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Strengthening of Concrete Specimens with Glass Fiber Reinforced Polymer Sheets

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Abstract

This study details the specimens, material qualities, testing setup, instruments, and technique. The experimental programme featured five cylinders, four cubes, and ten PC beams. The cylinder specimen had 200 mm sides and 100 mm diameter. The 100*100*100-mm cube specimen had length sides. Beam specimens were 500 mm long and 100*100 mm wide. The specimens were loaded to failure under increasing static stresses. Cylinder, cube, and beam specimens were examined for compressive and flexural strength, respectively. The compressive and bending strength testing followed ECP 203-2018, the Egyptian Code for Design and Construction of Reinforced Concrete Structures. Two specimens of each type were control specimens. Externally Bonded (EB) Fibreglass Sheets with varied strip widths reinforced the other sample. ECP 208-2005, the Egyptian Code of Practise for the Use of Fibre Reinforced Polymer (FRP) in Construction, guided the strengthening process. Faculty of Engineering, Nile Higher Institute, Mansoura city, conducted all experiments in the Material Lab. The results show that the researched strengthening methods can improve the compressive and flexural behaviour of concrete specimens with GFRP sheets and increase load capacity compared to the control specimens.

Keywords: Flexural behavior; GFRP laminates; Fibrous concrete jacket

1. Introduction

RC structures are extensively utilized in the construction of housing and bridges, among other applications [1-3]. RC structures that are typical will need to be updated or replaced and they're in poor condition, not only due to natural disasters, material deterioration, and the change of useful function but also due to errors made all through design and execution [4-8]. Additionally, most existing structures are constructed as per out-of-date norms and codes [7-15]. As a result, they do not comply with modern design requirements, and ASCE 2009 classifies them as structurally deficient [16]. It is both economic and environmentally advantageous to reinforce existing structures rather than completely replace them, as the cost of new constructions has risen significantly [17,18]. As a result, designers must discover novel materials and building strategies to handle the problem of reinforcing existing RC structures [7].

The industry offers a variety of reinforcing materials, including steel plates, Ferro cement, and fiber-reinforced polymer (FRP) laminate [19]. The use of FRP materials is amongst the most outstanding methods for increasing the ultimate sustainable load capacity of existing RC structures [20-24]. When comparing cost-effective strengthening solutions, corrosion resistance, ease of installation, strength-to-weight ratio, use, durability performance, fatigue resistance, and availability in a range of shapes and sizes, FRP materials outperform traditional strengthening materials like steel sheets [25-27]. Externally bonded reinforcement (EBR) and near-surface mounted reinforcement (NSM) are two techniques of strengthening RC structures with FRP [7,28,29]. Externally bonding involves bonding one or more FRP laminates to the tensile surface of concrete members to the bending strengthening of concrete elements. The major processes in strengthening RC elements using the NSM technology include inserting FRP rods or strips into pre-cut grooves on the tension side of the elements and filling the pre-cut grooves with a high-strength glue composed primarily of epoxy resin [30,31]. Strengthening structures with the installation of RC layers and jackets is a widely utilized technology. Numerous practical, theoretical, and modeling research on columns, beams, and slabs reinforced with FRP sheets, steel plates, and ordinary concrete jackets have been published [32-38].

The concrete shrinkage strain of the added layers/jackets is a critical parameter in this procedure, as it can significantly affect the lifetime and performance of the strengthened structures. Further stress is introduced into stronger materials, resulting in the new layer breaking and/or debonding [39-45]. Thus, a novel technique for enhancing the performance of current structural parts is to connect them with extra fiber RC layers or jackets [46], resulting in improved mechanical qualities of these structures and enriching both their resistance and durability [46]. On the other hand, the fiber content is a critical characteristic determining the flexural strength and ductility of RC members. As per reported experimental research [47-49], increasing the ratios of synthetic or natural fibers resulted in an increase in flexural strength at the expense of ductility and improve the brittle behavior of concrete. Kang and Kim [50] studied the influence of fiber orientation and dispersion in the mix. As per this research [50], whereas fiber distribution and orientation have a minimal effect on pre-cracking action, they have a major impact on post-cracking properties of materials .

2. Research significance

This study aimed to investigate the flexural behavior of beams strengthened with numerous systems to increase the ultimate load capacities and improve the deformation of RC elements. In addition, determine which system is affected to improve the flexural behavior and toughness of the beams.

