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An Experimental Investigation of CFRP Strengthening Efficiency on the Retrofitted Damaged Geopolymer Concrete Beams

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Highlights

- This paper examined the efficiency of CFRP strengthening on damaged Geopolymer Concrete Beams.
- An experimental investigation was carried out on retrofitted Geopolymer Concrete Beam.
- The results were examined in terms of strength, stiffness and ductility of the tested beams.

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Abstract

In this study, beams produced by geopolymer concrete (GC) with different properties such as compressive strengths, stirrups ratios, and shear-span to effective depth ratio (a/d) were tested up to the failure to attain the load-deflection behaviors. Then, tested damaged beams were retrofitted using Carbon Fiber Reinforced Polymer (CFRP) in both shear and flexure to examine the CFRP strengthening efficiency. A three-point flexural test was conducted on both reference and retrofitted GC beams. According to this study, applying the CFRP strengthening to damaged GC beams increased the load-carrying capacity between 4% - 72%, depending on the compressive strength, stirrups spacing, and a/d with reference to the reference GC beams. The area calculated under the load-deflection graph of the retrofitted GC beams was lower than the reference beams in all tested series. The initial stiffness in the tested retrofitted beams was generally obtained lower compared to the reference GC beams. The deflection capability of the retrofitted beams in the tested series was between 18% -80% lower than the reference beams.

1. INTRODUCTION

The usage of environmentally friendly and surplus material in structural member is important for sustainability and efficient use of natural resources. Cement is construction materials used much commonly, which causes a high amount of CO_2 emission during its production [1-6]. Davidovits [4] expressed that 0.8-1 tons of carbon dioxide gas is discharged into the nature during the manufacturing of one ton of cement. Reducing the use of cement or replacing the cement with more environmentally friendly materials that can be used as a binder in concrete are one of the fundamental issues in terms of sustainability. Therefore, materials such as geopolymer concrete (GC), which is produced without cement and achieves its binding property by virtue of the reaction of pozzolanic materials with chemical solutions [7-10], are of vital importance and attract the attention of researchers nowadays when important problems such as climate change and global warming are discussed. The bacterial self-healing performance of geopolymer composites was investigated by Ziada et al. [11,12]. In addition, previous studies [13,14] have investigated the impact of a variety of fibers on physico-mechanical characteristic of geopolymer composites produced with different waste materials. In the literature, there are studies that experimentally examine the ideal mixing ratios of GC [15,16] and the structural performance of GC beams [17-36]. Krishna Rao & Kumar carried out an experimental examination on the impact of various alkaline binder ratio on the properties of the GC [15]. It has been stated by Sarker [18] that the greater tensile strength of GC resulted in the bond strength between reinforcement steels and GC to be greater compared to normal concrete. In addition, it has been concluded experimentally by some researchers [22,23,27] that GC beams have similar behaviors

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with concrete manufactured by ordinary Portland cement (OPC) in terms of ductility, crack structures, and strength. Madheswaran et al. [30] has determined that the equations given by the codes in the calculations of the shear strength of RC beams yielded compatible results with the experimental values of geopolymer concrete beams. Yacob et al. [31] has produced based on fly-ash GC and ordinary Portland cement concrete (OPCC) beams with varying a/d and stirrup ratios and concluded that the crack composition occurring in GC specimens own similar properties to those of beams produced with ordinary Portland cement concrete (OPCC). Ahmet et al. [32] stated in their review article on some basic properties of geopolymer concrete that geopolymer has similar or superior properties than normal reinforced concrete. Ozturk and Arslan [35,36] carried out experimental investigations on GC beams to investigate the ideal mixing ratios and structural behavior such as shear and flexure.

A composite construction material named Fiber reinforced polymer (FRP) has superior characteristic such as corrosion resistance, ease of application, and high strength. Thanks to these superior properties, the number of strengthening applications using FRP in reinforced concrete (RC) components and experimental [37-67] and analytical studies [68-70] on FRP-strengthened specimens has been increasing. Accordingly, it has been expressed that the load-carrying, deflection and ductility capacities of the FRP-strengthened specimens are greater than those of the reference specimens. It is expressed in experimental studies that the stirrups ratios [37-40,42,44,45,49-51,54,55,57,59], a/d [39,41,43,46,49,52,57,59] and size effect [30,40,47,48,53] are effective variables on the behavior and performance of beams strengthened with FRP. However, the number of researches investigating the behavior and performance of GC beams strengthened with FRP [71,72] is limited compared to FRP-strengthened RC beams. In addition, experimental investigations carried out on damaged/loaded GC beams loaded up to fracture state and then repaired by methods of both epoxy and repair mortar and finally strengthened with FRP is so scarce. Most of the experimental research performed on FRP- strengthened beams were carried out on undamaged beams or without existing cracks. In addition, experimental studies on the damaged beams represent the behavior and performance more realistically due to the damages and cracks in existing structures. Therefore, it is essential to perform more experimental investigations on the FRP-strengthened damaged GC beams in shear/flexure to better understand the strengthening efficiency of FRP and structural performance of the GC beams.

