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Research Article

Shear Strengthening of Recycled Lightweight Coarse Aggregate Concrete Beams Using NSM Technique

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ABSTRACT

The NSM technique began to apply as a modern technique to treat defects in structural elements and to increase the shear and flexural strength of structural elements. For this technique to be effective, a series of practical experiments were conducted to characterize the behavior of the element strengthened by the NSM technique for flexure and shear. Shear strengthening with GFRP rods is the focus of this paper for concrete beams that contain 30% coarse aggregate replacement ratio of bonza (volumetric ratio) obtained from the rubble of demolished buildings. A total of 7 beams were loaded under four-point load test, the parameters examined were the angle of inclination and the distance between the GFRP bars, the presence and absence of stirrups and the bonza aggregate replacement ratio. The characterization of the tested beams includes failure mode, load-deflection curves, load-strain curves of stirrups, rebars and GFRP rods and the surface concrete strain in the shear zone of beam. The results showed that the use of GFRP rods used to strengthen concrete beams was relatively effective, especially in the presence of stirrups, where the gain in shear strength was 8.8% and 4.1% when the distance between the vertical GFRP bars was (200 and 300) mm, respectively, with the presence of stirrups. While the gain in shear strength was (5.9%) when the GFRP bars were inclined at 45o with presence of stirrups. The deflection of strengthened beams was greater than the deflection of unstrengthened beam, where the maximum deflection of strengthened beams reaches 29.6mm at 177kN, while the maximum deflection of unstrengthned beam was 18.9mm at 185kN.

1. INTRODUCTION

The tremendous development of the world in the field of building and construction requires to find other materials for use in concrete rather than traditional materials. On the other hand, there was a huge increase in the amount of waste daily produced throughout the world, due to the expired lifetime of the buildings and the wars are becoming an environmental problem [1], the concept of sustainable development, which includes energy conservation, environmental protection, and maintenance of natural not renewable resources [2]. The growing consumption of natural aggregate calls to think about finding alternative sources of aggregate. The Federal Highway Administration (FHWA, 2004) estimates that two billion tons of new aggregate are produced each year in the United States, and it is expected to increase to more than 2.5 billion tons by the year 2020[2–4]. Since aggregate represents about (60%-80%) of the volume of concrete. On the other hand, approximately 3 billion tons of waste is generated in the European Union each year [5–7]. In line with the increase in demand for natural aggregate and increasing construction waste production, it is necessary to search for sustainable solutions in the recycling of the waste materials and use it for production of new concrete as recycled concrete aggregate. The reinforced concrete beams can become deficient during their service life and need to be strengthened and repaired.

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Strengthening the structural element in bending may result in shear failure rather than giving the desired load carrying capacity. "Strengthening", includes modifications in a building to increase its load capacity, hardness, ductility and stability[8, 9]. Several methods are available for designers to choose from shear strengthening. Such as external addition of stirrups, jacket, external plate bonding using epoxy or bolts and bonding external FRP segments, [10][11]. Islam et. al., [12][13], used the Near Surface Mounted (NSM) technique to investigate the influence of Carbon Fiber Reinforced Polymer (CFRP) on shear strength. The study included only four concrete beams, including one control beam and three model beams. The beams were strengthened in shear by using (#3) CFRP bars placed vertically at a distance of 152 mm on either side. The shear strength has been found to increase from 17% to 25%, as a result of using CFRP bars with the NSM technique. The shear span to effective depth ratio plays an important role in the effectiveness of CFRP bars used for strengthening in shear. Sharaky, et. al., [14], experimentally and numerically studied the behavior of reinforced concrete beams strengthened by near-surface mounted (NSM) (GFRP) rods with and without anchor end. The results showed that the load-carrying capacity for the reinforced concrete beams strengthened by bottom (NSM) bars is relatively high when compared to beams strengthened only with side (NSM) bars. Thamrin et al., [15], studied nine models of reinforced concrete beams without stirrups, (800mm span with 125×250 mm cross-section). The beams were tested under a four-point loading system and were strengthened with NSM steel bars with 45o and 90o to the axis of the beam. It was found that the steel bars increase the shear capacity of the strengthened beams (three longitudinal reinforcement ratios were used 1%, 1.4%, and 2.4%). The strengthened beams with reinforcement ratios of 1% and 1.4% not failed in shear but reached the required flexural capacity. Tang and Lo [16], considered eight beams that were tested under a four-point loading system, (1200mm×180mm×250mm) dimensions. The type and inclination of NSM bars were examined in addition to the type of adhesives. The results showed that the strengthening with 45o inclined GFRP bars is more effective for shear strengthening. The failure mode became a concrete compression failure rather than shear failure with remaining the system of NSM intact with beams without debonding. Also, it was found that the presence of stirrups is more effective on strengthening the shear capacity with the NSM technique. Rahman et. al., [17], studied the behavior of reinforced concrete beams strengthened with (NSM) technique with steel bars to get quick and economic strengthening solution. Seven beams (125×250×2000mm) in dimensions were tested to obtain the mode of failure, failure load, strain behavior and deflection response. The highest improvement of load capacity reached was 46.8%, and the noticed failure modes were very similar. Mostofinejad, et. al. [18], used four beams (200×300×2000mm in dimensions) strengthened in shear with near-surface mounted (NSM) laminates technique. They studied different concrete compressive strength values and the presence of steel stirrups in the beams. The experimental results showed that the shear capacity of the beams was increased up to 69% and 41% for beams with and without stirrups, respectively due to the NSM technique. Also, the FRP (Fiber-Reinforced Polymer) shear contribution decreases in presence of the stirrups. This experimental research goals the application of Near Surface Mounted (NSM) technique, incorporating Glass Fiber Reinforced Polymer (GFRP) rods, to fortify structural elements. The study specifically delves into the shear strengthening aspect, concentrating on concrete beams with a 30% replacement of coarse aggregate using lightweight material called bonza. Through a series of practical experiments involving seven beams subjected to four-point load tests, the investigation assesses various parameters such as the angle of GFRP rod inclination, spacing, presence of stirrups, and aggregate replacement ratio. The research aims to characterize the behavior of these strengthened elements by analyzing failure modes, load-deflection curves, load-strain responses, and surface concrete strain in the shear zone. Notably, the results indicate the effectiveness of GFRP rods in shear strengthening, especially in the presence of stirrups, showcasing improvements in shear strength and deflection compared to unstrengthened beams. The study addresses the critical need for sustainable solutions in construction materials by incorporating lightweight coarse aggregate replacements, aligning with contemporary considerations of environmental impact and resource conservation.