3. Experimental work

3.1 Materials and concrete mixes

one mixtur was used to caste cubes, cylinders, and beams Ordinary Portland cement-type OPC- I 42.5N and OPC-I 52.5N were used in Mo and MR, respectively. Silica fume (SF) was used as binder materials (B) in the used mix. The chemical composition, phase composition, and physical properties of binder materials are listed in Table 1. Ordinary Portland cement tests were carried out according to ASTM C150/C150M-21 [51]. Natural sand (S) with a fineness modulus of 2.6 and specific gravity (SG) of 2.67 was used as fine aggregate for the two mixes. Gravel (G) with a specific weight of 2.6 with water absorption of 3% and nominal maximum size (NMZ) of 19 mm were utilized as coarse aggregates of mix. The grading of gravel and sand is shown in Fig.1. The sulphate content of S and D were 0.25% and 0.19%, respectively. Aggregate tests were carried out according to ASTM C33/C33M-18 [52]. [53 [53] Components of concrete mix is presented in Table 2. The mix was blended with the same procedures of a previous study [54]. The sand was 36% of total aggregates, while water was calculated as percentages of binders. Cement content (C), water to binder ratio (w/b), and SF/C ratio of mix were 400 kg/m^3, 0.5, and 0.15 , respectively. Six cylinders with a diameter of 150 mm and a height of 300 mm were used for quality control and in the same treatment conditions for the RC beams. The stress /strain curve of Mo and MR concrete are shown in Fig 2. The conventional cylinder splitting test was used to determine the average tensile strength of the concrete (fct) for Mo, MR and it was found to be 2.44MPa, and 3.6MPa, respectively.

The Mechanical characteristics of mild and high-strength steel reinforcement used in the experimental study are shown in Table 3. The material for strengthening was the GFRP laminate Sikawrap_430 from Sika Egypt, steel plate, and Epoxy Sikadur-330 from sika Egypt to bond GFRP laminate and the steel plate on the concrete surface of the strengthened beams in this study. The properties of strengthening materials are shown in Table.4.

Properties		OPC I-42.5N	SF
Chemical Properties			
CaO	%	63.64	0.21
SiO_2	%	19.58	97.20
Al_2O_3	%	5.41	0.25
Fe_2O_3	%	3.41	0.54
SO_3	%	2.29	0.11
MgO	%	0.91	0.43
K_2O	%	-	0.45
Na_2O	%	0.83	0.15
Cl	%	0.048	-
F-CaO	%	1.1	-
LOI	%	4.65	0.74

Nile Journal of Architecture &Civil Engineering

Journal Webpage: https://njace.journals.ekb.eg

Volume 2, June 2023

Table 1: The chemical composition, phase composition, and physical properties of binder materials

Phase composition			
C_3S	%	68.11	-
C_2S	%	4.64	-
C_3A	%	6.56	-
C_4AF	%	10.22	-
Physical Properties			
Water for standard consistency	%	27.2	-
Specific surface area (Blain)	cm^2/g	2984	17.8×10^3
Specific weight		3.15	2.15
Soundness (Le-Chatelier)	mm	1.5	-
Initial setting time	min.	150	-
Final setting time	min.	189	-

Nile Journal of Architecture &Civil Engineering

Journal Webpage: https://njace.journals.ekb.eg

Volume 2, June 2023

Table 2: Mixture proportions of concrete mixes, all the component unit is with kg/m^3

Mix No.	B. materials: OPC I-42.5N	B. materials: SF	S	D	W		f_{cu}
Mo	400	60	622	1088	200	8	35 MPa

Notes: B: materials: Binder materials (C+SF) W: Water G: Gravel as the coarse aggregate
S: Sand as the fine aggregate SF: Silica fume SP1: Sikament-NN

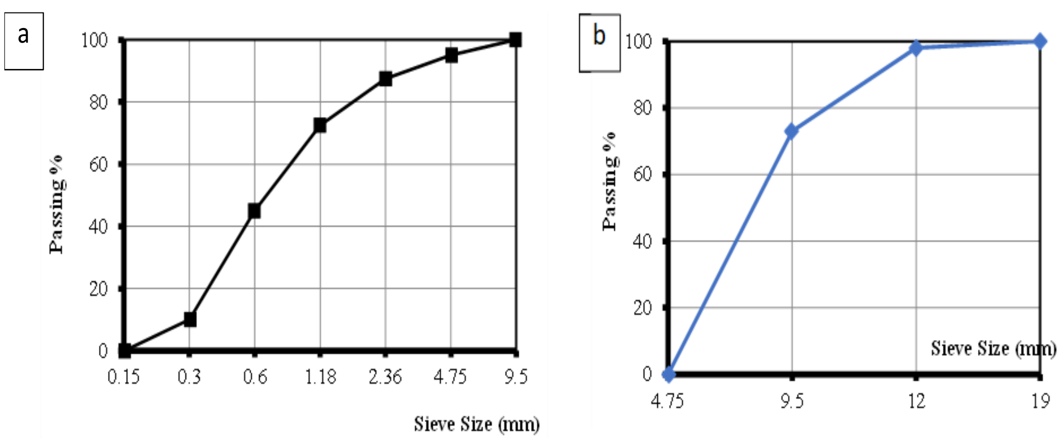

Fig. 1: Grading curve; a) fine aggregate (sand); b) coarse aggregate (Gravel).

