

Flexural behavior of steel fiber reinforced concrete beams comprising coarse and fine rubber and strengthened by CFRP sheets

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Abstract

Despite having many advantages, using rubber to produce reinforced concrete members like beams is still restricted. When there is more waste tire rubber in concrete structures, rubber concrete's flexural and compressive strengths gradually decrease. However, this study used steel fibers to improve compressive strength and externally bonded carbon fiber-reinforced polymer (CFRP) sheets to increase flexural strength. Four groups of three reinforced concrete beams each were established for the study's use. The first and third groups of concrete beams used a volumetric replacement of fine and coarse aggregates with 5% and 10% waste tire rubber. However, steel fibers were added to the second and third groups at a rate of 1.25% of the concrete volume. Waste tire rubber and steel fibers were not replaced or added to the fourth group, the main reference group. The dimensions of each beam were 2.1×0.2×0.3 m. A concrete beam's first member is always free of external reinforcement, followed by its second member, which has one layer, and its third member, which has two layers of CFRP sheet. ABAQUS, a finite element analysis program, was used numerically to represent the third strengthening layer. The results showed that strengthening the reinforced rubberized concrete beams with a single layer of CFRP sheets increased the load at first crack and failure by 8.57% and 17.64%, respectively, compared to the unreinforced reference beam, compensating for the loss caused by the production of rubberized concrete and adding additional flexural strength. These loads increased by 31.43% and 26.45%, respectively, due to the steel fibers added to the beams containing these waste tire rubber. Strengthening with two layers of CFRP sheets increased the load at first crack and failure by 17.14 and 34.27, respectively. The steel fibers added to the beams that contained these amounts of waste tire rubber, on the other hand, caused these loads to increase by 42.86 and 49.23%, respectively. Strengthening with three layers numerically results in an exponential increase in load at the first crack and the failure by 8.03 and 52.88%, respectively. On the other hand, the loads on the beams that contained these quantities of waste tire rubber increased by 50.49% and 104.47%, respectively, when steel fibers were added to them.

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1. Introduction

Numerous studies on how to deal with the loss of mechanical properties, such as the flexural strength of reinforced concrete substrates, as a result of the addition or replacement of waste tire rubber in producing these substrates have been conducted, with various levels of success. The purpose of this study is to investigate the

use of externally adhered CFRP sheets on the beam soffits to reinforce rubberized concrete beams with flexural reinforcement, which is very effective at enhancing structural members, including beams, as well as the use of steel fibers as an additive to the concrete mix to help raise the compression strength that has decreased as a result of the production of rubberized concrete.

Due to its widespread use as one of the most common building materials on earth, concrete consumes a lot of natural resources every year. Concrete is produced using natural resources, which are gradually running out. For the concrete industry, locating natural aggregate at a reasonable cost is of utmost importance [1]. On the other hand, the growing workforce and the middle class's social advancement have led to a significant rise in vehicle demand globally. As a result, more car tires are being thrown away every year. Because used tire waste doesn't biodegrade, disposing of it seriously threatens the ecosystem. The management of used tires has grown more problematic over the last few years [2]. Therefore, using waste tire granules in concrete benefits the environment in two ways: reducing the consumption of natural resources in producing concrete and adequately managing waste tires. Concrete that has been rubberized uses waste tire rubber to substitute the fine and/or coarse aggregate partially. Rubberized concrete's material properties have been the subject of numerous studies over the years [3]. Waste tire rubber is used to improve the structural properties of concrete, such as resistance to repeated freezing and thawing, deformation capacity, damping capacity (impact resistance), and energy dissipation. Rubberized concrete was found to have a lower unit weight and suitable workability when compared with ordinary concrete. But as the rubber content rises, the tensile, compressive, and flexural strengths, as well as the elastic modulus of the concrete, may also be reduced [4, 5]. The cement matrix and rubber have poor adhesion due to the rubber's low elastic modulus and hydrophobicity. Rubberized concrete's mechanical and durability properties are improved due to the rubber surface being changed physically or chemically, strengthening the bond between the cement and rubber interface. Pre-coating the rubber with cementitious materials, like silica fume (SF), lime powder (LP), and cement paste improved the interfacial transition zone (ITZ) adhesion and elastic modulus, enhancing rubberized concrete's durability and mechanical properties. The raw materials required for the pre-coating method were also easy to locate. It had a wide range of uses, which suggests that it might be feasible to produce rubberized concrete in significant quantities for structural services [6]. The ductility index, ultimate deflection, and strain measured by the steel bar and concrete strain gauges, as well as the stress-strain curve of the rubberized beam, have all improved in comparison to the hybrid beam, which had two double layers: rubberized reinforcement concrete on top of the beam and reinforcement concrete on the bottom, with 10%, 12.5%, and 15% of crumb rubber used to replace the sand river aggregate (by volume) [7]. The production of high-strength rubberized concrete using partially replaced crumb rubber to replace fine aggregate in three different mixes in amounts of 10%, 20%, and 30% of the total volume demonstrated decreasing density as rubber content was increased and increased resistance to impact under flexural loading up to 83.33% as the rubber content increased. A 30% rubber-content mixture can be used for bridges and harbors. However, a systematic loss of nearly 50% in flexural, tensile, and compressive strength was seen when the rubber content was increased by up to 30% [8]. The behavior under monotonic loading of simply supported steel fiber content-reinforced self-compacting rubberizing concrete beams using different ratios of waste tire rubber 10% and 20% by weight of fine and coarse aggregates showed an ability to carry greater loads by adding micro steel fiber. The deflection at maximum load dropped by approximately 30.4%. Furthermore, the characteristic strengths (splitting tensile strength, modulus of rupture, and compressive strength) were reduced as rubber content was raised [9]. Even with a maximum rubber size of 12 mm and a replacement ratio of 25%, it produced a flowable mix with a controlled compression strength reduction with well-graded rubber. This is due to the effects of particle packing caused by using a good grade of rubber aggregates, which improved the concrete's properties compared to the data found in the previous works. Compared to conventional concrete, well-graded rubber particles instead of 25% of the aggregates increased the damping ratio to a level close to 90%. This concrete can perform better when used in locations with high dynamic loads, such as earthquake-prone structures. Concrete's brittle failure pattern was changed to a ductile failure pattern by adding rubber aggregates [10]. The amount of rubber aggregate in the mix can significantly impact concrete's flexural

properties. Overall, it was found that adding rubber to concrete can improve its flexural qualities, such as ductility, deformability, and energy absorption. The percentage of replacement rubber in the concrete mix should be at most 10% to ensure the best flexural performance of the concrete. Based on these findings, it can be said that high-strength concrete structures such as bridges cannot be built using rubberized concrete. Conversely, rubberized concrete can produce constructions other than load-bearing ones, such as flooring, wall panels, roads, etc. Consequently, employing rubber instead of natural aggregates might be the best way to address the issue of waste tires worldwide. The flexural properties of rubberized concrete need to be enhanced, requiring more investigation [11]. The concrete's damping ratio and period of vibration of crumb rubber-built reinforced concrete frame structures were increased by partially adding rubber crumbs. The crumb rubber concrete frame's maximum seismic response acceleration was 20.40% lower than the traditional concrete frame, indicating that the concrete structure with rubber crumbs will be subjected to lower seismic forces than a conventional concrete frame during an earthquake [12].

There are several ways to improve a reinforced concrete beam's flexural performance, and the most effective one depends on several factors. These elements include the price of strengthening, an increase in size, the rate of load capacity improvement, and the availability of used materials. Fiber-reinforced polymer (FRP) composites that are externally bonded can improve compression members' confinement and ductility while improving shear and flexural strength. Strengthening concrete structural members can be accomplished by utilizing carbon fiber reinforced polymers CFRP, which exhibit beneficial qualities like corrosion resistance, ease of installation, and excellent specific strength [13]. With each additional layer of the CFRP sheet, the load-bearing capacity of the reinforced concrete beams increased. The ductility of strengthened beams is significantly lower than that of un-strengthened beams [14]. Combining longitudinal CFRP sheets and U-side strips increases shear and flexure strength. To strengthen the longitudinal CFRP bond and U-side CFRP bond of the beam, use mechanical anchors and CFRP strips on the U-side. U-side CFRP strips could also be used to prevent debonding failure between the CFRP sheets and the beam soffit [15]. Carbon fiber reinforced polymers CFRP, an externally adhered strengthening system, enhance beams with a lower percentage of steel reinforcement 1%. The load growth rate varies between 26% and 50%. However, the rate of load growth is roughly between 17% and 33% with the highest percentage of reinforcement at 1.5%. Due to the brittle failure caused by end debonding of the CFRP strengthening, the ductility has decreased [16]. The strength capacity of reinforced concrete beams can be significantly increased by adding a second layer of FRP composite material; samples of strengthened beams display an increase of 114% [17]. The structural performance of the reinforced concrete beams' ductility, load-carrying capacity, and stiffness were all improved by soffit-mounted, side-extending CFRP-wrapped reinforced concrete beams, both with and without end anchors [18]. When reinforced with CFRP sheets, all repaired beams typically regain close to 80% of their original bearing capacity. The strengthened beam has an increased flexural strength of 30 to 40%. Deflections were significantly decreased because the exterior reinforced beams became stiffer. Some shear cracks are stopped from spreading by CFRP exterior strengthening, while others take longer to form [19]. Rupture happens when only one layer is used, while de-bonding occurs when two layers are used. As the number of layers increases, debonding is more likely to occur than rupture [20].

This study will investigate using externally adhered CFRP sheets on the beam soffits and steel fibers to improve the flexural strength of the concrete beams, which has decreased due to the production of rubberized concrete.

2. Program and equipment for experiments

2.1. Specimens' configuration

In total, there are four groups of three reinforced concrete beams. Each group's beams share the mixture. Waste tire rubber was used as a volumetric replacement for fine and coarse aggregates in the first and third groups of concrete beams 5% and 10% respectively. However, in the second and third groups, steel fibers were added at a rate of 1.25% of the volume of the concrete. The reference group, the fourth group of beams, had no additions or substitutions. The dimensions of each beam are 2.1 m in length, 0.2 m in width, and 0.3 m in height designed

according to the ACI Code (318-19) [21]. Each of the four groups' beams is reinforced with the same proportion (ρ_{min}) of steel bars. As with the tensile zone, two 12 mm diameter rods were used to reinforce the compression zone, and every 200 mm center-to-center stirrup was used to resist shear stress, as shown in Figure 1. The beams in each group were strengthened as follows: the first beam was left un-strengthened, the second beam received a single reinforcement layer, and the third beam received two, as shown in Figures 2 and 3. The CFRP sheets adhered to reinforce the lower side of the beams externally with dimensions 2.1×0.2 m. ABAQUS, a program for finite element analysis, was used to numerically represent the third reinforcing layer. Furthermore, each beam had the same amount of silica fume admixture and the same ratio of water to cement; the superplasticizer was changed to maintain the slump at 110 ± 5 mm. The TML Japanese-made strain gauges were fixed in the middle of each beam's tensile reinforcement. Figures 4 and 5 show that two strain gauges were affixed in the middle of each CFRP layer.

