (B1)							
Beam	Load	Beam	Load						
BR-0	149.7	B2-0	143.5	–	–	4.14	–	4.14	–
BR-1	172.3	B2-1	168.3	–	17.28	–	12.42	2.32	–
BR-2	218.7	B2-2	222.0	–	54.70	–	48.30	–	1.51

Load at the first crack (KN)				Comparative ratio to the beam (B2-0) (%)		Comparative ratio to the beam (BR-0) (%)		Comparative ratio to a similar reference beam (%)	
The reference group (BR)		Group (B1)							
Beam	Load	Beam	Load	Lower by	Greater by	Lower by	Greater by	Lower by	Greater by
Deflection at failure (mm)									
The reference group (BR)		Group (B1)							
Beam	Deflection	Beam	Deflection						
BR-0	23.397	B2-0	33.621	–	–	–	43.70	–	43.70
BR-1	16.565	B2-1	18.064	46.27	–	22.79	–	–	9.05
BR-2	16.834	B2-2	24.382	27.48	–	–	4.21	–	44.84

3- Load-deflection relationship of the group (B1) beams is shown in Figure 7 which makes it obvious that the external adhering of a single and dual layer of (CFRP) sheets to the beam (B1-1) and (B1-2) respectively, reduces deflection at similar load levels while increasing the failure loads and decreasing failure deflection. Figure 8 shows the load-deflection diagram of the reference group (BR) beams. Figure 9 shows the convergence between the load defection curves for the beams (B1-0) and (BR-0) in most stages of loading with a slight decrease in the curve of the beam (B1-0), because the replacement rate of fine aggregates is low (5%) and the waste rubber tires are well graded. Figure 10 demonstrates the convergence of the load defection curves for the beams (B1-1) and (BR-1) in most loading stages with a slight decrease in the beam's curve (B1-1), with greater

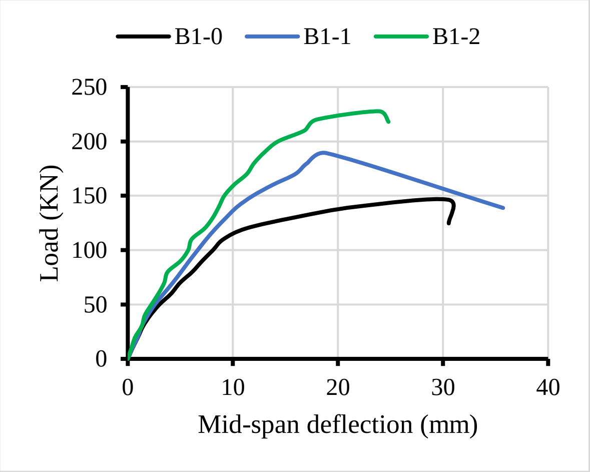

Figure 7. Group (B1) beams' load-deflection diagram

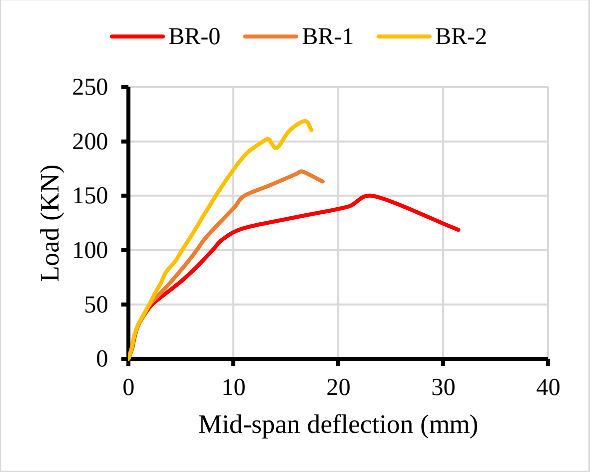

Figure 8. Group (BR) beams' load-deflection diagram

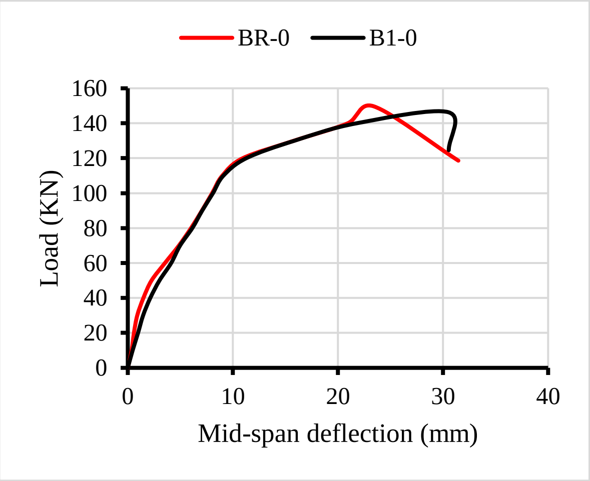

Figure 9. The beams' (BR-0) load-deflection diagram, and (B1-0)

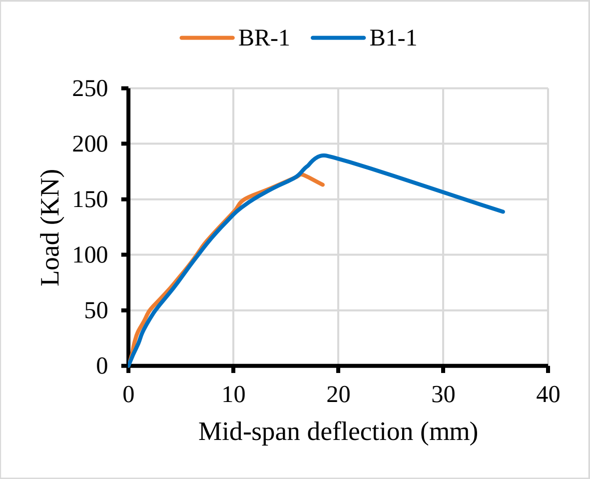

Figure 10. The beams' (BR-1) load-deflection diagram, and (B1-1)

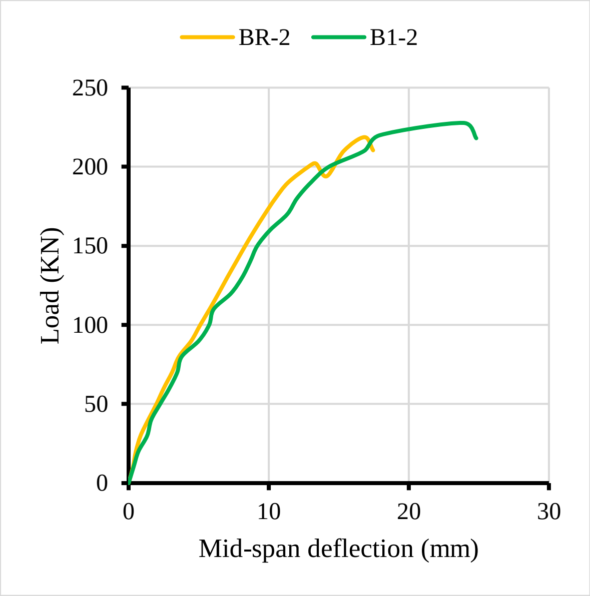

Figure 11. The beams' (BR-2) load-deflection diagram, and (B1-2)

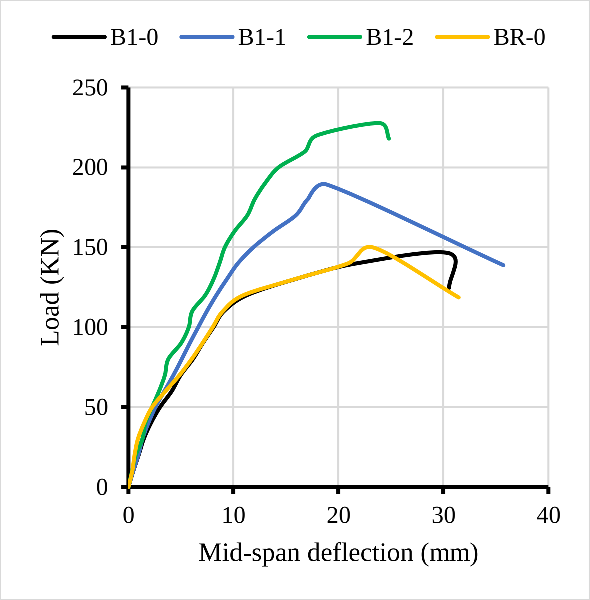

Figure 12. Group (B1) beams' load-deflection diagram, and (BR-0)

4- Figure 13's depiction of the load-deflection relationship for the group (B2) beams makes it clear that adding a single or dual layer of (CFRP) sheets to the beams (B2-1) and (B2-2), respectively, externally reduces deflection at the same load levels while increasing the failure loads and lowering failure deflection.