Table (3): characteristics of strengthening materials.

Strengthening	Thickness (mm)	Elastic	Tensile
GFRP laminate (Sikawrap_430)	0.168	70	1500
Epoxy resin-(Sikadur-330)	-	3.4	33.8

3.2 Specimens and experimental Set-up

The test program consisted of 5 cylinder specimens, 4 cube specimens, and 10 PC beam specimens. The first group was a set of two reference specimens without strengthening for each type. The strengthened specimens with externally bonded (EB) Fiberglass sheets, with different strip widths for each specimen, were shown in Table (4) and Figs. 2 and 3.

3.3 Specimens casting and strengthening

After being cleaned and sprayed with water, mold forms were used to cast the specimens. Then, the concrete mix was poured in. The side forms were removed after one day of casting. All specimens were cured for 12 days at the surrounding environmental ambient temperature. Strengthening materials were applied to specified specimens as mentioned earlier. This specimen was strengthened with GFRP sheets as discussed earlier. Figure (3-25) presents the steps of strengthening with EB-GFRP:

a) The concrete surface was made free from dust, oil, and an angle grinder was used to smooth the surface before applying GFRP sheets. In addition, a blower was used to remove the fine dust particles. Before applying the sheets, the surface was dried.
b) A GFRP sheet would be cut into pieces to be applied on a surface.
c) GFRP strips were then glued to the smooth surface using two layers of epoxy.
d) air bubbles were removed using a soft card.
e) The final installation and finishing of GFRP sheets for the specimen (S5).

3.4 Test setup

Every specimen was loaded up to failure under increasing static loads. For the Cylinder, cube, and beam specimens, Cylinder and cube specimens were tested against compressive resistance, and the beam specimens were tested against flexure resistance. The compressive and bending strength tests were carried out according to ECP 203-2018. To ensure the best results outcome throughout the overall test, the concentrated load was used to apply load gradually on tested specimens.

Table (4): Program details for tested specimens

Group	Specimens	Terminology	Properties	Strengthening method
I	S1, S2	S-CY	Two control cylinder specimens with no strengthening	–
	S3, S4	S- CU	Two control cube specimens with no strengthening	–
	S5, S6	S-B	Two control beam specimens with no strengthening	–
II	S7	S7-CY- 2×5	Cylinder strengthened with two strips of 50 mm width	GFRP-(EB)
	S8	S8-CY-3×5	Cylinder strengthened with three strips of 50 mm width	GFRP-(EB)

	S9	S9-CY-1×10	Cylinder strengthened with one strip of 100 mm width	GFRP-(EB)
III	S10	S10-CU-2×5	Cubes strengthened with two strips of 50 mm width	GFRP-(EB)
	S11	S11-CU-1×10	Cubes strengthened with one strips of 100 mm width	GFRP-(EB)
	S12	S12-B-5×15	Beam strengthened with one strip of 50 * 100 mm on the tension side	GFRP-(EB)
	S13	S13-B-10×15	Beam strengthened with one strip of 100 * 100 mm on the tension side	GFRP-(EB)
	S14	S14-B-5×25	Beam strengthened with one strip of 50 * 250 mm on the tension side	GFRP-(EB)
	S15	S15-B-10×20	Beam strengthened with one strip of 100 * 200 mm on the tension side	GFRP-(EB)
IV	S16	S16-B-30×15*2 U	Beam strengthened with two strips of 300 * 150 mm on tension side- U shaped @ 1/3 & 2/3 beam	GFRP-(EB)
	S17	S17-B-5×10*8 I I	Beam strengthened with two sets of four strips of 100 * 50 mm on each vertical side @ equal distances	GFRP-(EB)
	S18	S18-B-10×50	Beam strengthened with one strip of 100 * 500 mm on the tension side	GFRP-(EB)
	S19	S19-B-10×90 PA	Beam strengthened with one strip of 100 * 900 mm on tension side - U shaped - longitudinally	GFRP-(EB)

Configuration of the tested specimens

Schematic detailing of the Specimens

Figs. (2). (3), and (4) show isometric 3D models of the main details for control and strengthened specimens.

