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REHABILITATION OF DAMAGED FLAT SLAB USING FIBER REINFORCED POLYMERS FRPS

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A B S T R A C T

Flat reinforced-concrete (RC) slabs are widely adopted in modern construction due to their structural efficiency and architectural versatility, yet they remain susceptible to punching shear and flexural cracking. This study experimentally evaluates the rehabilitation of damaged RC flat slabs using externally bonded carbon and glass fibre-reinforced polymer (FRP) textiles. Six bidirectional RC panels measuring 500 × 500 × 50 mm were prepared with square and circular column supports and internally reinforced with 6 mm bars spaced at 80 mm. After 28 days of curing, specimens were strengthened with FRP composites bonded using Sikadur 330 epoxy and tested under single-point loading at a displacement rate of 1 mm/min. The concrete compressive strength averaged 40.5 MPa, exceeding Iraqi Specification IQS No. 5 (1984) limits. Strengthened specimens demonstrated a 20–25% increase in ultimate load capacity and reduced mid-span deflection compared to unstrengthened controls, with tape-oriented FRP configurations showing the most significant improvement. Panels supported by square columns consistently sustained higher loads than those with circular columns, indicating a pronounced interaction between column geometry and FRP configuration. These findings highlight that tailoring FRP type and fibre orientation to column shape enhances punching-shear resistance and extends the service life of RC slabs, providing a practical and cost-effective approach for rehabilitating ageing concrete structures while minimizing construction time and disruption.

1. INTRODUCTION

Flat slabs are widely used in modern construction for their structural efficiency and architectural flexibility. However, they are susceptible to shear stress and flexural cracking. Conventional repair methods are often time-consuming and inconvenient. Fibre-reinforced polymers (FRPs) offer an attractive alternative; however, limited research has addressed the combined effect of column geometry and FRP composition on rehabilitation effectiveness. This study addresses this gap through an experimental investigation of reinforced concrete flat slabs reinforced with different types of FRP textiles and epoxy systems with varying column shapes. Flat slab structures have gained popularity in construction projects because of their integrative constructional features, such as economic constructional features, as well as their efficiency and flexibility in

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construction styles (Chan & Chan, 2002; Sarı & Çalışkan, 2024). However, these slabs may reach a point where they are vulnerable to different kinds of damage like cracking, deflection, or even collapse, which will lead to an implication of the structural stability of the building (Sagaseta et al., 2016; Ulaeto, 2018). For example, common repair and rehabilitation practices may entail intrusive measures such as concrete stripping and patching, which may take lots of time, funds, and inconvenience the inhabitants of the building (Hyman, 2005; Abellán-García et al., 2024). Due to the increasing scale of flat slab structures that have been damaged by fires or other causes, FRP has appeared as one of the renovating agents that has the potential to be widely used for this purpose in the future (Harle, 2024; Li et al., 2024). FRPs are composite materials made up of high-strength fibers in the polymer matrix, and they are preferred for many reasons as they are lightweight, corrosion-resistant materials that can be applied easily (Gudonis et al., 2013; Amran et al., 2018). These materials have been proven to be useful for their objective in reinforcement works, which includes usage in bridges, columns, and beams, among others (del Rey Castillo et al., 2024).

The process of utilizing FRP composites for the rehabilitation of damaged flat slabs requires the use of FRP sheets/strips bonded to the undersides of the slabs, thereby increasing the flexural and shear strength of the slabs and alleviating damage (Yagar et al., 2024). This approach has many advantages over traditional repair methods, which include the following: less construction time than when making a new construction, disruption to the occupants of the building is greatly reduced, and the structure is less likely to be damaged again in the future (Tang, 2021; Zaki et al., 2021; Khodadadi et al., 2024). Many studies involving FRP technique improvements presented in ailing flat slabs rehabilitating or strengthening with a new set of strategies (Amer et al., 2023; Dey et al., 2023; Preethichandra et al., 2023). For example, the studies explored a strategy that combined different fibers with different resin matrices to gain an improved overall FRP performance at a lower cost (Nikam et al., 2023; Ribeiro et al., 2024). A strategy was applied to achieve a stronger border between the composites of FRPs and the substratum of concrete to get a durable repair system (Manawadu et al., 2023). Further, evolution in the ways of assessing the effectiveness of rehabilitation measures through Non-Destructive Testing (NDT) or Structural Health Monitoring (SHM) enables engineers to understand the overall effectiveness of the FRP rehabilitation measures as well as the structural integrity of the structures so rehabilitated, even after they are rehabilitated (Hassani & Dackermann, 2023; Rossi & Bournas, 2023; Shiotani et al., 2024).