In this research, to evaluate the CFRP strengthening effectiveness in terms of load carrying, deflection, ductility capacities, reference beams with various compressive strengths, four distinct stirrup ratios, and two distinct a/d were first damaged by being loaded to the failure to get load-deflection curves. Then, some repairing methods such as epoxy injection was applied as well as repair mortar before the CFRP strengthening. Finally, shear and flexural strengthening by CFRP were implemented to repaired GC beams and tested under three-point bending test.

2. EXPERIMENTAL PROGRAM

2.1. Description

Reference GC beams examined by Ozturk and Arslan [35] up to the failure state to obtain the load-deflection curves were restored and strengthened in both shear and flexure by CFRP. The authors' previous work (Ozturk and Arslan [36]) could be used to obtain more detailed information on the production of geopolymer concrete and the materials used. The repairment and CFRP strengthening were implemented to the damaged GC beams, then these retrofitted GC beams were subjected to the three-point flexural test to monitor the CFRP strengthening efficiency.

Two 16 mm steel rebars (2Ø16) were used as tensile reinforcements in all specimens. 2Ø12 steel bars were placed as compression reinforcements at the top of the beams with stirrups. The stirrups (Ø8) spaced at three different spacing (100,150, and 200mm) across the entire beam span were utilized as shear reinforcements. The unidirectional CFRP fabric with high tensile strength and modulus of elasticity was selected to better examine the strengthening efficiency. The mechanical properties of both tensile/shear reinforcements, CFRP and, epoxy was presented in Table 1.

***Table 1.** Material properties*

Materials		Yield strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)	Thickness(mm)
Steel	D=16 mm	596	740	200	-
	D=12 mm	506	662	200	-
	D=8 mm	610	788	200	-
FRP	CFRP	-	4400	255	0.34
Epoxy			40	3.5	

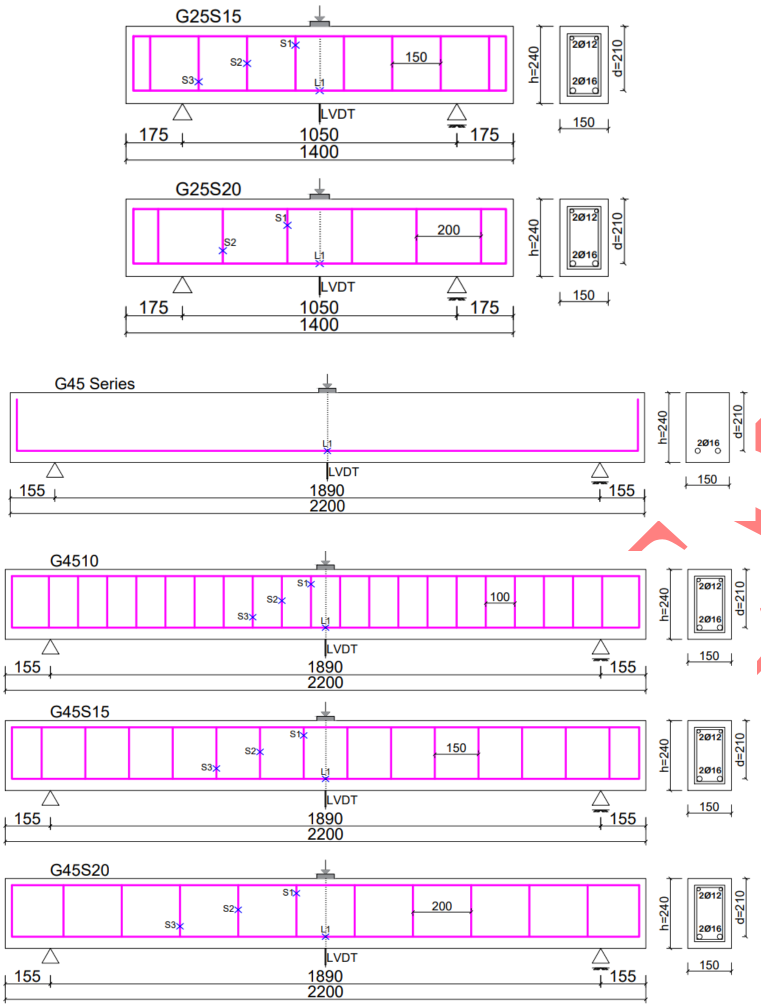
The procedure of repair mortar and epoxy injection were applied in the repairing of the existing cracks and damages in the reference beams. The details of the repairing and CFRP strengthening applied to the damaged GC beams were given in the following section. Both flexural and shear strengthening by CFRP were implemented due to the existing cracks to better understand the effect and efficiency of CFRP strengthening. Flexural strengthening was performed by bonding CFRP sheets with two layers (w_f=150 mm width) to the bottom of the all beams. All surfaces were covered by discrete CFRP strips called as completely wrapping method in shear strengthening to minimize the possibility of CFRP peeling off due to the existing shear cracks. Khalifa & Nanni [69] stated that the distance between discrete CFRP strips (s_f) should be less than the sum of the strip width (w_f) and one quarter of the beam effective depth (d) ($s_f \leq w_f + d/4$). CNR-DT200R1 [73] recommended 5 cm as the minimum strip width (w_f). Considering these results, the FRP strip width (w_f) and center to center distance (s_f) to be applied in strengthening were selected. The features of the all beams such as reinforcement details and dimensions as well as strengthening configuration of CFRP were introduced in Figures 1a and 1b. The specimens tested were classified into some series considering the stirrups ratios (ρ_w) and the different a/d to much clearly assess the experimental findings. CFRP strengthening details applied were given for each tested beam in Table 2.