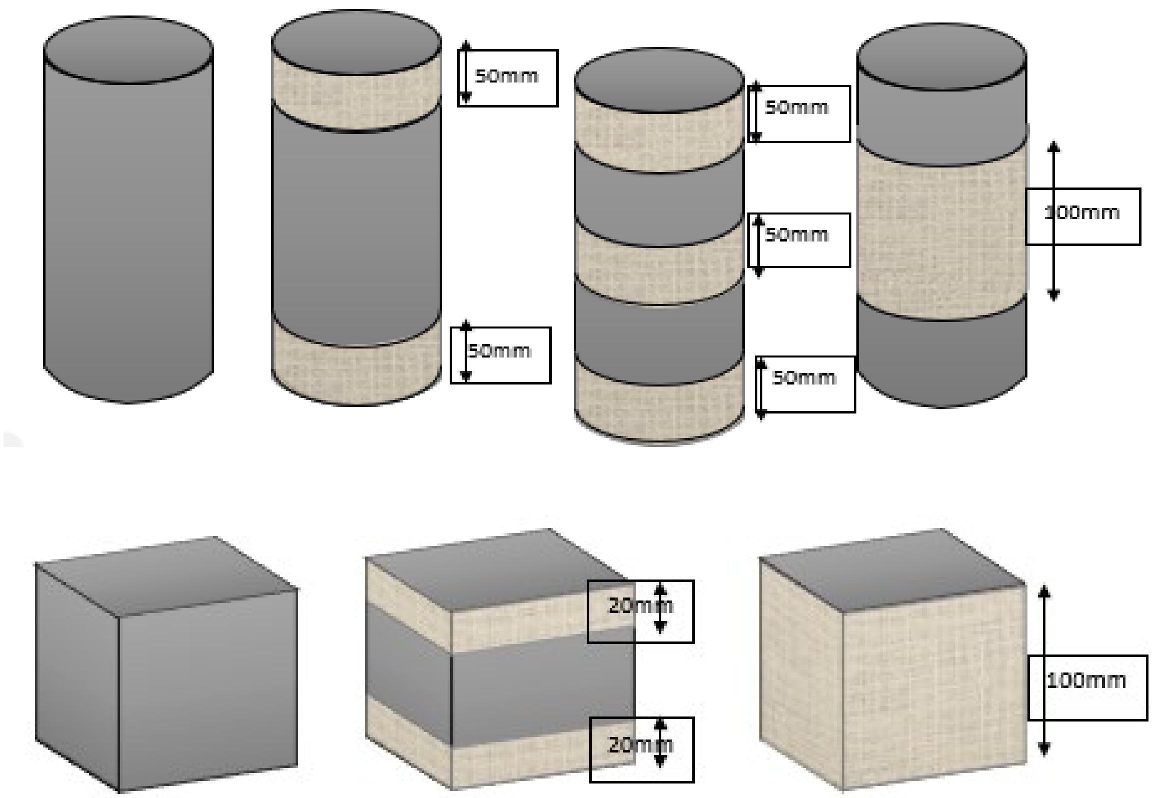

Fig. 2: Schematic details of the cylinder and cube specimens.

