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STRENGTHENING OF REINFORCED CONCRETE ONE-WAY SLABS USING CFRP IN FLEXURAL

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ABSTRACT

The present study examines the potential of using carbon fiber reinforced polymer (CFRP) strip technique in repairing or strengthening of preloaded, cracked, reinforced concrete one-way solid slabs. The reinforced concrete (RC) slabs specimens were casted with dimensions of 1400×450×90 mm. Totally, seven specimens are tested, including one reference specimen without strengthening and six specimens strengthening with CFRP strips. CFRP strips are placed along the slabs with different lengths and configurations. Before strengthening, The slabs were preloaded to level of 60% from the ultimate load capacity of the slabs. Length and configuration of CFRP strip are the main parameters that are investigated in this experimental research. The strengthening slabs are divided into two groups according to configuration of CFRP strip, each group consist of three slabs, in both groups, effect of length of CFRP strip using three lengths (600mm, 800mm and 1000mm) was studied, but in the first group one segment of CFRP strip with (100mm) width was used , while in the second two segments of CFRP strip with (50mm) width were used. The slabs were loaded under two point static load up to failure and the structural response of each slab specimen was investigated in terms of the onset of cracking, deflection, ultimate load and failure mode. The efficiency of using CFRP strips technique to repair or strengthening and their effects on the structural behavior of cracked concrete slab had been analyzed. It was observed that the strengthening technique used in this study is affect the load carrying capacity, deflection, stiffness, concrete compressive strain, cracking load and crack width of the slab. This repair or strengthening technique was found to be able to restore and enhance the structural capacity of cracked concrete slabs.

KEYWORDS: Strengthening, Carbon Fibre Reinforced Polymers CFRP, One Way Slabs.

INTRODUCTION

Concrete is known as a brittle material with a low bearing capacity for deformation under tensile stress. The development of these tensile stresses may be a result of mechanical loading, harmful reactions and environmental loading. Cracks adversely affect the performance of concrete result frequently from these stresses. Cracking is one of the most common defects observed in reinforced concrete slabs and beams. In order to restore the structural capacity of the distressed structural elements, retrofitting and/or strengthening are needed [1, 2, 3 and 4]. There are different techniques available for retrofitting and strengthening of different reinforced concrete structural elements including cement grout, epoxy injection, fiber reinforced polymers, ferrocement and steel plates. The selection of a suitable method for repairing depends on many factors, such as amount of damage, repair material, construction cost and time [5, 6, 7, 8 and 9].

This study investigates the strengthening behavior of cracked reinforced concrete one way slabs under 60% preloading level. Carbon Fiber Reinforced Polymers (CFRP) strip technique was employed to repair the cracked concrete slabs to study the effects of length of CFRP strip with two deferent configuration. The slabs were preloaded to 60% of the ultimate capacity of the slabs and the structural response of each slab specimen was analysed in terms of deflection, variation of strain in concrete, collapse loads and failure modes.

EXPERIMENTAL PROGRAM

Test Specimens and Material

The experimental program included casting, preloading, strengthening and testing with load up to failure , seven RC one-way slabs. The dimensions of the slabs were 1400 mm long, 450 mm wide and 90 mm in height. The slabs were designed according to ACI 318-14 procedures (ACI Committee 2014) [10]. The main reinforcement steel was 4ϕ10, representing a steel ratio of 0.01, this steel ratio is selected since it is generally used in the practice according to the ACI 318-14 and it is economical. The secondary reinforcement (temperature and shrinkage) was 9 ϕ10 in the transverse direction. One of these seven slabs is tested without strengthening as a reference specimen and the others were initially preloaded to 60% of the ultimate load and tested with strengthening using CFRP strip. The strengthening slabs were divided into two main groups, each group consist of three slabs and studies the effect of length of CFRP strip (LCFRP = 600mm, 800mm and 1000mm), but in the first group one segment of CFRP strip) was used at width of (100mm and in the second group two segments of CFRP strip at width of (50mm) were used. Properties of the specimens are given in Table (1). Geometrical dimensions and reinforcement details of the specimens are presented in Figure (1) and Figure (2).

Table 1: Properties of specimens

Specimen	% Preloading	Strengthening	CFRP strip length (mm)	CFRP strip width (mm)	Number of CFRP strip	f'_c MPa
S1	---	---	---	---	---	40.8
S2	60	CFRP strip	600	100	1	41.1
S3	60	CFRP strip	800	100	1	40.3
S4	60	CFRP strip	1000	100	1	40.5
S5	60	CFRP strip	600	50	2	42.1
S6	60	CFRP strip	800	50	2	39.3
S7	60	CFRP strip	1000	50	2	41.4

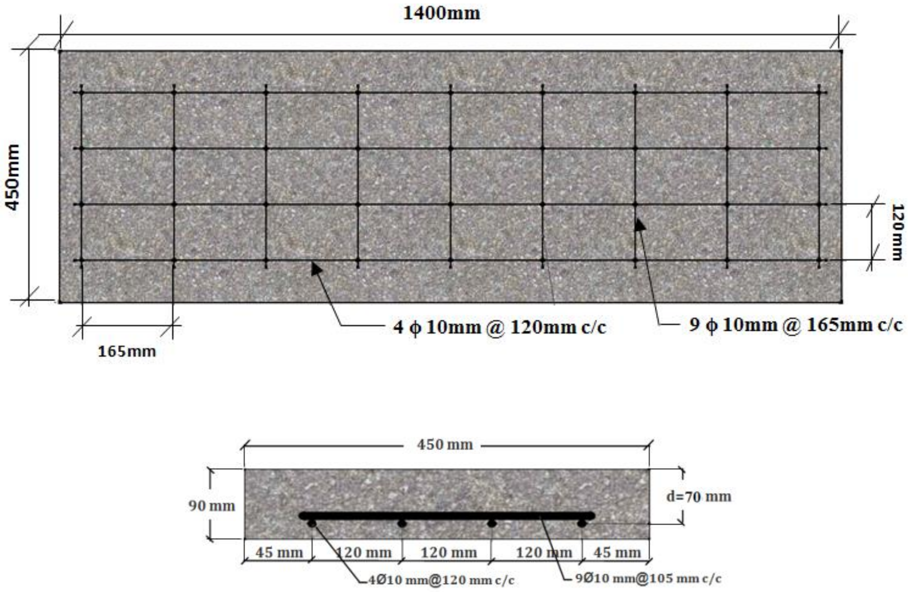

Figure 1: Dimensions and reinforcement details of specimens

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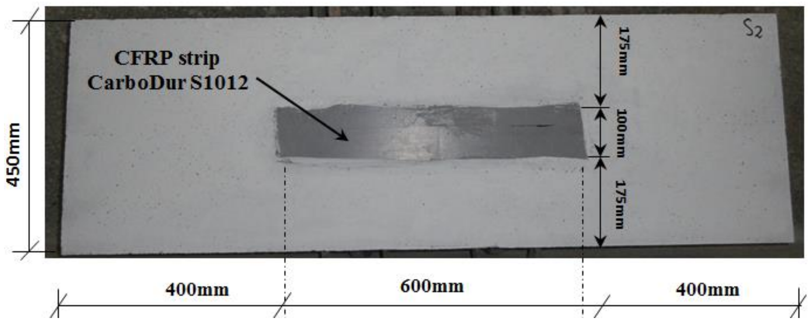
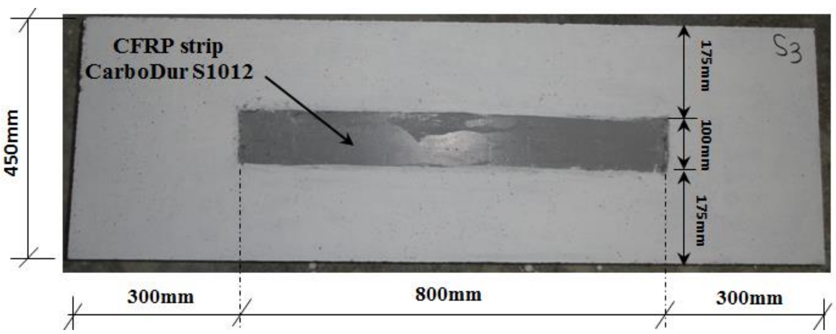
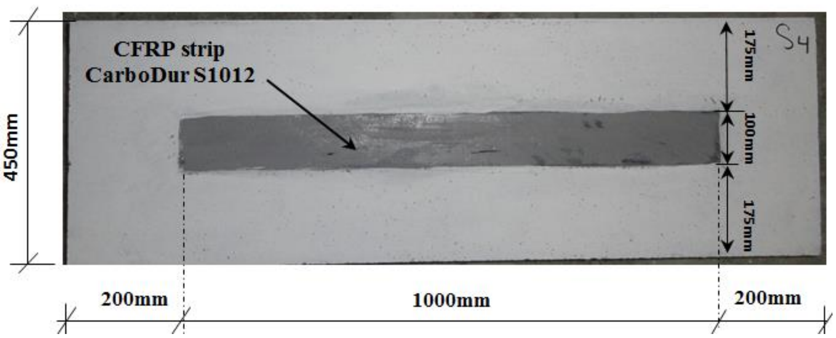
a: S1 Reference slab (without strengthening)



b: S2 Strengthened slab by CFRP strip [one segment, L=600mm, W=100mm]

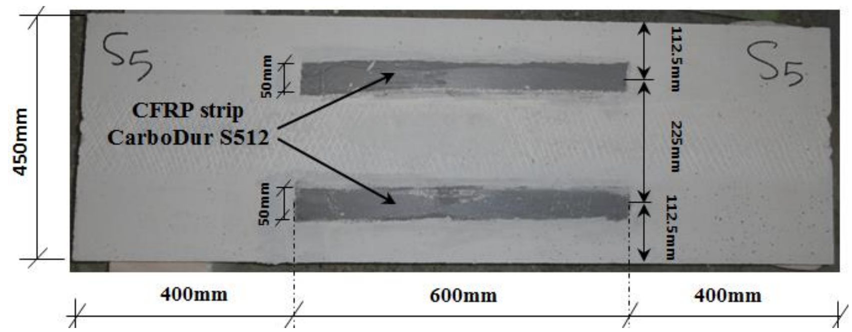


c: S3 Strengthened slab by CFRP strip [one segment, L=800mm, W=100mm]