Instituted reinforced Concrete RC structures are found to be dominant in many structures globally. RC structures are characterised by internal reinforcement corrosion, unpredictable excessive loading, and poor design. As the structures deteriorate because of the above challenges, making retrofitting an effective method is demanded. Many techniques can help to increase the capacity of the structural members, and as a result, the structural function of the structure can be effectively performed. So the aim of this study was to examine the performance of Fiber Reinforced Polymers (FRPs) in enhancing the ultimate bending capacity of reinforced concrete slabs. The paper presents the main advantages and problems expected in the further implementation of this technology for improving load-carrying capacity and service life of the flat slabs in engineering constructions, bridging the opportunities of principal contractors, engineers, and owners.

2. METHODOLOGY

2.1 Specimens details

Six panels of bidirectional Reinforced Concrete (RC) plate are shown in Figure 1, with dimensions of length 500 mm, width 500 mm, and thickness 50 mm, which were cast, externally modified, and statically tested under single-point loading.

Figure 1. Bidirectional RC plate

The performance of FRPs in enhancing the ultimate bending capacity of reinforced concrete slabs was inspected. Reinforcing steel bars with a diameter of 6 mm were used for internal reinforcement, and the distance between the bars was 80 mm in the longitudinal direction and 80 mm in the transverse direction and a 25 mm thick concrete cover was used. The rebar is closer to the top in the direction of tension.

2.2 Materials used for concrete

The type of cement in this research experiment was Ordinary Portland cement. In Tables 1 and 2, the physical characteristics and the chemical structure were reported, respectively.

Testing was presented based on the Iraqi standards specifications (I.Q.S.No.5,1984). Coarse aggregate passing through sieve size 13 mm (Table 3).

Table 1. Cement physical characteristics.

Cement's physical characteristics	Setting	Testing	Iraq Specification Limits No. (5/1984)
Time setting using Vicat's needle	Preliminary time (hours: minutes) Ultimate time (hour: minutes)	1:30 7:10	45 minutes or more 10 hours or less
Compressive-strength MPa	Three days Seven days	34.2 36.15	15 MPa lower limit 23 MPa lower limit

Table 2. Chemical structure of the cement.

Structure	Contents	Iraqi specifications limits
CaO	60.1	-
Al_2O_3	4.06	-
Sio_2	20.3	21% Max
Fe_2O_3	3.67	5%
Mgo	2.03	5%
SO_3	2.02	2.8%
Loss on Ignition (L.O.I)	2.95	4%
Insoluble Material	1.17	1.5%
Lime Saturation Factor (L.S.F)	0.9156	(0.66-1.02)
C_3S	52.1	-
C_2S	19.08	-
C_3A	6.12	-
C_4AF	11.17	-

Table 3. Classes of course aggregate.

Size of sieve in mm	ASTM limits C33-03	Cumulative per cent of passing
12.5	90 to 100	100
9.5	40 to 70	61.7
4.75	0 to 15	6.5
2.36	0 to 5	1.7

The sand that was used to prepare the concrete mix was normal sand, which is capable of passing through a sieve size No. 4, 75 mm. The investigations were carried out using deformed 6 mm diameter steel bars in this study. The test was performed on steel reinforcement according to ASTM A615 M-05. Three samples out of the bar were taken in the laboratory to measure the averages of the initial strength and the final strength. Table 4 shows steel reinforcement tensile testing.