Nile Journals

Nile Journal of Architecture &Civil Engineering

Journal Webpage: https://njace.journals.ekb.eg

Volume 2, June 2023

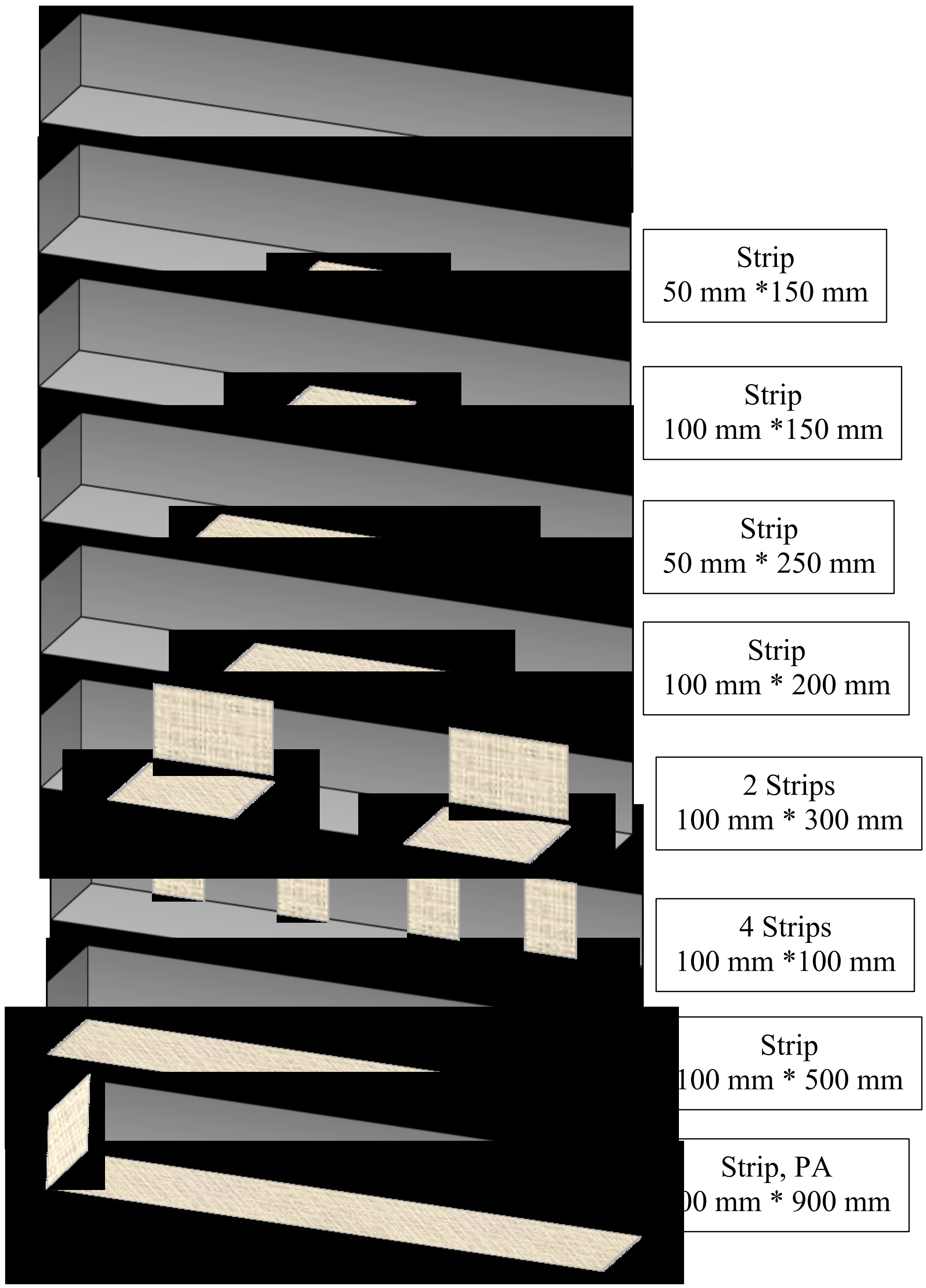

Fig.(3): Schematic details of the beam specimens

Nile Journals

Nile Journal of Architecture &Civil Engineering

Journal Webpage: https://njace.journals.ekb.eg

Volume 2, June 2023

4. Results and discussions

***4.1** Crack pattern propagation*

4.1.1 Crack pattern for cylinder specimens

S1&S2 (S-CY)

For the control cylinder specimens S1&S2, the crack and failure shape of the specimen can be clearly seen for the photo illustrated in Fig.(4). Effect of the friction between the tested cylinder specimen and the two chords of testing machine on the resulting failure as well as the compressive strength can de noticed.

Fig. (4): Failure shape of S1

When loading the horizontal surfaces of the test sample, this sample is compressed vertically or deflated due to the pressure stresses on it, while the sides of the sample try to stretch horizontally, but this lateral expansion movement will be resisted by the friction that arises at this

Nile Journal of Architecture &Civil Engineering
Journal Webpage: https://njace.journals.ekb.eg
Volume 2, June 2023

moment between the two metal plates and the two horizontal surfaces of the test sample. These friction forces are generated with a maximum value at the edges of the two surfaces of the sample and their value gradually decreases as we head inward until they vanish completely as shown in Fig. (4).

S7 (S-CY- 2×5)

For the strengthened cylinder specimen S7 with two GFRP strips 50 mm wide as illustrated in Fig. (5), the crack pattern and failure shape of the specimen can be clearly seen at the middle height of the specimen with no strengthening. This is due to the more confinement provided by the GFS at both ends of the specimen. Moreover, no rupture was noticed for the strengthening GFS material.

Fig. (5): Failure shape of S7

S8 (S-CY- 3×5)

For the strengthened cylinder specimen S8 with 3 GFRP strips 50 mm wide, as described in photo in Fig. (6), the crack pattern and failure shape of the specimen can be clearly seen at the middle height of the specimen S8 similar to S7. This is due to the more confinement provided by both the GFS at both ends of the specimen larger than that provided at middle height and the friction provided during the test at the specimen surfaces (top and lower).

