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Strengthening of Reinforced Concrete Slabs using Carbon Fiber Polymers

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Keywords
Strengthening, Slabs, CFRP, experimental models, laminates, bonding

Abstract

Several existing reinforced concrete structures (RC) require improvement in performance for reasons of deterioration. This is due to many factors such as the change in code requirements. The current study was assisted by experimental models to investigate the behavior of RC slabs strengthened with carbon fiber reinforced polymer (CFRP) laminates and sheets. Seven RC slabs strengthened with CFRP (laminates and sheets) were tested. The slabs were divided into four groups. The first phase includes one slab without strengthening (reference slab), the second phase includes one slab strengthened with CFRP laminates, and the third phase includes one slab strengthened with CFRP sheets. The fourth phase includes four slabs strengthened with different areas of sheets. The major test parameters included the different types of strengthening materials and the corresponding types of epoxies used for each type of CFRP. A comparison between the two types of CFRP was conducted. The load deflection, load strain and mode of failure were investigated. Test results demonstrated that the flexural strength increased, and the ductility reduced with the increase in the area of CFRP sheets. for almost equivalent applied area, CFRP Sheets has more significant influence on the behavior of the strengthened slabs than laminates. Strengthening of RC slabs with CFRP improves the flexural strength capacity for both types. For the same CFRP strength, the sheets showed a cost reduction of 70%. The difference is attributed to the difference in the mechanical properties and the bonding quality of the CFRP material

1. Introduction

strengthening of concrete structures with fiberboard is an advanced method for increasing load-bearing capacity and extending life. In recent years, carbon fiber reinforced polymer (CFRP) composites have been widely used to repair and strengthen weak and damaged RC structures [1].

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There are several theoretical and experimental studies on the load-bearing behavior of CFRP reinforced RC elements. Using CFRP laminates to reinforce RC panels is considered highly beneficial if it increases the panel's bending capacity without affecting collapse modes [2]. The use of FRP composites for strengthening reinforced concrete structures has the potential to be significantly more durable and economically viable [3]. Applying strips of CFRP sheets in two perpendicular directions and bonded to the bottom of the slabs improved the punching shear strength of slab [4]. For panels with particularly pronounced bending behavior, FRP efficiency decreases with increasing number of composite layers [5]. CFRP reinforcement significantly improved the punch shear strength and predicted failure loads compared well with experimental results [6]. Strengthening techniques have a great impact on increasing strength. The near-surface (NSM) shear strengthening technique using CFRP laminates is very effective for his RC beams with an average concrete compressive strength of 60 MPa [7]. There is an increase in strength and deflection, over the unanchored but strengthened control counterparts [8]. Other research [9] includes the use of end-anchoring techniques. The end-anchor technique increased the ultimate failure load but could not prevent spalling. Reinforcement techniques using FRP include external bonding of laminates to concrete slabs and beams and wrapping of concrete columns [10]. Using an externally bonded (EB) FRP reinforcement system without end anchorages increased yield and failure loads by about 38% and 46%, respectively [11]. In general, GRP materials are characterized by high strength-to-weight ratio, corrosion resistance, short processing times and flexible use. These materials are readily available in a variety of forms, from factory-made laminates to dry fiberboard that can be wrapped to the shape of the structure. Recently, studies of slab systems have been extended to topics related to environmental impact and sustainability, such as the sensitivity analysis of the life cycle assessment [12] and the development of metamodels based on deep-learning methods [13]. This study presents experimental investigations for the use of carbon FRP laminates and sheets with different strengthening techniques and sheet arrangements. The effect of CFRP bonded to the slabs is explored in terms of the mode of failure, load-deflection characteristics, stress-strain characteristics.

2. Experimental Work

2.1 Materials

Seven RC slabs with dimensions (150 cm x 100 cm x 8 cm) were prepared. All slabs were rectangular in cross-section and prismatic. The examined average compressive strength, tensile strength and modulus of elasticity of concrete at 28 days were 30 MPa, 4 MPa, and 35 GPa, respectively. The slabs were reinforced with five rebar of diameter 8 mm per meter length in short direction and seven rebar of diameter 8 mm per meter length in long direction. The properties of the CFRP (type laminates and sheets) were taken from the manufacturer's product data sheets and installation instructions. Table 1 shows the mechanical properties of CFRP used in this study.