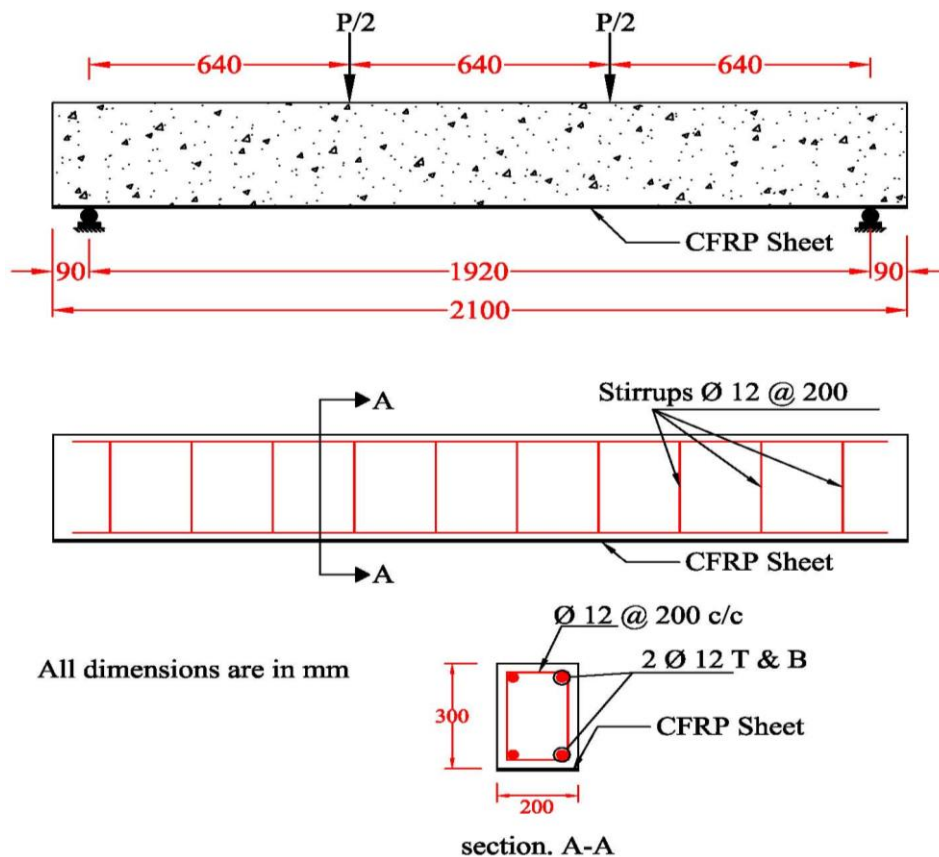


Figure 1. Dimensions and reinforcement specifications for the beam



Figure 2. Beam soffit preparation before CFRP sheets are installed



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

The following ingredients were used to create a reference mixture: water, cement, fine aggregate, coarse aggregate, silica fume (MegaAdd MS(D)), and superplasticizer (Sika ViscoCreate®-5930L). This mixture was

required to have a compression strength at 28 days of at least 45 MPa. The specific composition of the mix is detailed in Table 1.

Table 1. The reference concrete mix's design properties

Cement (kg/m³)	Silica fume (kg/m³)	Super plasticizer (Liter/m³)	Fine aggregate (kg/m³)	Coarse aggregate (kg/m³)	W/C ratio
500	25	1.5 – 2.5	680	1020	0.37

The technical report for this product states that in each group's casting process, the superplasticizer admixtures' proportion to cement weight ranged from 0.3% to 0.5%.

2.3. Rubber sizes used in place of fine aggregates

Table 2 displays the used waste tire rubber sizes that replace 5% of fine aggregates.

Table 2. Sieve analysis of rubber employed as a fine aggregate according to IQS No. 45/2019 (zone 2) [22]

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

2.4. Rubber sizes used in place of fine aggregates

Table 3 displays the used waste tire rubber sizes that replace 10% of coarse aggregates.

Table 3. Sieve analysis of rubber employed as a coarse aggregate according to ASTM C 33/2003 [23]

Sieve size (mm)	Passing (%)	Limits (9.5 to 1.18 mm)
12.5	100	100
9.5	95	90 – 100
4.75	38	20 – 55
2.36	18	5 – 30
1.18	5	0 – 10

2.5. Steel fiber

For two concrete groups, concrete with micro-steel fibers measuring 13 mm in length were produced. Table 4 provides a list of the steel fiber's characteristics.

Table 4. Properties of the used steel fiber (according to the datasheet of the manufacturer)

Description	Straight
Tensile strength	2600 MPa
Density	7800 kg/m ³
Diameter	0.2 mm
Length	13 mm

2.6. CFRP sheets for external strengthening

Using unidirectional CFRP sheets, concrete beams' flexural qualities were improved. Table 5 below provides a detailed list of the CFRP sheets' specifications through lab test verification and authorized specifications next to each experimental finding.

Table 5. 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	
Laminates elasticity modulus (KN/mm ²)	220	210	ASTM D 3039-
Laminates elongation at break in tension (%)	1.59	–	2000 [24]
Tensile resistance (N/mm)	585	534	

2.7. Material quantities employed in research

Table 6 below shows the amounts of raw materials, waste tire rubber, and additives used in the concrete beam mixtures.

Table 7. Materials quantities used in concrete beams executing

Group No.	Group symbol	Beam symbol	Water (Liter)	Cement (Kg)	Coarse aggregate (Kg)	Fine aggregate (Kg)	Coarse tire rubber (Kg)	Fine tire rubber (Kg)	Fiber tire rubber (Kg)	Filer tire rubber (Kg)	Steel fiber (Kg)	Silica fume (Kg)	Superplasticizer (Liter)	CFRP layers (No.)	Strain gauges (No.)
Group 1	B1	B5-0	27.1 3	73.3 3	134.6 5	94.7 5	5.8 4	1.9 9	–	–	–	3.6 7	0.3 5	0	2
		B5-1	27.1 3	73.3 3	134.6 5	94.7 5	5.8 4	1.9 9	–	–	–	3.6 7	0.3 5	1	4
		B5-2	27.1 3	73.3 3	134.6 5	94.7 5	5.8 4	1.9 9	–	–	–	3.6 7	0.3 5	2	6
Group 2	B2	B8-0	27.1 3	73.3 3	149.6	99.7 5	–	–	–	–	13.9 7	3.6 7	0.4 5	0	2
		B8-1	27.1 3	73.3 3	149.6	99.7 5	–	–	–	–	13.9 7	3.6 7	0.4 5	1	4
		B8-2	27.1 3	73.3 3	149.6	99.7 5	–	–	–	–	13.9 7	3.6 7	0.4 5	2	6
Group 3	B3	B11-0	27.1 3	73.3 3	134.6 5	94.7 5	5.8 4	1.9 9	–	–	13.9 7	3.6 7	0.4	0	2
		B11-1	27.1 3	73.3 3	134.6 5	94.7 5	5.8 4	1.9 9	–	–	13.9 7	3.6 7	0.4	1	4
		B11-2	27.1 3	73.3 3	134.6 5	94.7 5	5.8 4	1.9 9	–	–	13.9 7	3.6 7	0.4	2	6
		B11-3	27.1 3	73.3 3	134.6 5	94.7 5	5.8 4	1.9 9	–	–	13.9 7	3.6 7	0.4	3	8
Group 4	B R	BR-0	27.1 3	73.3 3	149.6	99.7 5	–	–	–	–	–	3.6 7	0.4	0	2
		BR-1	27.1 3	73.3 3	149.6	99.7 5	–	–	–	–	–	3.6 7	0.4	1	4
		BR-2	27.1 3	73.3 3	149.6	99.7 5	–	–	–	–	–	3.6 7	0.4	2	6

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 following the guidelines in ASTM C143-01a [25]. The superplasticizer was adjusted for each group mix to keep 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

According to BS (1881 - part 116:2000), concrete was tested for compression strength (f_{cu}) at 28 days of age and the beam test age [26]. The rupture modulus (f_r) was confirmed for flexural testing using ASTM C78-02 [27]. Using the ASTM C496-04 [28] specifications for beam test specimens, the splitting tensile strength (f_t) at the testing age was calculated. According to ASTM C469-02 [29], concrete's static elasticity modulus (E_c) was calculated.

4. Layout of experimental study

When used in place of a specific percentage of fine and coarse aggregate and the addition of steel fibers 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 and the addition of steel fibers, compared to the properties of reference concrete from Group (BR), the values for hardened rubberized concrete are shown in Table 8.

At 28 days, rubber concrete's mechanical characteristics (density, compressive strength, rupture modulus, splitting tensile strength, and elastic modulus) were compared to those of reference concrete (BR). If the fine and coarse aggregate replacement rate is 5 and 10% in group one (B1), the properties decreased by 3.81, 23.49, 17.35, 29.33, and 12.04%, respectively. When steel fiber was added to group two (B2) by 1.25% of concrete volume, the properties increased by 3.42, 34.66, 14.59, 15.81, and 16.02%, respectively. But when fine and coarse aggregate replacement rate is 5 and 10% with the addition of steel fiber by 1.25% of concrete volume in group three (B3), the density increased by 0.04%, and the other properties decreased by 16.74, 13.67, 18.32 and 8.08%, respectively.

Table 8. Results of rubberized concrete's properties

Group No.	Beam Groups		Ave. Density	Ave. (f_{cu})	Ave. (f_r)	Ave. (f_t)	Ave. (E_c)
	Group symbol	Beams included	(kg/m^3)	28 days (MPa)	28 days (MPa)	28 days (MPa)	28 days (MPa)
Group 1	B1	B1-0, B1-1 & B1-2	2248	35.008	3.405	2.708	25339
Group 2	B2	B2-0, B2-1 & B2-2	2417	61.619	4.721	4.438	33423
Group 3	B3	B3-0, B3-1 & B3-2	2338	38.098	3.557	3.130	26479
Group 4	BR	BR-0, BR-1 & BR-2	2337	45.759	4.120	3.832	28808

5. Results and discussion

The experimental results are shown in Table 9 and include the load and deflection at the first crack with the load and deflection at the failure, which show the flexural response to two-point monotonic loading applied to these four groups of concrete beams.