Moreover, a clear rupture was noticed for the strengthening GFS material at specimen middle height.

Fig. (6): Failure shape of S8**.**

S9 (S-CY- 1×10)

For the strengthened cylinder specimens S9 with one GFRP middle strip 100 mm wide at the middle height of the specimen as described in photo in Fig. (7), can be clearly seen at the weakest parts at the two ends of the S9-specimen that left without strengthening and extended to the whole specimen at its middle height of the specimen similar to both S7 and S8 specimens. Moreover, unlike S7, no rupture was noticed for the strengthening GFS material at the middle height of specimen S9.

4.1.2 Crack pattern for cubes specimens

S3&S4 (S-CU)

Similarly as previously illustrated for cylinder specimens, the crack and failure shape for the control cube specimens S3&S4, is shown in Fig. (8) photo.

Fig. (7): Failure shape of S9

Nile Journals

Nile Journal of Architecture &Civil Engineering

Journal Webpage: https://njace.journals.ekb.eg

Volume 2, June 2023

Fig. (8): Failure shape of S3&S4.

S10 (S-CU-2×5)

For the strengthened cube specimens S10 with two GFRP strips 50 mm wide, its crack pattern and failure shape is shown in Fig. (9).

Fig. (9): Failure shape of S10.

S11 (S-CU-1×10)

For the strengthened cube specimens S11 with one GFRP strips 100 mm wide, its crack pattern and failure shape is shown in Fig. (10)**.**

Nile Journals

Nile Journal of Architecture &Civil Engineering

Journal Webpage: https://njace.journals.ekb.eg

Volume 2, June 2023

Fig. (10): Failure shape of S11.

4.1.3Crack pattern for beam specimens

S5 &S6 (S-B)

For the control beam specimens S5 &S6, its crack pattern and failure shape is shown in Fig. (11).

Fig. (11): Failure shape of S5

S12 (S-B-5×15)

For the strengthened beam specimens S12 with one GFRP strips 50 * 150 mm, its crack pattern and failure shape is shown in Fig. (12).

Fig. (12): Failure shape of S12

S13 (S-B-10×15)

For the strengthened beam specimens S13 with one GFRP strip 100 * 150 mm, its crack pattern and failure shape is shown in Fig. (13).

Fig. (13): Failure shape of S13

S14 (S-B-5×25)

For the strengthened beam specimens S14 with one GFRP strips 50 * 250 mm, its crack pattern and failure shape is shown in Fig. (14).

Fig. (14): Failure shape of S914

S15 (S-B-10×20)

For the strengthened beam specimens S15 with one GFRP strips 100 * 200 mm, its crack pattern and failure shape is shown in Fig. (10).

Fig. (15): Failure shape of S15

*S16 (S-B-30×15*2 U)*

For the strengthened beam specimens S16 with one GFRP strips 150 * 300 mm as U-shape shear strengthening at the 2 beam ends, its crack pattern and failure shape is shown in Fig. (16).

Nile Journals

Nile Journal of Architecture &Civil Engineering

Journal Webpage: https://njace.journals.ekb.eg

Volume 2, June 2023

Fig. (16): Failure shape of S16.

*S17 (S-B-5×10*8 I I)*

For the strengthened beam specimens S17 with four GFRP strips 100 * 50 mm at the two vertical sides only, its crack and failure shape is shown in Fig. (17).

Fig. (17): Failure shape of S17

S18 (S-B-10×50)

The crack and failure shape of the strengthened beam specimens S18 with one GFRP strips 100 * 500 mm at the beam tension side, is shown in Fig. (18).

Fig. (18): Failure shape of the specimen, S18

S19 (S-B-10×90U)

The crack pattern and failure shape of the strengthened beam specimens S19 with one GFRP strips 100 * 900 mm at the beam tension side as a perfect Anchor, PA, U-shape along the beam longitudinal direction, is shown in Fig. (19).

Nile Journals

Nile Journal of Architecture &Civil Engineering

Journal Webpage: https://njace.journals.ekb.eg

Volume 2, June 2023

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Journal Webpage: https://njace.journals.ekb.eg
Volume 2, June 2023

Fig. (19): Failure shape of the specimen S19

4.2 Resulted strengthes of the specimen

4.2.1Results of cylinder specimens

The following figure showed that S9 is the better of the tested cylinders.