Figure 14 shows that the beam (B2-0) fails with less load and greater deflection than the beam (BR-0), despite having a lower load-deflection curve. Figure 15 shows that the beam (B2-1) fails with less load and deflection than the beam (BR-1), and has a lower load-deflection curve. According to Figure 16, the beam (B2-2) has a lower load-deflection curve and fails at a larger load and deflection than the beam (BR-2). Figure 17 shows the improvement in the load-deflection curves of beams (B2-1) and (B2-2) compared to beam (BR-0).

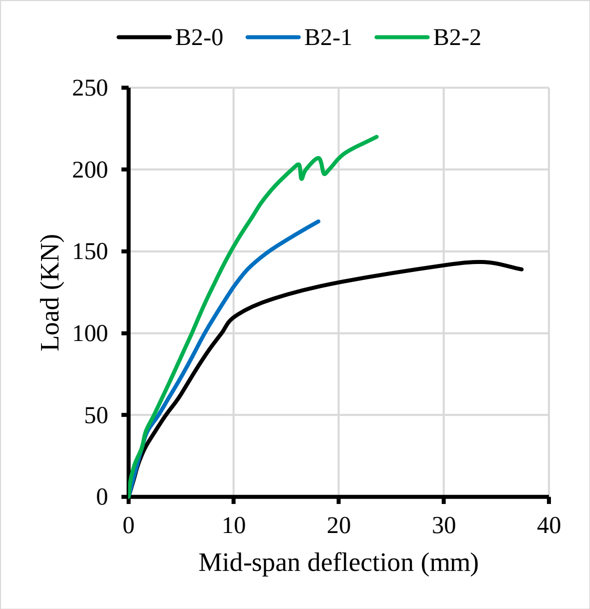

Figure 13 Group (B2) beams' load-deflection diagram

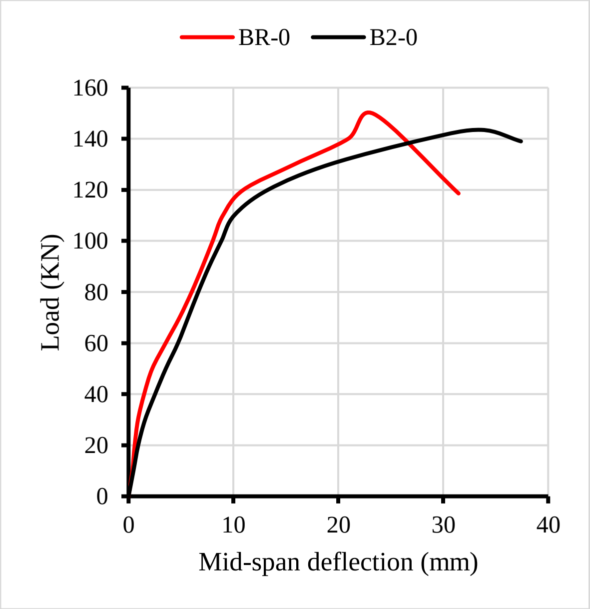

Figure 14. The beams' load-deflection diagrams (BR-0) and (B2-0)

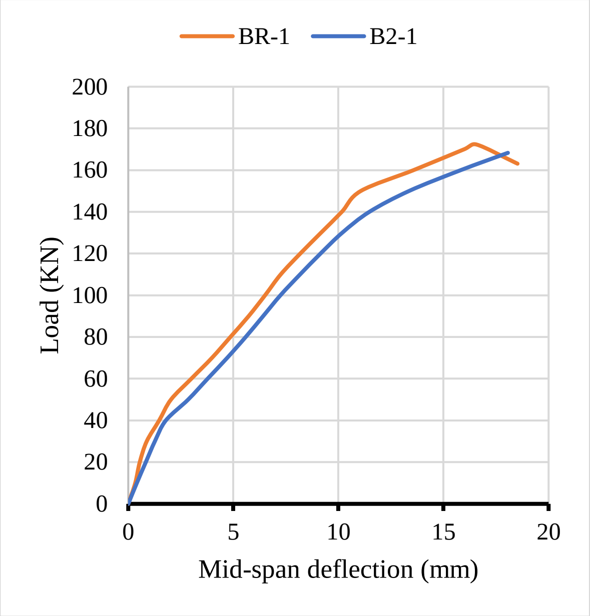

Figure 15. The beams' load-deflection diagrams (BR-1) and (B2-1)

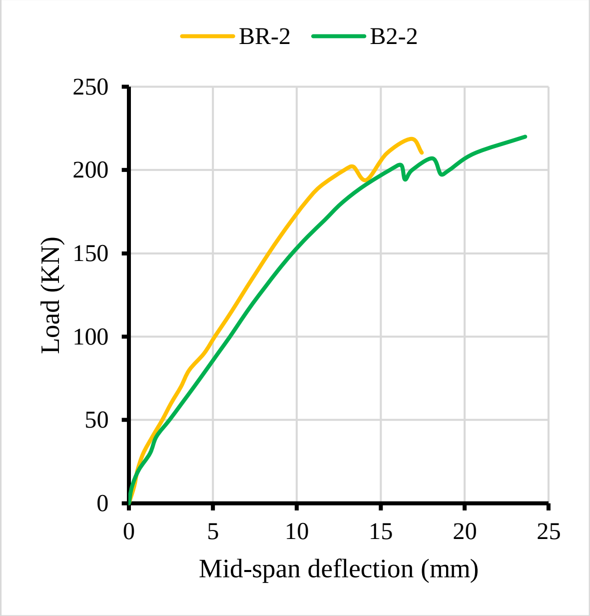

Figure 16. The beams' load-deflection diagrams (BR-2) and (B2-2)

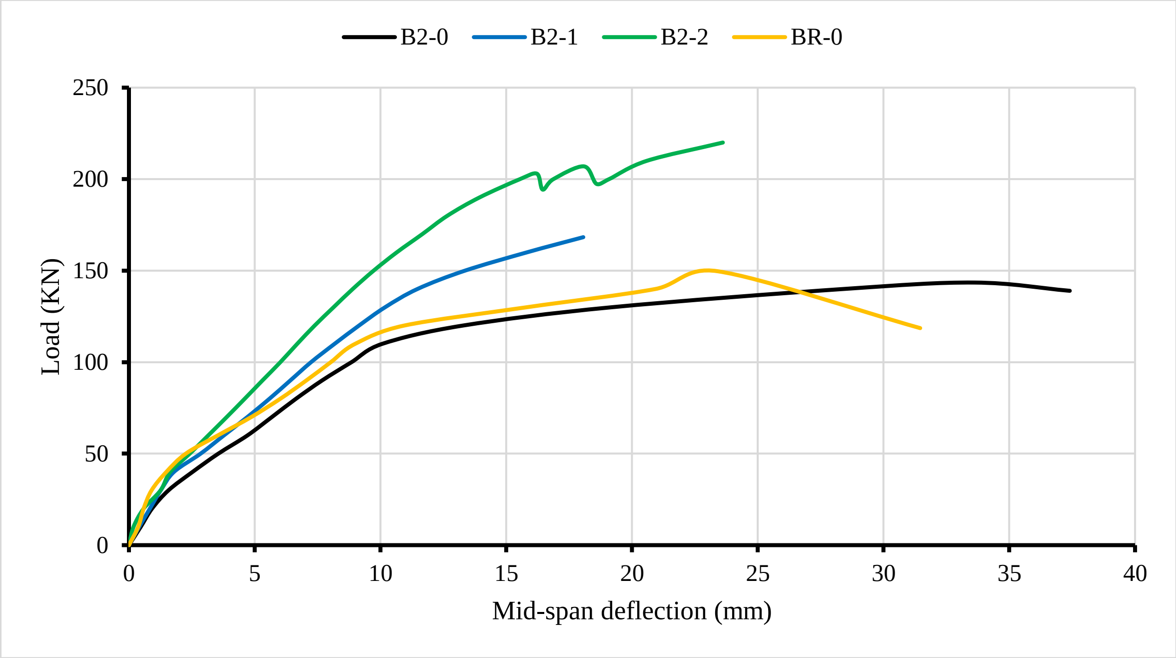

Figure 17. Group (B2) beams' load-deflection diagram, and (BR-0)