Table 4. Steel reinforcement tensile testing.

Diameter in mm	Initial stress in MPa	Definitive stress in MPa	Per cent of elongation
6	672	715	6.1

2.3 Mixing and casting procedure

All trial mixes were conducted in a 0.1 m³ capacity rotary mixer. Figure 2 shows the process for preparing the specimens.

Figure 2. The process of preparing the specimens.

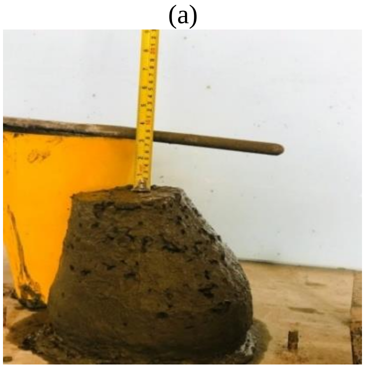
The mixing procedures involved setting the aggregate in the mixer, where fine aggregate was added to the mixer, followed by spinning the mixer. Then the cement was incorporated into the mixture, and gradually water was added to the mix to achieve the desired consistency of the studied concrete mix. Then, five minutes were applied to agitate the concrete mix to attain a satisfactory level of fluidity.

Furthermore, a vibrator was utilized to eliminate air bubbles from the concrete in layers, with each layer vibrating for a duration of 5 to 15 seconds. The mixing process consisted of 57 kg of coarse aggregate, 31 kg of fine aggregate, 25 kg of cement, and 9.5 kg of water, and the reinforcing steel in the rebar was on the tension side.

2.4 Pouring the concrete

Six panels and six cubes were cast. Three of the panels had square columns and three had circular columns. Before casting the models, a precipitation test was conducted for the concrete to determine the consistency of the concrete, as shown in Figure 3.

(a)



(b)

Figure 3. Pouring the concrete (a) slabs with different column configurations, (b) Concrete slump test.

Precipitation was acceptable, and the consistency of the concrete was good and suitable for the pouring process. After completing the casting process, the models were cured for 28 days, as shown in Figure 4.

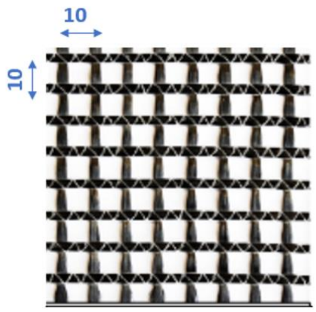
Figure 4. Processing forms.

2.5 Specimens are prepared using Epoxy Resin.

Regarding the specimens that were prepared with epoxy as their binding material, Sikadur® 330 epoxy resin was used. This agent consists of two parts with a mixing ratio of (1:4) using (weight). According to the product datasheet, the tensile strength, modulus of elasticity, and glass transition temperature (T_g) of this adhesive were 30 MPa, 3.8 GPa, and 68○C, respectively.

2.6 Used textile materials

In this research work, two different textile materials were employed as the external strengthening material on RC slabs. Here, it is necessary to state the fact that these textiles were carbon and glass fiber materials. They were produced with the bundles in two perpendicular directions with the same amounts. The carbon fiber textiles were represented by the symbol. In the text, the Carbon fiber textile is shown in Figure 5, which depicts equal fiber rovings that are situated perpendicularly and in parallel.



Material: carbon fibers(c)
Density:1.83 g/cm^3
Nominal thickness:0.0765mm
Weight:140g

Figure 5. Carbon fiber textile.

2.7 Compressive strength test and test setup

Thus, the strength of concrete can be determined by subjecting concrete cubes to compressive force after 28 days of casting and curing. The compression test was conducted according to the standard test method BS 1881-part 108 on cube specimens of size 150mm using a universal testing machine that has a capacity of 2000 KN with a loading rate of 0.25±0. 05 MPa per second. A conflict in the overall compressive strength (f_cu) of about three cubes' average was used to obtain it. In this way, the load is imposed through the sides of the cube perpendicular to the direction in which the casting takes place.