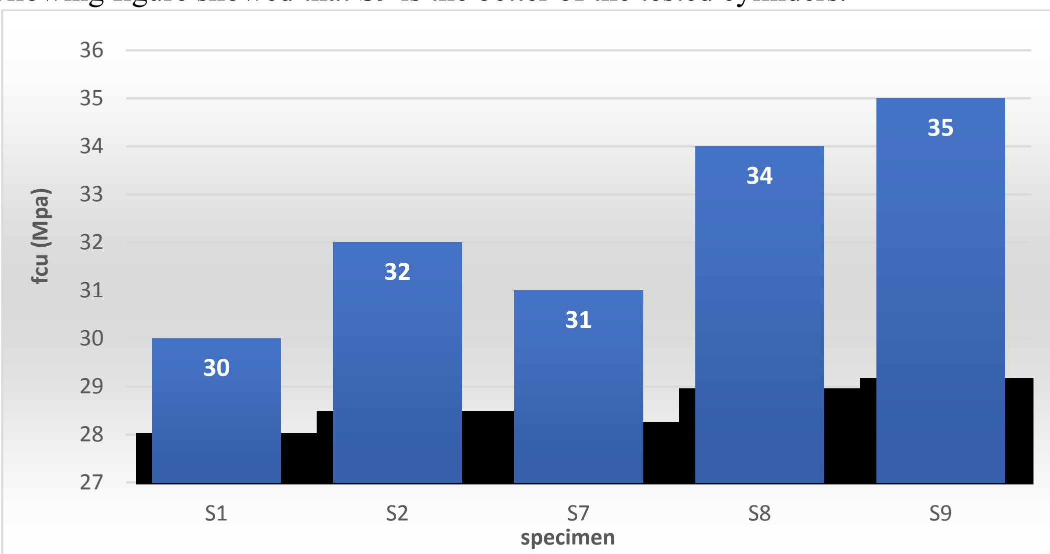
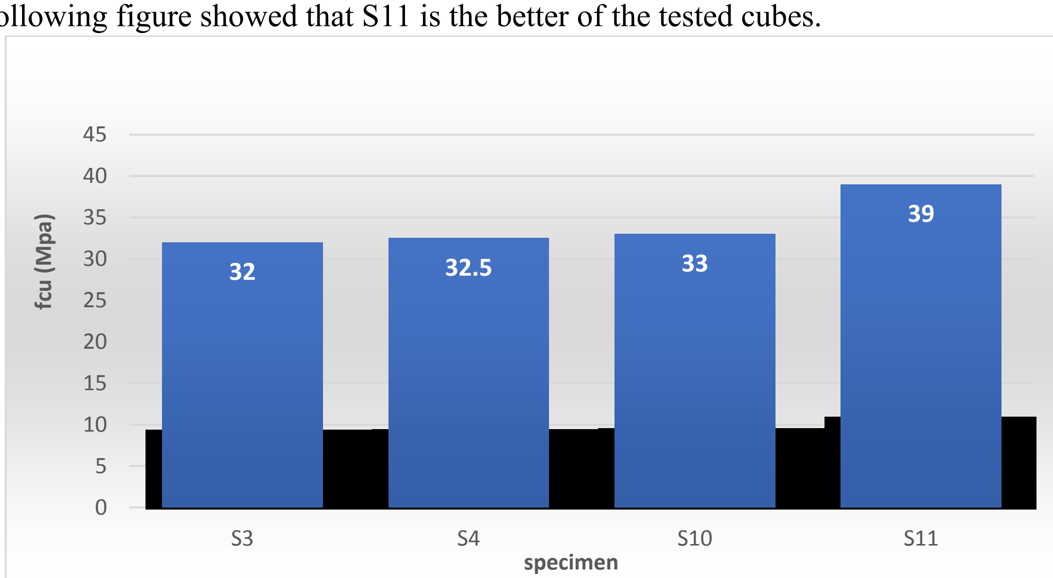


Fig. (20): Results of cylinder specimens.

4.2.2 Results of Cube specimens

The following figure showed that S11 is the better of the tested cubes.



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Nile Journal of Architecture &Civil Engineering

Journal Webpage: https://njace.journals.ekb.eg

Volume 2, June 2023

Fig. (21): Results of cube specimens.

4.2.3 Results of beam specimens

The following figure showed that S19 is the better of the tested beams.