2 SUSTAINABILITY OF LIGHTWEIGHT AGGREGATE

Sustainability became a standard term with the definition of the Brundtland Report (World Commission on Environment and Development, 1987). Sustainability now is an integral part of the agenda of governments and companies, and their aims have become central to the work of research laboratories and universities worldwide [19–22]. It is an action looking for satisfying current needs and leave coming generations the possibility to satisfy their requests, it is the main conception of science capable of discovering the solution for the related problem [23][24]. Because of the huge quantity of concrete produced every day even a slight decrease in the use of raw materials in concrete mixtures will lead to significant benefits to the environment [25][26]. The best solution for achieving sustainability in concrete production is the use of waste materials and construction waste residues[27][28]. Recently, the concept of sustainability has evolved, in addition to the physical and mechanical properties of materials, taking into consideration economic and environmental issues, to obtain a successful and sustainable innovative product[29][30]. Numerous researchers recommend that (30%) as the maximum ratio for using recycled coarse aggregate as a replacement of coarse normal aggregate [31–38]. Many researchers were looking for an alternative to use as a coarse aggregate, one of the waste materials was used as a replacement for coarse aggregate in concrete, bonza (pumice material) were used in this research. RAC refers to Recycled Aggregate Concrete is defined as prepared concrete using recycled aggregates or a combination of recycled and natural aggregates [39–42].

3 TEST SPECIMENS

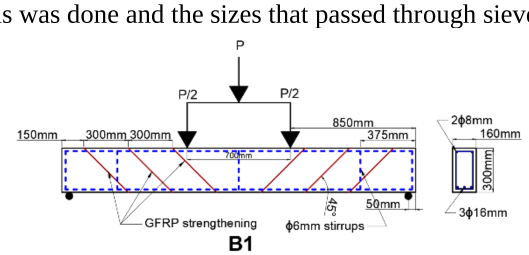
In this study, seven beams were tested with a length of 2400mm, 160mm width and 300mm height. Two of them remained without strengthening. The first one was cast with normal concrete and the second was cast with 30% bonza coarse aggregate replacement ratio to compare the beam failure mode and the decrease in the load carrying capacity due to partial replacement of natural aggregate with bonza. The remaining five beams were cast with 30% coarse aggregate replacement ratio of bonza (volumetric ratio), two of them which do not contain stirrups. The beams were designed to have a high flexural capacity to ensure the failure occurs in the shear zone. Three 16mm bars (had a 580MPa yield strength) were used as reinforcement for flexural, and 6mm stirrups bar (250MPa yield strength) @200mm, with two 8mm (420MPa yield strength) top bars. The loading system was four-point bending load, the details of beams and loads are shown in Figure 1. All beams had the same longitudinal reinforcement but differed in the presence or absence of stirrups. Five styles of Near-Surface Mounted (NSM) strengthening configuration were used for shear strength by (GFRP) bars, the diameter of the used (GFRP) bars was 6mm. The models also differ in the style of strengthening configuration, there were five different patterns. The first pattern was inclined strengthening without stirrups, the second type was inclined strengthening with stirrups, the third one was vertical strengthening with a distance of 300 mm without stirrups, the fourth type was vertical strengthening with a distance of 200 mm with stirrups and the fifth type was vertical strengthening with a spacing of 300 mm with stirrups. One of the beams remained without strengthening, as shown in table 1 and Figure 1. beam specimens were loaded under a four-point loading system as simply supported beams as shown in Figure 1. The load was increased until failure of beams. The deflection at mid-span was collected by using LVDT, while the strains were recorded by data acquisition.