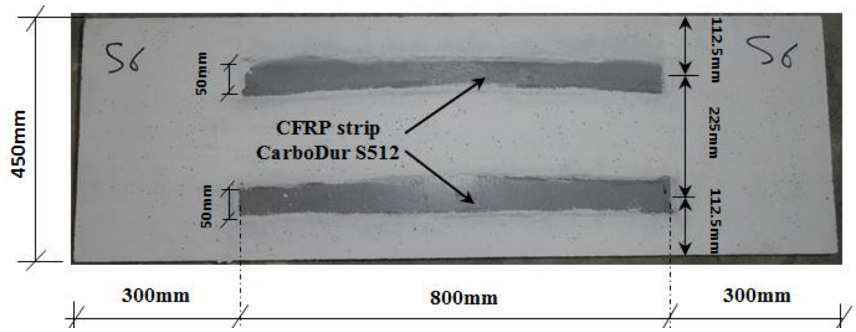


d: S4 Strengthened slab by CFRP strip [one segment, L=1000mm, W=100mm]

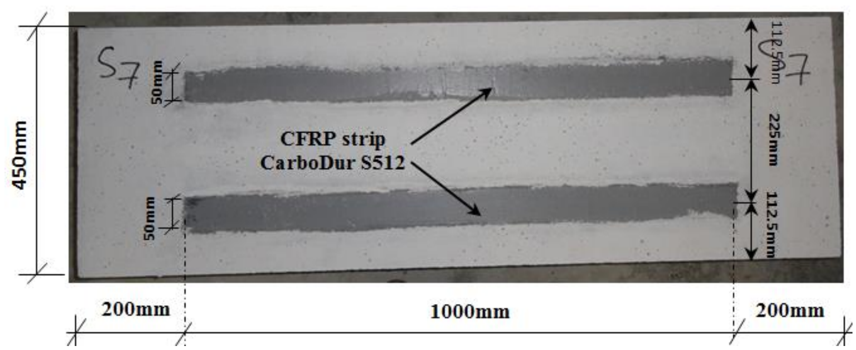
Figure 2: Detailing of reinforced concrete slabs, Cont,d



e: S5 Strengthened slab by CFRP strip [two segment, L=600mm, W=50mm]



f: S6 Strengthened slab by CFRP strip [two segment, L=800mm, W=50mm]



g: S76 Strengthened slab by CFRP strip [two segment, L=1000mm, W=50mm]

Figure 2: Detailing of reinforced concrete slabs

Four moulds were prepared using 20mm thick wood and the reinforcing steel cages were placed inside the moulds with proper spacer prior to casting the concrete mixture. The concrete mixing was achieved using a titling a horizontal rotary mixer machine of 0.15m^3 capacity available in the material construction laboratory, College of Engineering, Diyala University. The mixture ingredients were pre-batched to the required weights. The volume of each batch was sufficient to cast two slabs and four testing cylinders of dimensions (150×300mm). The concrete mix proportions are presented in Table (2). Targeted compressive strength of the concrete is 40MPa and obtained concrete compressive strengths after testing are given in Table (1). Mechanical properties of reinforcements, which are used in the specimens, are presented in Table (3). The slabs were casted in two layer and compacted using an electrical rode vibrator to achieve a satisfactory compaction. The specimens were de-moulded after 24 hour from casting, and immersions in a tank of water for 28 day. After curing, the specimens were transferred to the open laboratory environment for five days before applying the preloading. The aforementioned steps are displayed in Figure (3).

Table 2: Concrete Mix design

Mix designation	Cement kg/m^3	Aggregate kg/m^3		Water kg/m^3	w/c for Slump 120±10 mm
		Sand	Gravel		
C40	400	850	950	200	0.50

Table 3: Mechanical properties of reinforcement

Reinforcement Diameter (mm)	Yield strength (MPa)	Ultimate tensile strength (MPa)	Type
10	460	605	Deformed

a: Wooden moulds

b: Steel cage erected inside mould

c: Tilting rotary mixer

d: Concrete casted in moulds

e: Curing

f: Slabs after curing

Figure 3: Photos showing the steps of concrete casting until curing

The CFRP used in the strengthening application were (Sika CarboDurS1012 and Sika CarboDurS512) unidirectional flexible strip. The structural adhesive paste used for bonding the Sika CarboDur strips to the concrete substrate was (Sikadur-30) which is high-modulus high-strength two component (A and B) product, see Figure (4). (100 mm and 50 mm) wide CFRP strips (Sika CarboDurS512 and Sika CarboDurS1012) are used. Uniaxial CFRP strips are placed as a single layer for strengthening and two component epoxy adhesive is used for bonding. Layouts of the CFRP strips are shown in Figure (2). Before bonding of CFRP members onto concrete surface, special consideration was given to the slab tension face preparation. CFRP strip locations onto tension face of the slabs were roughened mechanically by a grinding machine down to aggregate level, and then grinded surface was brushed. Surfaces were vacuum cleaned for removing loose particles and dust. Prepared mixture of epoxy was spread over the grinded surface up to 2mm thickness approximately. CFRP strips were bonded on their predefined places at tension face of the slab. After bonding of CFRP strips, some pressure was applied on them by hand along the fiber directions to get rid of air bubbles entrapped between CFRP strips and concrete surface, and CFRP strips were soaked with applied epoxy on concrete, see Figure (5). The temperature during application was 20 ± 2 ċ in all cases. After bonding operations was completed, specimens were cured for 7 days under laboratory conditions before testing. Properties of CFRP strips and epoxy, which are suggested by the manufacturer, are presented in Tables (4) and (5).

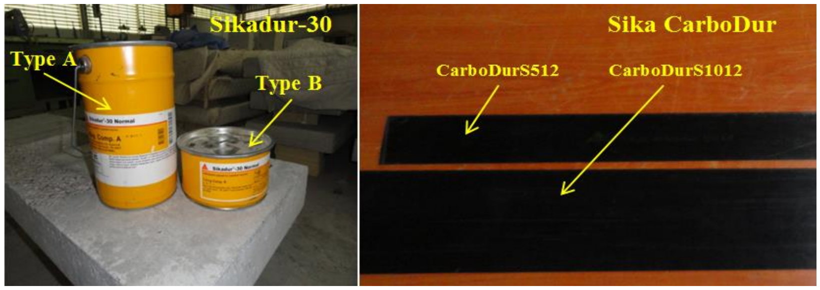


Figure 4: Manufactured forms of CFRP materials

a: Removing the weak layer surface ***b: Cleaning the slab surface*** ***c: Mixing the epoxy materials***

d: Applying of CFRP strip ***e: Specimen just after strengthening***

Figure 5: Steps of strengthening by CFRP strip

Table 4: Properties of CFRP strip (Sika CarboDurS512 and Sika CarboDurS1012)*

Fiber type	**High strength carbon fibers**
Base	Carbon fiber reinforced polymer with an epoxy resin matrix
Shelf Life	Unlimited (no exposure to direct sunlight)
Color	Black
Tensile Strength	Mean Value 3100 MPa Design Value 2800 MPa
Modulus of Elasticity	Mean Value 165000 MPa Design Value 160000 MPa
Elongation at Break	1.69%
Design Strain	0.85%
Thickness	1.2 mm
Temperature Resistance	>150°C
Fiber Volumetric Content	>68%
Density	1.60 g/cm3
Physical Properties	

Product	Thickness	Width	Cross Sectional Area	Tensile Force
Type S512	1.2 mm	50 mm	60 mm^2	168 kN
Type S1012	1.2 mm	100mm	120 mm^2	336 kN

*** Provided by the manufacturer**

Table 5: Properties of Sikadur-30 (Impregnating Resin)*

Color	Light gray
Storage Conditions	Store dry at (4°-35°C). Condition material to (18°- 29°C) before using
Consistency	Non-sag paste
Pot Life	Approximately 70 minutes @ 23°C (1 qt.)
Mixing Ratio	Component ‘A’: Component ‘B’ = 3:1 by volume
Density	**1.65 kg/l (mixed)**
Tensile Properties (ASTM D-638) 7 day	Tensile Strength (24.8 MPa) Elongation at Break 1% Modulus of Elasticity (4482 MPa)
Flexural Properties (ASTM D-790)14 day	Flexural Strength (Modulus of Rupture) (46.8 MPa) Tangent Modulus of Elasticity in Bending (11721 MPa)
Shear Strength (ASTM D-732) 14 day	Shear Strength (24.8 MPa)

*** Provided by the manufacturer**

Experimental Setup

A schematic view of the test setup and the arrangement of the measurement devices are shown in Figure (6). The specimens were constructed in the Structural Laboratory of the College of Engineering / Diyala University. All specimens were tested as simple beam under four point loading with shear span to effective depth ratio (a/d) equal to 5.71. Load on the midpoint of separator beam was divided symmetrically into two concentrated load and applied to the specimens. Load was applied with a 2000kN capacity hydraulic jack and was measured with a 600kN capacity load cell. Vertical deflections have been measured at three points (D1, D2 and D3) as central deflection and at under point of loads in both sides of the slab using a three dial gauges of (0.01mm) accuracy with (50mm) total stroke. The dial gauges have been attached to the soffit of the tested slabs. All specimens were instrumented with one concrete strain gauge bonded on the top surface of the slab at the center. The concrete strain gauge used in the experimental program was type PFL-30-11-3L from TML, with the following characteristics: wire-type, with a resistance of 120.4±0.5 Ω, a gauge factor of 2.13 ± 1%, a gauge length of 30mm and a gauge width of 2.3mm with a maximum strain of 2%; see Figure (7 b). The strain gauge was bonded, using CN-E cyanoacrylate adhesive, to the previously treated surface of the slab with PS-XC09F two component adhesive; see Figure (7 c and d). Figure (7 a) shows the arrangement of the concrete strain gauge. The load was increased gradually at increments of (2.5kN) to record the deflection up to failure. To measure crack widths, an optical micrometer with an accuracy of (0.02mm), as shown in

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Figure (8), was used for all slabs specimens. The slab surfaces were painted with white color to make it easy to see the crack and measured it, as shown in Figure (9).