5- At failure, the tensile reinforcement of the beam (B1-0) experiences greater strain than the beam (BR-0) as illustrated in Figure 18. But at symmetrical loads up to (85%) of failure load, the beam's (BR-0) steel reinforcement strain is greater than that of the beam (B1-0).
The first layer of the (CFRP) sheet on the beams (BR-1) and (B1-1) experiences more strain under symmetrical load than their steel reinforcement as shown in Figure 19.
Under symmetrical load, the second layer of (CFRP) sheet of the beams (BR-2) and (B1-2) experiences higher strain than the first layer of the beams (BR-1) and (B1-1), which itself experiences higher strain than the strain of the steel reinforcement of the beams (BR-0) and (B1-0) as shown in Figure 20.

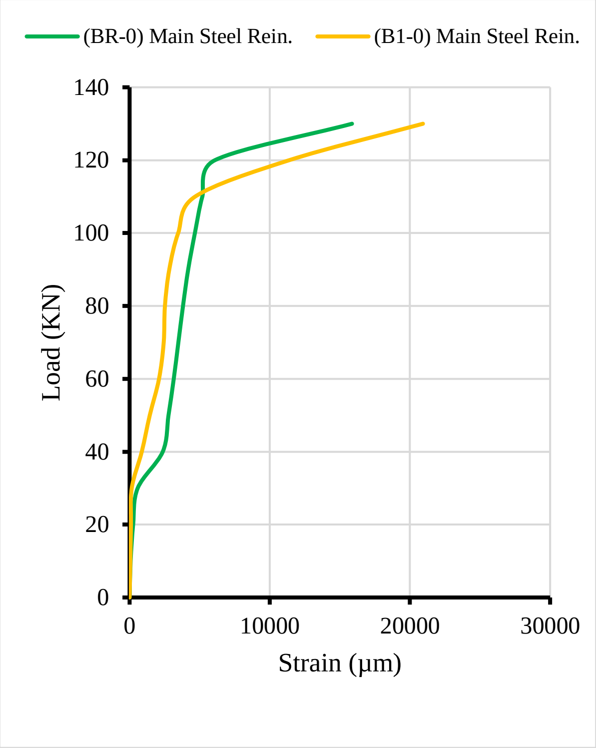

Figure 18. Diagram of the main steel reinforcement load-strain for the beams (BR-0) and (B1-0)

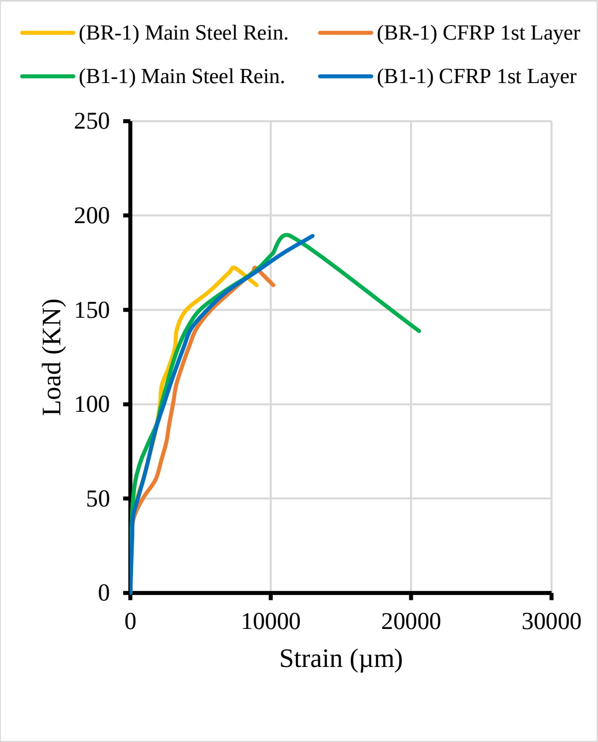

Figure 19. Load-strain diagram of (CFRP) sheet and main steel reinforcement of the beams (BR-1) and (B1-1)

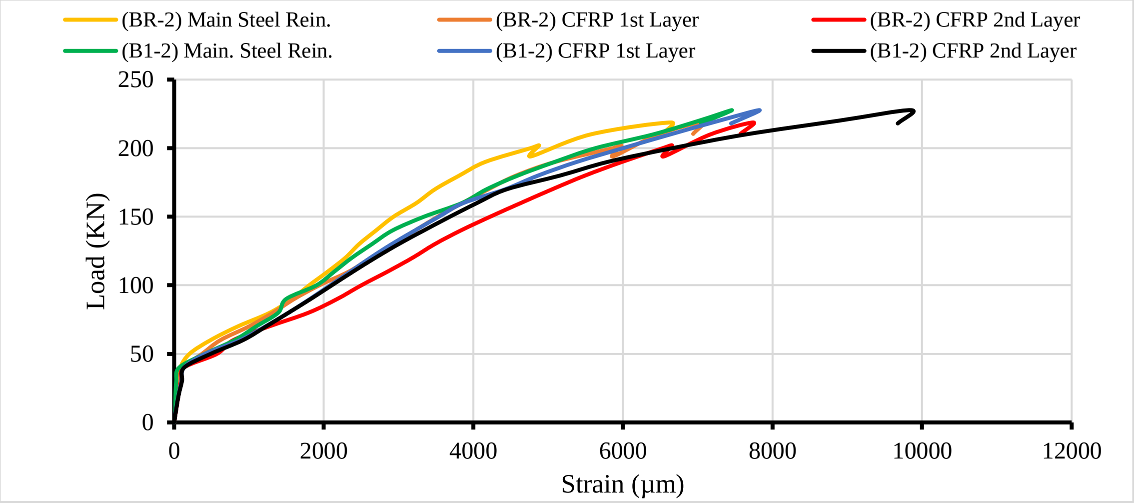

Figure 20. Load-strain diagram of (CFRP) sheet and main steel reinforcement of the beams (BR-2) and (B1-2)

6- As shown in Figure 21, the tensile reinforcement of the beam (B2-0) experiences more strain at failure than the beam (BR-0). However, under symmetrical loads, the (BR-0) steel reinforcement of the beam experiences a greater strain than the beam (B2-0) itself. Under symmetrical load, the (CFRP) sheet's first layer on beams (BR-1) and (B2-1) experiences greater strain than the steel reinforcement as illustrated in Figure 22. According to Figure 23, under symmetrical load, the second layer of (CFRP) sheet of the beams (BR-2) and (B2-2) experiences higher strain than the first layer of the beams (BR-1) and (B2-1), which in turn experiences higher strain than the strain of the beams' steel reinforcement (BR-0) and (B2-0).