TABLE I. DETAILS OF TESTED BEAMS.

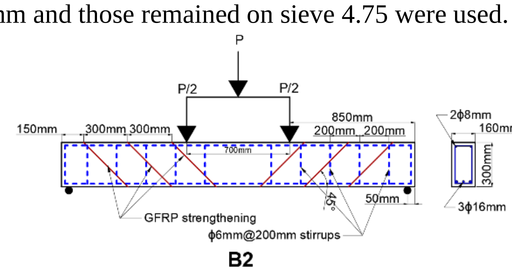
Beam N	**ght coarse aggregate volumetric repla**	**Steel stirrups details**	**Spacing of Strengthening Gl**
B1	30% bonza	without stirrups	0mm GFRP at 45o to the beam
B2	30% bonza	Ø6@200mm	0mm GFRP at 45o to the beam
B3	30% bonza	without stirrups	Ø6mm@ 300mm vertical GF
B4	30% bonza	Ø6@200mm	Ø6mm@ 200mm vertical GF
B5	30% bonza	Ø6@200mm	Ø6mm@ 300mm vertical GF
B6	30% bonza	Ø6@200mm	-------
B7	Normal concrete 0% bonza	Ø6@200mm	-------

4. MATERIALS

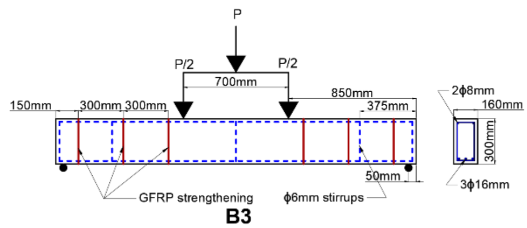
Ordinary Portland cement available in the local market has been used for the concrete mixtures approved for this research. The natural coarse aggregate of 4.75-19 mm in size was used. Where the samples were taken according to ASTM specifications, sieve analysis was done for samples and the obtained gradients were within the limits of the specifications. For fine aggregate, samples were also taken according to the ASTM specifications, and the results of the sieve analysis of the samples used were within the limits of the ASTM specifications. The lightweight aggregate was obtained from the remains of the broken bonza, where it was re-crushed to a size similar to the size of the natural coarse aggregate. The sieve analysis was done and the sizes that passed through sieve were 19 mm and those remained on sieve 4.75 were used.



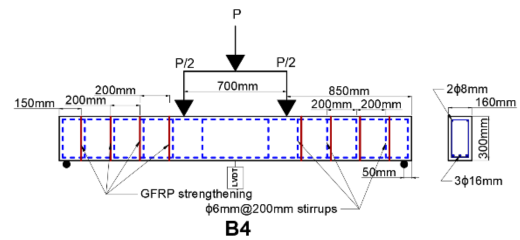
a. (B1)



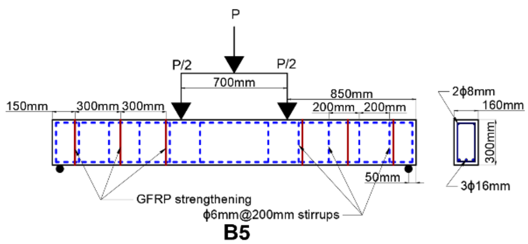
b. (B2)



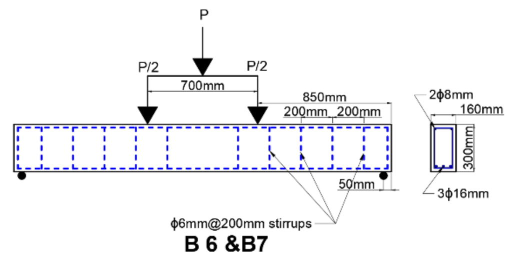
c. (B3)



d. (B4)



e. (B5)



f. (B6) & (B7)

Fig. 1. Details of used beams in the test

5 CONCRETE MIX DESIGN

The approved mixture proportions were 1: 1.8: 2 with a water-cement ratio of 0.38, where the compressive strength was 35MPa at 28 days. Also, part of the coarse aggregates was replaced with lightweight aggregates of bonza with (30%), volumetric ratio. The compressive strength at 7 and 28 days was tested using standard cylinders measuring (150 * 300 mm) in addition to testing the hardened concrete for flexural and splitting tensile strengths at 28 days, as shown in tables 2, 3 and 4.