Later on, the strengthened materials are air-dried, and then the specimens are painted with white paint so as to easily notice the cracks developing. The specimens were just placed on two parallel upper supports with a stiff steel frame for load-bearing only. The load was applied on the specimens under displacement control of 1, which means that the cross-head speed of the testing machine was set to cross-head displacement of 1mm per minute, 2 mm /sec using a Universal Testing Machine called SANS with a rated load capacity of 2000 KN up to failure. Figure 6 shows the compressive strength test and test setup.

(a) (b)

Figure 6. Strength test: (a) Compressive strength test, (b) Test set-up.

The measured variable selected for the recorded data was the mid-span deflection with the help of a dial gauge up to 0. To determine the point of contact between the insert and the substrate, the displacement accuracy of 01 mm and the applied load were measured using a crank fitted with a load cell of 500 kN capacity.

3. RESULTS AND DISCUSSION

The average 28-day cube compressive strength was 40.5 MPa, exceeding specification limits. The strengthened specimens exhibited a 20–25% higher ultimate load, and the mid-span deflection was reduced compared to the control specimens. The strip-oriented FRP treatment provided the highest load capacity. Square column specimens generally sustained greater loads than circular specimens, highlighting the interaction between column shape and FRP reinforcement pattern. Statistical analysis of the mean values and observed variance indicates continued improvement, although full inferential testing requires expanded data sets.

3.1 Testing the compressive strength of concrete cubes

The compressive strength of concrete is the ability to withstand forces acting on it from pressure or external pressure. It is measured in units of pressure such as pascals or kilopascals. The compressive strength of concrete can be affected by factors such as the quality of materials used in the mixture, the water-cement ratio, and the curing and hardening process.

Compression test on 7-day-old and 28-day-old concrete cubes to determine the bearing capacity of the concrete, as shown in Table 5 and Figure 7.

Table 5. The compressive strength cubes.

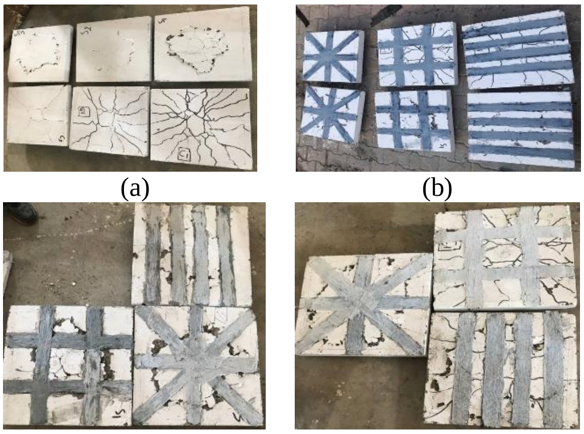
NO.	**7 days old**		**28 days old**	
	Stress (MPa)	Load (KN)	Stress (MPa)	Load (KN)
1	31.02	698.0	38.84	874
2	32.10	722.3	37.69	848
3	37.39	841.2	44.97	1012
Average	33.5033	753.833	40.5	911.33

Figure 7. The compressive strength cubes

The comparison between concrete cubes aged seven days and twenty-eight days. The average resistance percentage for cubes was seven days old, 33.5033 MPa, and the average resistance percentage for cubes was twenty-eight days old, 40.5 MPa. The resistance rate of the cubes at the age of seven was 82.7% of the resistance rate at the age of twenty-eight days, and this is considered good concrete and suitable for use.

3.2 Failure inspection of concrete surfaces

A load was applied to a model until it reached the stage of failure, and we considered this model a reference for the rest of the models. This method was used in both cases (cylindrical column and cubic column), as in Figure 8.