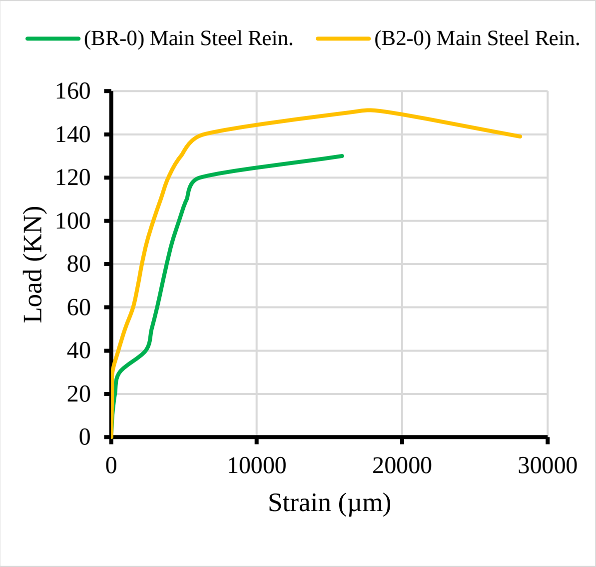

Figure 21. Diagram of the main steel reinforcement load-strain for the beams (BR-0) and (B2-0)

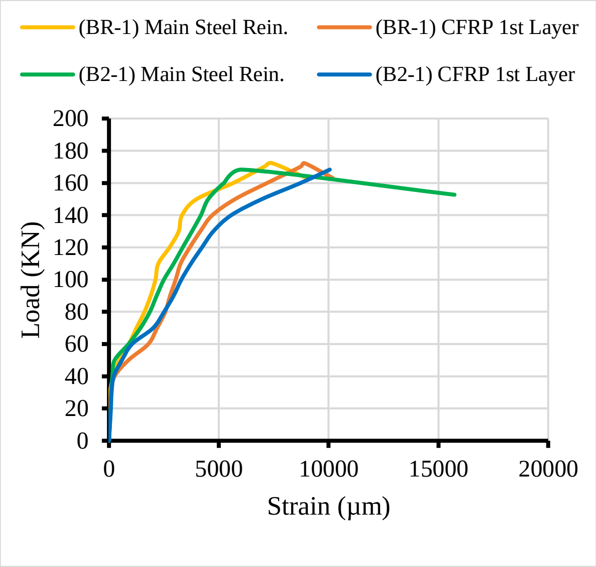

Figure 22. Load-strain diagram of (CFRP) sheet and main steel reinforcement of the beams (BR-1) and (B2-1)

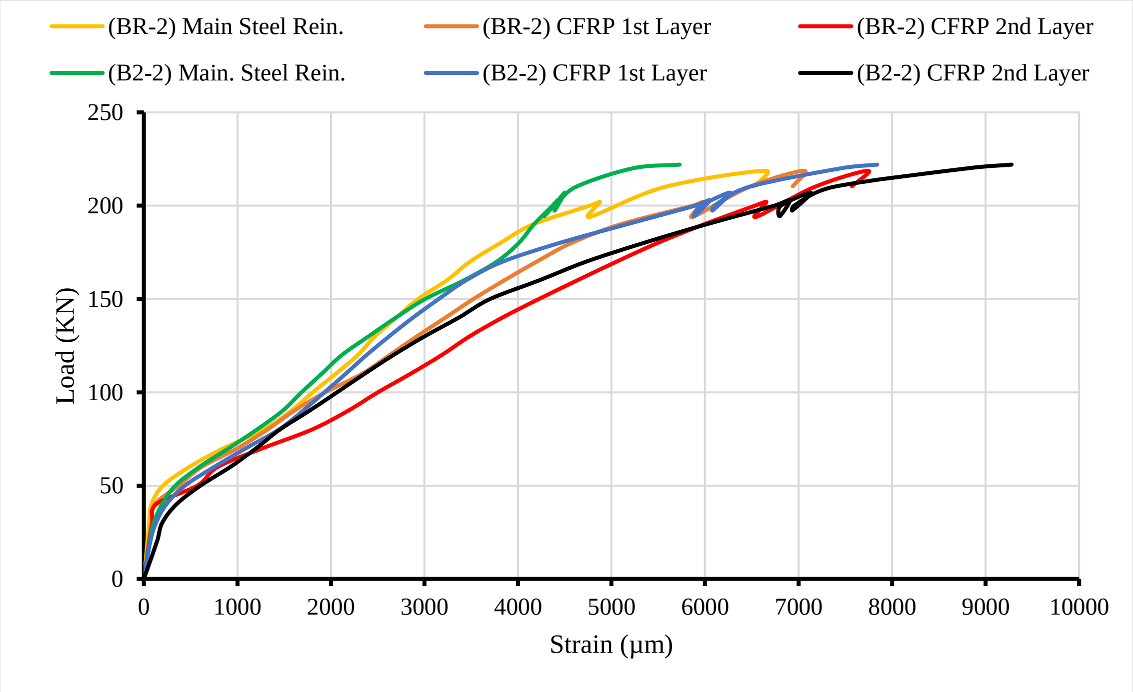

Figure 23. Load-strain diagram of (CFRP) sheet and main steel reinforcement of the beams (BR-2) and (B2-2)

7- The failure mode of beams externally reinforced with a single layer of CFRP sheet, such as the beams (BR-1), (B1-1), and (B2-21), 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), (B1-2), and (B2-2) 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. Figures 24, 25, and 26 show the deformation patterns of all beams.

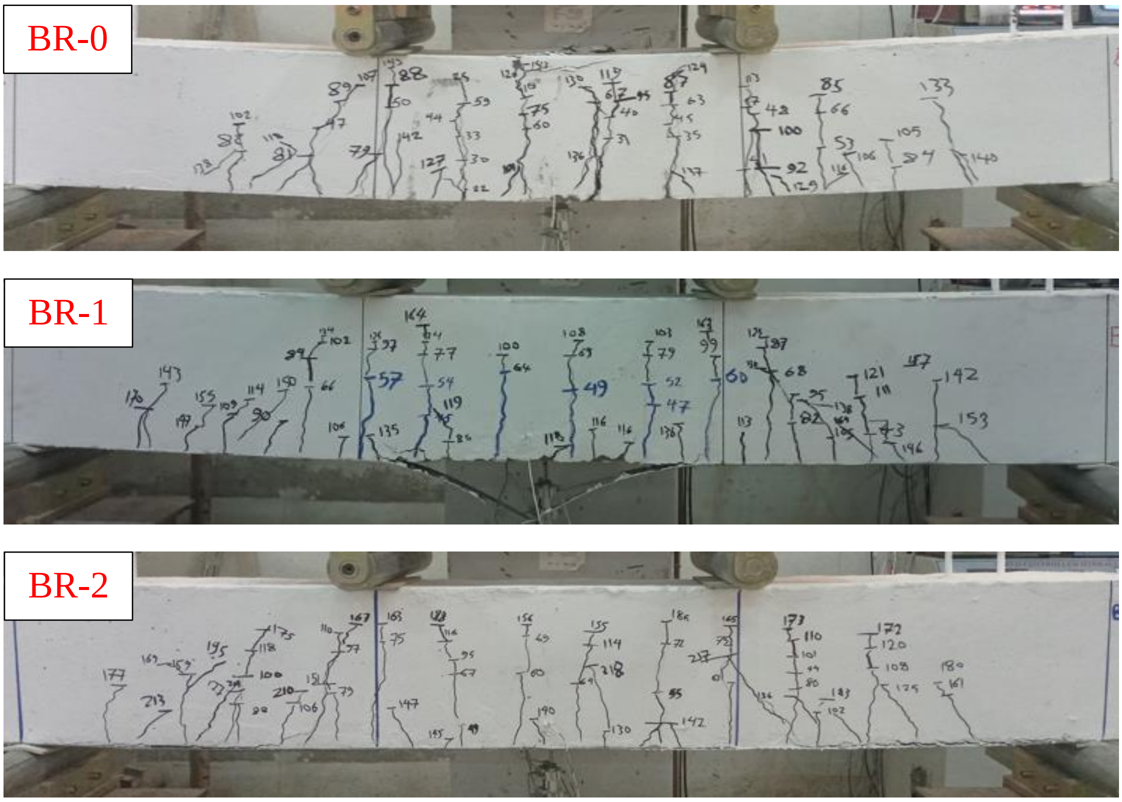

Figure 24. The group (BR) beams, BR-0, BR-1, and BR-2 deformation pattern.