Table 1 Properties of Laminates® S512 and Sheets Hex® -230C

Properties	Laminates® S512 properties	Sheets Hex® -230C properties
Areal weight (±10)	230 ± 10 (g/m^2)	230 ± 10 (g/m^2)
Density	1.60 (g/cm3)	1.78 (g/cm3)
Adhesion to concrete	4 (MPa)	4 (MPa)

Fiber tensile strength (nominal)	3100 (MPa)	4300 (MPa)
Fiber tensile modulus (nominal)	165,000 (MPa)	234,000 (MPa)
Fiber breaking elongation	1.7 (%)	1.8 (%)
fabric design thickness	1.20 (mm)	1.13(mm)

2.2 CFRP Application

CFRP was applied after 28 days of slab water curing. The required area was polished followed by water and air cleaning. The slabs were kept drying in the open air. Epoxy was finally applied in two coats – above and underneath the CFRP sheet. A special steel roller was used to ensure the absence of any air voids and ensure full contact of CFRP sheet to the concrete surface. The specimens were kept for ten days in open air to cure, hardened and then tested (this is according to manufacturing company recommendations).

2.3 Test Program

The slabs were examined statically by a self-made loading frame equipped with a single loading hydraulic jack located at its center. A schematic view of experimental setup and the arrangement of the measurement devices are shown in Figure 1. They were examined as one-way slabs along their longest span. Figure 2 shows the reference slab without any strengthening. Details and description of the tested specimens are shown in Figures 3, 4, 5 and 6. The slabs were divided into four groups. List of slabs with different strengthening conditions are shown in Table 3. The first phase includes one slab without strengthening (reference slab), the second phase includes one slab strengthened with CFRP laminates, and the third phase includes one slab strengthened with CFRP sheets. The fourth phase includes four slabs strengthened with different areas of sheets. The purpose of the second and third phases of testing is to compare the degree of enhancement of CFRP to the stiffness of slabs for the two types. The purpose of the fourth phase of testing is to capture the enhancement in the stiffness of slabs with different areas of CFRP sheets.