TABLE II. DETAILS OF CONCRETE MIXTURES

L.W. rep. %	Kg/m^3
0 normal concrete	

L.W.=Lightweight, F.A.=Fine aggregate, C.A.=Coarse aggregate, %=Volumetric ratio, rep. = Replacement

TABLE III. COMPRESSIVE STRENGTH OF CONCRETE AT (7 & 28) DAYS.

Mix Nc	Replacement ratio. (%)	f'c after 7 days (MPa)	f`c after 28 days (MPa)	Drop in f'c (%)
1 rete)		30.84	35.26	---
2	30	22.3	26.3	25.5

TABLE IV. SPLITTING TENSILE STRENGTH AND MODULUS OF RUPTURE OF THE MIXTURES.

Mix Nc	Replacement ratio %	splitting tensile strength (MPa)	Modulus of rupture (MPa)
1	0 (normal concrete)	3.45	3.95
2	30	3.07	3.3

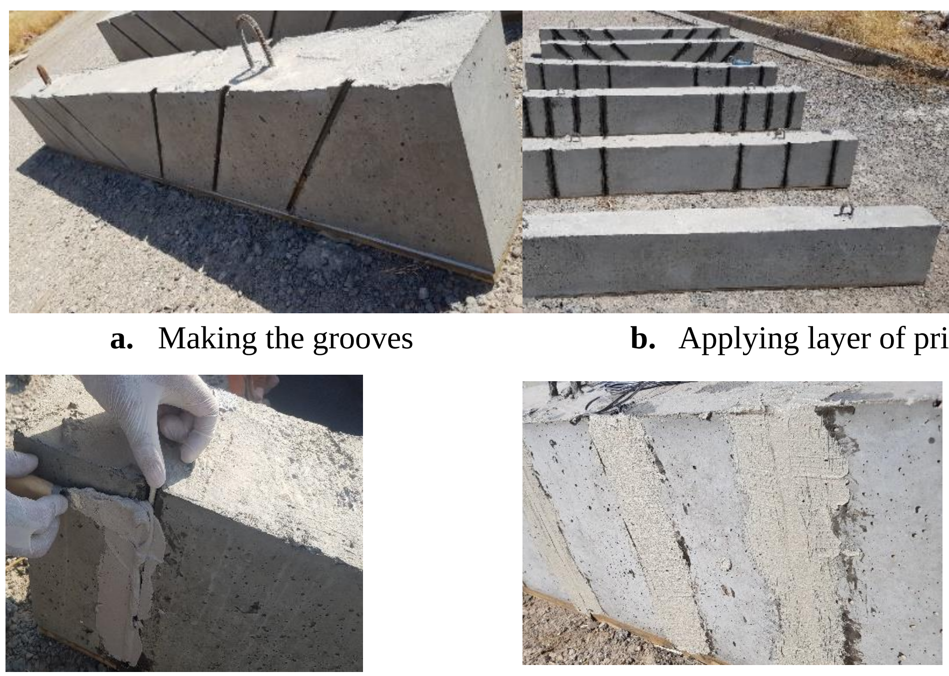
It is normal for the density of concrete to decrease when replacing the natural aggregates with lightweight aggregates such as bonza. Certainly, the percentage of decrease in density depends on the type of the lightweight aggregate replaced and also the percentage of aggregate ratio. Table 5 shows the concrete density for different proportions of replacement with lightweight aggregates of bonza.

TABLE V. DENSITY OF CONCRETE WITH AND WITHOUT BONZA AGGREGATE REPLACEMENT RATIO.

Mix No	Replacement ratio (%)	Density of concrete (Kg/m^3)	Drop in density (%)
1	0 (normal concrete)	2407.9	0
2	30	2257.87	7.25

6 STRENGTHENING OF BEAM SPECIMENS

To strengthen the beams using the NSM technique, (6 mm) diameter GFRP bars were used, with (400 MPa) breaking strength. Five patterns of configuration have been used to strengthening the beams, while the reference beams have not been strengthened for sake of comparison, as shown in Figure 1 and table1. The NSM technique that has been used in this research was done as follows: Firstly, grooves of (12*12mm) were made on both sides of the beam according to the specific locations, a thin layer applied on the grooves of primer base (which consists of a mixture of two materials produced by the DCP company), then it was left for 24 hours to dry. Then the GFRP bars were glued to the surface of the beams with an adhesive designated (Sikadur-31) was used as an adhesive to attach the GFRP bars to the concrete surface as a second layer (it was applied in the form of a 2-component thixotropic epoxy adhesive). The grooves that the GFRP rods installed into them were filled. Figure 2 shows pictures of the installation stages of the GFRP rods on the beams.