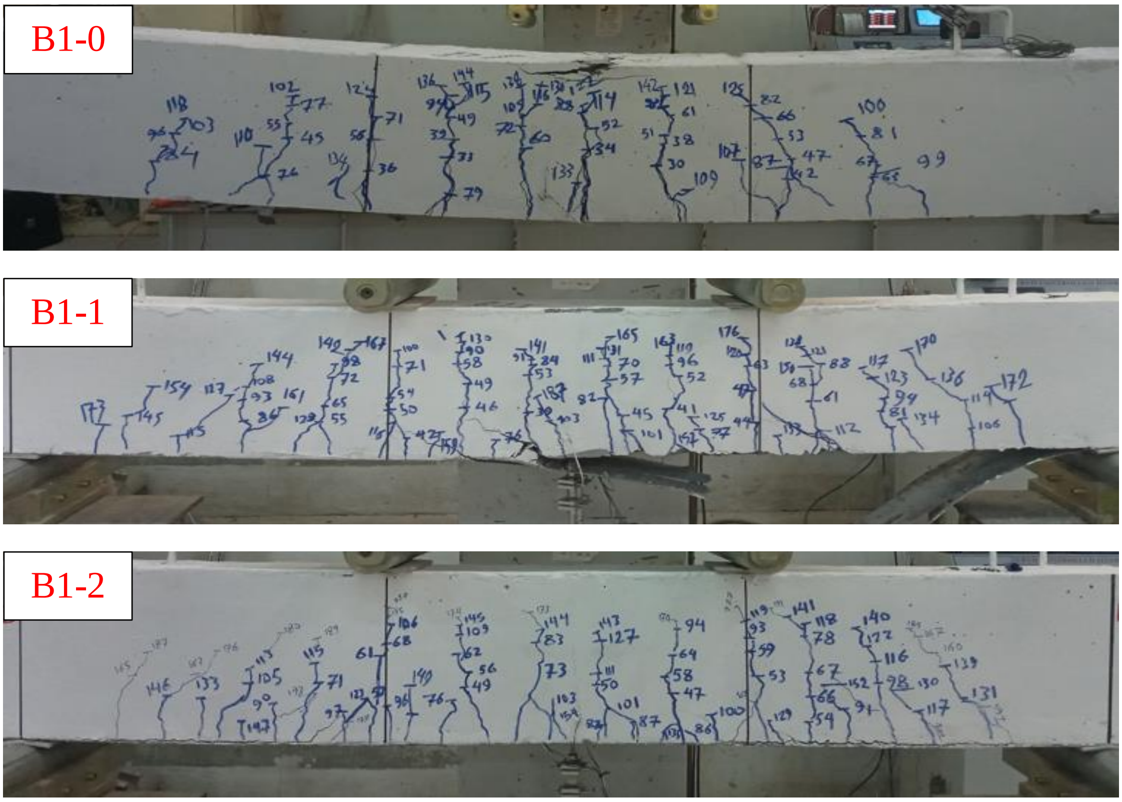

Figure 25. The group (B1) beams, B1-0, B1-1, and B1-2 deformation pattern.

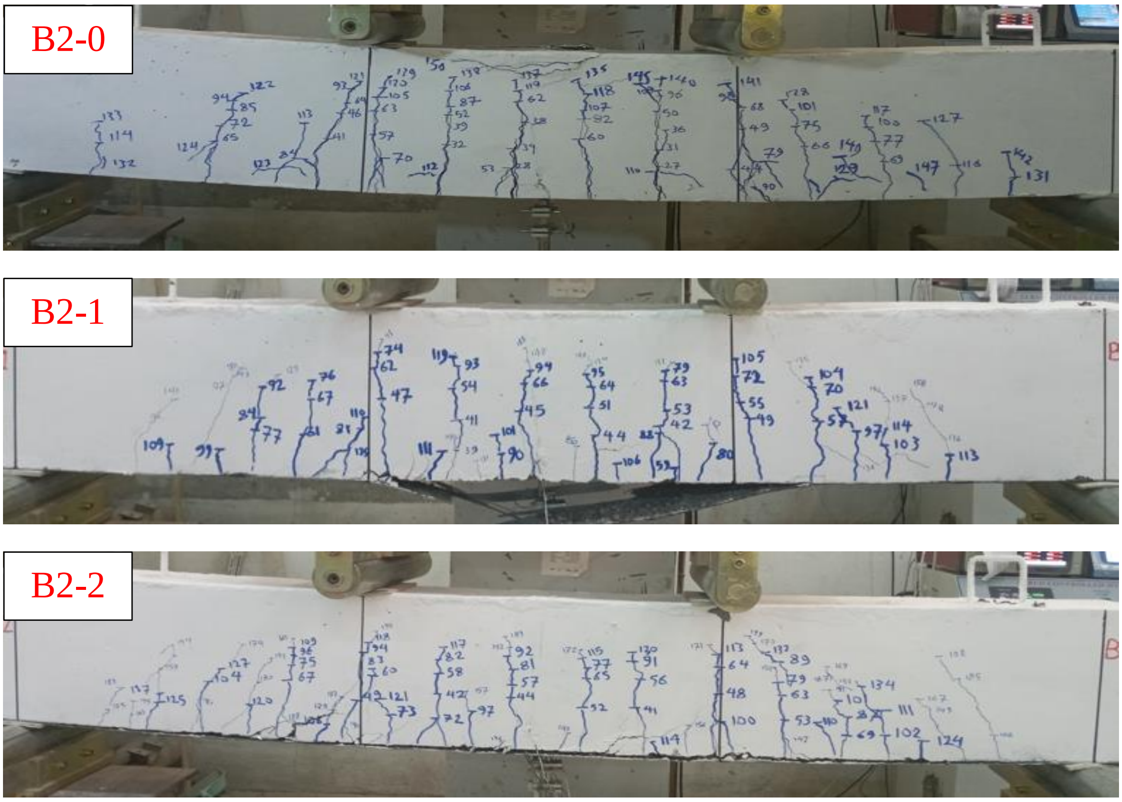

Figure 26. The group (B2) beams, B2-0, B2-1, and B2-2 deformation pattern.

8- Using the ABAQUS finite element program (version 2021) [32], the flexural behavior of the beams in each of the three groups was investigated. Then, for one beam from each group, three layers of strengthening by CFRP sheet were represented by numerical simulations. Figure 27 shows how the beam has been mesh (divided) into excessive small maximum sizes for finite elements (25) mm in each direction.

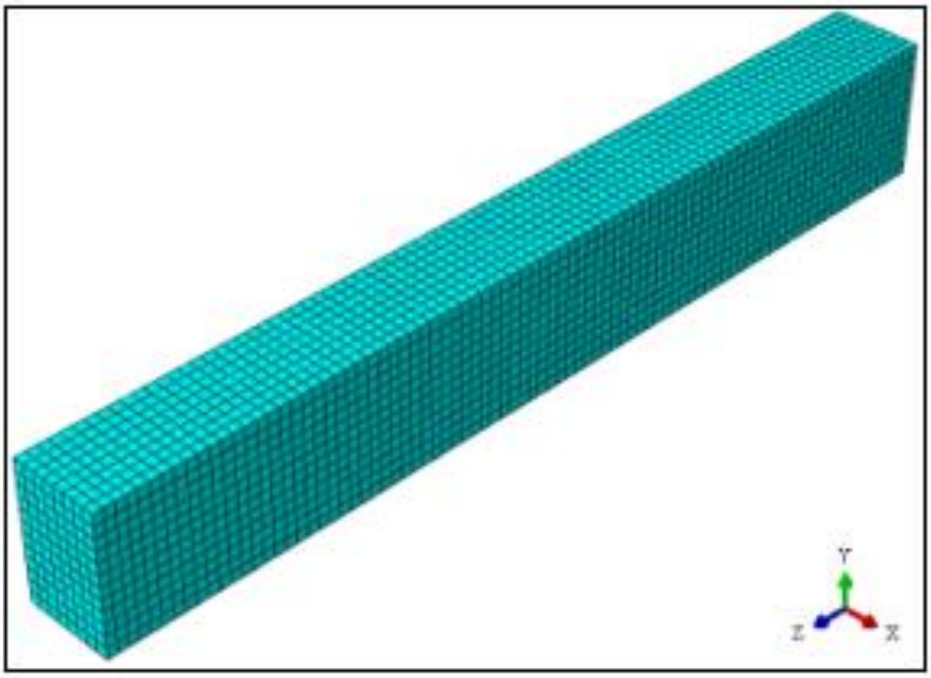

Figure 27. Simulating beam specimens with finite element meshes

The beam was simply supported at both ends. A (Y) direction constraint was used to transform one of the supports into a roller (UY = 0). By constraining the (X, Y, and Z) directions, another support was transformed into a hinge (UY = UX = UZ = 0). According to Figure 28.