Some letters and numbers were used to constitute the names of beams. G imply geopolymer beams.25/45 indicates a/d (2.5 and 4.5). R is for the retrofitted beams by CFRP; S represents GC beams with stirrups and 10, 15, 20 represents stirrups spacing in cm.

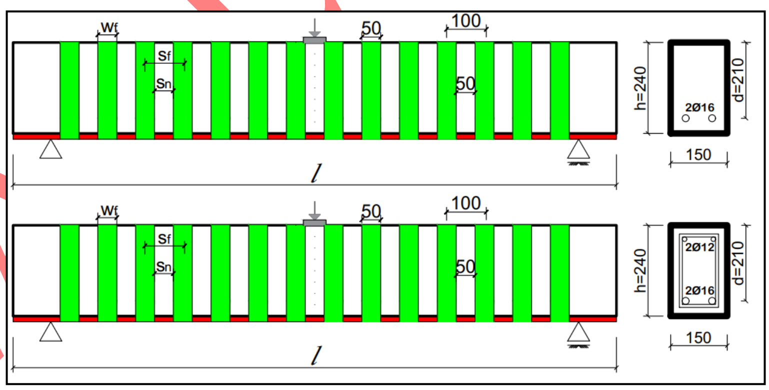
***Table 2.** The details of CFRP strengthening*

Series	Specimens	a/d	b_f (mm)	n_f	w_f (mm)	s_f (mm)	n_s	s (mm)	ρ_w %	f'$_c$ (MPa)
G45	G45	4.5	-	-	-	-	-	-	-	77.05
	G45R		150	2	50	100	1	-	-	
G45S10	G45S10 [35]		-	-	-	-	-	100	0.67	71.00
	G45S10R		150	2	50	100	1			
G45S15	G45S15 [35]		-	-	-	-	-	150	0.45	66.40
	G45S15R		150	2	50	100	1			
G45S20	G45S20 [35]		-	-	-	-	-	200	0.34	56.14
	G45S20R		150	2	50	100	1			
G25S15	G25S15	2.5	-	-	-	-	-	150	0.45	64.20
	G25S15R		150	2	50	100	1			
G25S20	G25S20		-	-	-	-	-	200	0.34	70.43
	G25S20R		150	2	50	100	1			

s_f: Center to center (c/c) space of CFRP shear strips; **A_s:** The area of the stirrups; **b_f:** CFRP width used for flexural strengthening; **f'$_c$:** Cubic compressive strength of GC at the day of testing; **s:** Stirrups spacing; **w_f:** CFRP width for shear strengthening; **n_f** and **n_s:** The number of CFRP layers employed in flexural and shear strengthening, respectively; **ρ_w:** Stirrups ratios ($A_s/b_w s$);



a)



b)

Figure 1. *a) Experimental setup b) CFRP strengthening schemes*

2.2. Repairing Procedure and Steps of CFRP Strengthening

The application of CFRP is a sensitive process that significantly affects the efficiency of FRP strengthening and performance of structural members. The preparation steps in the repairing and CFRP strengthening were summarized as follows. First, epoxy injection method was used to repair the existing capillary shear and flexural cracks in the damaged GC beams (Figure 2a). The way epoxy injection was applied is as follows. The first step was to properly clean the cracked area and remove any loose debris or contaminants to ensure proper adhesion between the epoxy and concrete surfaces. Small holes were strategically drilled across the crack or around the damaged area for epoxy injection. These holes provide access points for epoxy injection. A low-pressure injection system was used to inject the epoxy into the drilled holes. The epoxy flowed into the cracks and voids, effectively filling and bonding the concrete surfaces. After injection, the epoxy was allowed to cure and harden. Epoxy injection together with repair mortar were used for wider cracks that cannot be strengthened by epoxy injection alone (Figure 2b). The surface of the GC beams was sandpapered to improve the bonding between CFRP and concrete surface. Sharp corners of the tested beams were rounded off in order to avoid the tearing of CFRP strips due to the stress concentrations which can result in premature ruptures and reduce in strengthening efficiency. Surface preparations were ended with blowing the dust which can have an adverse effect on adhesion from surface using an air compressor (Figure 2c). CFRP sheets were cut into appropriate sizes for flexural and shear retrofitting (Figures 2d and 2e). Epoxy was prepared by mixing determined amounts (given by the manufacturer) of the resin and hardener (Figure 2f). The prepared epoxy was uniformly applied using a roller through CFRP sheets on the selected surfaces for targeted performance demands; for flexural (Figure 2h) along the bottom surface in axial direction and for shear (Figure 2i) wrapping around transverse surfaces perpendicular to beam axis. A retrofitted specimen prepared according to the procedure above was shown in Figure 2j.

a) b) c) d) e)

f) g) h) ı)

j)

Figure 2. *Steps of CFRP strengthening*

3. EXPERIMENTAL FINDINGS

An effort was given to explain the experimental findings of the both reference and retrofitted GC beams, such as initial stiffness, ductility, and load carrying/deflection capacity, considering the experimental values in Table 3 and the load-deflection graphs shown in Figure 3.