(a) (b)

(c)

Figure 8. Failure inspection (a) the models after failure, (b) the models after processing them using carbon fiber and epoxy as a binder, and (c) failure patterns after the curing process

3.3 Square roof with square column, and circular column

Table 6 shows the data obtained through tests on the models. Figure 9 shows the failure profile of concrete and curing for square column specimens.

The comparison of the load between the structures previously discussed shows that the square roof with the square column (C1) has higher loads than the square roof with a circular column (S1) for all treatments.

Table 6. The obtained data through tests on the models.

Square roof	Sample	Load (KN)	Deflection (mm)	Relay type
Square roof with square column	C1	58.213	10.447	Reference
	C1-1	36.045	4.236	Orthogonal treatment
	C1-2	68.516	6.453	Tape treatment
	C1-3	30.260	3.292	Diagonal treatment
Square roof with circular column	S1	48.556	11.178	Reference
	S1-1	30.235	3.387	Orthogonal treatment
	S1-2	36.500	5.715	Tape treatment
	S1-3	29.523	6.189	Diagonal treatment

The deflection depends on the treatment processes. Treatment by orthogonal generally gives better results in regard to their deflections compared to other treatments. Under all the treatments and configurations, the Tape treatment produces a higher load compared to the other treatments.

The above findings show the loads and the deflections of the various treatments, depicting that Diagonal has slightly smaller loads and deflections than the other treatments, except for the square roof with circular column (S1), where the deflection value was slightly higher than the Orthogonal treatment.

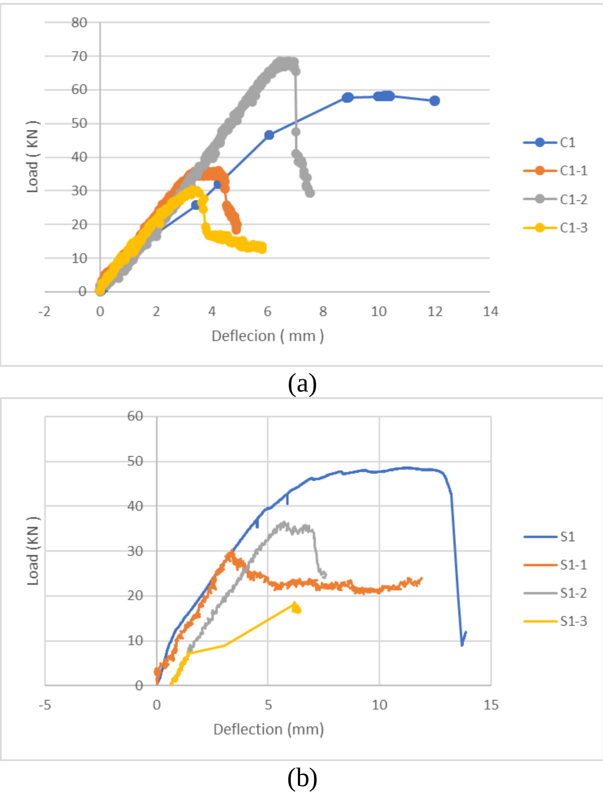


Figure 9. Failure profile of (a) square column, (b) circular column.

3.4 Mode of failure

Flexural cracks are cracks that occur in a material, such as concrete or steel, due to bending or flexing forces. They are often caused by excessive loads or inadequate structural support. "Structural cracks" refer to any cracks that compromise the integrity or stability of a structure, which can include flexural cracks but also other types such as shear or torsional cracks. Figure 10 describes the failure pattern occurring in the square column and circular column models.