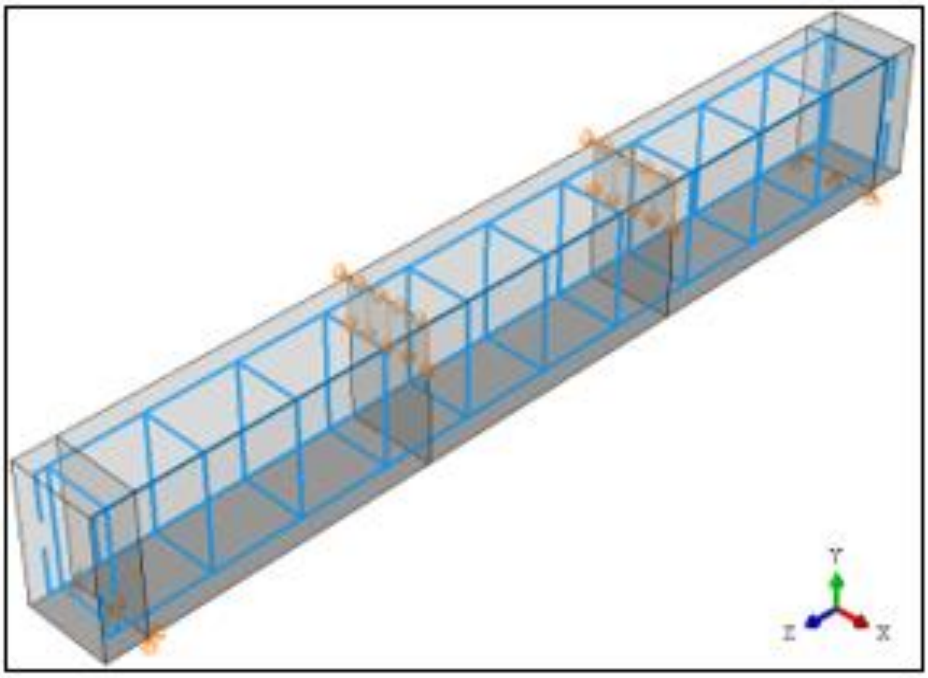

Figure 28. Boundary conditions

It was possible to determine the stress-strain curve for each beam using curves for rubberized concrete evaluated by Kristina Stryker [33], curves for composite concrete determined by P. Kmiecik and M. Kamiski [34], and the ABAQUS user's guide [32]. Table 9 shows the standard ABAQUS data as well as steel reinforcement data.

Table 9. Steel reinforcement and the default ABAQUS input data

Steel reinforcement area (mm^2)	113
Steel yield strength (MPa)	442
Steel elasticity modulus (MPa)	200000
Steel Poisson's ratio (assumed)	0.3
Concrete Poisson's ratio	0.2
Dilation angle	36°
Eccentricity	0.1
$\sigma b0/\sigma c0$	1.16
K	0.667
Viscosity parameters	0.001

The load-deflection diagrams for the beams that were numerically strengthened with three layers of (CFRP) sheets are shown in Figures 29, 30, and 31; each beam's curve is drawn within the curves of the other beams in its group. The load-deflection curve of the beam (BR-3) that externally strengthening with three layers of (CFRP) sheets shows lower deflection at matched load levels, higher failure load, and lessens deflection when the beams fail. For the beams (B1-3) and (B2-3), the deflection is less at symmetrical loads than it is for the beam strengthened with two layers of CFRP sheets, roughly up to 75% of the load-deflection curve, but then the opposite occurs due to the subsequent debonding brought on by the concrete cover layer's weakened state at the location of the adhesive to transfer the load applied to three layers of CFRP sheets.

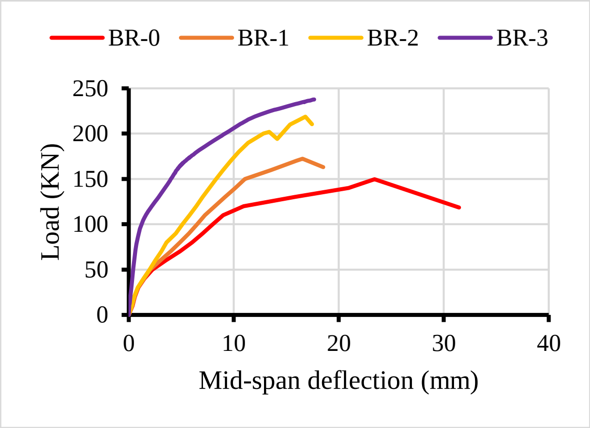

Figure 29. The beam's (BR-3) numerical load-deflection diagram with the remaining group beams' experimental load-deflection diagram

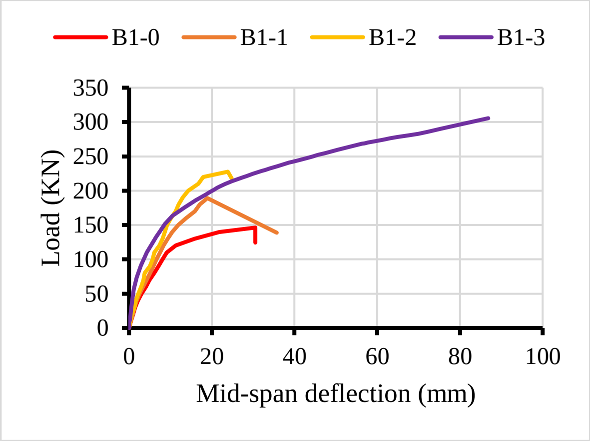

Figure 30. The beam's (B1-3) numerical load-deflection diagram with the remaining group beams' experimental load-deflection diagram

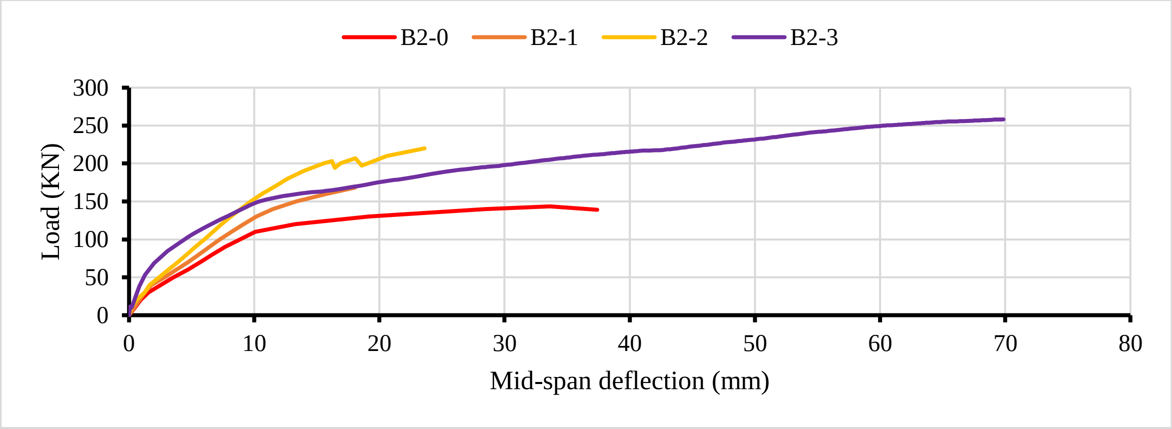

Figure 31. The beam's (B2-3) numerical load-deflection diagram with the remaining group beams' experimental load-deflection diagram

Tables 10 and 11 also show the behavior of beams in terms of first crack loading with deflection and failure loading with deflection, and the findings were contrasted with the behavior of the other beams in the reference group. Figure 32 illustrates the deflection pattern of beams (BR-3), (B1-3), and (B2-3).