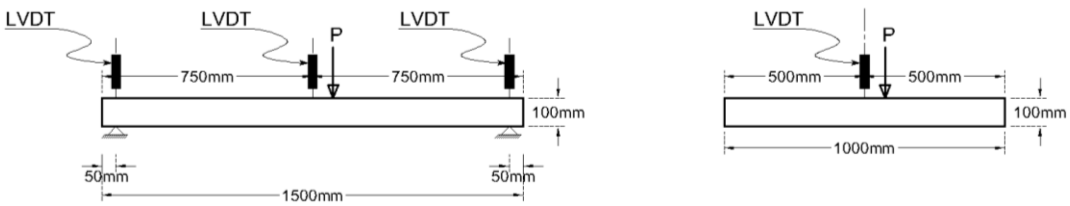


Figure 1-a Typical Section Showing Load, and LVDTs Locations

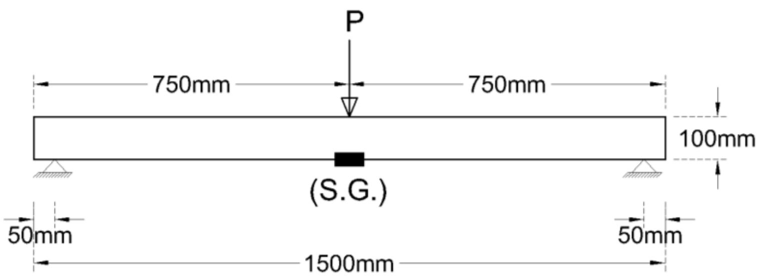


Figure 1-b Strain Gauge Locations of Slabs Specimens

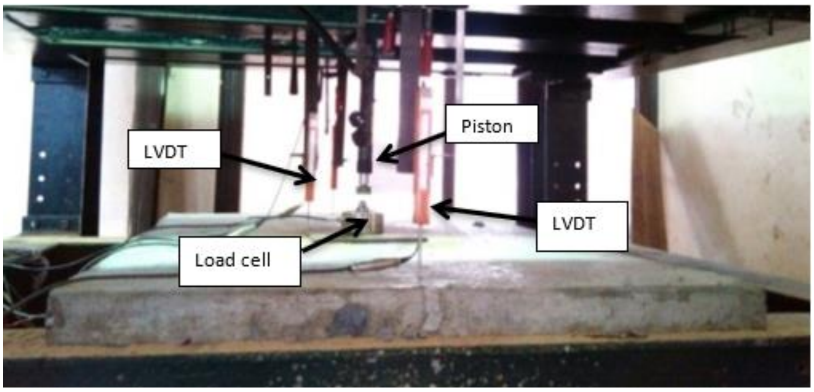
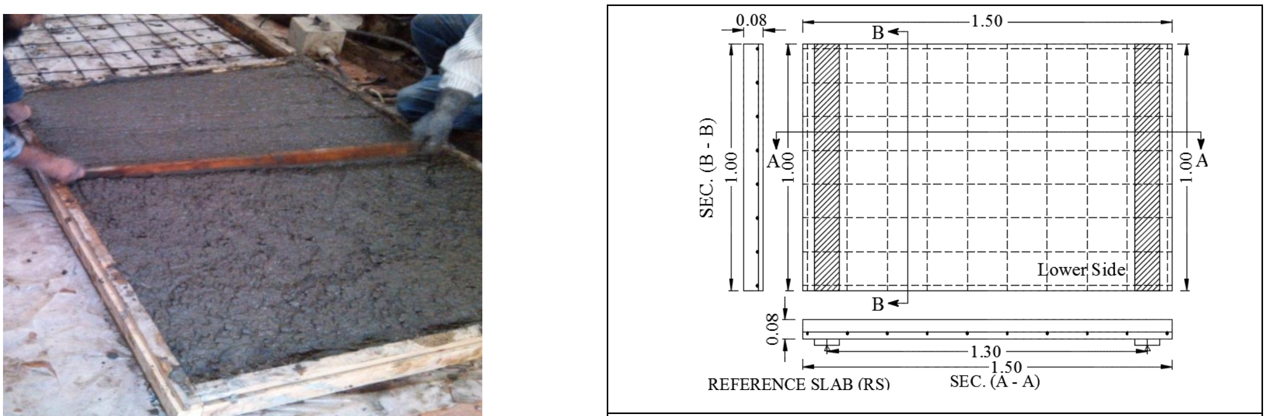


Figure 1-c Photo Describing Testing and Instrumentations Setup of slabs.



Reference Slab (RS)

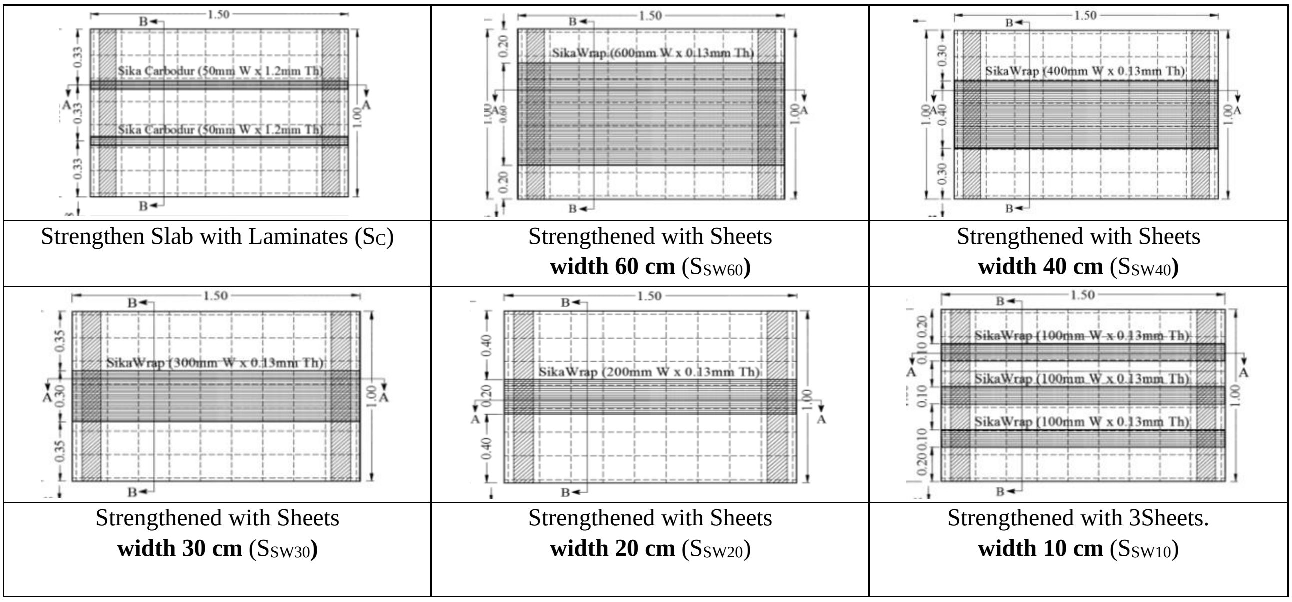
Fig. 2 Details of reinforced mesh of the reference slab (RS).