a. Making the grooves **b.** Applying layer of primer

The GFRP bar was glued by sikadur-3 **d.** Finishing beam surface

Fig. 2. Stages of installing GFRP bars

7 INSTALLATION OF STRAIN GAUGES

Two types of strain gauges (Tokyo Measuring Instruments Lab.) were used. The first type was mounted to the steel with a length of (5 mm) and the other type was applied on concrete surface with a length of (30 mm) with their adhesives obtained from the same corporation. Strain gauges were fixed at six locations of the beam, as shown in Figure 3. Two of them were mounted to the stirrups at the left and right sides of the beam, and one was mounted to the middle of main longitudinal reinforcing steel bar, two were mounted on the concrete surface at the shear zone. They were inclined at an angle of 45o normal to the direction of the shear cracks. The last strain gauge was fixed on one of the GFRP bars. The data were collected by the (data acquisition) that was connected with the computer and the strains were recorded during the test for all stages of loading.

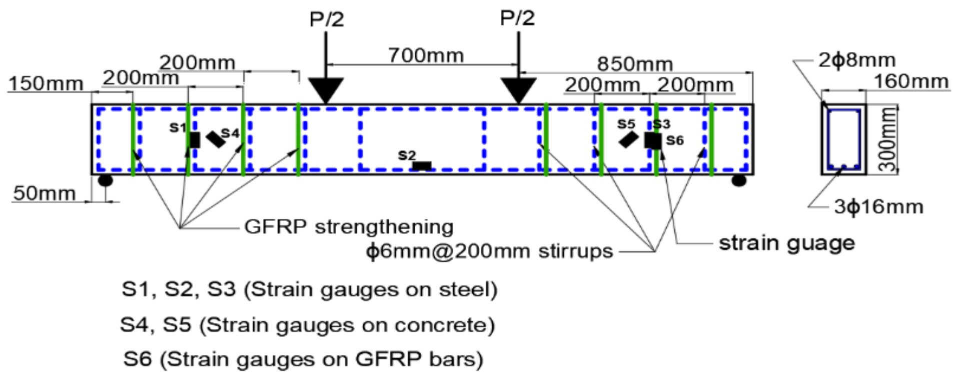


Fig. 3. Locations of strain gauges on a typical tested beam.

8. RESULTS AND DISCUSSION

The results have been divided into many categories, load carrying capacity, load deflection curves, load strain response and mode of failure.

8.1. Load carrying capacity

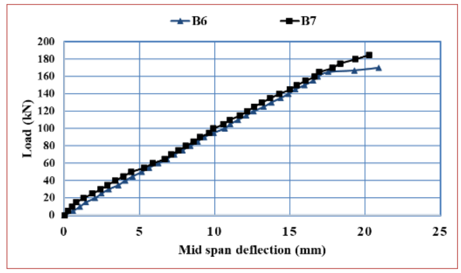
When observing table 6, it is noticed that the maximum gain in load capacity was occurred in beam B4, where the ultimate load is increased by 8.8% compared to unstrengthened beam B6. Beams B1 and B3 had not a gain in a load carrying compared to B6, that’s due to the absence of stirrups, the GFRP bars used to strengthened were not able to reach the strength of stirrups to shear. The table shows the effect of the angle of inclination of GFRP strengthening rods on the load carrying capacity of beams in the absence of stirrups. The gain was in the load carrying capacity of the beam by 5.9% compared to the gain in the load carrying capacity of the beam B5 by 4.1%. As the beam B2 was has the same number of GFRP rods compared with beam B5 but with 45o inclination with the longitudinal axis of the beam.

8.2. Load-deflection response

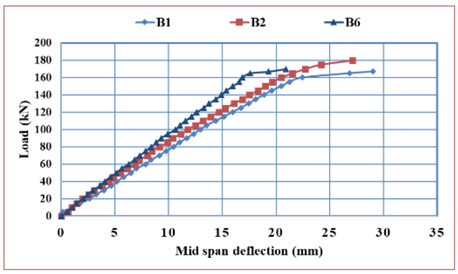
All the deflections were measured up to the failure load, the location of the (LVDT) was at the midspan of the beams. Figure 4 shows the load versus mid-span deflection of the tested beams. Although the beams strengthened with GFRP bars had a maximum loads larger or smaller than the beam B6, all the maximum deflection of these beams was greater than the maximum deflection of the unstrengthened beam (B6), as shown in table 6. By observing Figure 4-a, it is evident that the deflection of beams B6 and B7 (which were tested without external strengthening) were identical to a large extent at all stages of loading. This gives an indication that the response of a beam that contains 30% of bonza lightweight aggregates has a behavior similar to that of a beam that cast with normal concrete. Beams B1 and B2, that had been strengthened with 45o inclined GFRP rods, had a deflection higher than the beam B6 at all loading stages. The same is true for beams B3, B4 and B5 (which have been strengthened with vertical GFRB rods), the deflection of which is greater than that of the beam B6 for all loading stages, Figure 4-b and c.