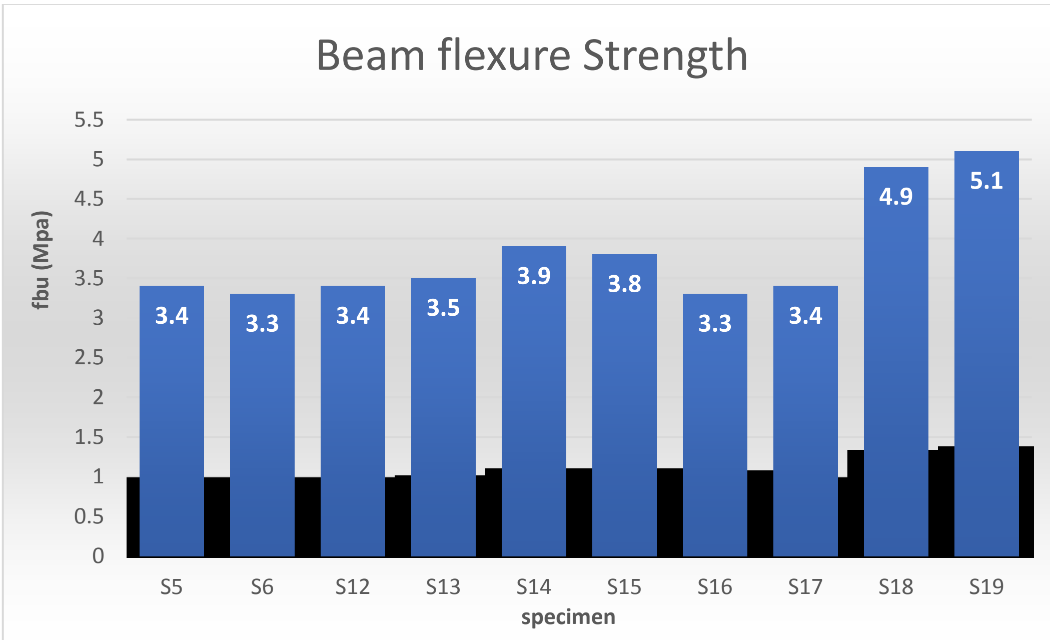

Fig. (22): Results of beam specimens.

5. Conclusion

The main objective of this study is to investigate the behavior of concrete strengthened with different configurations of GFRP sheets under monotonic loading using both compression and bending test. Primarily, the experimental study concentrates on the behavior of simple specimens with a focus on how the different strip width configurations affect such behavior. Through this investigation, it was possible to assess the best strengthening technique for different specimen types based on the compared results illustrated in details in the previous chapter. According to the aforementioned, the following sections provide detailed conclusions obtained from experimental evidence as well as recommendations for future research. From the results and observations presented in this study, the following conclusions can be highlighted from each phase of the investigation:

- The results of the test demonstrate that the strengthening systems can be used to reinforce concrete specimens with GFRP sheets and even that load capacity can be increased compared to the control un-strengthened specimen. Load-carrying capacities for cylinder and cube specimens reinforced with GFRP were increased by 16% and 21.8% for the cylinder specimen strengthened with one middle strip of 100 mm width, and for a cube, specimens strengthened with one strip of 100 mm width respectively compared to the control specimens.
- For the beam specimens, the ultimate load carrying capacity increases explicitly for the specimens S18 and S19 specimens by 50%. Strengthening with one strip of 500 & 900 mm of GFRP results in the highest increase of ultimate load-carrying capacity.
- For the cylinder and cube specimens, there was a slight increase in load carrying capacity in the specimens strengthened with 2 strips of GFRP with 50 mm width, as the total buckling edge length of such specimens was decreased due to upper and lower confinement by GFRP strips.
- In the strengthened beam specimens with 50*150 and 100*150 GFRP strips on the tension side, the development length of such strips was not adequate and the crack pattern propagate around the strips.
- In the strengthened beam specimens S16 and S17 in shear only, the strengthened technique was insufficient and nonrealistic due to a lack of GFRP strips (insufficient length) on the tension side.

6. Future studies recommendations

Based on the findings of this work, the following areas are suggested for future investigation:

- Further experimental tests should be undertaken to investigate the behavior of strengthened RC beams and column specimens with GFRP strips under static loads.
- As the current study is conducted using Glass FRP strips, it is recommended to investigate the bond behavior between GFRP and the concrete surface.
- Further researches are required to examine the structural behavior of RC specimens with different dimensions and strengthening techniques using different FFP materials.
- The empirical design equations for every investigated RC element should be derived taking into account the volume (both area and thickness) of strengthening materials.
- Exchange experience is urgently needed through establishing a mechanism for mutual attendance of some meetings for graduated students all over the world, especially for both in the European Union and in Egypt.

- The aim of this mechanism is to ensure that students are familiar with the latest and recent techniques and materials and to exchange local experience of each other.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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