Fig.3 Fixing laminates and Sheets on the Tension Face of Slab.

Fig.4 Fixing Strain Gauges.

Table 2 explanation of the application of CFRP to the tested slabs

Group	samples	Slab Code	Carbon Fiber Type Laminates			Carbon Fiber Type sheets				Epoxy Type
			Length (cm)	Width (cm)	No. of strips	Area (cm^2)	Length (cm)	Width (cm)	No. of strips	
1	Reference Slab (control)	RS	control slab without CFRP							
2	Strengthen Slab with Laminates	S_{SC}	150	5	2	-----	-----	-----	-----	Sika dure -30
3	Strengthen Slab With sheets	S_{SW60}	-----	-----	-----	9000	150	60	1	Sika dure -330
4	Strengthen Slab With different sheet area	S_{SW40}	-----	-----	-----	6000	150	40	1	
		S_{SW30}	-----	-----	-----	4500	150	30	1	
		S_{SW20}	-----	-----	-----	3000	150	20	1	
		S_{SW10}	-----	-----	-----	4500	150	10	3	



Strengthen Slab with Laminates (S_C)

Strengthened with Sheets **width 60 cm** (S_{SW60})

Strengthened with Sheets **width 40 cm** (S_{SW40})

Strengthened with Sheets **width 30 cm** (S_{SW30})

Strengthened with Sheets **width 20 cm** (S_{SW20})

Strengthened with 3Sheets. **width 10 cm** (S_{SW10})

Fig. 5 Details of CFRP Strengthening for Test Specimens.

3. Results and Discussions

The ultimate load and maximum deflection results for the control and reinforced slab samples are tabulated below in Table 3. The results showed that the Failure Load increased, and displacement decreased when implementing sheets, Fig. 6. When implementing sheets with equivalent force of laminates, the failure load increased 1.5 times and the deflection decreased, Fig. 7. As shown in Figure 8, as the area of the sheet increased, the ultimate load increased, and the displacement decreased. The uniform distribution of CFRP sheets showed approximately the same performance when applying the equivalent sheet area as one piece, Fig.9.

Table 3 Maximum deflection and Ultimate load obtained for all the samples.

Slab code	First crack load P_{cr} (KN)	collapse Load P_f (KN)	Maximum Deflection at middle span(mm)	Max. Strain at middle span X10^6	% Increased Capacity $(Pf - P_{f\,RS})/ P_{f\,RS}$	% Deflection reduction $(Df - D_{f\,RS})/ D_{f\,RS}$
RS	17.67	23.83	32.57	1000	--------------	--------------
S_{SC}	38.73	45.5	15	4500	90.9	53.9
S_{SW60}	49.73	69.74	19.8	7400	192.7	39.2
S_{SW40}	42.28	49.45	22.38	6500	107.5	31.3
S_{SW30}	34.03	47	22.905	5000	97.2	29.7
S_{SW20}	24.74	41	28.675	3500	72.1	12.0
S_{SW10}	39.09	49.46	28.31	4500	107.6	13.1