TABLE VI. TEST RESULT OF MAXIMUM LOAD AND DEFLECTION.

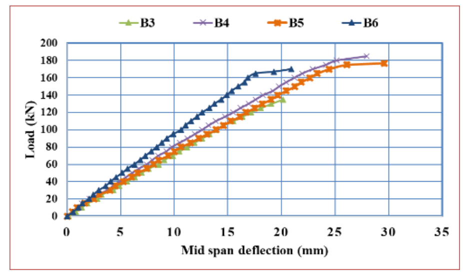
Beam	Stirrups mo	Maximum L (kN)	ximum deflecti	n maximum load compar	h maximum deflection co (%)	Mode of failu
B1	Without stirru	167	29.04	-1.8	53.6	Shear
B2	With stirrup	180	27.12	5.9	43.5	Shear
B3	Without stirru	135	20.13	-20.6	6.5	Shear
B4	With stirrup	185	27.95	8.8	47.9	Concrete crusl
B5	With stirrup	177	29.59	4.1	56.6	Shear
B6	With stirrup	170	18.9	-		Shear
B7	With stirrup	185	20.13	8.6	6.5	Shear



a. Load deflection curves of unstrengthened beams (**B6** and **B7)**



Load deflection curves of beams **B1**, **B2** anc



oad deflection curves of beams **B3**, **B4**, **B5** an

Fig. 4. Load deflection relationships of tested beams.

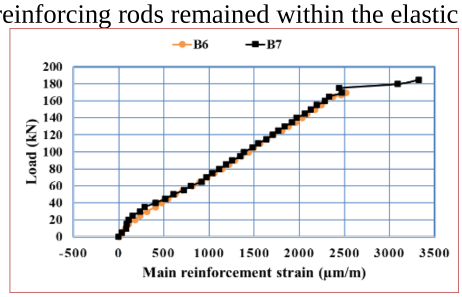
8.3. Load-strain response

As previously mentioned, the strain gauges have been placed at six locations on the beams as shown in Figure 3. Table 7 shows the value of strain that has been recorded at failure load of each beam.

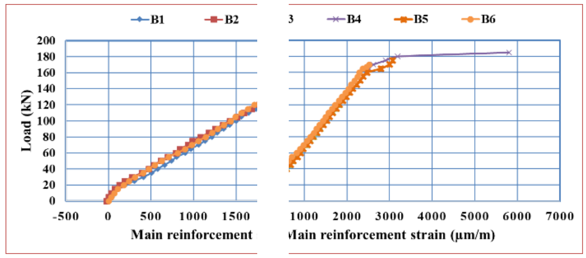
TABLE VII. STRAIN VALUES AT THE FAILURE LOAD FOR EACH LOCATION OF THE BEAMS (μm/m)

Beam N	Maximum lo (kN)	Left side on sti	Main reinforcem	ght side on s	eft side on co	ight side on co	GFRP
B1	167	2037	>10000	1264	>10000	-19	1192
B2	180	>10000	>10000	1204	22	-74	1833
B3	135	705	2046	1236	28	54	1516
B4	185	651	5807	1318	446	985	2016
B5	177	1139	>10000	921	5914	-95	>10000
B6	170	308	2518	1403	-19	-87	------
B7	185	2062	3322	1597	21	2072	------

By noting Figure 5 which illustrates the strains occurring at the main reinforcing rods for all beams, it can be noted that the strains have almost the same pattern as that of the reference path beam which had a linear response until reaching the failure load. This trend can be attributed to the main reinforcement in the beams which was designed to resist high moments and loads. Therefore, the strains in the main reinforcing rods remained within the elastic range.



a. Load-steel strain curves of beams **B6** and **B7**



b. Load-steel strain curves of beams **B1**, **B2** and **B6**

c. Load-steel strain curves of beams **B3**, **B4**, **B5** and **B6**

Fig. 4. Load-steel strain relationships at mid-span of longitudinal bottom rebars.