Table 9. Beam flexural test results

Concrete group details			Load at the first crack (KN)	Load at failure (KN)	Deflection at the first crack (mm)	Deflection at failure (mm)	Compressive strength at the age of testing (MPa)
Group No.	Group symbol	Beam symbol					
Group 1	B1	B1-0	26	138.9	1.395	36.799	36.333
		B1-1	38	176.1	1.615	20.297	
		B1-2	41	201	1.814	22.130	
Group 2	B2	B2-0	50	152.8	1.782	17.953	64.833
		B2-1	55	206.6	2.336	20.921	
		B2-2	67	255	2.550	22.472	
Group 3	B3	B3-0	35	139.4	1.729	25.607	39.676
		B3-1	46	189.3	2.211	20.505	
		B3-2	50	223.4	2.247	21.888	
Group 4	BR	BR-0	35	149.7	1.018	23.397	48.167
		BR-1	47	172.3	1.647	16.565	

As shown in Tables 10, 11, and 12, the first crack load of the second and third beams in the group (B3), which were externally reinforced with one and two layers of CFRP sheets, respectively, increased in ascending ratios by 31.43 and 42.86% in comparison to the un-strengthened beam (B3-0), respectively. This increase has occurred due to using CFRP sheets for external strengthening.

In comparison to the un-strengthened reference beam (BR-0), the load at the first crack was similar for beam (B3-0) and increased upward by 31.43% and 42.86% for beams (B3-1) and (B3-2). The load at the first crack also increased proportionally by 34.62%, 76.92%, and 92.31% compared to the (B1-0) un-strengthened beam. The load at the first crack for beam (B3-2) was comparable to the un-strengthened reference beam (B2-0), whereas for beams (B3-0) and (B3-1), it increased by 30.00% and 8.00%, respectively.

When comparing the equivalent beams in the (B3) group to the reference group (BR), the first crack load was similar for beam (B3-0), decreased by 2.13% for beam (B3-1) and increased by 2.04% for beam (B3-2). The first crack load also increased in several ratios 34.62%, 21.05%, and 21.95% compared to the corresponding beams in the group (B1). On the other hand, in contrast to the corresponding beams in the reference group (B2), the load at the first crack decreased in various ratios of 30.00%, 16.36%, and 25.37%, respectively.

In comparison to the un-strengthened beam (B3-0), the load at failure of beams (B3-1) and (B3-2) strengthened with one and two layers of CFRP sheets increased at ascending rates of 35.80% and 60.26%, as shown in Tables 10, 11, and 12. This development resulted from the use of CFRP sheets for reinforcement.

However, the load at failure of the (B3) group beams increased in ascending order by 26.45% and 49.23% for the beams (B3-1) and (B3-2) compared to the un-externally strengthened reference beam (BR-0), with a decline of 6.88% for the beam (B3-0). The failure load, however, increased by 0.36%, 36.29%, and 60.84% compared to the unreinforced beam (B1-0). Furthermore, compared to the un-strengthened reference beam (B2-0), the load at failure for beam (B3-0) was 8.77% lower, while for beams (B3-1) and (B3-2), it increased by 23.89% and 46.20%, respectively.

Comparing the equivalent beams in the reference group (BR) with those in the (B3) group, the failure load increased in declining ratios for the beams (B3-1) and (B3-2), rising by 9.87% and 2.15%, respectively, but dropping by 6.88% for the beam (B3-0). Furthermore, compared to the equivalent beams in the group (B1), the failure load rose in various ratios 0.36%, 7.50%, and 11.14%, respectively. Additionally, compared to the matching beams in the reference group (B2), the failure load decreased in various ratios of 8.77%, 8.37%, and 12.39%.

In comparison to the unreinforced beam (B3-0), the first crack deflection of the beams in the group (B3) with one and two layers of external reinforcement CFRP sheets, respectively, increased in ascending ratios of 27.88% and 29.96%, as shown in Tables 10, 11, and 12. This has occurred because external strengthening increased the first crack load.

Additionally, adding waste tire rubber to the (B3) group beams increased the first crack deflection by 69.84%, 117.2%, and 120.7% in comparison to the reference beam that wasn't strengthened (BR-0). Furthermore, compared to the un-strengthened beam (B1-0), the first crack deflection increased by a factor of 23.94%, 58.49%, and 61.08%. Comparing the strengthened beams to the reference beam that hadn't been strengthened (B2-0), the first crack deflection for the beam (B3-0) decreased by 2.97% while rising by 24.07% and 26.09% for the beams (B3-1) and (B3-2).

The deflection at the first crack increased in descending ratios 69.84%, 34.24%, and 18.14% in comparison to the corresponding beams in the reference group (BR), despite the reinforcement provided by the CFRP sheets for beams (B3-1) and (B3-2) and the addition of waste tire rubber to those beams.

Furthermore, the first crack deflection was more significant than the equivalent beams in the group (B1) in several ratios 23.94%, 36.90%, and 23.87%. Contrary to the matching beams in the reference group (B2), the deflection at the first crack decreased in escalating ratios of 2.97, 5.35, and 11.88%, respectively.

As shown in Tables 10, 11, and 12, the failure deflection of beams (B3-1) and (B3-2) with one and two layers of CFRP sheets, respectively, was reduced in descending ratios by 19.92 and 14.52% compared to the un-strengthened beam (B3-0).

When compared to the reference beam without external reinforcement (BR-0), the failure deflection of the (B3) group beams increased by 9.45% due to the use of rubber but decreased in declining rates by 12.36 and 6.45% due to external reinforcement using one and two layers of CFRP sheets, respectively. Comparing the failure deflection to the beam with no external reinforcement (B1-0) showed that it decreased at different rates by 30.41%, 44.28%, and 40.5%, respectively.

Comparatively, the failure deflection increased concerning the beam without external strengthening (B2-0) at varying rates of 42.63%, 14.21%, and 21.92%, respectively.

When compared to equivalent beams in the reference group (BR), the group (B3)'s failure deflection increased by 9.45%, 23.79%, and 30.02% with the addition of waste tire rubber. The deflection at failure, however, varied between the equivalent beams in the group (B1), increasing for beam (B1-1) and decreasing for beams (B1-0)

and (B1-2), respectively, by 1.02%, 30.41%, and 1.09%. When waste tire rubber was added, the deflection at the failure of beams (B3-0) increased by 42.63%, but strengthening techniques reduced the deflection at the failure of beams (B3-1) and (B3-2) by 1.99% and 2.60%, respectively, in comparison to the equivalent beams in the reference group (B2).

Table 10. Load with the deflection at the first crack and load with the deflection at failure comparison results of the group (BR) and (B3) beams

Load at the first crack (KN)				Comparative ratio to the beam (B3-0) (%)		Comparative ratio to the beam (BR-0) (%)		Comparative ratio to similar reference beam (%)	
The reference group (BR)		Group (B3)							
Beam	Load	Beam	Load	Lower by	Greater by	Lower by	Greater by	Lower by	Greater by
BR-0	35	B3-0	35	—	—	equal		equal	
BR-1	47	B3-1	46	—	31.43	—	31.43	2.13	—
BR-2	49	B3-2	50	—	42.86	—	42.86	—	2.04

Load at failure (KN)				Comparative ratio to the beam (B3-0) (%)		Comparative ratio to the beam (BR-0) (%)		Comparative ratio to similar reference beam (%)	
The reference group (BR)		Group (B3)		Lower by	Greater by	Lower by	Greater by	Lower by	Greater by
Beam	Load	Beam	Load						
BR-0	149.7	B3-0	139.4	–	–	6.88	–	6.88	–
BR-1	172.3	B3-1	189.3	–	35.80	–	26.45	–	9.87
BR-2	218.7	B3-2	223.4	–	60.26	–	49.23	–	2.15

Deflection at the first crack (mm)				Comparative ratio to the beam (B3-0) (%)		Comparative ratio to the beam (BR-0) (%)		Comparative ratio to similar reference beam (%)	
The reference group (BR)		Group (B3)		Lower by	Greater by	Lower by	Greater by	Lower by	Greater by
Beam	Deflection	Beam	Deflection						
BR-0	1.018	B3-0	1.729	–	–	–	69.84	–	69.84
BR-1	1.647	B3-1	2.211	–	27.88	–	117.2	–	34.24
BR-2	1.902	B3-2	2.247	–	29.96	–	120.7	–	18.14

Deflection at failure (mm)				Comparative ratio to the beam (B3-0) (%)		Comparative ratio to the beam (BR-0) (%)		Comparative ratio to similar reference beam (%)	
The reference group (BR)		Group (B3)		Lower by	Greater by	Lower by	Greater by	Lower by	Greater by
Beam	Deflection	Beam	Deflection						
BR-0	23.397	B3-0	25.607	–	–	–	9.45	–	9.45
BR-1	16.565	B3-1	20.505	19.92	–	12.36	–	–	23.79
BR-2	16.834	B3-2	21.888	14.52	–	6.45	–	–	30.02

Table 11. Load with the deflection at the first crack and load with the deflection at failure comparison results of the group (B1) and (B3) beams

Load at the first crack (KN)				Comparative ratio to the beam (B3-0) (%)		Comparative ratio to the beam (B1-0) (%)		Comparative ratio to similar reference beam (%)	
The reference group (B1)		Group (B3)							
Beam	Load	Beam	Load	Lower by	Greater by	Lower by	Greater by	Lower by	Greater by
B1-0	26	B3-0	35	–	–	–	34.62	–	34.62
B1-1	38	B3-1	46	–	31.43	–	76.92	–	21.05
B1-2	41	B3-2	50	–	42.86	–	92.31	–	21.95

Load at failure (KN)									
The reference group (B1)		Group (B3)							
Beam	Load	Beam	Load						
B1-0	138.9	B3-0	139.4	–	–	–	0.36	–	0.36
B1-1	176.1	B3-1	189.3	–	35.80	–	36.29	–	7.50
B1-2	201	B3-2	223.4	–	60.26	–	60.84	–	11.14