3.1. Overall Behavior

The following comments might be made from the test results of both retrofitted and reference GC beams. Application of the CFRP strengthening to the damaged GC beams increased the load-carrying capacity between 18% - 72%, depending on the compressive strength, stirrups spacing (s), and a/d in comparison to the reference beams (Table 3). Except for the G45 series, the maximum deflection values in the retrofitted GC beams of the other investigated series was between 18% -80% lower than the reference beams. The initial stiffnesses (I) were calculated by the slope of the first section of the load-deflection curves (Table 3). Although the existing cracks of the GC beams damaged were initially repaired and flexural and shear strengthening were implemented to the beams, the initial stiffness in the retrofitted GC beams was figured out to be lower than the reference beams except for the G45S10 series. Even though the beams without stirrups in the G45 series had higher compressive strength, the loss of initial stiffness (31%) was higher than the average loss (16%) in the series with stirrups (G45S10, G45S15, and G45S20). It can be concluded that the stirrups limit the amount of decrease in initial stiffness in the beams with the identical a/d by preventing the cracks to be widen. It might be evaluated considering the dissipated energy equal to area values under the load-deflection graphs of G45S15- G45S20/ G25S15- G25S20 that if the a/d was the same, the area values under the load-deflection graphs (A) and the ductility index values (δ_u/δ_y) of the beams generally improve as the stirrups spacing (s) decreases. In all tested series, the area values under the load-deflection graphs (A) in the retrofitted beams was lower compared to the reference beams due to the failure modes occurring suddenly in the retrofitted beams, except for the G45 and G45S20 series. Since G45S10, G45S15, and G45S20 failed due to the flexural cracks in the midsection of the beams, the effect of the stirrups spacings (s) on the load-carrying values was limited and the load-carrying capacities close to each other were obtained. Even though the beams in the G45S15 and G45S20 series had lower compressive strength as seen in Table 2, the increment in the load-carrying capacity owing to the FRP strengthening was higher than in the G25S15 and G25S20 series. From this point of view, it can be evaluated that a/d affects the maximum loads and the enhancement in the load-carrying capacity owing to the FRP strengthening. However, the initial stiffness's of the G25S15 and G25S20 were higher than the G45S15 and G45S20. When the results of the G25S15 and G45S15, which have the same reinforcement arrangement and almost the same compressive strength, were compared, it could be seen that the load-carrying capacity of the tested beams reduced as a/d increased.

Table 3. *Obtained results in the experiment*

Series	Specimens	P_n (kN)	Increase at P_n (%)	δ_u (mm)	δ_y (mm	δ_u/ δ_y	I (kN/mm)	A (kNmm)
G45	G45	79.926	-	10.00	2.96	3.38	9.78	470.11
	G45R	105.556	32	77.98	-	-	6.79	7255.84
G45S10	G45S10 [35]	111.539	-	103.26	-	-	10.22	10835.33
	G45S10R	192.203	72	20.20	-	-	11.35	2349.66
G45S15	G45S15 [35]	114.468	-	80.66	2.84	28.40	9.63	7673.42
	G45S15R	154.690	35	41.02	-	-	8.91	4900.80
G45S20	G45S20 [35]	111.708	-	44.06	2.70	16.32	10.89	4127.56
	G45S20R	147.351	32	52.12	-	-	8.24	5950.54
G25S15	G25S15	211.240		46.70	1.96	23.83	26.13	8608.34
	G25S15R	249.550	18	13.34	-	-	15.15	2055.08
G25S20	G25S20	202.202		18.45	1.00	18.45	30.34	2830.71
	G25S20R	220.334	9	11.48	-	-	20.39	1469.50

A: Area of the load-deflection graph (Dissipated Energy); **δ_u/ δ_y:** Ductility index; **P_n:** Maximum load; I: The initial stiffness; **δ_y:** Deflection at yielding; **δ_u:** Maximum deflection at failure corresponding to 80% of the maximum load