Table 10. Load with the deflection at the first crack comparison results of numerically strengthened beams by three layers of (CFRP) sheets with reference beams

Load and deflection at the first crack						Load at the first crack comparison			Deflection at the first crack comparison		
Reference group (BR)			Groups (B1) and (B2)			Comparative ratio to:			Comparative ratio to:		
Beam	Load (KN)	Def. (mm)	Beam	Load (KN)	Def. (mm)	unstren-gthen beam in the same group (%)	(BR-0) beam in the reference group (BR) (%)	(BR-3) beam in the reference group (BR) (%)	unstren-gthen beam in the same group (%)	(BR-0) beam in the eference group (BR) (%)	(BR-3) beam in the reference group (BR) (%)
BR-3	50.68	0.412	B1-3	40.33	0.76	+ 34.43	+ 15.23	– 20.42	– 47.84	– 25.34	+ 84.47
			B2-3	38.10	0.82	+ 41.11	+ 8.86	– 24.82	– 19.13	– 19.45	+ 99.03

Table 11. Load with the deflection at failure comparison results of numerically strengthened beams by three layers of (CFRP) sheets with reference beams

Load and deflection at failure						Load at failure comparison			Deflection at failure comparison		
Reference group (BR)			Groups (B1) and (B2)			Comparative ratio to:			Comparative ratio to:		
Beam	Load (KN)	Def. (mm)	Beam	Load (KN)	Def. (mm)	unstren-gthen beam in the same group (%)	(BR-0) beam in the reference group (BR) (%)	(BR-3) beam in the reference group (BR) (%)	unstren-gthen beam in the same group (%)	(BR-0) beam in the reference group (BR) (%)	(BR-3) beam in the eference group (BR) (%)
BR-3	237.7	17.65	B1-3	275.1	62	+ 88.04	+ 83.77	+ 15.73	+ 103.2	+ 165	+ 251.2
			B2-3	247.9	58.8	+ 72.75	+ 65.6	+ 4.29	+ 74.89	+ 151.3	+ 233.1

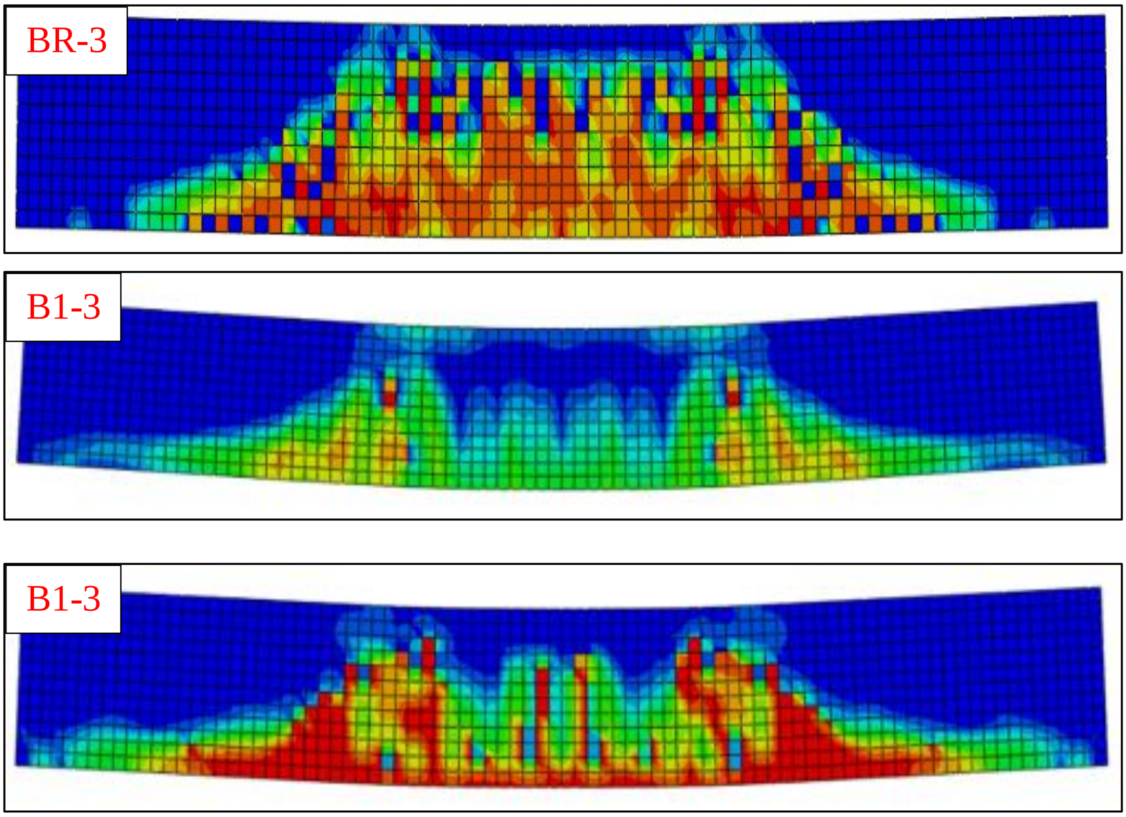

Figure 32. the beams (BR-3), (B1-3), and (B2-3) failure pattern

5. Conclusion

The main objective of this study is to demonstrate the recoverability of the flexural strength lost during the production of rubberized reinforced concrete beams. As a logical consequence, the comparison that is most relevant to the research's goal will be between rubberized reinforced concrete beams that were strengthened by one, two, or three layers of CFRP sheets and the reference reinforced concrete beam which is non-rubberized and non-eternally strengthened.

First, when waste tire rubber was used to replace fine aggregates in a volumetric ratio of (5%), All mechanical properties decreased, including rupture modulus, splitting tensile strength, density, elasticity modulus, and compression strength, and a (10%) replacement ratio was used to increase the percentage decline. Experimental and numerical results demonstrated that the external strengthening with one, two, and three layers of (CFRP) sheets for reinforced concrete beams and rubberized by volumetric replacement of well-graded fine aggregates in two proportions (5 and 10) % enhance the flexural strength as follow:

1- Reinforced concrete beams rubberized by volumetric replacement with (5) % of well-graded fine aggregate:
  - With a single layer of (CFRP) sheet:
    Increasing the load at the first crack and failure by (1.11 and 1.26), increasing the deflection at the first crack by (1.8), and decreasing the deflection at failure by (0.81).
    Load-deflection curve: Increasing failure load and deflection, and decreasing deflection at symmetrical loads.
  - With two layers of (CFRP) sheets:
    Increasing the load at the first crack and failure by (1.34 and 1.52), increasing the deflection at the first crack and failure by (2.14 and 1.02).
    Load-deflection curve: Increasing failure load with decreasing failure deflection, and decreasing deflection at symmetrical loads.
  - With three layers of (CFRP) sheets:
    Increasing the load at the first crack and failure by (1.15 and 1.83), decreasing the deflection at the first crack by (0.74), and increasing the deflection at failure by (2.65).
    Load-deflection curve: Increasing failure load and deflection, and decreasing deflection at nearly (75%) of symmetrical loads.

2- Reinforced concrete beams rubberized by volumetric replacement with (10) % of well-graded fine aggregate:
  - With a single layer of (CFRP) sheet:
    Increasing the load at the first crack and failure by (1.11 and 1.12), increasing the deflection at the first crack by (1.61), and decreasing the deflection at failure by (0.77).
    Load-deflection curve: Increasing failure load with decreasing failure deflection, and decreasing deflection at symmetrical loads.
  - With two layers of (CFRP) sheets:
    Increasing the load at the first crack and failure by (1.17 and 1.48), increasing the deflection at the first crack and failure by (1.67 and 1.04).
    Load-deflection curve: Increasing failure load with decreasing failure deflection, and decreasing deflection at symmetrical loads.
  - With three layers of (CFRP) sheets:
    Increasing the load at the first crack and failure by (1.09 and 1.65), decreasing the deflection at the first crack by (0.81), and increasing the deflection at failure by (2.51).
    Load-deflection curve: Increasing failure load and deflection, and decreasing deflection at (67%) of symmetrical loads.