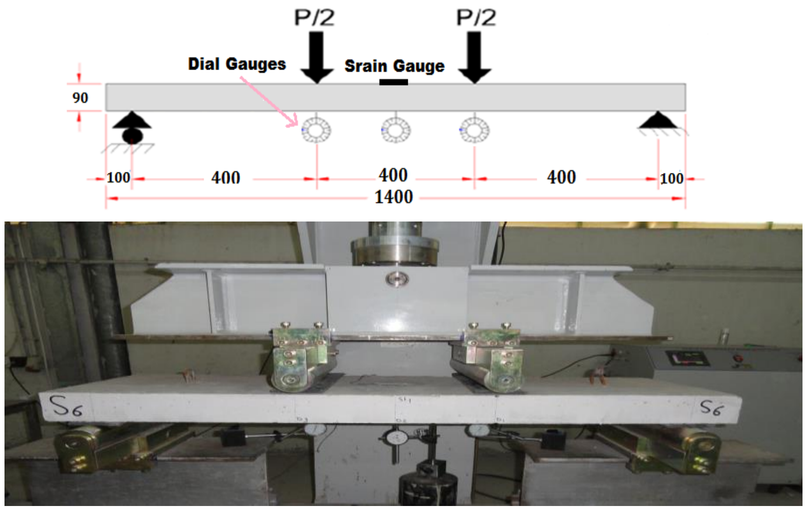

Figure 6: Test setup and instrument

a) Strain gauges arrangement b) PFL-30-11-3L strain gauge c) PS-XC09F adhesive d) CN-E adhesive

Figure 7: Strain gauge type, Arrangement, and Adhesive materials

Figure 8: Optical micro-meter

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Figure 9: Painted the RC slab with white color

EXPERIMENTAL RESULTS

Deformation Behavior

Deflection profile was measured along the length of tested slabs (at the center of slabs, 200mm from the center along X-axis in both sides) by means of (0.01 mm) dial gauges, and readings from this gauge were recorded for each load increment. The deflection profiles for all specimens are shown in Figures (10 to 16). The structural behavior of the slabs is presented in the form of load–deflection curves. The curves of load versus deflection identifying three specific regions; a linear region to yield, a transition region of continuous yield, and a region of full plastic deformation until failure. The slope of linear elastic portion of the load deflection curve represents the stiffness (modulus of elasticity) of the slab ($E = P/\delta$) and the area under the curve represents the toughness.

Figures (17, 18 and 19) show the load–central deflection curves of strengthened 60% preloaded slabs. It is clear from the Figures that the curves have a pre-cracking portion that approximates a straight line. At cracking, the slope of the curve changes indicating a reduction in the stiffness. The post-cracking segment sloped upward indicating that the strengthening slabs have significant influence on the post-peak behavior. For all the strengthened slabs, there was an increase in the flexural capacity and stiffness. However the failure was in a more brittle manner. For specimens strengthened with CFRP strips, there were a noticeable reduction in the mid-span deflections, and there was large increases in stiffness and loss in the ductility; the post-cracking segment for the load–deflection curves is absent or very small. This behavior refers to the high stiffness of the CFRP used, and for those specimens the failure mode was more brittle failure compared to the control.

The corresponding ultimate capacity of the reference and strengthened slabs, the mid-span deflection at service stage (at 70% of reference ultimate load) [11] and at ultimate stage are presented in Table (6).

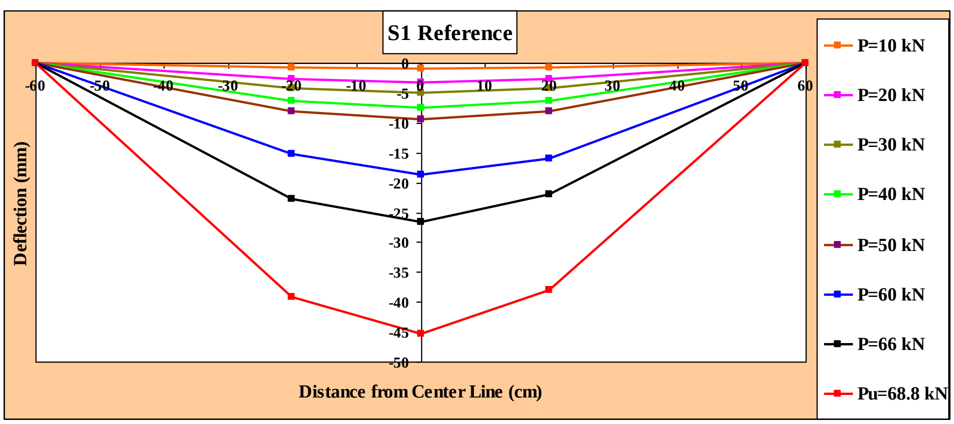

Figure 10: Deflection profile for specimen S1

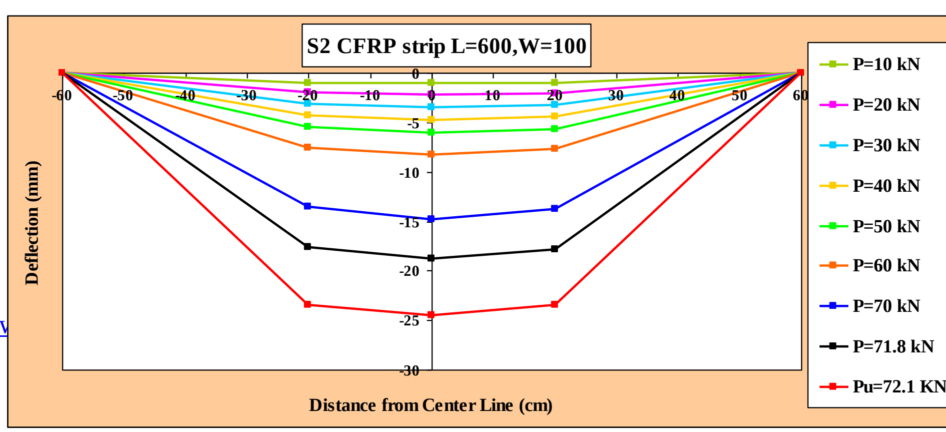

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Figure 11: Deflection profile for specimen S2