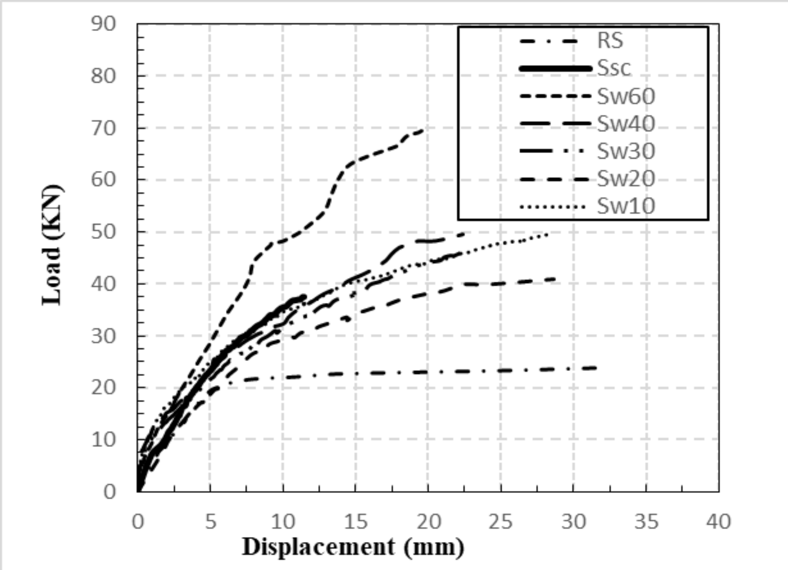


Fig.6 Relationship between load and mid-span displacement for different slabs

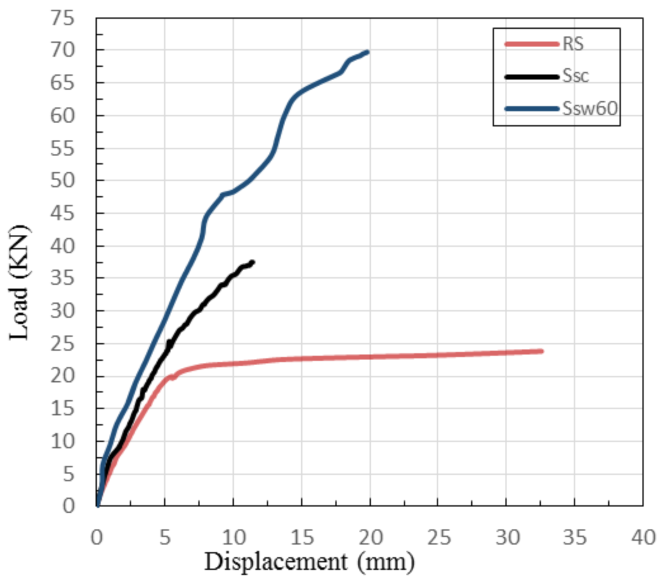


Fig. 7 Relationship between RS, Ssc, S SW60 load and intermediate displacement

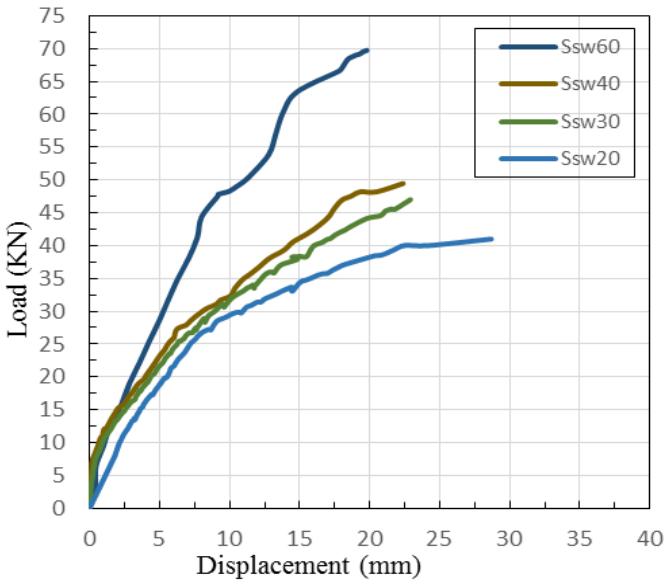


Fig. 8 Relationship between load and intermediate displacement of slabs with different Sheet Areas.