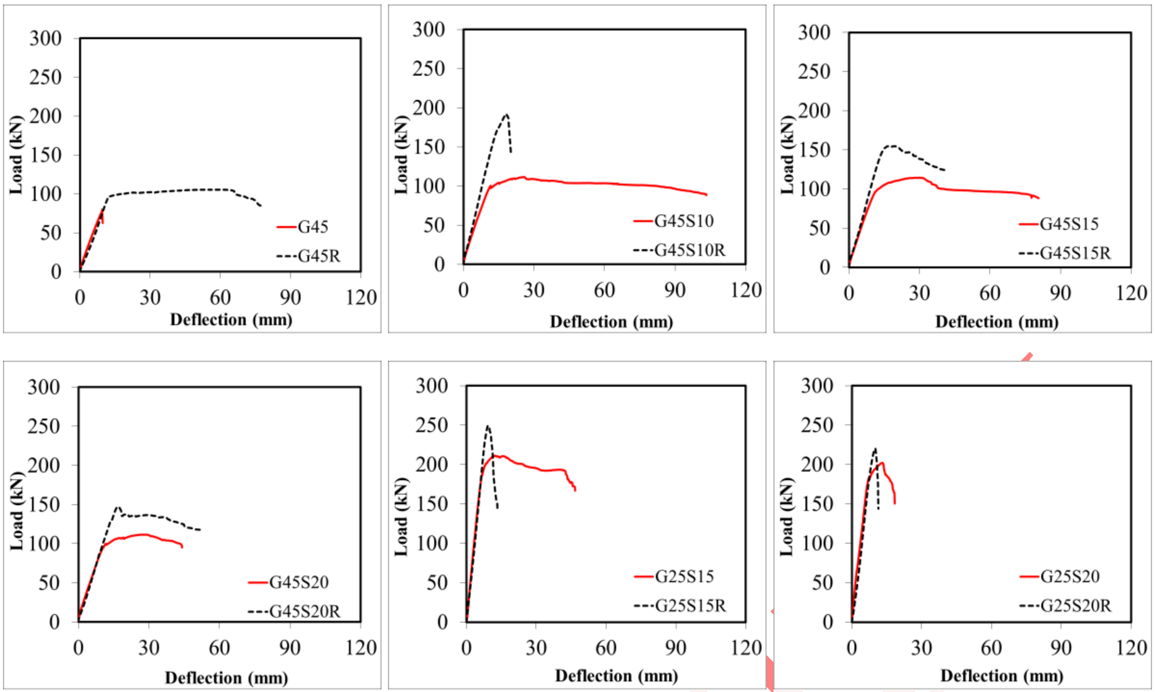
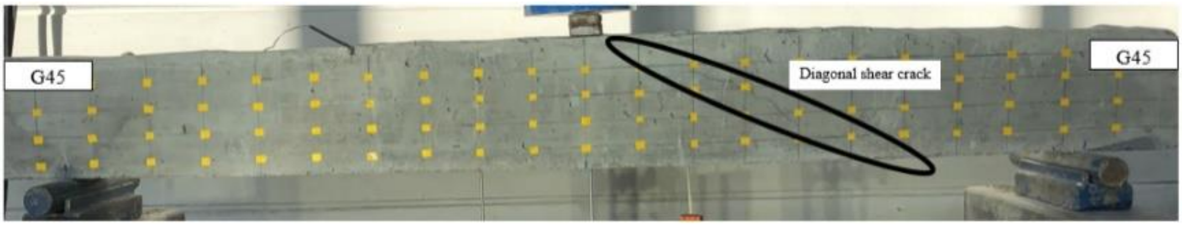


Figure 3. *Load-deflection graphs*

3.2. Failure Modes and Cracking Patterns

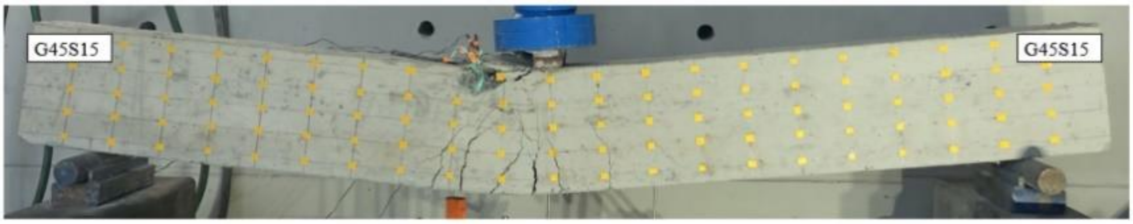
Shear collapse owing to the diagonally occurred cracks in the right span was observed in reference G45 beam as seen in Figure 4a. G25S15 reached its load-carrying capacity by concrete crushing by virtue of flexural cracks occurring in the mid-span and diagonal shear cracks occurring at a length of effective depth (d) from the load-application point. G25S20 could not bear the tensile stresses along the diagonal shear crack and reached its ultimate capacity by shear failure (Figure 4a). The number and size of prominent bending cracks in the mid-span of the G25S15 was higher compared to the G25S20 due to the greater deflection and ductility capacities. G45S10, G45S15, and G45S20 collapsed in flexure by concrete crushing under the load application point as a result of the compressive stresses caused by the bending moment. In series with a/d=4.5 (G45, G45S10, G45S15, and G45S20), the number of flexural cracks around the mid-span enhanced as the stirrups ratio (ρ_w) increases or stirrups spacings (s) decreases.