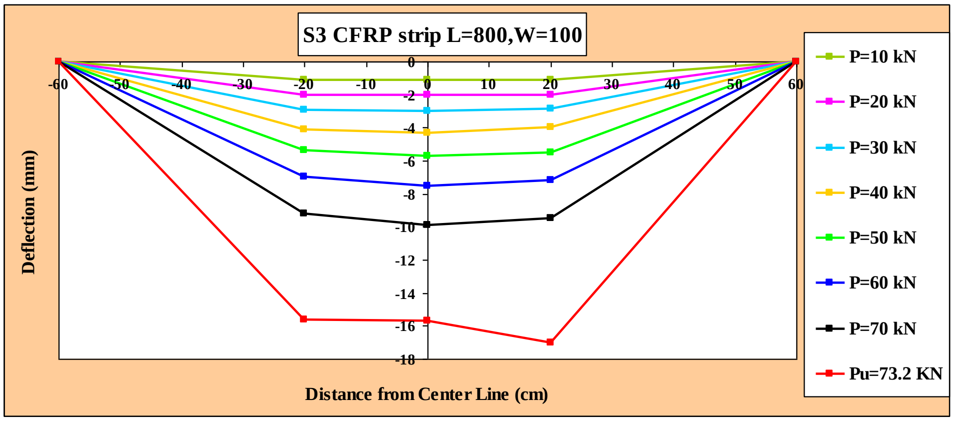

Figure 12: Deflection profile for specimen S3

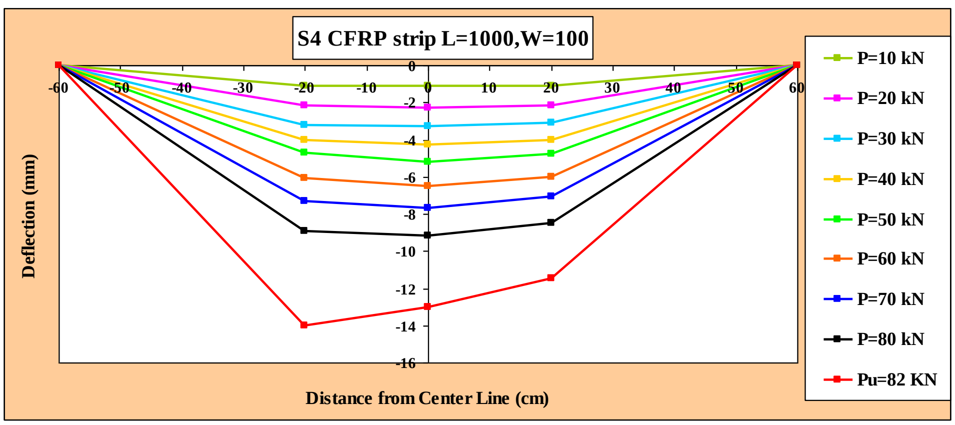

Figure 13: Deflection profile for specimen S4

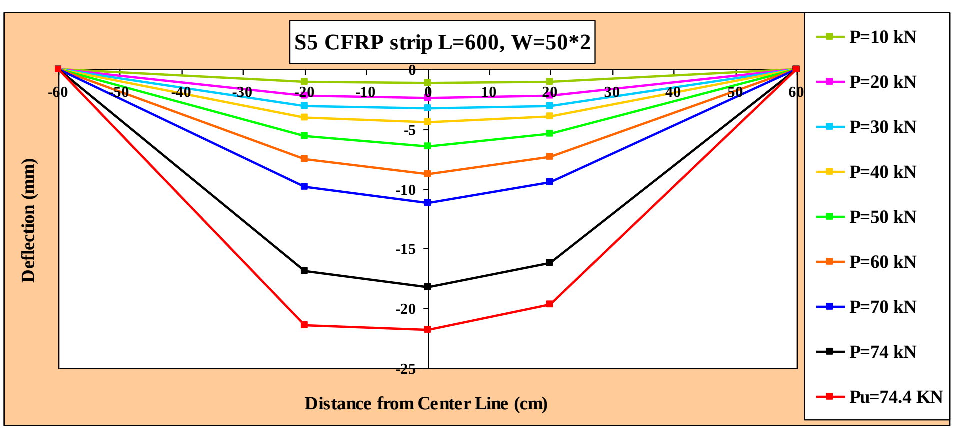

Figure 14: Deflection profile for specimen S5

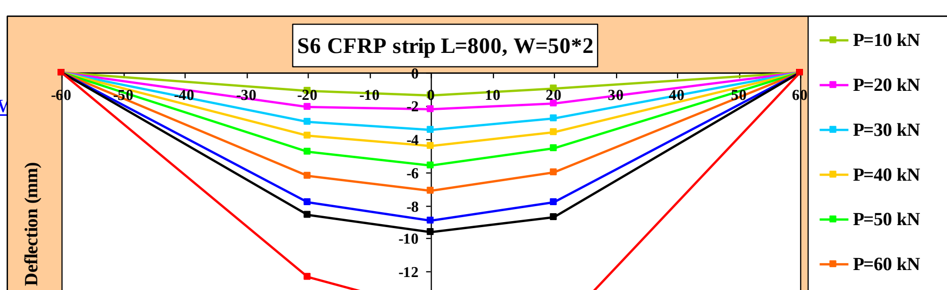

Figure 15: Deflection profile for specimen S6

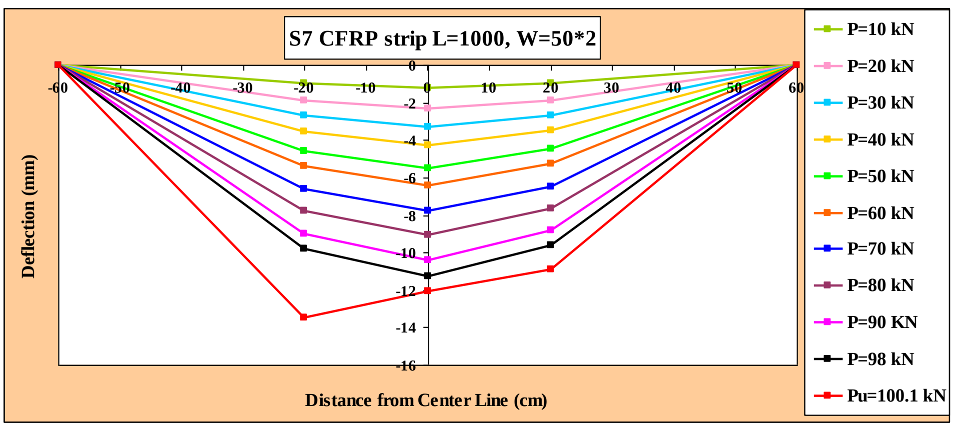

Figure 16: Deflection profile for specimen S7

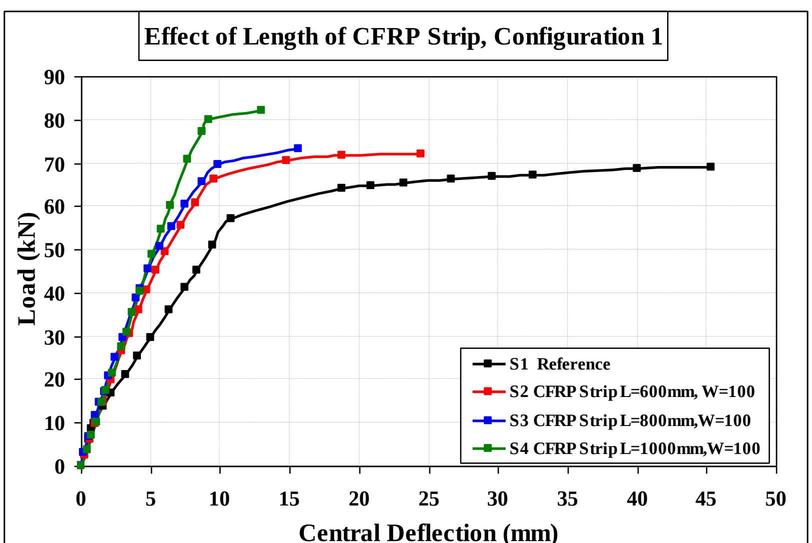

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Figure 17: Effect of length of CFRP strip on load-deflection curve, configuration 1

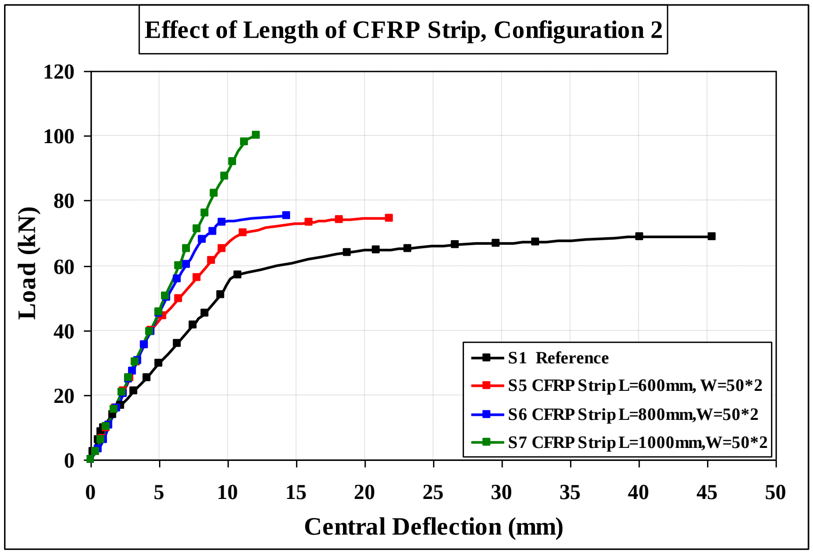

Figure 18: Effect of length of CFRP strip on load-deflection curve, configuration 2

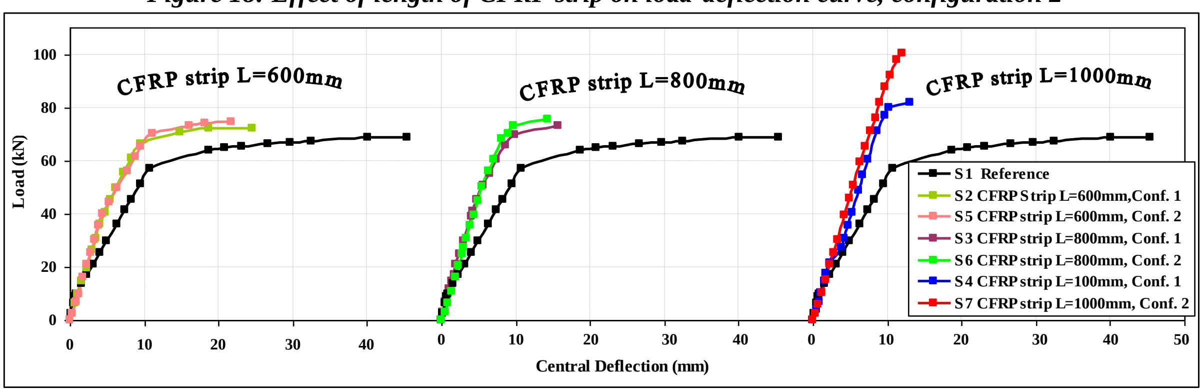

Figure 19: Effect of configuration of CFRP strip on load-deflection curve

Table 6: Experimental results of tested slabs

Specimen	Crack load P_{cr} (kN)	Ultimate load P_u (kN)	Service mid-span deflection Δ_s (mm)	Ultimate mid-span deflection Δ_u (mm)	Service Strain εs *10^-3	Ultimate Strain εu *10^-3	Service crack width W_s (mm)	Ultimate crack width W_u (mm)
S1	9.9	68.8	8.97	45.39	1.327	4.148	0.225	2.400
S2	14.5	72.1	6.10	24.50	1.024	1.475	0.150	0.504
S3	17.1	73.2	5.40	15.70	0.835	1.400	0.127	0.336
S4	17.3	82.0	5.20	13.00	0.721	1.330	0.138	0.372
S5	21.1	74.4	5.90	21.80	0.870	1.400	0.116	2.170
S6	27.2	75.2	5.30	14.30	0.765	1.350	0.153	1.200
S7	30.0	100.1	5.10	12.10	0.645	1.280	0.126	0.400

Effect on Load Capacity

A general view on the obtained results shows that all the strengthened slabs gave a significant increase in the ultimate load carrying capacity when compared with that for the reference slab specimens. There was a noticeable improvement in the flexural behavior of the strengthened slabs. The increase in the ultimate load ranges from 5% to 46%. The highest increase in the ultimate load capacity was achieved using two segments of 50mm width and 1000mm length of the CFRP strip. For CFRP strengthened slabs with length of strip are (600mm, 800mm and

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1000mm), the ratios between the strengthened length and the slab specimen length are (50%, 67% and 83%) respectively. However, the increase in the ultimate capacity was about (5%, 6% and 19%) for 100mm strips width (one segment, configuration 1) and (8%, 9% and 46%) for 50mm strips width (two segments, configuration 2). The numerical values for the percentage increase in the ultimate load capacity (Pu) are shown Figure (20).