Deflection at the first crack (mm)									
The reference group (B1)		Group (B3)							
Beam	Deflection	Beam	Deflection						
B1-0	1.395	B3-0	1.729	–	–	–	23.94	–	23.94
B1-1	1.615	B3-1	2.211	–	27.88	–	58.49	–	36.90
B1-2	1.814	B3-2	2.247	–	29.96	–	61.08	–	23.87

Deflection at failure (mm)									
The reference group (B1)		Group (B3)							
Beam	Deflection	Beam	Deflection						
B1-0	36.799	B3-0	25.607	–	–	30.41	–	30.41	–
B1-1	20.297	B3-1	20.505	19.92	–	44.28	–	–	1.02
B1-2	22.130	B3-2	21.888	14.52	–	40.50	–	1.09	–

Table 12. Load with the deflection at the first crack and load with the deflection at failure comparison results of the group (B2) and (B3) beams

Load at the first crack (KN)				Comparative ratio to the beam (B3-0) (%)		Comparative ratio to the beam (B2-0) (%)		Comparative ratio to similar reference beam (%)	
The reference group (B2)		Group (B3)							
Beam	Load	Beam	Load	Lower by	Greater by	Lower by	Greater by	Lower by	Greater by
B2-0	50	B3-0	35	–	–	30.00	–	30.00	–
B2-1	55	B3-1	46	–	31.43	8.00	–	16.36	–
B2-2	67	B3-2	50	–	42.86	equal		25.37	–

**Load at failure
(KN)**

The reference group (B2)		Group (B3)							
Beam	Load	Beam	Load						
B2-0	152.8	B3-0	139.4	–	–	8.77	–	8.77	–
B2-1	206.6	B3-1	189.3	–	35.80	–	23.89	8.37	–
B2-2	255	B3-2	223.4	–	60.26	–	46.20	12.39	–

**Deflection at the first crack
(mm)**

The reference group (B2)		Group (B3)							
Beam	Deflection	Beam	Deflection						
B2-0	1.782	B3-0	1.729	–	–	2.97	–	2.97	–
B2-1	2.336	B3-1	2.211	–	27.88	–	24.07	5.35	–
B2-2	2.550	B3-2	2.247	–	29.96	–	26.09	11.88	–

**Deflection at failure
(mm)**

The reference group (B2)		Group (B3)							
Beam	Deflection	Beam	Deflection						
B2-0	17.953	B3-0	25.607	–	–	–	42.63	–	42.63
B2-1	20.921	B3-1	20.505	19.92	–	–	14.21	1.99	–
B2-2	22.472	B3-2	21.888	14.52	–	–	21.92	2.60	–

Figure 7 shows how, for the beams (B3-1) and (B3-2), respectively, the external strengthening with single and pair layers of CFRP sheets improves the load-deflection curve by reducing deflection at symmetrical load levels and increasing failure loads while decreasing failure deflection. As opposed to the unenhanced beams (B3-0), this.

Figure 8 shows the behavior of the load-deflection curve for the beam (B3-0), which has a lower deflection at similar load levels than the beam (B1-0) but comes together a little lower than that of the beam (BR-0) but higher than that of the beam (B2-0).

Figure 9 illustrates the behavior of the load-deflection curve of the beam (B3-1) with a convergent and slightly lower deflection at equal load levels and a higher failure load for the beam (BR-1), but a lower failure load than the beam (B2-1).

Figure 10 illustrates the behavior of the load-deflection curve for the beam (B3-2), which exhibits greater deflection at symmetrical load levels and a higher failure load than the beam (B1-2), but less deflection than the beams (BR-2) and (B2-2).

When compared to reference beams (BR-0), (B1-0), and (B2-0) with higher failure loads, the deflection of the beams (B3-1) and (B3-2) at symmetrical load levels significantly decreases due to strengthening with one and two layers of CFRP sheets. It is depicted in Figures 11, 12, and 13.

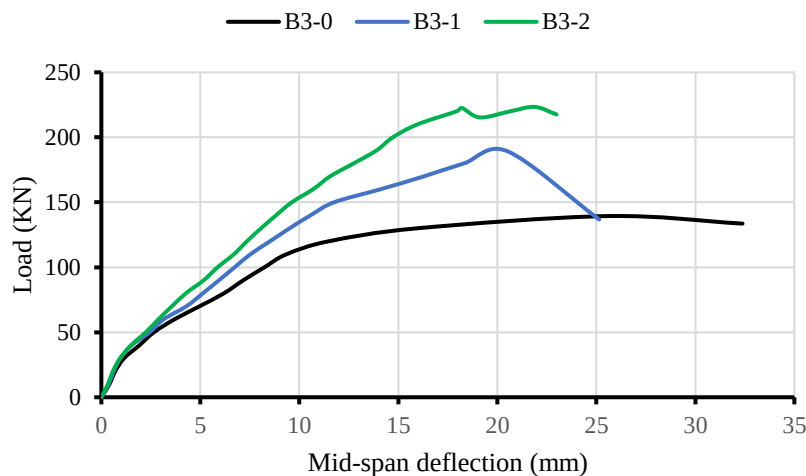


Figure 7. Load-deflection diagram of group (B3) beams

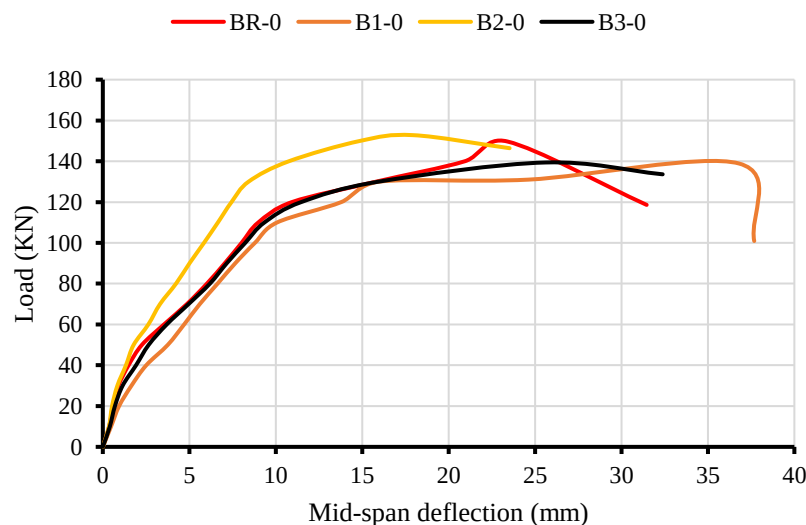


Figure 8. Load-deflection diagram of the beams (BR-0), (B1-0), (B2-0), and (B3-0)

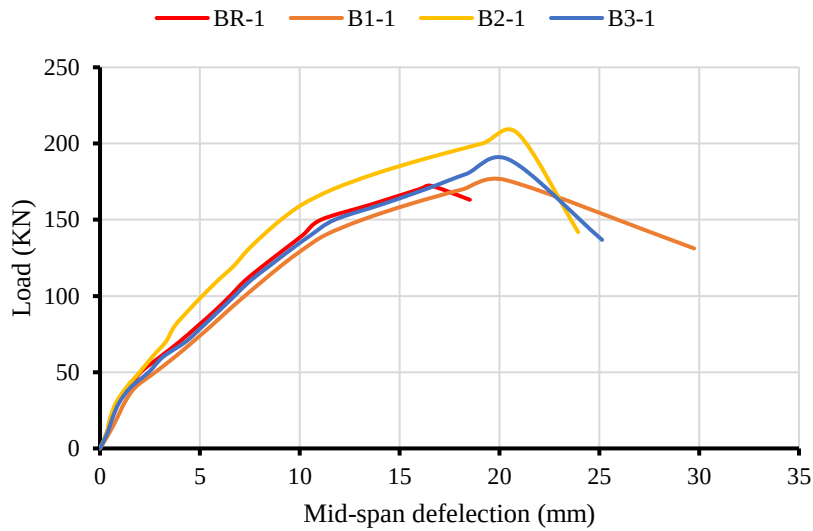


Figure 9. Load-deflection diagram of the beams (BR-1), (B1-1), (B2-1), and (B3-1)

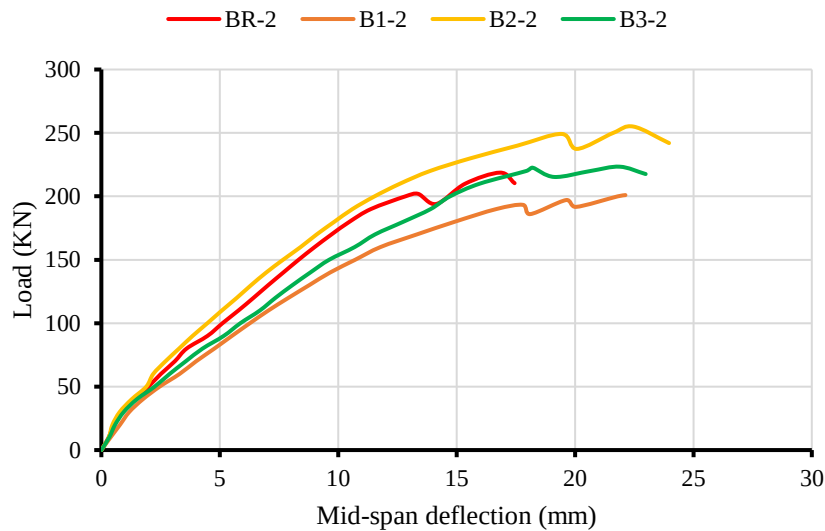


Figure 10. Load-deflection diagram of the beams (BR-2), (B1-2), (B2-2), and (B3-2)

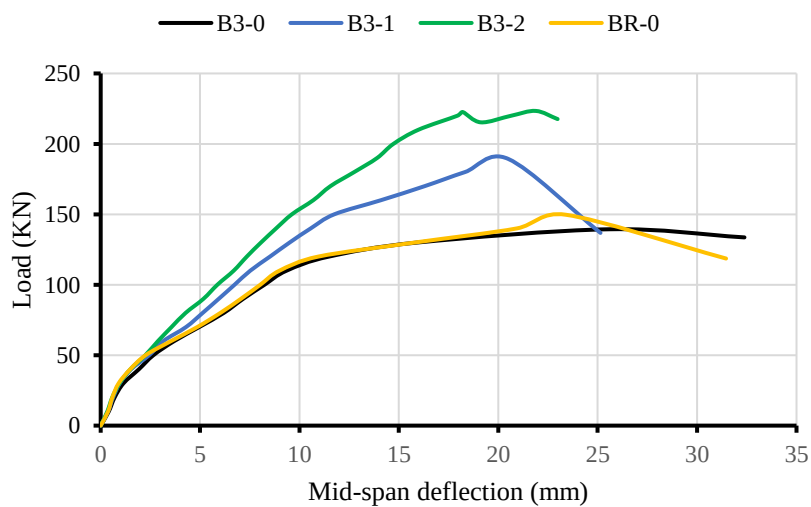


Figure 11. Load-deflection diagram of group (B3) beams and (BR-0)