The G25S15R and G25S20R reached their load-carrying capacities when the CFRP strips used in shear intersected by the diagonally occurring shear crack was slipped from the overlapping parts (Figure 4b). The G45R, G45S10R, G45S15R, G45S20R collapsed due to the sudden rupture in the CFRP strips intersecting shear and flexural cracks around the mid-span of the retrofitted beams. In previous studies [59,64], It is expected that the completely-wrapped RC beams with CFRP in shear generally achieved load-carrying capacity owing to the fracture of the CFRP shear strips. However, since the CFRP shear strips slipped at the overlapping parts due to inadequate impregnation by epoxy resin (Figure 4b) in G25S15R and G25S20R, the collapse of these beams occurred abruptly and therefore the strengthening efficiency of CFRP was obtained lower compared to the different retrofitted beams in G45, G45S10, G45S15, and G45S20 series. Similar findings were also expressed in the study of Ozturk et al. [63].

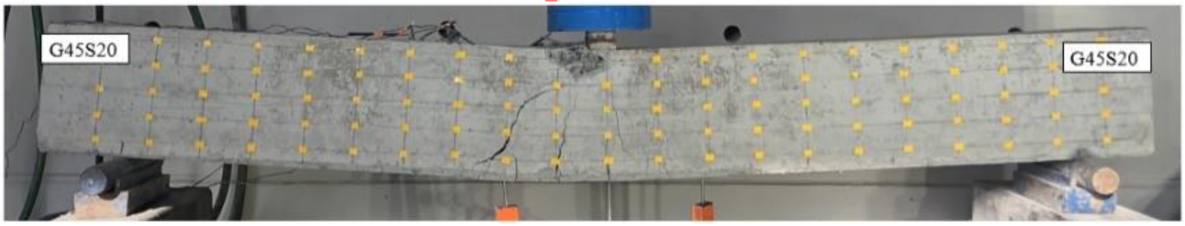


G45

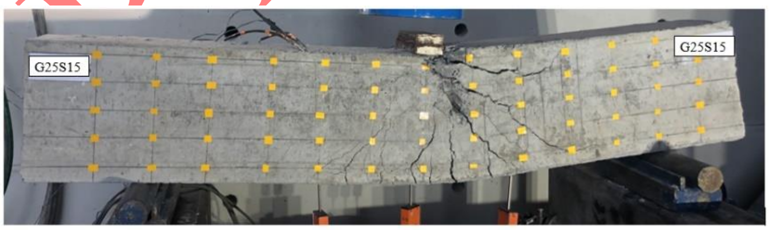
G45S10 [35]

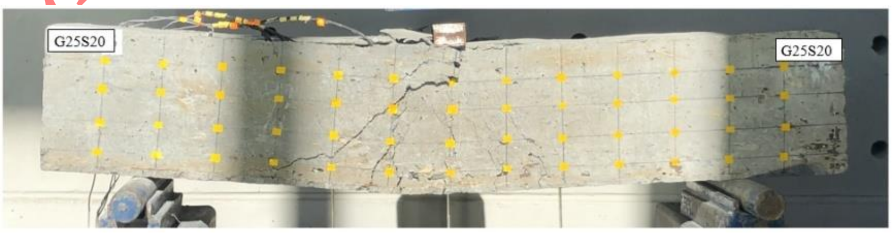


G45S15 [35]