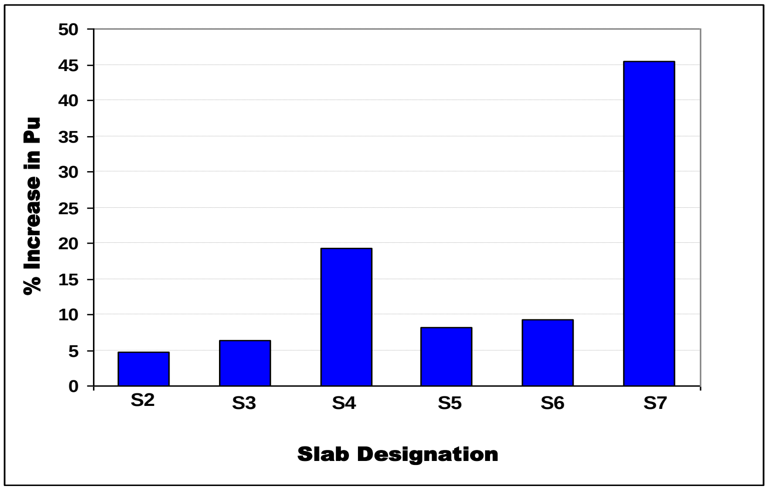

Figure 20: Percentage increase in ultimate load capacity due to strengthening by CFRP strip

Effect on Mid-Span Deflection

The strengthening technique has significant effects on the mid-span deflection for the slabs; there was a reduction in the mid-span deflection (at service and ultimate stage) by an average ratio of (40% and 70%), respectively. This may refers to the nature for the material used in strengthening, where the CFRP are considered brittle materials which have approximately 1.5% strain at failure which does not permits a considerable deformation. The percentage decrease in the mid-span service and ultimate deflections are shown in a bar chart in Figures (21 and 22) respectively.

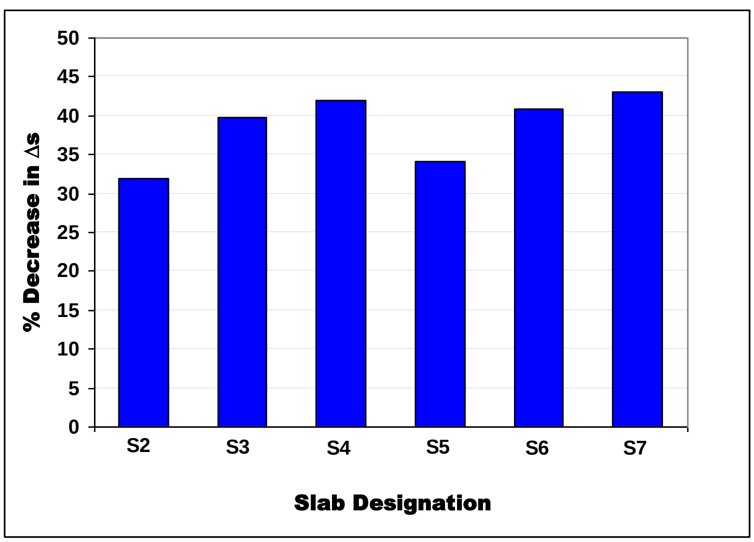

Figure 21: Percentage decrease in service mid-span deflection due to strengthening by CFRP strip

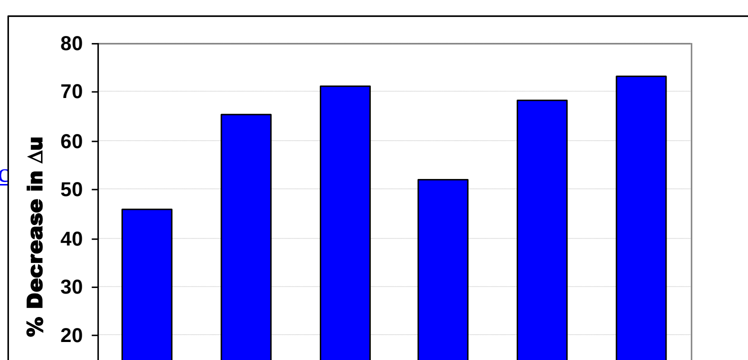

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Figure 22: Percentage decrease in ultimate mid-span deflection due to strengthening by CFRP strip

Effect on Concrete Compressive Strain

The strains in the concrete at compression face of the tested slabs have been measured by strain gauge along the length of slab at center line. Figure (7-a) shows the position of strain gauge. From Figures (23, 24 and 25), it can be seen that the concrete compressive strain is small at elastic stage as loading is applied, and then it increases after the first crack when loading is continued. Positive values in the diagrams refer to compression strain. The CFRP strips gave a considerable decrease in concrete compressive strain. This is because of the large stiffness for this material. The results are shown in Table (6). The percentage decrease in service (ε_s) and ultimate (ε_u) concrete compressive strain are shown in a bar chart in Figures (26 and 27) respectively.

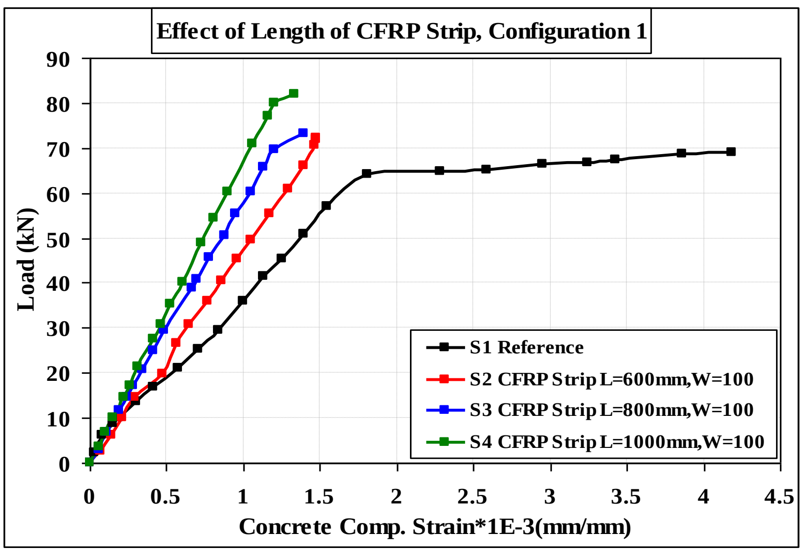

Figure 23: Effect of length of CFRP strip on load- concrete compressive strain curve, configuration 1

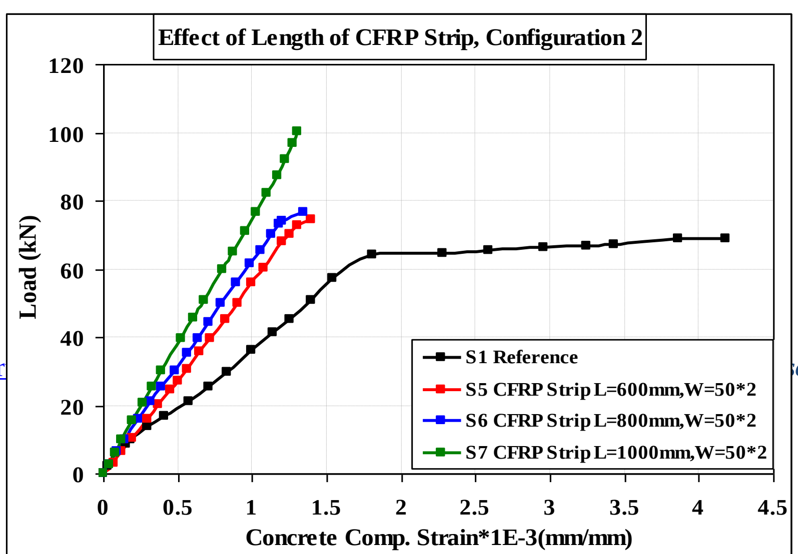

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Figure 24: Effect of length of CFRP strip on load- concrete compressive strain curve, configuration 2

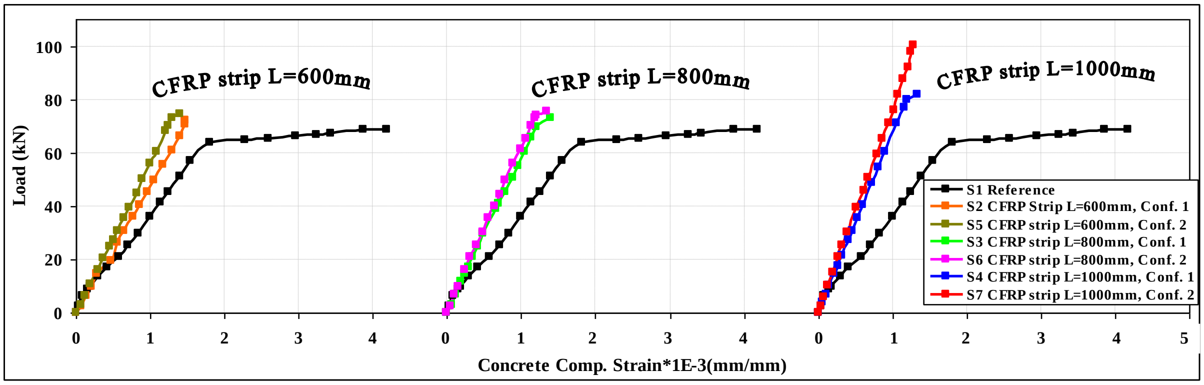

Figure 25: Effect of configuration of CFRP strip on load- concrete compressive strain curve