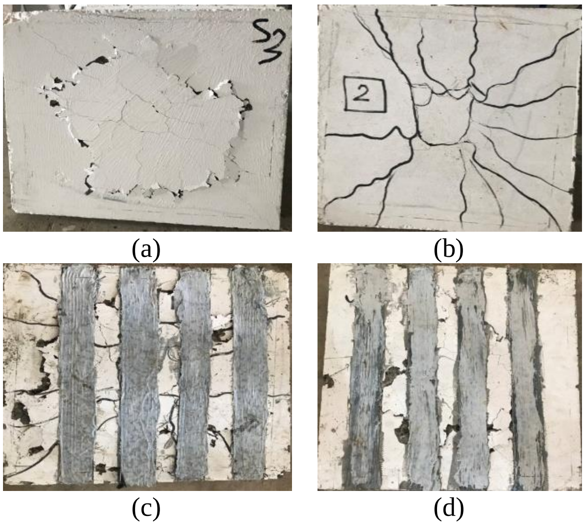


Figure 10. Failure pattern occurs in (a) the square column before the curing process, (b) the circular column before the curing process, (c) the square column after the curing process, (d) the circular column after the curing process.

Flexural cracks typically occur in materials like concrete or masonry when subjected to bending or flexural stresses. These cracks often appear near supports or areas of high-stress concentration. They can vary in size and orientation depending on the magnitude and distribution of the applied loads. Proper reinforcement and design can help minimise the occurrence and propagation of flexural cracks in structures. The biggest danger of failure in a flat slab is from the punching shear from columns. In most cases, the thickness of the slab must be determined to resist the punching shear; no shear reinforcements are used. By subjecting the models to a failure load, we found that the models with a circular column experienced punching shear failure, while the models with a square column experienced linear failure, and these models were before the curing process. Also, after subjecting the models to a failure load, we found that both models with a circular and square column experienced punching shear failure after the curing process.

4. CONCLUSION

This improved experimental program confirms that external FRP reinforcement, with careful consideration of column geometry, significantly improves the deflection response to load and service life of flat reinforced concrete slabs. This work contributes new insights for improving the use of FRP in practical engineering rehabilitation projects.

Concrete compressive strength is a key property that characterizes the effectiveness and structural competence of concrete under applied pressure. According to the values obtained from the compression tests of seven-day-old and twenty-eight-day-old concrete cubes, it is clear that concrete gains in strength with time and that the twenty-eight-day-old concrete cubes have a uniformly higher compressive strength average of 40. 5 MPa compared to 33.50 compressive strength at 7 days for the cubes. This shows that the strength of the concrete at seven days is about 82 percent. Requires only 7% of its strength at twenty-eight days, which proves that concrete can be effectively used in structures.

Failure inspection analyses identified diverse patterns of failure in the concrete models under applied load. The specimens with the square columns displayed linear structural failure, and it was observed that the fusion members with circular columns had punching shear failure, which was manifested before and after the curing procedure. This shows that the shape and size used in the construction of the column have a significant influence on the overall failure that occurs in concrete structures under load.

The study also described the presence of flexural cracks, which are a result of bending forces and which might cause problems when not contained. Such cracks are acceptable, but proper reinforcement and design selection are crucial to reduce or avoid such cracks and enhance the durability and strength of concrete systems. The analysis of flat slabs and their failure modes revealed that punching shear failure is the major one, especially when circular columns are used; thus, it underlined the importance of slab thickness to protect structures from such force without the need for shear reinforcements.

The quality of the concrete should be enhanced by the use of quality materials in the minimum proportion for maximum strength. This would therefore require that effective curing methods be put into practice to allow the concrete to reach its maximum strength. This includes the necessary temperature and humidity requirements during the curing process of the item. Relying on the observation patterns of failure, the nature of all the columns included in the design should be taken into account. Circular columns are generally more efficient than square ones and have a lower chance of punching shear failure. In such structures that are vulnerable to high punching shear forces, it would be advisable to either provide thicker slabs or incorporate shear reinforcement, especially in areas close to circular columns. Proper techniques for managing flexural cracks and reinforcing the structures should be used in the enhancement of concrete structures. This involves such things as placing reinforcement bars in areas that are believed to have stress concentrations. The current requirements for strengthening in areas such as the failure inspection study indicate that new techniques, such as increased carbon fiber products, such as epoxy, are used as binders in the existing concrete structures.

If these changes are sought, it will be possible to greatly enhance the durability, safety, and performance of concrete structures so that they will have longer service life and resistance.

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