4. Crack pattern and Failure Mechanism

Two types of failures were observed during testing. The reference slab had a crack parallel to the support line and in the region of maximum positive moment (the bottom of the slab), resulting in a flexural failure. The slab Ssc initially exhibited bending cracks initiated in the region of maximum positive moment parallel to the support line. As the load increased, additional bending cracks formed and widened. The main crack appears in the center. The failure was slightly sudden due to a small area of fiber bond attached to slab surface as shown in Fig.10. Failure mode of the slabs strengthened with sheets mainly due to debonding failure of the CFRP sheets, as shown in Figure 11. However, the rupture was preceded by the yielding of steel. The capacity at failure was relatively greater for the CFRP strengthened slabs. This was attributed to the failure mode of slabs strengthened with sheets gradually due to the large area of bond attached to slab surface.

The comparison between strengthening with laminates and Sheets shows that Strengthening using Sheets was more effective than strengthening with laminates as it gives higher strength reach to 170%.

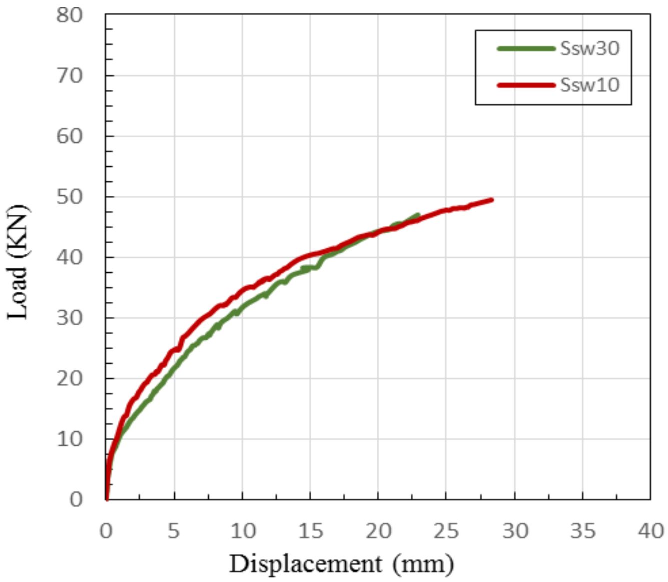


Fig. 9 Relationship between load and intermediate displacement of SSW30 and SSW10

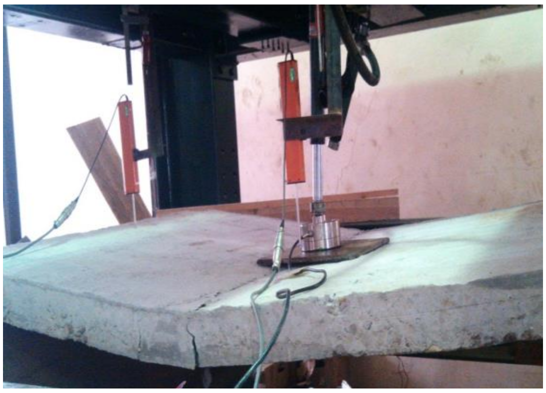


Fig.10 Crack Pattern and Mode of Failure for Slab SSC.

Fig.11 Crack Pattern and Mode of Failure for Slab SSW60.

5. Comparison of Experimental Results and Egyptian Code of Practice for CFRP.

5.1 Capacity calculated by code:

5.1.1 Slab strengthened with laminates (S_{SC})

Figure12 shows the Internal Strain and Stress Distribution for a Rectangular Section of the reinforced concrete slab under Flexure at Ultimate Stage.