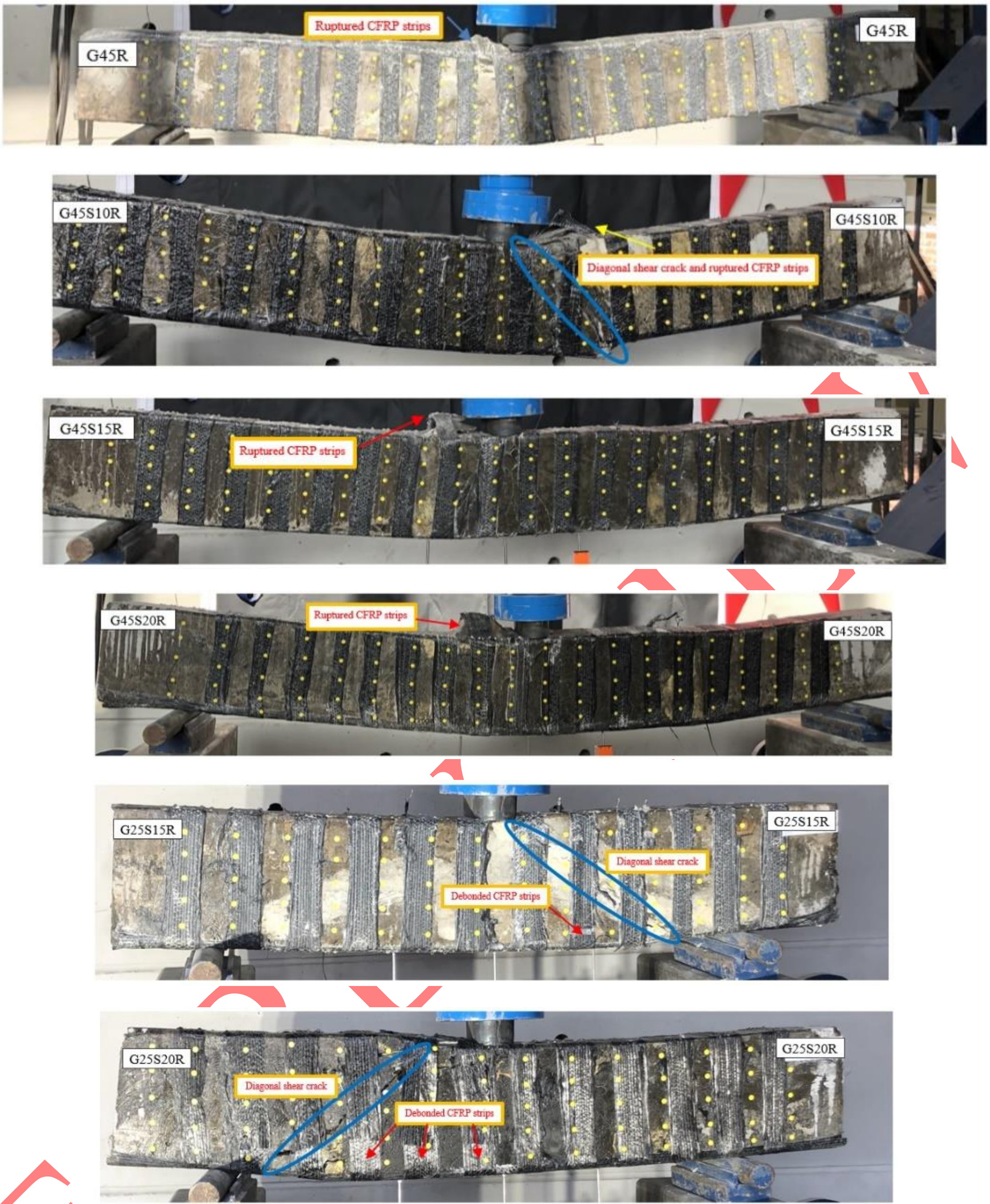


G45S20 [35]





a) Reference beams



b) Retrofitted GC beams

Figure 4. *Conditions of the beams (Failure modes)*

3.3. Strain Behavior

The maximum strains obtained during the experiment and yield strains of the tensile and transverse (stirrups) reinforcements were given in Table 4. The highest strains occurring in the rebars were obtained at different load values based on the location of the reinforcement relative to the occurred cracks. Due to the technical problems occurring during the experiment, strains could not be measured in all reinforcements (L1, S1, S2, S3) of the G45S10, the stirrups S1 and S3 in the G25S20, and S1 in the (Table 4). The significant bending cracks developed in the middle of the reference GC beams where the strain gauge was located, the tensile reinforcement yielded before failure took place in Figure 5.

The stirrups S2 and S3 in G45S15/G45S20; S1, S2 and S3 in G25S15; and S2 in G25S20 yielded before failure occurred. The positions of strain gauges S1, S2 and S3 were given in Figure 1a for all reference GC beams. The strains in the stirrups (S1, S2, and S3) varied based on the settlement and size of the flexural and shear cracks in the reference GC beams (Table 4). Since the widths of the cracks in the reference GC beams were more pronounced in the region of the second stirrup (S2), the strains recorded in the S2 were higher than the others (S1, S3). In elements G45S15, G45S20 and G25S15, the stirrup (S1) closest to the load-application point had lower strains than other stirrups (S2, S3) because it was located in the position where the crack widths were limited.

Table 4. *Measurable the highest strain values recorded on the reinforcement of tested GC beams*

Specimens	L1	S1	S2	S3	$\varepsilon_{y.tensile}$	$\varepsilon_{y.stirrups}$
G45	0.0101	-	-	-	0.003044	0.003049
G45S10	-	-	-	-		
G45S15	0.0150	0.0024	0.0204	0.0044		
G45S20	0.0110	0.0012	0.0038	0.0033		
G25S15	0.0132	0.0077	0.0127	0.0121		
G25S20	0.3057	-	0.0076	-		