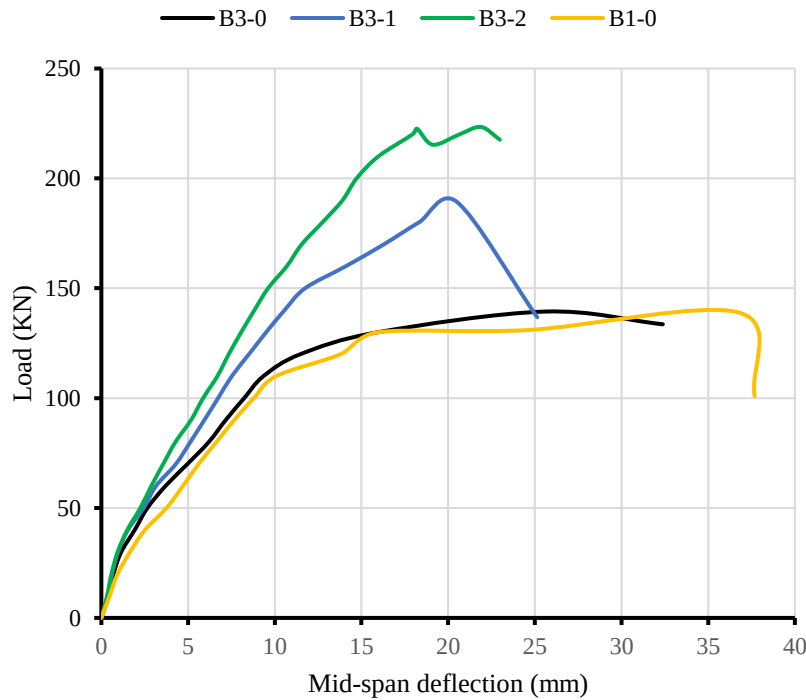


Figure 12. Load-deflection diagram of group (B3) beams and (B1-0)

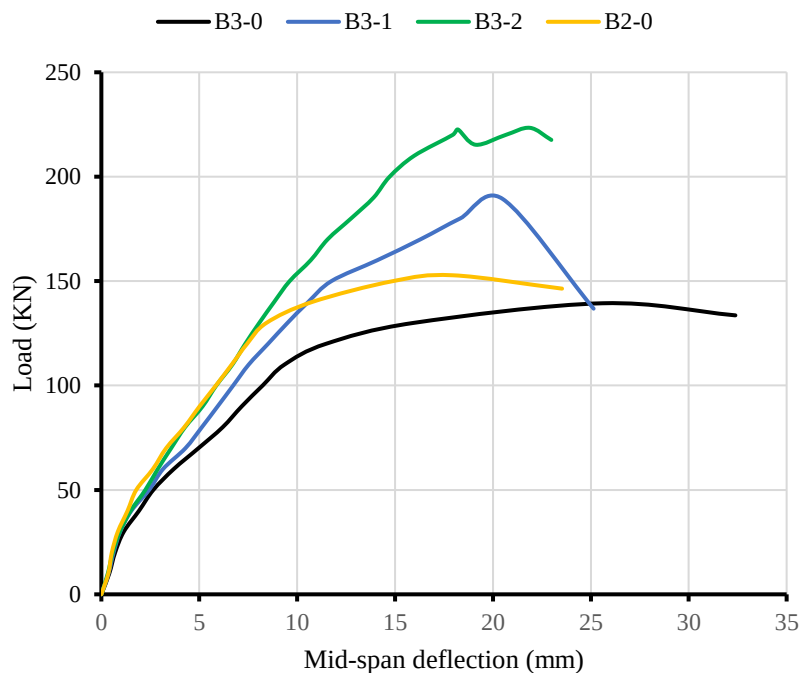


Figure 13. Load-deflection diagram of group (B3) beams and (B2-0)

Figure 14 illustrates how, under symmetrical loads, the main steel reinforcement of the beam (B3-0) experiences more significant strain than that of the beams (B2-0) and (BR-0) but less strain than that of the beam (B1-0). According to Figures 15 and 16, the tensile steel reinforcement of beam (B3-1) and one layer of reinforcing CFRP sheets both show less strain under the most similar loads than beam (B1-1), with more strain than beams (B2-1) and (BR-1). Tensile steel reinforcement and the first and second layers of CFRP sheets used to reinforce the beam externally (B3-2) experience less strain than the beam (B1-2) but more strain than the beams (BR-2) and (B2-2) under the most similar loads as shown in Figures 17, 18, and 19.

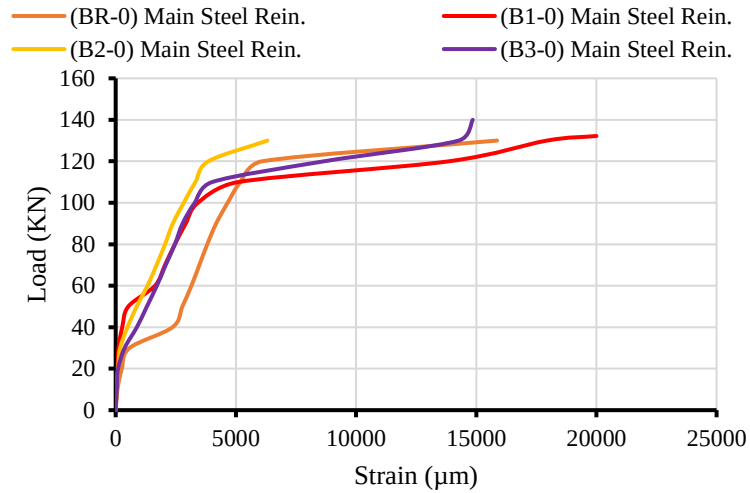


Figure 14. Main steel reinforcement load-strain diagram of the beams (BR-0), (B1-0), (B2-0), and (B3-0)

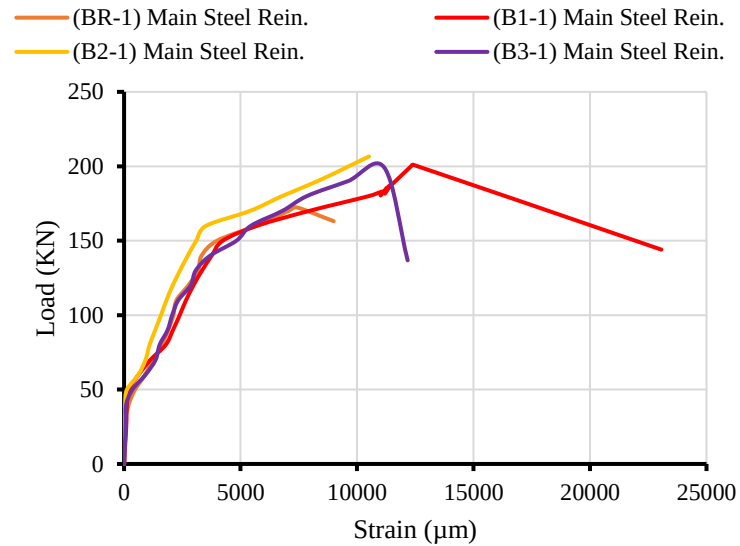


Figure 15. Main steel reinforcement load-strain diagram of the beams (BR-1), (B1-1), (B2-1), and (B3-1)

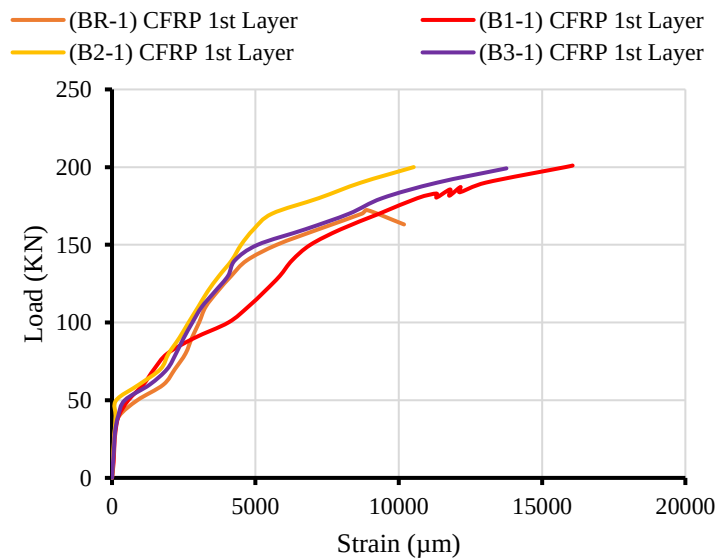


Figure 16. 1st layer of CFRP sheet load-strain diagram of the beams (BR-1), (B1-1), (B2-1), and (B3-1)

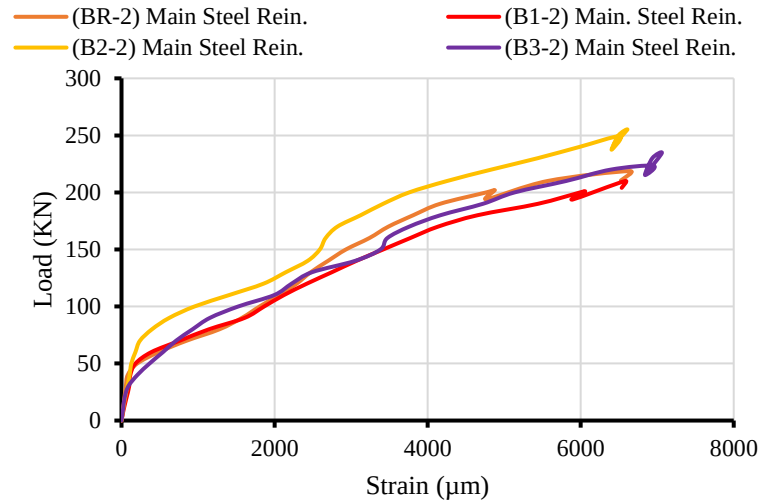


Figure 17. Main steel reinforcement load-strain diagram of the beams (BR-2), (B1-2), (B2-2), and (B3-2)