For the strain on the stirrups that shown in (Figure 5 a to f). It can be noted that the recorded strain at stirrups was recognized at a load level of about (40-50 kN) approximately, that indicates the beginning of the transferring of loads from the cracked concrete to the stirrups at this stage. These values are close to the values of concrete strength that is calculated using equation (1).

$$Vc = \lambda \frac{\sqrt{fc'}}{6} * bw * d \tag{1}$$

where λ is the modification factor to reflect the reduced mechanical properties of lightweight concrete relative to normal weight concrete [43]. The value of λ equals to 1 for normal concrete, and equal to 0.75 for concrete contained lightweight coarse aggregate. In this case when the replacement ratio of coarse aggregate with lightweight thermstone equal to 30%, the value of λ is equal to 0.925, by interpolation. The values of shear force that calculated using equation (1) are listed in table (8), and are compared with actual value obtained from strain recorded at left and right stirrups at loading.

As for the strain on the GFRP strengthening rods. It begins to be significant the transfer of loads to the GFRP rods early at load level of about 40 kN for beams without stirrups, (Figure 6-a), and at a loaded of 110 kN for beams that have stirrups, (Figure 6-b). These values of the loads are obtained when adding the values of concrete shear strength that computed using equation (1), with the resistance of the stirrups calculated using equation (2)

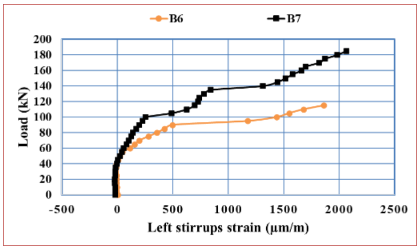
$$Vs = \frac{Av.fy.d}{s} \tag{2}$$

Table 8 shows the values of strength of concrete and stirrups depending on equations (1 & 2), and the actual load carrying by GFRP bars depend on the tests results.

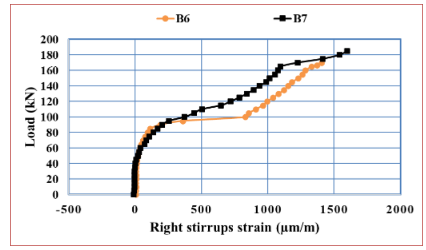
TABLE VIII. SHEAR STRENGTH OF CONCRETE AND STIRRUPS OF STRENGTHENED BEAMS

(1) Beam N	(2) f'c at 28 da (MPa)	(3) calculated by eq (kN)	(4) calculated by eq (kN)	(5) calculated by eq (kN)	(6) imental shear forc (kN)	(7) ual load-carried by (kN) (col.6-col.5)
B1	26.28	33	-----	33	83.5	50.5
B2	26.28	33	18.45	51.45	90	38.55
B3	26.28	33	-----	33	67.5	34.5
B4	26.28	33	18.45	51.45	92.5	41.05
B5	26.28	33	18.45	51.45	88.5	37.05

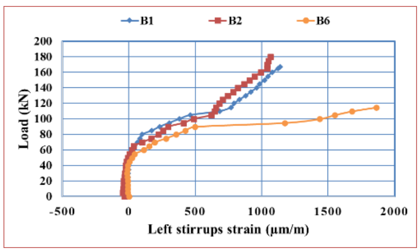
By observing table 8, it can be seen that the beams B2, B3 and B5 (in which the failure was a shear failure), the load carried by GFRP bars was almost a constant value (ranging from 34 to 38 kN). The average surface concrete strain at the left and right side of shear zone of the beams is shown in Figure 7. The shape of the curves that were recorded on this zone of the beam was affected by the shear cracks that had occurred in this zone as a result of applying the load. Since cracks affect the value of the strain that was recorded and reduce its values, and also caused a damage in the strain gauges readings.



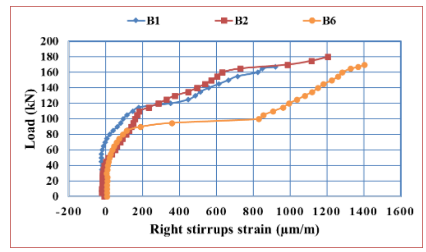
a. Left side stirrups strain for beams **B6** and **B7**.



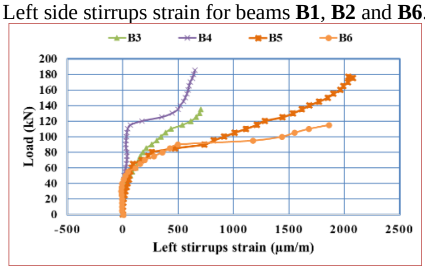
b. Right side stirrups strain for beams **B6** and **B7**.



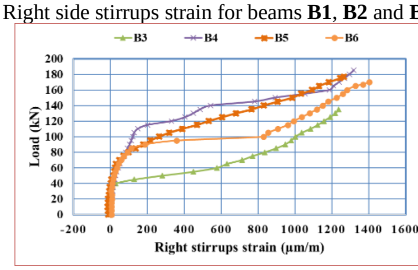
c. Left side stirrups strain for beams **B1**, **B2** and **B6**.



d. Right side stirrups strain for beams **B1**, **B2** and **B6**.