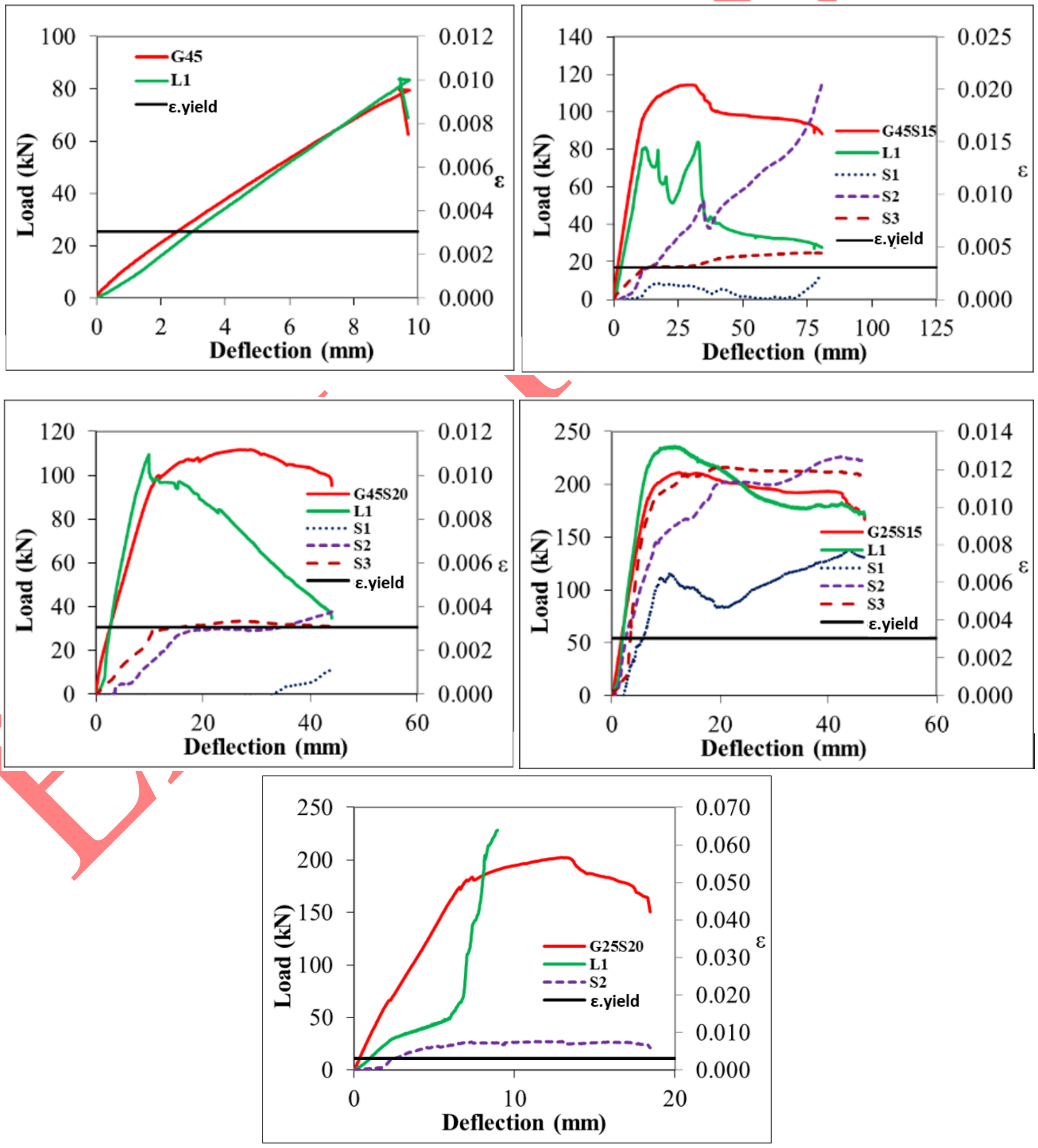


Figure 5. *The graphs of strains, deflections, and loads*

4. CONCLUSIONS

In this experimental study, six GC beams were tested up to the failure situation to obtain load-deflection behavior and the retrofitted in both flexure and shear by CFRP to examine the strengthening efficiency. Within the knowledge of the authors, the number of works performed experimentally on damaged GC beams loaded to collapse form and then repaired and finally strengthened with CFRP was limited. The influence of CFRP strengthening on the experimental performance of retrofitted and reference beams was examined from the point of load carrying, deflection, ductility and failure modes. The main findings acquired in this study were as follows:

- CFRP strengthening was found out highly effective in enhancing the load-carrying capacity on average 4%-72% in comparison to the damaged reference GC beams, based on the compressive strength, stirrups spacing, and a/d with reference to the reference beams.
- The deflection capacity in the retrofitted GC beams of G45S10, G45S15, G45S20, G25S15, and G25S20 series was generally obtained lower between 18% -80% with respect to the reference beams due to the sudden failure.
- The initial stiffness in the retrofitted GC beams was calculated to be inferior compared to the reference beams in all investigated series except for the G45S10 series even though the existing cracks were repaired. Thus, it could be expressed that CFRP strengthening applied to the damaged beams was not effective to increase the initial stiffness.
- Stirrups limit the amount of decrease in initial stiffness of the beams with the identical a/d.
- As the stirrups spacing decreases, ductility index values and the areas calculated under the load-deflection graph of the tested beams generally improve.
- The area values calculated under the load-deflection graph in the retrofitted GC beams was lower with respect to the unstrengthened reference GC beams in all series except G45 and G45S20 series.

The experimental research conducted on retrofitted GC beams with different FRP strengthening scheme named U-wrapped, side-bonded, and U-wrapped with anchor using different FRP types (GFRP, AFRP, BFRP) is required for a better understanding of the parameters and also the real behavior of the retrofitted beams.

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CONFLICTS OF INTEREST

No conflict of interest was declared by the authors.

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