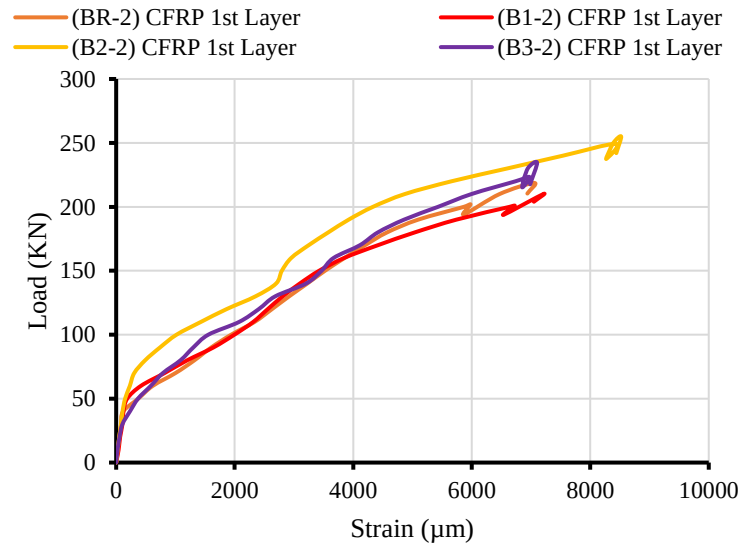


Figure 18. 1st layer of CFRP sheet load-strain diagram of the beams (BR-2), (B1-2), (B2-2), and (B3-2)

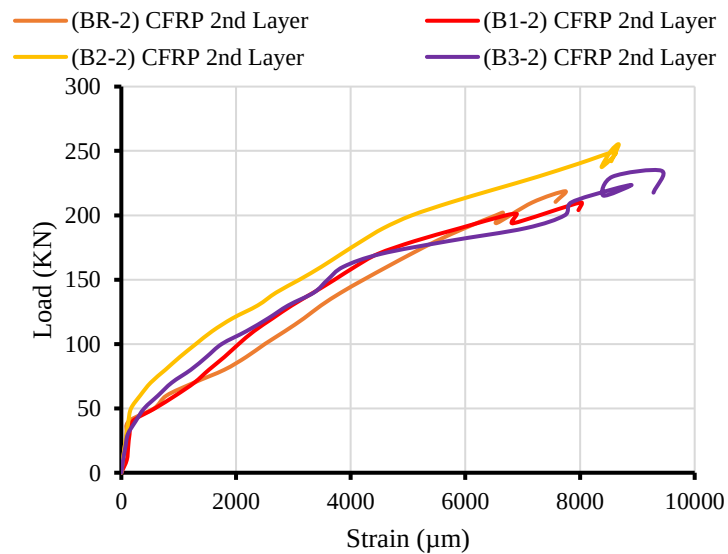


Figure 19. 2nd layer of CFRP sheet load-strain diagram of the beams (BR-2), (B1-2), (B2-2), and (B3-2)

The rupture of the CFRP sheet following the yielding of the tension steel reinforcement, which takes place when the tensile strain of the CFRP sheets reaches its design rupture strain, was the mode of failure for beams externally reinforced with a single layer of CFRP sheet, such as the beams (BR-1), (B1-1), (B2-1), and (B3-1). Debonding of the CFRP sheet, which can result in the delamination of the concrete cover or the debonding of the CFRP sheets, occurred in the beams (BR-2), (B1-2), (2-2), and (B3-2) that were reinforced with a dual layer of CFRP sheet. This occurs when the force in the CFRP sheets is too great to be transferred to the bonded concrete beam. All beams' deformation patterns are depicted in Figures 20, 21, 22, and 23.

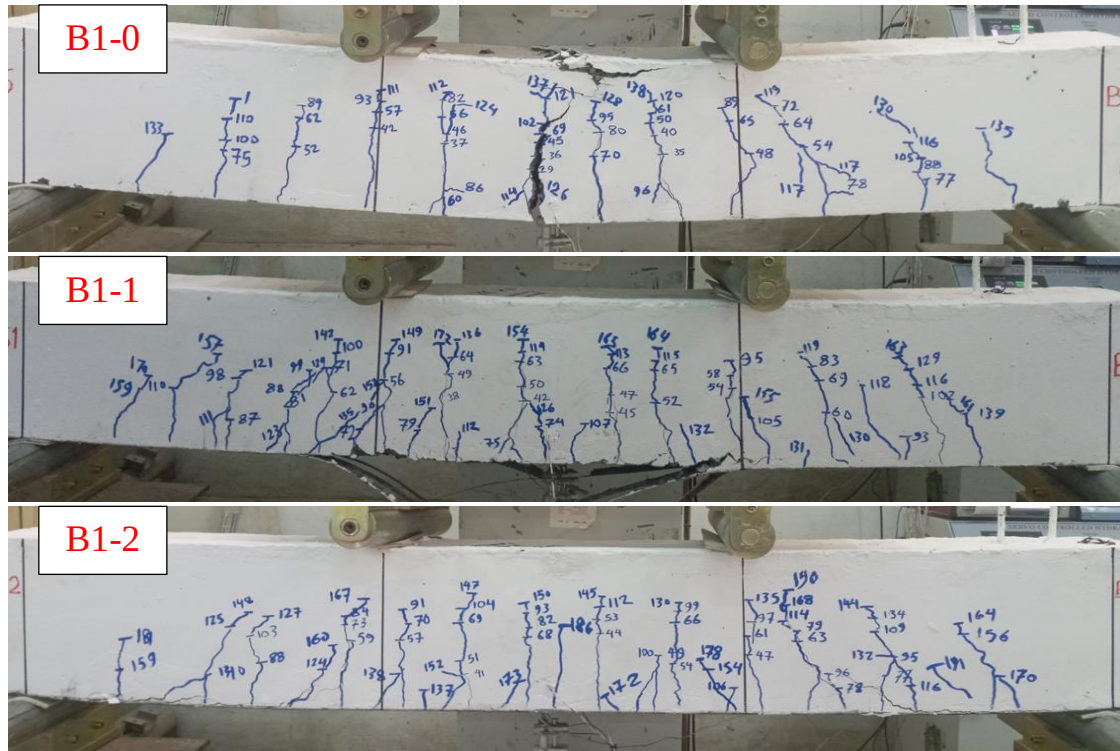


Figure 20. The group (B1) beams, B1-0, B1-1, and B1-2 deformation pattern

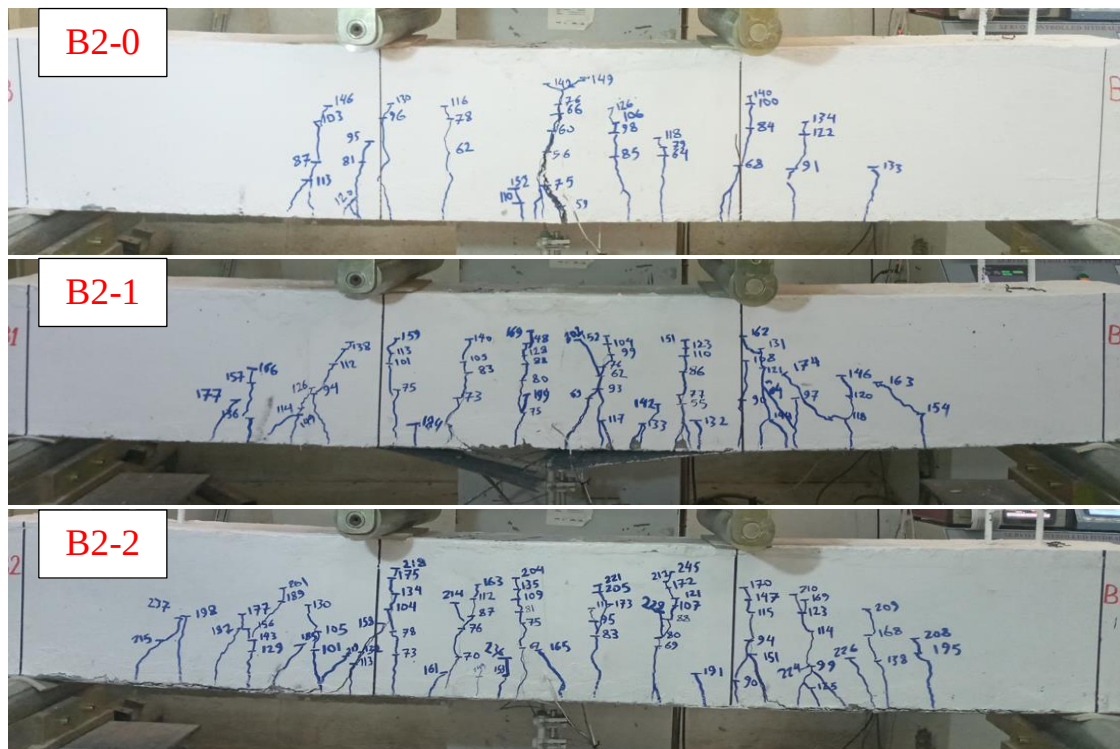


Figure 21. The group (B2) beams, B2-0, B2-1, and B2-2 deformation pattern



5. Finite element representation

As shown in Figs. 24 and 25, numerical simulations in the finite element program ABAQUS (version 2021) [30] were used to evaluate the structural performance of the beam in each of the four groups and determine the flexural strength after the third layer of the CFRP sheet was added.