Declaration of competing interest

The authors declare that they have no known financial or non-financial competing interests in any material discussed in this paper.

Funding information

No funding was received from any financial organization to conduct this research.

References

[1] S.M.M. Agampodi, S. Al-Deen and M. Ashraf, "Flexural shear behavior of reinforced Crumbed Rubber Concrete beam", Journal of Construction and Building Materials, vol. 166, pp. 779–791, 2018.
[2] AA. Al-Azzawi1, D. Shakir and N. Saad, "Flexural behavior of rubberized reinforced concrete beams", International Journal of Engineering & Technology, vol. 7, pp. 316-320, 2018.
[3] S. Gurung, "Flexural analysis of rubberized concrete beams using finite element method", Ph.D. thesis, Arcada University of Applied Sciences, Helsinki, Finland, 2020.
[4] R.A. Assaggaf, M.R. Ali, S.U. Al-Dulaijan, and M. Maslehuddin, "Properties of concrete with untreated and treated crumb rubber - A review", Journal of Materials Research and Technology, vol. 11, pp. 1753–1798, 2021.

[5] T. M. Hasan and A. S. Ali, "Flexural behavior of fiber reinforced self-compacting rubberized concrete beams", Journal of Engineering. Vol. 26, Issue 2, pp:111-128. 2020.

[6] E.Ganjian, M. Khorami, and A. A. Maghsoudi, "Scrap-tyre-rubber replacement for aggregate and filler in concrete", Journal of Construction and Building Materials, vol. 23 issue. 5 pp. 1828-1836, 2009

[7] H. Su, J. Yang, T.Ch. Ling, G.S. Ghataora, and S. Dirar "Properties of concrete prepared with waste tyre rubber particles of uniform and varying sizes", Journal of Cleaner Production vol. 91 pp. 1-9, 2014.

[8] C. Xiong, Q. Li, T. Lan, H. Li, W. Long, and F. Xing, "Sustainable use of recycled carbon fiber reinforced polymer and crumb rubber in concrete: mechanical properties and ecological evaluation", Journal of Cleaner Production, vol. 279, Art. 123624, 2021.

[9] B.S. Thomas and R.Ch. Gupta, "Properties of high strength concrete containing scrap tire rubber", Journal of Cleaner Production, pp. 1-7, 2015, doi:10.1016/j.jclepro.2015.11.019.

[10] P. Asutkar, S.B. Shinde, and R. Patel, "Study on the behavior of rubber aggregates concrete beams using analytical approach", Engineering Science and Technology, an International Journal, vol. 20, pp. 151–159, 2017.

[11] T. Gupta, S. Siddique, R.K. Sharma, and S. Chaudhary, "Behaviour of waste rubber powder and hybrid rubber concrete in aggressive environment", Journal of Construction and Building Materials, vol. 217, pp. 283–291, 2019.

[12] Y. Li, X. Zhang, R. Wang, and Y. Lei, "Performance enhancement of rubberised concrete via surface modification of rubber: A review", Journal of Construction and Building Materials, vol. 227, art. 116691, 2019.

[13] A. Siddika, M.A. Al Mamun, R. Alyousef, Y.H. M. Amran, F. Aslani, and H. Alabduljabbar, "Properties and utilizations of waste tire rubber in concrete: A review", Journal of Construction and Building Materials, vol. 224, pp. 711–731, 2019.

[14] A. Habib, U. Yildirm, and O. Eren, "Mechanical and dynamic properties of high-strength concrete with well graded coarse and fine tire rubber", Journal of Construction and Building Materials", vol. 246, art. 118502, 2020.

[15] I. Khan, K. Shahzada, T. Bibi, A. Ahmed, and H. Ullah, "Seismic performance evaluation of crumb rubber concrete frame structure using shake table test", Journal of Structures, vol. 30, pp. 41–49, 2021.

[16] A. Al-Khafaji, H. Salim, A. El-Sisi, "Behavior of RC beams strengthened with CFRP sheets under sustained loads", Journal of Structures, vol. 33, pp. 4690–4700, 2021.

[17] H. Toutanji, L. Zhao, and Y. Zhang, "Flexural behavior of reinforced concrete beams externally strengthened with CFRP sheets bonded with an inorganic matrix", Journal of Engineering Structures, vol. 28, pp. 557–566, 2006.

[18] Y.Ch. Wang, and K. Hsu, "Design recommendations for the strengthening of reinforced concrete beams with externally bonded composite plates", Journal of Composite Structures, vol. 88, pp. 323–332, 2009.

[19] F. Ceroni, "Experimental performances of RC beams strengthened with FRP materials", Journal of Construction and Building Materials, vol. 24, pp. 1547–1559, 2010.

[20] N. Attari, S. Amziane, and M. Chemrouk, "Flexural strengthening of concrete beams using CFRP, GFRP, and hybrid FRP sheets", Journal of Construction and Building Materials, vol. 37, pp. 746–757, 2012.

[21] A. R. Khan, and Sh. Fareed, "Behaviour of Reinforced concrete beams strengthened by CFRP wraps with and without end anchorages" Journal of Procedia Engineering, vol. 77, pp 123 – 130, 2014.

[22] Ch. Cazaucu, T. Galatanu, P. Mizgan, R. Muntean, and F. Tamas, "Experimental research in flexural behavior of carbon fiber polymer strengthened beams", Journal of Procedia Engineering, vol. 181 pp. 257 – 264, 2017.

[23] M.M. Ism and M. Rabie, "Flexural behavior of continuous RC beams strengthened with externally bonded CFRP sheets", Alexandria Engineering Journal, vol. 58, pp. 789–800, 2019.

[24] ACI318-19, ″Building Code Requirements for Structural Concrete, (ACI318M- 19) and commentary (318R-19) ″, Farmington Hills, Michigan, USA.

[25] IQS N45/1984 (zone2), Iraqi Specifications No. (45), 1984 for Aggregates of Natural Resources used for Concrete and Construction.

[26] ASTM D 3039- 2000 Standard Test Method for Tensile Properties of Polymer Matrix Composite Materials.

[27] ASTM C 143/C143M-03, "Standard Test Method for Slump of Hydraulic-Cement Concrete", Manual Book of ASTM Standards, Vol. 04.02 Concrete and Aggregates, West Conshohocken, PA, 2003, 4 p.

[28] BS 1881-Part 116:1983, "Method for determination of compressive strength of concrete cubes", British Standards Institute BSI, London, 2000, 11 p.

[29] ASTM C 78-02, "Standard Test Method for Flexural Strength of Concrete", Manual Book of ASTM Standards, Vol. 04.02 Concrete and Aggregates, West Conshohocken, PA, United States, 2002, 3 p.

[30] ASTM C 496/C 496M-04, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens", Manual Book of ASTM Standards, Vol. 04.02 Concrete and Aggregates, West Conshohocken, PA, United States, 2004, pp.5.

[31] ASTM C 469-02, "Standard Test Method for Static Modulus of Elasticity and Poisson’s Ratio of Concrete in Compression", Manual Book of ASTM Standards, Vol. 04.02 Concrete and Aggregates, West Conshohocken, PA, United States, 2002, 5 p.

[32] ABAQUS (version 2021), Abaqus/Cae User's Guide, analysis user's manual, 2021.

[33] K. Strukar, T.K. Šipoš, T. Dokšanovi´c, and H. Rodrigues, "Experimental study of rubberized concrete stress-strain behavior for improving constitutive models" Journal of Materials, vol. 11, art. 2245. 2018, doi:10.3390/ma11112245

[34] P. Kmiecik, M. Kamiński, "Modelling of reinforced concrete structures and composite structures with concrete strength degradation taken into consideration", Journal of Archives of Civil and Mechanical Engineering, vol. 3, 2011.