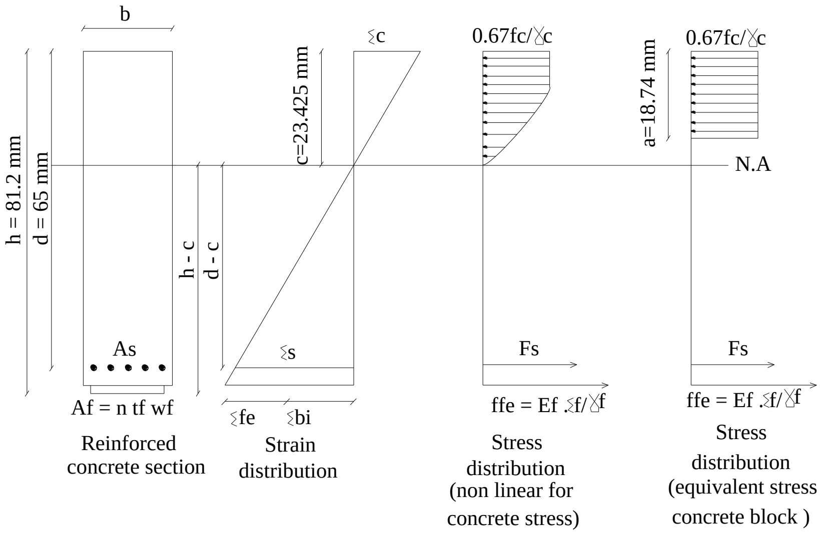


Fig.12 Internal Strain and Stress Distribution for a Rectangular Section under Flexure at Ultimate Stage.

Mu=Pu*L/4

Mu=As*fs*(d-a/2) + Af* Ffe*(h-a/2) Equ.1

a = (As* fs + Af * Ffe) / (0.67 * fcu * b / γc) Equ.2

Ff = Ef εfe / γf Equ.3

εfe =Km εfu* Equ.4

Km = 1/ (60 x εfu*) x (90000/ n x Ef x tf) Equ.5

εf = ε*fu =CE εfu Equ.6

CE=0.85 for elements exposed to environment (carbon/epoxy)

E_{fu}=1.7% (strain at break) from sika data sheet εf = 0.85 E_{fu}

γc = 1.50 , γs = 1.15 , γf = 1.40 For FRP laminates , εs = 0.005 for grade 240/360

The experimental results were compared to the results obtained from Egyptian code mathematical models for CFRP. Fig.13 and Table 5 shows the ultimate loads from the Egyptian code and the experimental work. It can be shown that the differences in the results are in very good agreement with a percentage difference of +10%.

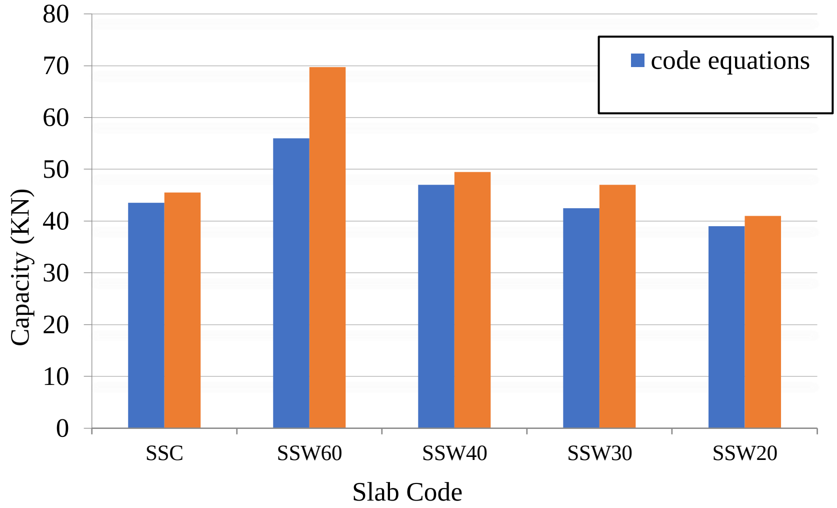


Fig.13 Comparison between Capacity obtained from CFRP code and Experimental Work

Table 5 Comparison between capacity obtained from Egyptian code and experimental results.