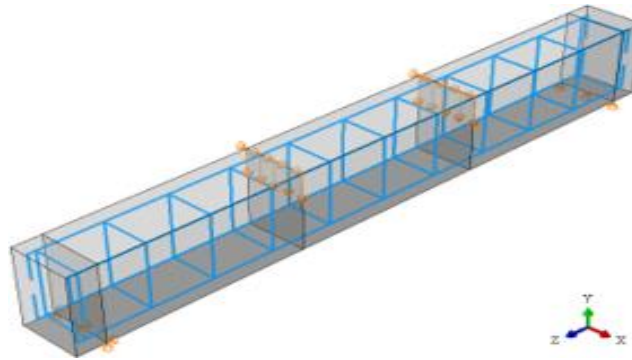


Figure 24. Boundary conditions

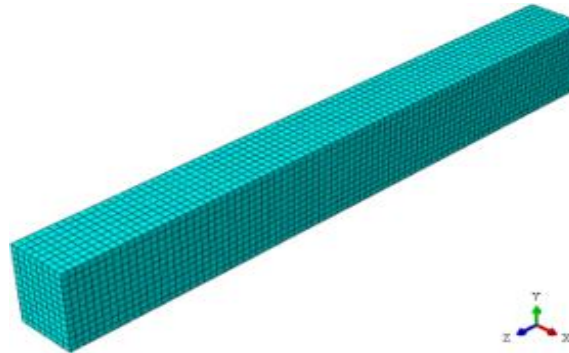


Figure 25. Simulating beam specimens with finite element meshes

In this program, four beams were used to symbolize the characteristics of the four different study groups for adding steel fibers and volume replacement waste tire rubber. The reinforcing steel is represented by a linear 3D two-node truss element (T3D2) with three degrees of freedom, while the concrete beams are represented by an 8-node linear brick (C3D8R). Steel reinforcement was restricted because of its perfect bond (no slip between reinforcing bar and concrete) and because it was embedded in the concrete. With a constraint in the Y direction (U2) on the right and a hinge constraint in the Z-Y direction (U2, U3) on the left, the boundary conditions of the reinforced concrete beams were modeled as rollers and hinges, respectively.

Displacement control was considered when calculating the load required for failure and simulating the applied load on reinforced concrete beams. The external reinforcement of each beam will be provided by three layers of CFRP sheets. The stress-strain curve for each beam could be calculated using curves for rubberized concrete that Kristina Stryker evaluated [31], curves for composite concrete that P. Kmiecik and M. Kamiski determined [32], and the ABAQUS user's manual [30]. Table 9 displays both the steel reinforcement data and the standard ABAQUS data.

Table 13. Steel reinforcement and the default ABAQUS input data

Steel reinforcement area (mm²)	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
σ_{b0}/σ_{c0}	1.16
K	0.667
Viscosity parameters	0.001

The load-deflection graphs for the three numerically reinforced layer CFRP beams are shown in Figs. 26, 27, 28, and 29. Inside each beam's curve, the curves for the other beams, including that beam's group. This illustrates how adding three CFRP sheets to the reinforcement of a beam decreases deflection at corresponding load levels, raises the load at failure, and lowers deflection if that beam fails.

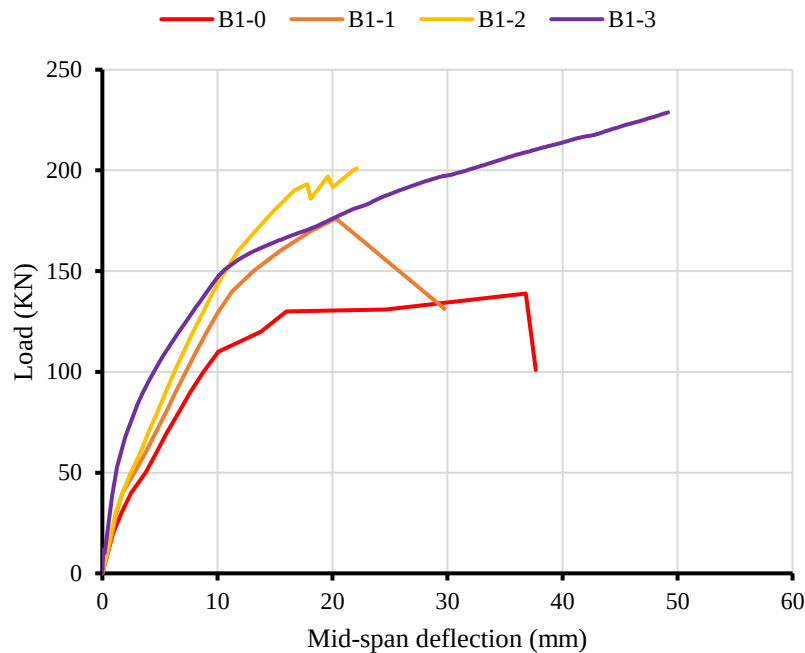


Figure 26. The numerical load-deflection diagram of the beam (B1-3) with the experimental load-deflection diagram of the remaining group (B1) beams

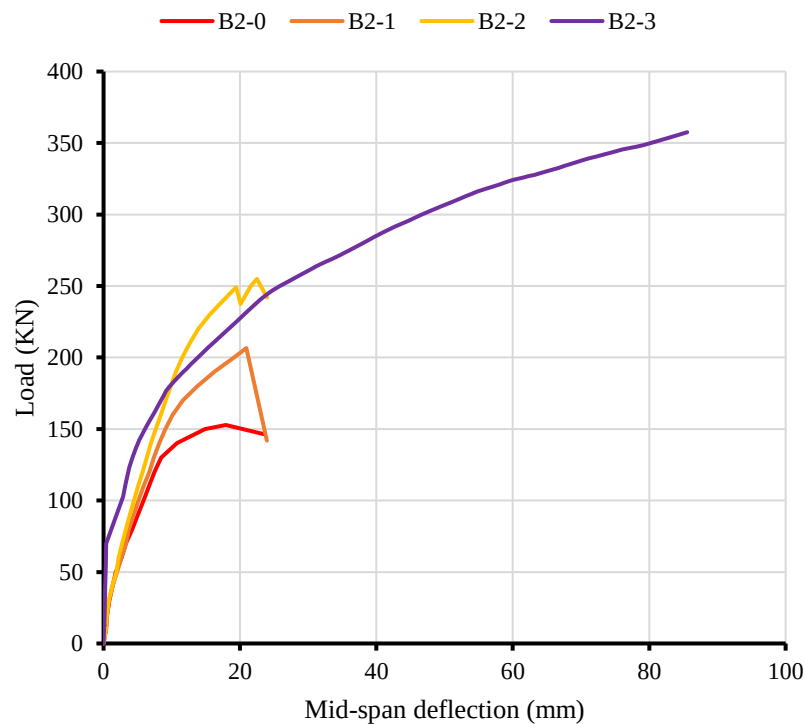


Figure 27. The numerical load-deflection diagram of the beam (B2-3) with the experimental load-deflection diagram of the remaining group (B2) beams

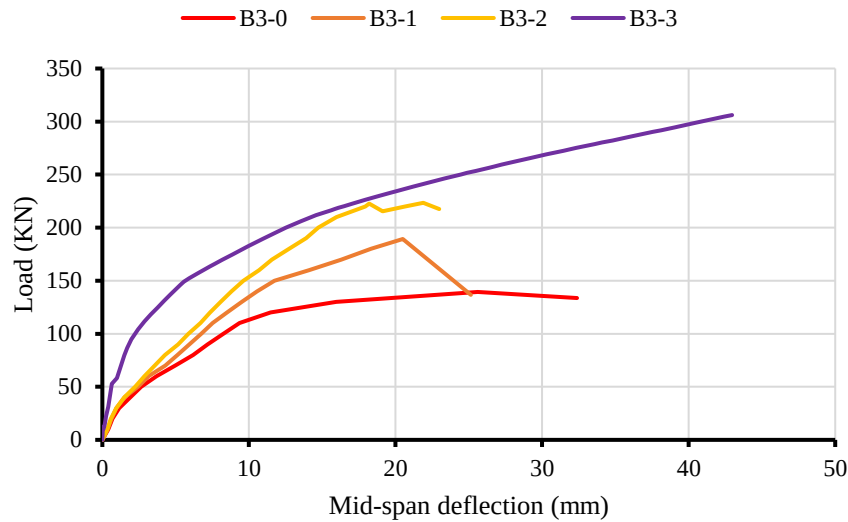


Figure 28. The numerical load-deflection diagram of the beam (B3-3) with the experimental load-deflection diagram of the remaining group (B3) beams

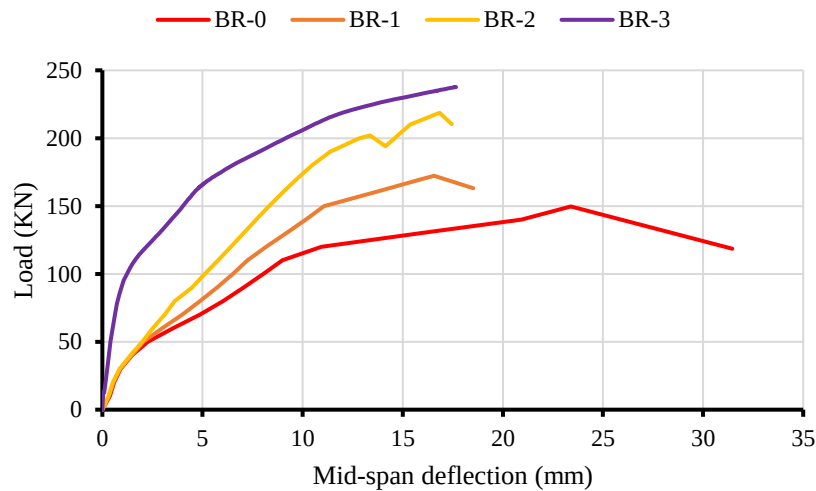


Figure 29. The numerical load-deflection diagram of the beam (BR-3) with the experimental load-deflection diagram of the remaining group (BR) beams

Tables 14, 15, and 16 also show the performance of beams that underwent numerical reinforcement using three sheets of CFRP and were evaluated for both the failure loading with deflection and the first crack loading with deflection. The outcomes were contrasted with the actions taken by the different beams in the control group. Steel fiber was an additive in the rubberized beam (B3-3) compared to the un-strengthened beam in the same group (B3-0); as a result, the first crack load increased by 38.61%, the first crack deflection decreased by 62.98%, and the load and deflection at failure increased by 119.58% and 83.61%, respectively. Comparing the first crack load and deflection to the un-strengthened beam (BR-0) in the reference group (BR), the first crack load increased by 50.49% and the first crack deflection decreased by 37.13%, respectively, while the load and deflection at failure increased by 104.47% and 83.61%. In comparison to the un-strengthened beam (B2-0) in the reference group (B2), the load at the first crack increased by 5.34%, and the deflection at the first crack decreased by 64.09%; however, the load and deflection at failure increased by 100.32% and 139.29%, respectively. When compared to the un-strengthened beam (B1-0) in the group (B1), the first crack load increased by 102.6% and the first crack deflection by 54.12%, whereas the load at failure and the deflection at failure increased by 120.37% and 16.82%, respectively.