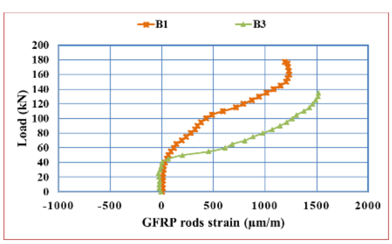


e. Left side stirrups strain for beams **B3**, **B4**, **B5** and **B6**.

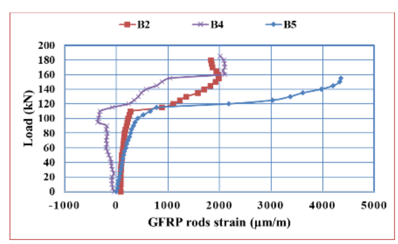


f. Right side stirrups strain for beams **B3**, **B4**, **B5** and **B6**.

Fig. 5. Load strain relationship at left and right stirrups for tested beams.

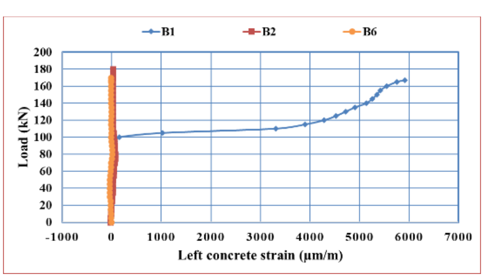


a. Load strain curves of beams **B1** and **B3**

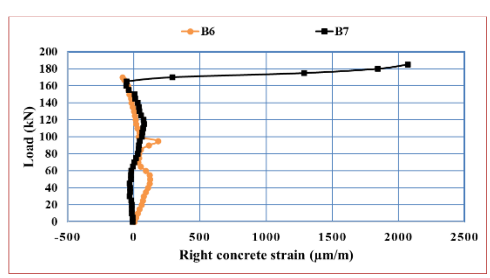


b. Load strain curves of beams **B2**, **B4** and **B5**

Fig. 6. Load strain relationship of GFRP rods.



a. Left side concrete strain for beams **B1**, **B2** and **B6**.



b. Right side concrete strain for beams **B6** and **B7**.

Fig. 7. Load strain relationship at left and right concrete shear zones for some sellected beams.

8.4 Mode of failure

Failure of beams B1 and B2 (that had the same strengthening pattern) was shear failure followed concrete crushing. The shear crack was was started from the crushing of concrete confined between the top of the inner GFRP bar with the bottom of the outer GFRP rod, passing through the middle bar. Failure of beams B3 and B5 (that had the same strengthening pattern) was shear failure. The cracks were confined between the top of the innr GFRP rod and the middle of GFRP rod. Failure of beam B4 was a concrete crushing failure, ther is no clear shar crack appear at the concrete shear zone, that is due to the small spacing between the strengthening GFRP bars compared to the distance used for other beams. Failure of beams B6 and B7 (that were tested without strengthening) was shear failure. The cracks were started from the applied point load toward the point of support. The crack width of the beam B7 was greater than the crack width of beam B6. As shown in Figure 8.

a. (B1) shear failure

b. (B2) shear failure

c. (B3) shear failure

d. (B4) concrete compression failure

e. (B5) shear failure

f. (B6) shear failure

(B7) shear failure

Fig. 8. Failure modes of all tested beams

9. CONCLUSIONS

The following conclusions are drawn from the results of the experimental tests:

- Using some pattern of NSM technique for shear strengthening of concrete beams containing lightweight coarse aggregate (bonza) replacement restores about (90-100%) of the shear capacity of normal concrete beams without lightweight coarse aggregates replacement.
- The effect of strengthening by GFRP bars on concrete beams is very small in the absence of stirrups espesially for strengthening with vertical GFRP bars.
- It is possible to use concrete containing 30% replacement of lightweight aggregate (bonza), for normal work because the density and compressive strength is decreased by only 7.25% and 25.5% respectively, and the density did not reach the lower limits of the specifications of lightweight concrete.
- The crack path is affected by the strengthening pattern more than by the absence and presence the stirrups.
- For unstrengthened beam, when the coarse aggregate was replaced by 30% of bonza lightweight aggregate, the maximum load was decreased by only (8.1%).
- The concrete compression failure that occurred in beam B4 (that strengthened with vertical 200mm GFRP bars) gives an impression that the reinforced concrete beam has reached the highest load that the beam can carry for this strengthening pattern.
- All the strengthened beams had a higher maximum deflection at maximum peack load than the unstrngthened beam, although some of these beams had a maximum load lower than the unstrengthened beam.

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Conflicts Of Interest

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