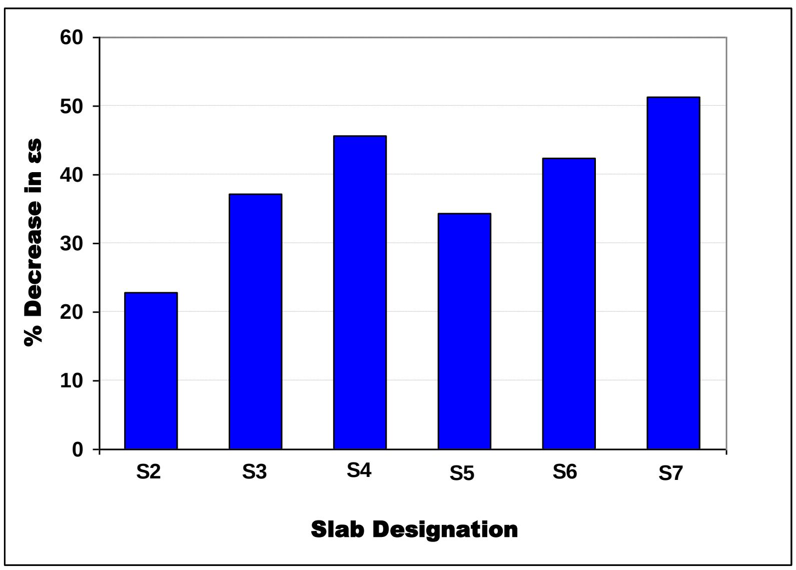

Figure 26: Percentage decrease in service concrete compressive strain due to strengthening by CFRP strip

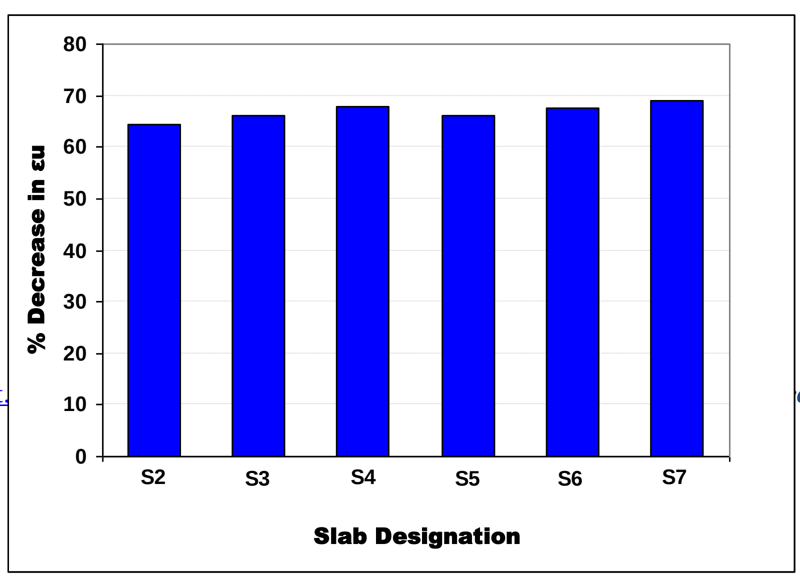

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Figure 27: Percentage decrease in ultimate concrete compressive strain due to strengthening by CFRP strip

Effect on Crack Patterns

The control slab specimen S1 was tested in order to have an unstrengthen slab to compare with CFRP strengthened slabs. The control slab behaved in an expected manner under flexural loading. It was gradually loaded until the initiation of cracking. The appearance of flexural cracks was first at 9.9kN within the maximum moment region between the two points of loads. As the load was increased further, several flexural cracks initiated in the tension face at intervals throughout the slab, gradually increased in number, became wider and moved upwards reaching the compression face of the slab. As the load was increased further, a loss of stiffness occurred and one mode of failure appeared which can be classified as flexural failure in tension by yielding of the steel reinforcement followed by crushing of concrete.

The strengthened slabs also showed similar behavior, but when the load reached yielding of steel, the CFRP strips contributed mainly in resisting the loads and increased the stiffness of the concrete slabs up to failure. The failure was usually recorded due to debonding of CFRP strip from the bottom face of slab specimens which was very sudden and the only indication of such failure was few popping sounds before debonding happened.

The test results of first cracking loads of slabs are presented in Table (6) and Figures (28, 29 and 30). When load is applied to these slab specimens, the first crack is formed at (14.4%, 20.1%, 23.4%, 21.1%, 28.4%, 36.2% and 30.0%) of the ultimate load of slab specimens (S1, S2, S3, S4, S5, S6 and S7), respectively.

The percentage increase in cracking load (P_{cr}) due to strengthening by CFRP strip is shown in a bar chart in Figures (31), the percentage decrease in first crack width at service (W_s) and ultimate (W_u) stage are shown in bar chart in Figures (32) and (33) respectively. Figures (34) to (40) illustrate crack patterns for all tested slabs.

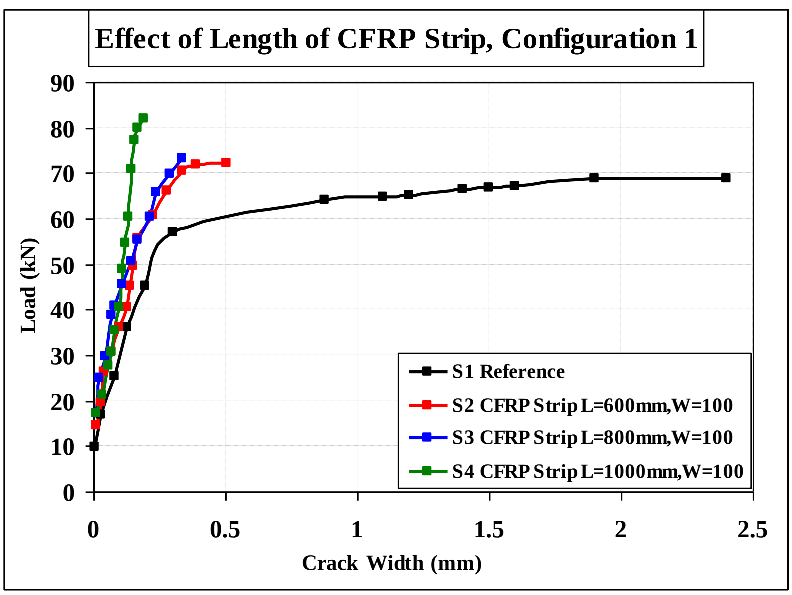

Figure 28: Effect of length of CFRP strip on load- crack width curve, configuration 1

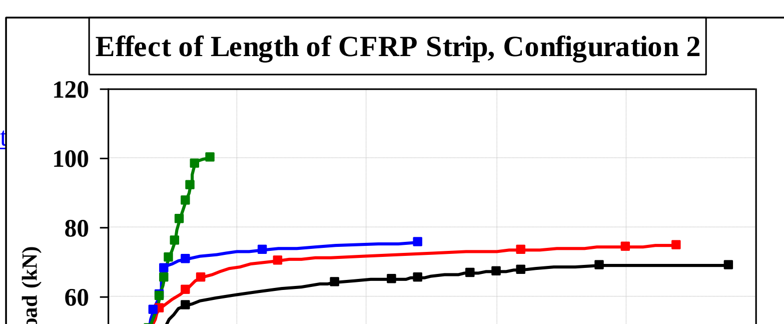

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Figure 29: Effect of length of CFRP strip on load- crack width curve, configuration 2

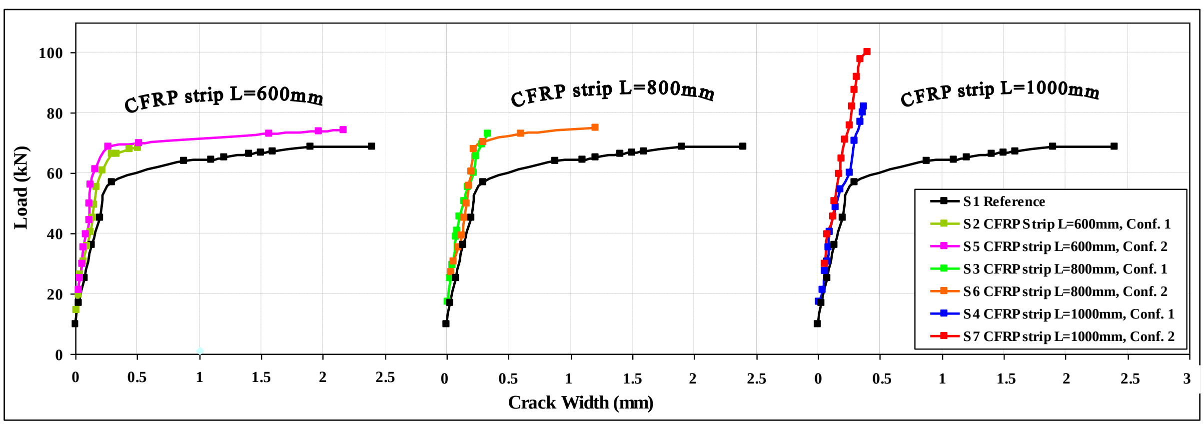

Figure 30: Effect of configuration of CFRP strip on load- crack width curve

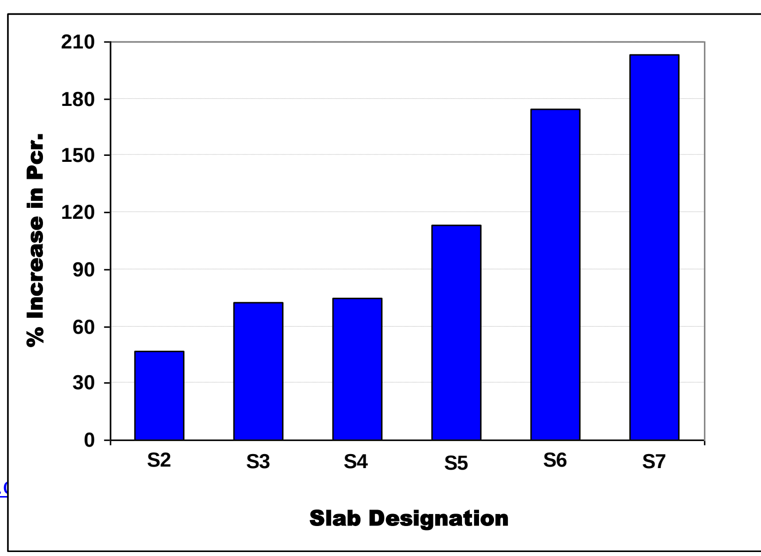

Figure 31: Percentage increase in cracking load due to strengthening by CFRP strip