Slab code	Collapse Load (KN)	
	Egyptian code	Experimental
RS	22.0	23.83
Ssc	43.5	45.5
Ssw60	56.0	69.74
Ssw40	47.0	49.45
Ssw30	42.5	47
Ssw20	39.0	41
Ssw10	43.0	49.46

It can be shown that the difference in failure load for laminates and sheets was attributed to difference in strain, where from calculations the strain of sheets was higher than strain of laminates. Calculated strength based on Egyptian code of practice for FRP showed 10% and 15% under estimation for laminates and sheets, respectively.

6. Conclusions

Based on the experimental results, the following conclusions could be obtained.

1- CFRP sheets bonded to tension surfaces from the outside are highly effective in increasing the ultimate load-bearing capacity of reinforced concrete slabs.
2- The collapse load of CFRP strengthened slabs with strips (laminates) was twice than that of reference slab. Deflection was found to reduce by 55%
3- The capacity of CFRP strengthened slabs (wrapping) was three times of reference slab. Deflection was found to reduce by 45%
4- Reinforcing the flexure with CFRP strips can help disperse numerous hairline cracks and limit the growth of wider cracks.

5- The failure mode of all reinforced slabs using both CFRP systems starts with the yielding of the rebar, followed by partial rupture of the CFRP sheets or strip, and finally cracking of the concrete in the compression zone., it can be specified as flexural failure followed by interfacial debonding.
6- CFRP sheet system improves maximum load-bearing capacity of reinforced concrete slabs by 170% of CFRP strip system, having same tensile strength. This agrees with the Egyptian Code for CFRP.
7- The failure mode of slabs in case of strengthening with sheets was a gradual failure due to the large area of fibre bond attached to slab surface, but in case of strengthening with laminates, the failure mode was sudden due to the small area of fibre bond attached to slab surface as observed in experimental work. This was attributed to the different mechanical properties and bonding qualities of CFRP materials.
8- The distribution of CFRP sheets showed to be more efficient for improving the performance of RC plates. We found that the bending capacity increased slightly when the panels were evenly spaced across the slab width.
9- Calculated strength based on Egyptian code of practice for FRP showed 10% and 15% under estimation for laminates and sheets, respectively.

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تدعيم البلاطات الخرسانية المسلحة باستخدام بوليمرات ألياف الكربون

تمثل هذه الدراسة نتائج برنامج تجريبي تم إجراؤه للتحقق من مدى إمكانية استخدام الياف الكربون **CFRP (**ألواح وشرائح) في تحسين سلوك البلاطات الخرسانية المسلحة. تم تصنيع واختبار سبعة عينات من البلاطات الخرسانية ذات أبعاد ١٥٠٠ × ١٠٠٠ × ٨٠ مم تحت حمل انحناء ثابت. هذه البلاطات عبارة عن بلاطة خرسانية بدون تقوية (عينة التحكم) ،بلاطة خرسانية مقواه بشرائح **CFRP** ،بلاطة خرسانية مقواه بألواح **CFRP**،٤ بلاطات خرسانية مقواه بمساحات مختلفة من الشرائح. تضمنت متغيرات الاختبار الرئيسية الأنواع المختلفة من مواد التقوية وأنواع الإيبوكسي المقابلة المستخدمة لكل نوع من أنواع **CFRP.**تم رصد وتسجيل قيم الاجهاد ،الانفعال، الترخيم ونمط التصدع وآلية انهيار البلاطات أثناء التحميل. أثبتت النتائج التجريبية لهذه الدراسة أن التقوية باستخدام نوعي **CFRP** حسّن من قدرة التحمل ، والإزاحة ، ومقاومة الانحناء ، وأخر انهيار البلاطات الخرسانية. لنفس مساحة ال **CFRP** اظهرت البلاطات المقواه بشرائح الكربون تحسن في قدرة مقاومة إنحناء أعلى من تلك المقواه بألواح الكربون وانخفاضًا في التكلفة بنسبة ٧٠٪. يُعزى الاختلاف إلى الاختلاف في الخواص الميكانيكية وجودة الترابط لمادة **CFRP.**