Table 14. Load with the deflection at the first crack and at failure comparison results of numerically strengthened beams (B1, B2, and BR) 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		
Group	Beam	Load (KN)	Def. (mm)	Comparative ratio to:			Comparative ratio to:		
				unstrengthened beam in the same group (%)	(BR-0) beam in the reference group (BR) (%)	(BR-3) beam in the reference group (BR) (%)	unstrengthened beam in the same group (%)	(BR-0) beam in the reference group (BR) (%)	(BR-3) beam in the reference group (BR) (%)
B1	B1-3	37.81	0.82	+ 45.42	+ 8.03	– 25.39	– 41.22	– 19.45	+100.00
B2	B2-3	69.85	0.39	+ 39.70	+ 99.57	+ 37.83	– 78.11	– 61.69	– 5.45
BR	BR-3	50.68	0.41	+ 44.80	+ 44.80	–	– 59.72	– 59.72	–
Load and deflection at failure				Load at failure comparison			Deflection at failure comparison		
Group	Beam	Load (KN)	Def. (mm)	Comparative ratio to:			Comparative ratio to:		
				unstrengthened beam in the same group (%)	(BR-0) beam in the reference group (BR) (%)	(BR-3) beam in the reference group (BR) (%)	unstrengthened beam in the same group (%)	(BR-0) beam in the reference group (BR) (%)	(BR-3) beam in the reference group (BR) (%)
B1	B1-3	228.86	49.18	+64.77	+ 52.88	–3.71	+33.64	+110.2	+178.64
B2	B2-3	299.71	46.50	+96.15	+100.21	+26.09	+159	+98.74	+163.46
BR	BR-3	237.69	17.65	+58.78	+58.78	–	–24.56	–24.56	–

Table 15. Load with the deflection at the first crack comparison results of the numerically strengthened beam (B3-3) 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		
Group	Beam	Load (KN)	Def. (mm)	Comparative ratio to:			Comparative ratio to:		
				unstrengthened beam in the same group (%)	(BR-0) beam in the reference group (BR) (%)	(BR-3) beam in the reference group (BR) (%)	unstrengthened beam in the same group (%)	(BR-0) beam in the reference group (BR) (%)	(BR-3) beam in the reference group (BR) (%)
B3	B3-3	52.67	0.64	+ 38.61	+ 50.49	+ 3.93	– 62.98	– 37.13	+ 55.15
Group	Beam	Load (KN)	Def. (mm)	Comparative ratio to:			Comparative ratio to:		
				unstrengthened beam in the same group (%)	(B2-0) beam in the reference group (B8) (%)	(B2-3) beam in the reference group (B8) (%)	unstrengthened beam in the same group (%)	(B2-0) beam in the reference group (B8) (%)	(B2-3) beam in the reference group (B8) (%)
B3	B3-3	52.67	0.64	+ 38.61	+ 5.34	– 24.60	–62.98	–64.09	+64.10
Group	Beam	Load (KN)	Def. (mm)	Comparative ratio to:			Comparative ratio to:		
				unstrengthened beam in the same group (%)	(B1-0) unstrengthened beam in reference group (B5) (%)	(B1-3) Similar beam in reference group (B5) (%)	unstrengthened beam in the same group (%)	(B1-0) unstrengthened beam in reference group (B5) (%)	(B1-3) Similar beam in reference group (B5) (%)
B3	B3-3	52.67	0.64	+ 38.61	+ 102.6	+ 39.30	– 62.98	– 54.12	– 21.95

Table 16. Load with the deflection at failure comparison results of the numerically strengthened beam (B3-3) by three layers of (CFRP) sheets with reference beams

Load and deflection failure				Load at failure comparison			Deflection at failure comparison		
Group	Beam	Load (KN)	Def. (mm)	Comparative ratio to:			Comparative ratio to:		
				unstrengthened beam in the same group (%)	(BR-0) beam in the reference group (BR) (%)	(BR-3) beam in the reference group (BR) (%)	unstrengthened beam in the same group (%)	(BR-0) beam in the reference group (BR) (%)	(BR-3) beam in the reference group (BR) (%)
B3	B3-3	306.09	42.96	+119.58	+ 104.47	+ 28.78	+ 83.61	+ 83.61	+ 143.4
Group	Beam	Load (KN)	Def. (mm)	Comparative ratio to:			Comparative ratio to:		
				unstrengthened beam in the same group (%)	(B2-0) beam in the reference group (B8) (%)	(B2-3) beam in the reference group (B8) (%)	unstrengthened beam in the same group (%)	(B2-0) beam in the reference group (B8) (%)	(B2-3) beam in the reference group (B8) (%)
B3	B3-3	306.09	42.96	+119.58	+ 100.32	+ 2.13	+ 83.61	+ 139.29	– 7.61
Group	Beam	Load (KN)	Def. (mm)	Comparative ratio to:			Comparative ratio to:		
				unstrengthened beam in the same group (%)	(B1-0) unstrengthened beam in reference group (B5) (%)	(B1-3) Similar beam in reference group (B5) (%)	unstrengthened beam in the same group (%)	(B1-0) unstrengthened beam in reference group (B5) (%)	(B1-3) Similar beam in reference group (B5) (%)
B3	B3-3	306.09	42.96	+119.58	+ 120.37	+ 33.75	+ 83.61	+ 16.82	– 12.65

Figure 30 illustrates the tensile damaged region of beams (B1-3), (B2-3), (B3-3), and (BR-3).

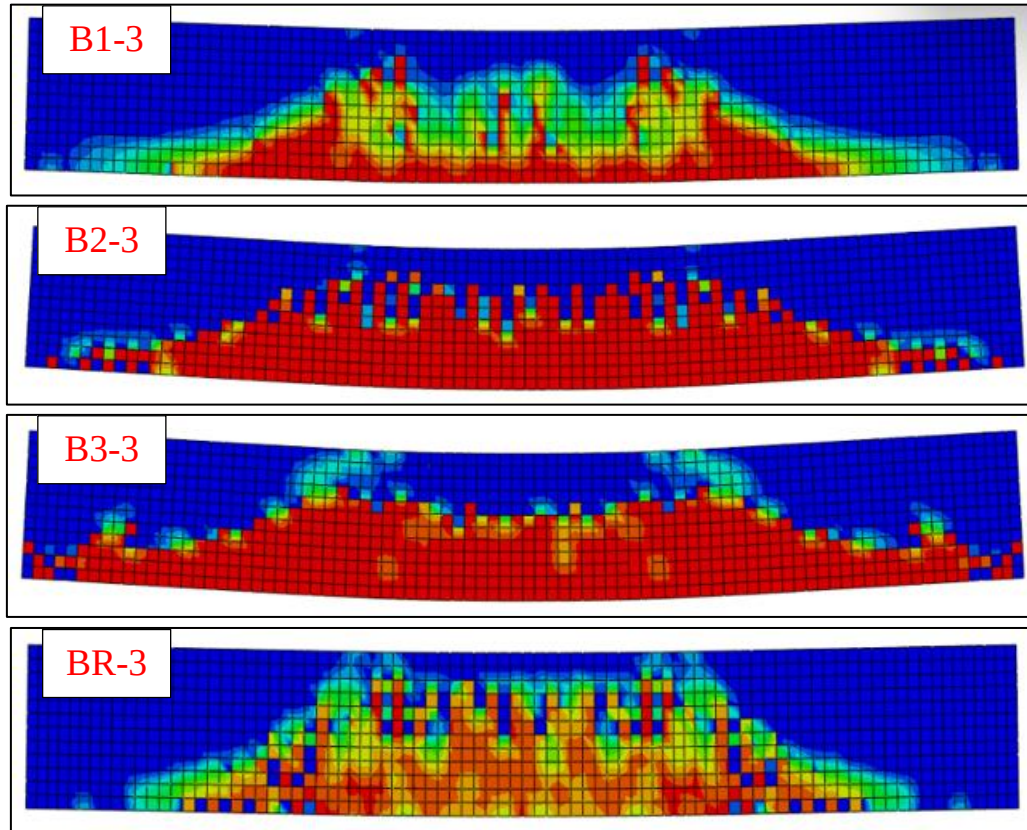


Figure 30. The beams (B1-3), (B2-3), (B3-3), and (BR-3) tensile damaged region

6. Conclusion

1. The addition of waste tire rubber causes Group (B1)'s mechanical properties (density, compressive strength, rupture modulus, splitting tensile strength, and elastic modulus) to all decrease in comparison to the reference group (BR). When steel fibers are added to group (B3), which contains rubber tire waste in the same proportion as group (B1), the loss in mechanical properties is less pronounced than in group (B1) above. Due to the addition of steel fibers, Group (B2)'s properties were superior to Group (BR)'s.
2. In comparison to the reference un-strengthened beams, a rubberized beam with a volumetric replacement of 10% coarse aggregate and 5% fine aggregate:
 - a. Due to rubberizing, the load at the first crack and failure decreased by 25.71% and 7.21%, respectively, but the deflection at the first crack and failure increased by 37.03% and 57.28%, respectively.
 - b. By adding one layer of CFRP sheet to the structure, the load at the first crack and failure are increased by 8.57% and 17.64%, respectively. The first crack deflection also increased by 58.64%, while the failure deflection decreased by 13.25%.

This rubberized beam's first crack and failure loads increase by 31.43% and 26.45%, respectively, and the first crack deflection rises by 117.2%. The failure deflection falls by 12.36% due to adding steel fibers to the concrete mix at 1.25% of the volume and strengthening with one layer of CFRP sheet.

- c. The load at the first crack and failure increased by 17.14% and 34.27%, the first crack deflection increased by 78.19%, and the failure deflection decreased by 5.42% when two layers of CFRP sheet were strengthened.

The rubberized beam's first crack and failure loads increase by 42.86% and 49%, respectively, while the first crack deflection increases by 120.7%, and the failure deflection decreases by 6.45% when steel fibers are added to the concrete mix at a rate of 1.25% of the volume and reinforced with two layers of CFRP sheet.

Compared to the reference un-strengthened beams, the first crack and failure load increased by 8.03% and 52.88%, respectively. The first crack deflection decreased by 19.45%, and the failure deflection increased by 110.2%. This was due to the volumetric replacement of the rubberized beam with 10% coarse aggregate and 5% fine aggregate.

Steel fibers, added to the concrete mix of this rubberized beam at a rate of 1.25% of its volume, increase the load at the first crack and failure by 50.49% and 104.47%, respectively, reducing the deflection at the first crack by 37.13%, and increasing the deflection at the failure by 83.61%.

Conflict of interest

The authors declare that they have no conflict of interest and all of the authors agree to publish this paper under academic ethics.

Author contributions

All the authors contributed equally to the manuscript.

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