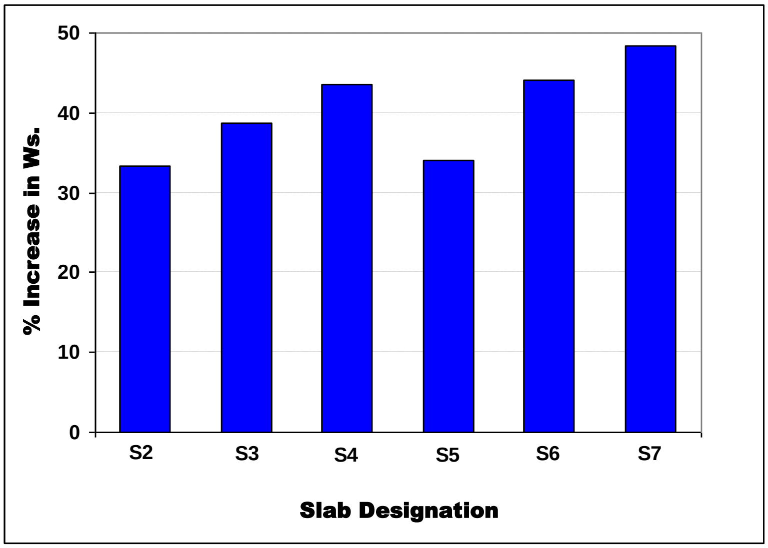

Figure 32: Percentage decrease in service crack width due to strengthening by CFRP strip

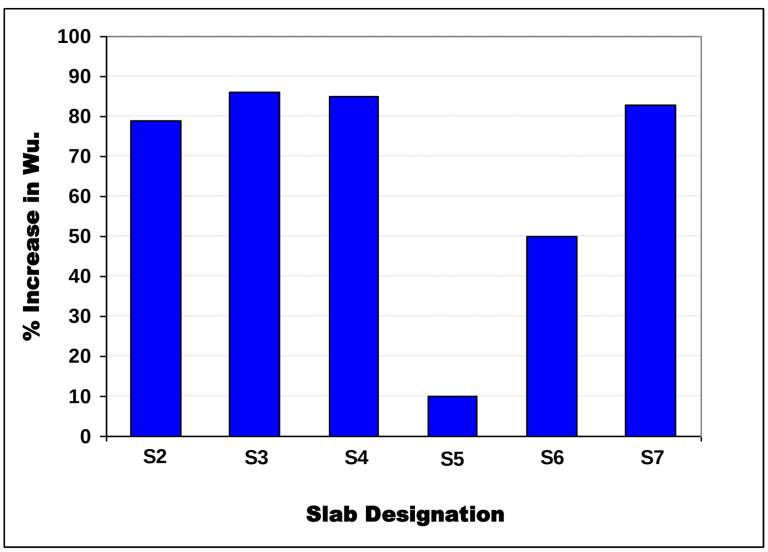

Figure 33: Percentage decrease in ultimate crack width due to strengthening by CFRP strip

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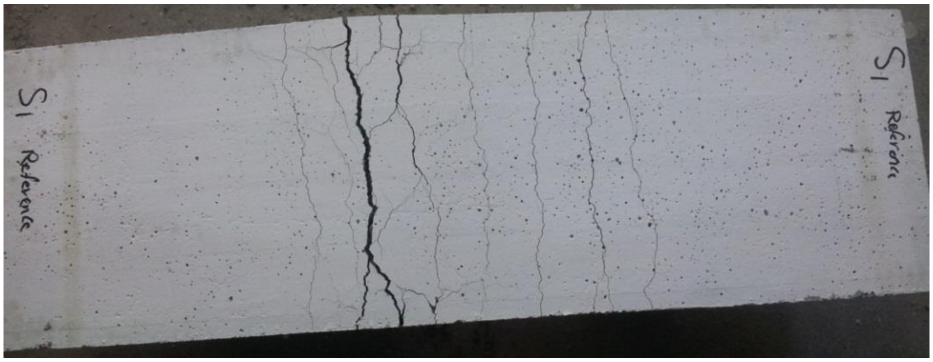

Figure 34: Crack pattern of control slab S1 (without strengthening)

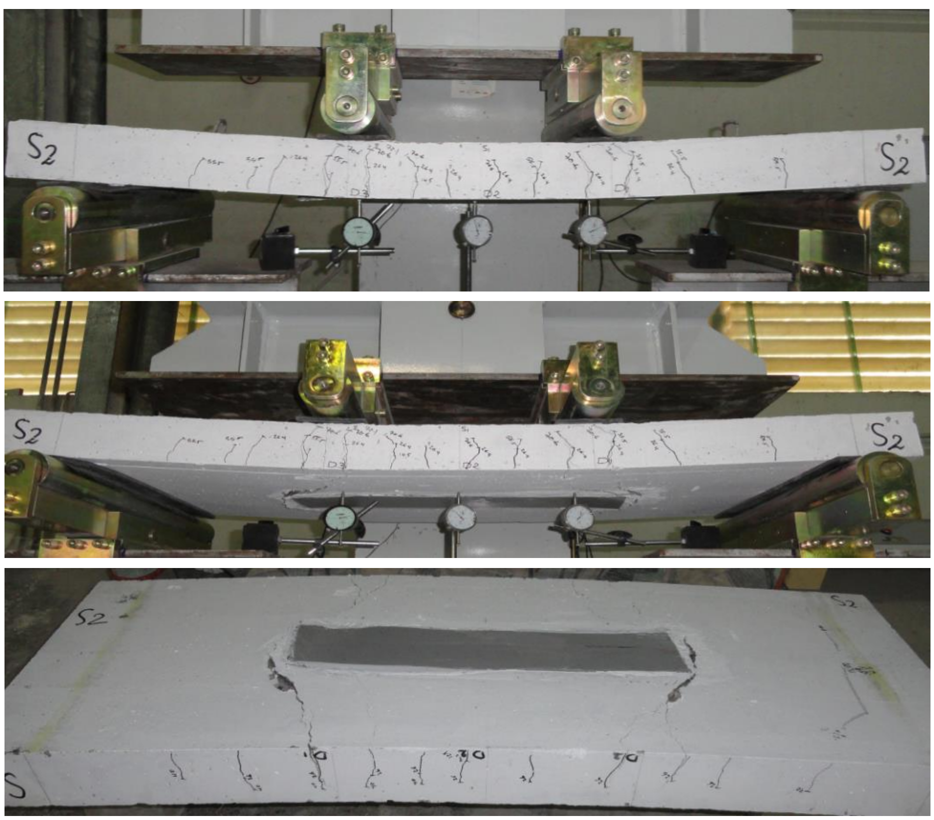

Figure 35: Crack pattern of strengthening slab S2

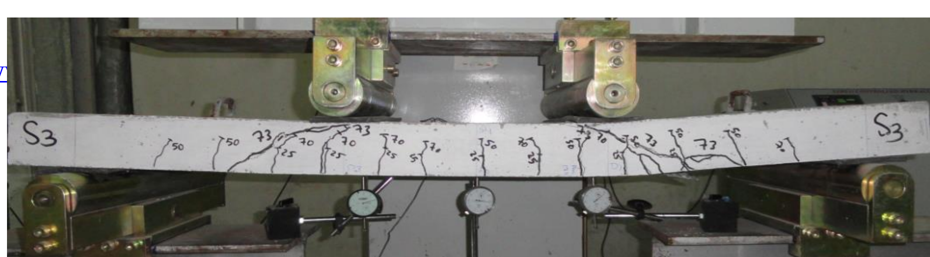

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Figure 36: Crack pattern of strengthening slab S3

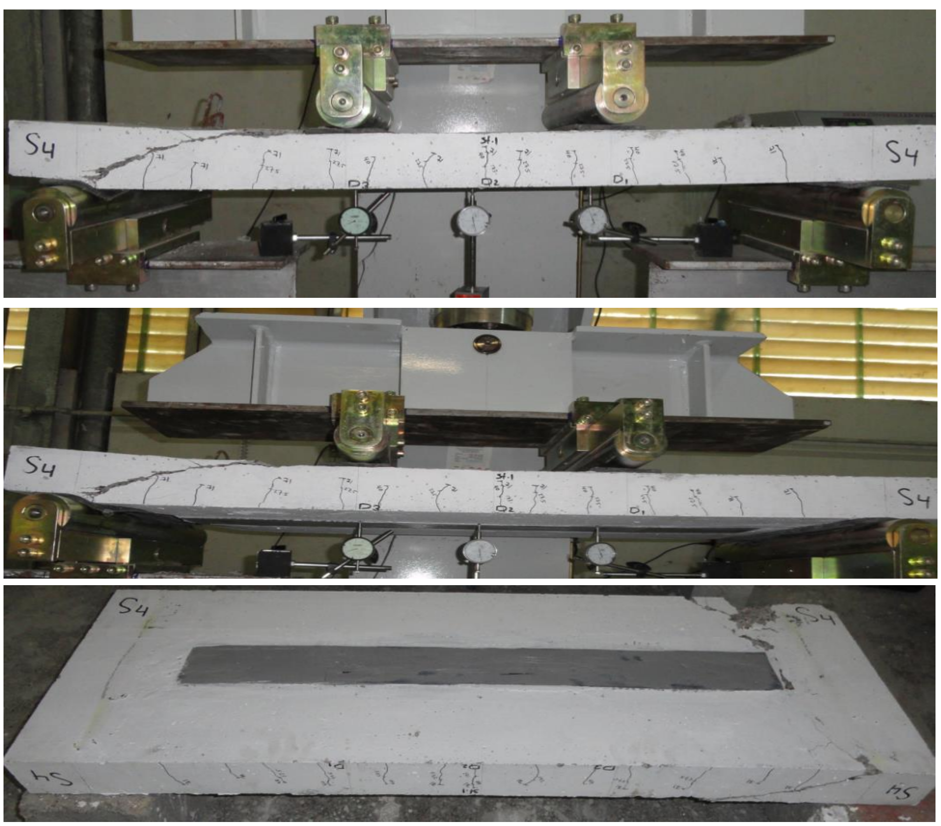

Figure 37: Crack pattern of strengthening slab S4

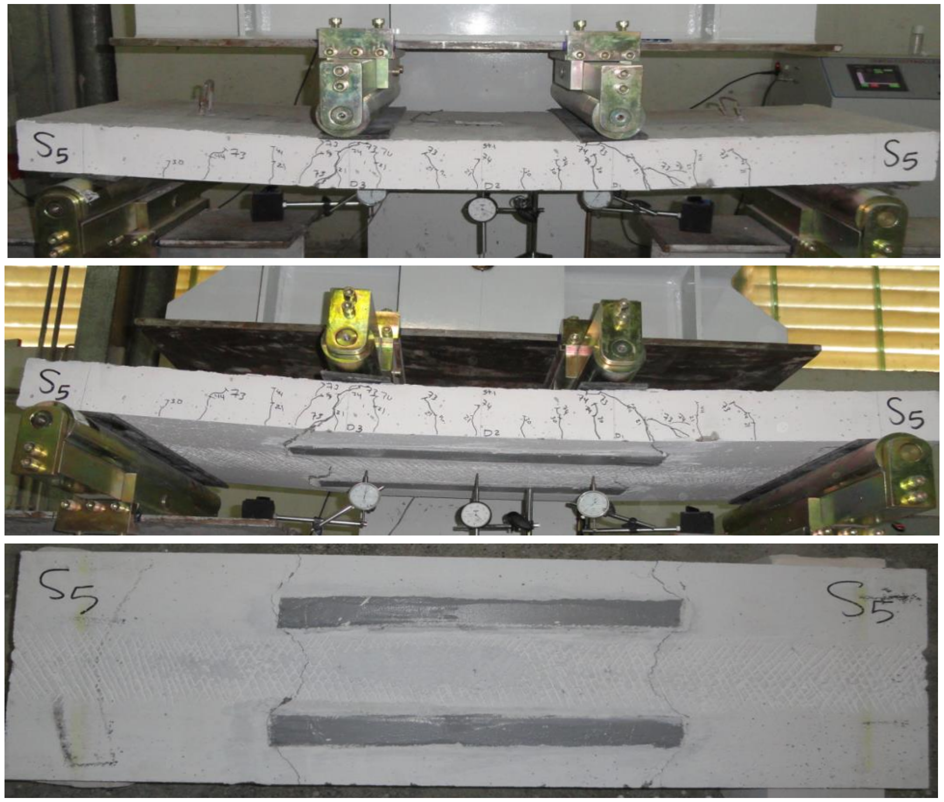

Figure 38: Crack pattern of strengthening slab S5

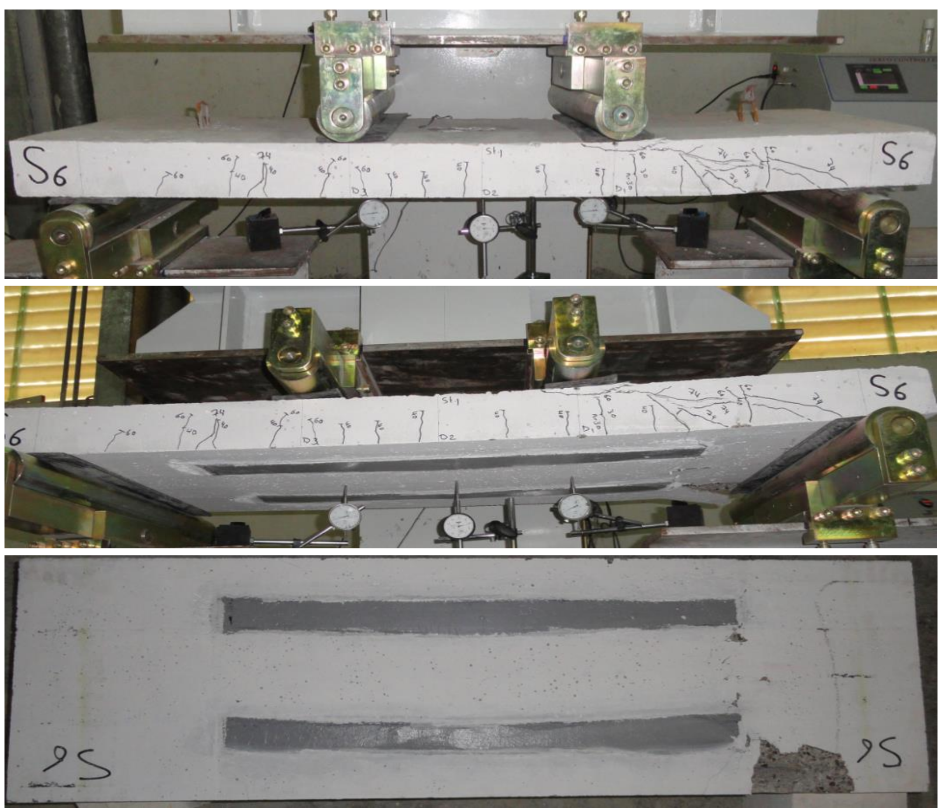

Figure 39: Crack pattern of strengthening slab S6

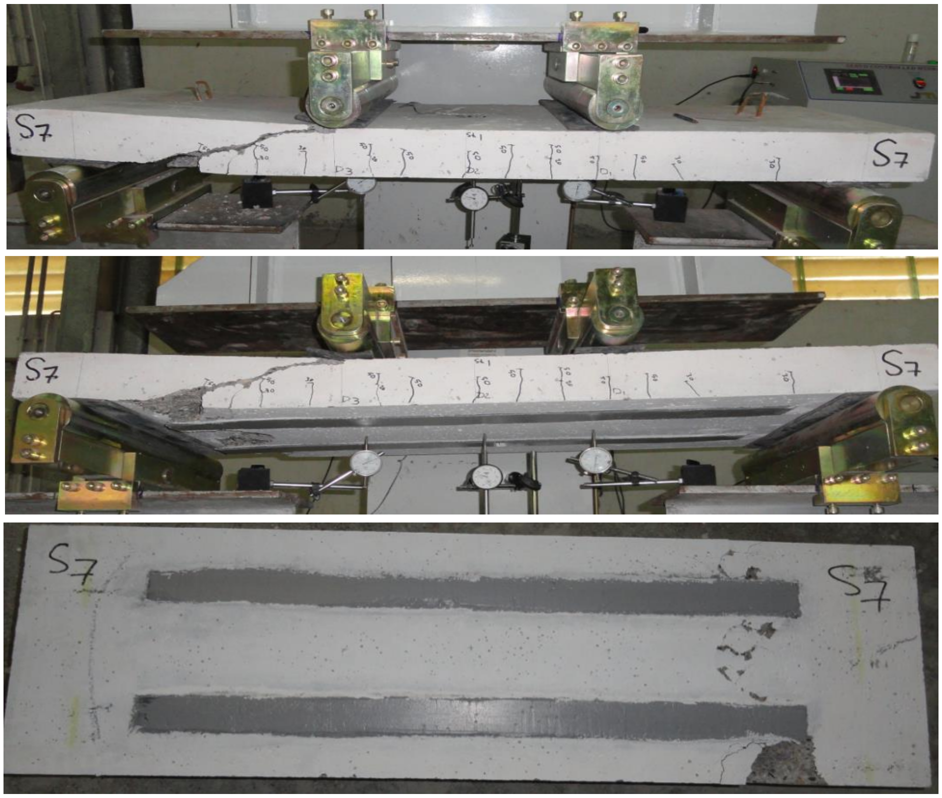

Figure 40: Crack pattern of strengthening slab S7

CONCLUSIONS

Based on the overall results obtained from the experimental work for the externally strengthened reinforced concrete slabs by CFRP strips, the following conclusions can be drawn as follows:

1. The externally strengthened reinforced concrete one-way slabs with bonded CFRP strips show a significant increase in ultimate loads capacity of the slabs, this increase is about (5% to 46%) compared with the unstrengthened control slab.
2. The external CFRP strips attached to the tension faces of reinforced concrete slabs increase the stiffness of the slabs at all stages of loading, and consequently reduce the service and ultimate deflection at corresponding loads, these decrease are about (32% to 43%) at service stage and about (46% to 73%) at ultimate stage, compared with the unstrengthened control slab.
3. The use of CFRP strips as external strengthening has a significant effect on crack pattern of the reinforced concrete one-way slabs by delaying the crack appearance and reducing the crack width, the increase in cracking loads is about (47% to 203%), and the reduced in crack width are about (32% to 48%) at service stage and about (10% to 86%) at ultimate stage, compared with the unstrengthened control slab.
4. The strengthening of the reinforced concrete slabs using CFRP strips show significant decreased in the concrete compressive strain. The decrease ranged from (23% to 51%) at service stage and about (64% to 69%) at ultimate stage compared with the unstrengthened control slab.
5. Strengthening using CFRP strips in form of two segments (configuration 2) showed superior structural performance in terms of cracking loads, ultimate load, deflection, concrete compressive strain and crack width, compared to the form of one segment of CFRP strips (configuration 1) with equivalent length and width.

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