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Strengthening of Hollow Core Prestressed Slabs Using CFRP Laminates.

By

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Abstract

Hollow core prestressed slabs is one of the commonly used floor systems, especially for structures with large spans. This is due to the fact that it offers minimum weight for the concrete floor in addition to speed of construction. Upgrading of these slabs is required to increase their ultimate carrying capacity and/or their serviceability. This paper presents an experimental program conducted to study the flexural behavior of hollow core prestressed slabs strengthened by carbon fiber reinforced polymer, (CFRP), laminates. The program consists of testing nine precast slabs with 4.8 m span, 200 mm thickness and 1.2 m width. The slabs were tested under monotonic four-points loading up to failure. The variables in the test program were: type of CFRP laminates (strips with 1.2 mm thickness and sheets with 0.38 mm thickness) and reinforcement ratio of CFRP laminates. Different anchorage systems are suggested to enhance the bond strength between the concrete and CFRP. An analytical model based on the mechanical characteristics of both the concrete and

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CFRP was adopted to predict the behavior of slabs. Different recommendations and design guidelines for hollow core prestressed slabs strengthened by CFRP laminates are introduced.

KEY WORDS:

Prestressed slabs ,Strengthened ,CFRP laminates ,Anchorage ,Analysis ,Testing.

1. Introduction:

Hollow core prestressed slabs are one of the most commonly used structural systems to cover large spans in both residential and industrial structures. This is mainly due to the fact that it reduces the time of construction and offers a cost-competitive alternative solution compared to other systems. Strengthening of these slabs may be required for several reasons. Among those reasons, change of the function of the structure and the high demand in use can lead to overloading of the structure beyond its structural capacity. Misuse, design defects and absence of maintenance are factors that could reduce the life expectancy of structures. Moreover, carbonation of concrete due to exposure to carbon dioxide gas, poor quality of construction, and fire are common reasons of deterioration of those structures.

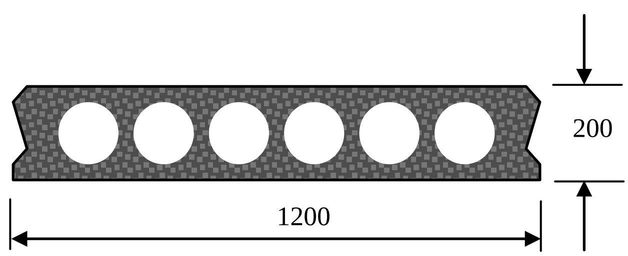
Carbon fiber reinforced polymers, (CFRP), laminates were successfully applied in different projects for strengthening concrete structures (Hosny and Abdelrahman 2002). CFRP laminates are characterized by their high tensile and fatigue strength as well as their durability since they are corrosion-free. They are also characterized by ease of application due to their lightweight, which is less than one fifth that of steel. Use of FRP is more feasible than conventional techniques for strengthening, for specific projects, especially if long life span and less maintenance are accounted for.

This paper introduces an experimental study to strengthen prestressed hollow core slabs using CFRP laminates. Nine slabs with 4.8-meter span were tested under flexural loading using four-points load configuration. The slabs were strengthened by CFRP strips and sheets glued to the bottom surface of the slabs. The varying parameters were the type of the CFRP laminates, and the CFRP reinforcement ratio. Different mechanical anchorage systems were used at the end of the laminates to improve the bond between the laminates and the slabs. The slabs were analyzed using the strain compatibility approach and their load-deflection behavior was predicted. Good agreement between the predicted and measured behavior of the slab was observed. Different recommendations and design guidelines for strengthening prestressed concrete slabs are introduced in the paper.

2. THE EXPERIMENTAL PROGRAM:

The experimental program was designed to examine the flexural capacity as well as the behavior of hollow core prestressed concrete slabs strengthened by CFRP laminates. The specimens were 1200 mm wide and 200 mm deep with an overall length of 5.0 meter. Each slab had 43 % voids and pretensioned by four 7-wire steel strands of 10 mm diameter and a reinforcement ratio of 0.223%. The span was kept constant as 4.8 meter with an overhang of 100 mm at each end. The specimens were simply supported and loaded using two concentrated loads 800 mm apart, as shown in Figure 1. The slabs were loaded using a hydraulic jack and a calibrated load cell of 600 kN capacity. The load was applied under a stroke control at a rate of 1.5 mm per min up to the cracking level and increased to a rate of 2.0 mm per minute up to failure.

A total of nine specimens were tested; the first slab was a control specimen, while the other specimens were divided into two series. The slabs of the first series were strengthened with CFRP strips with 50 mm width and 1.2 mm thickness. The varying parameters in this series were the number of strips and the mechanical anchorage at the end of the strips as given in Table 1. The CFRP strips in specimen (S3) was anchored by embedding the strips in a groove in the slab and filled by epoxy. Another anchorage was provided for specimen (S4) by adding steel plates bolted to the slab at the ends of the strips. In the second series, four slabs were strengthened with CFRP sheets of 305 mm width and 0.38 mm thickness. The number of the sheets varied from one to three. The CFRP laminates were applied to the concrete surface according to the specifications of the manufacturer (Sika-Egypt 1998).



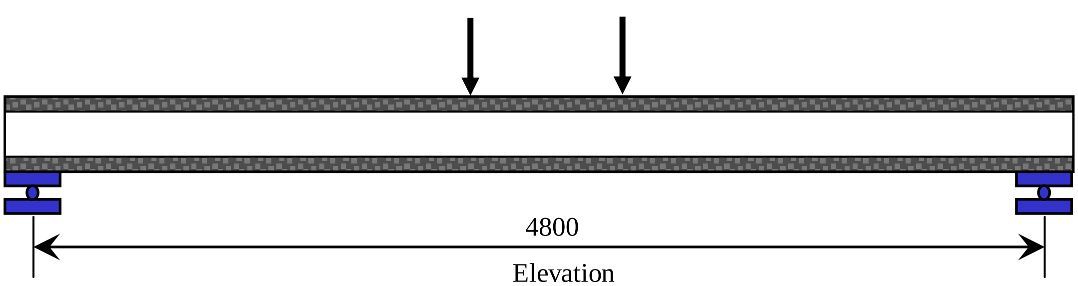
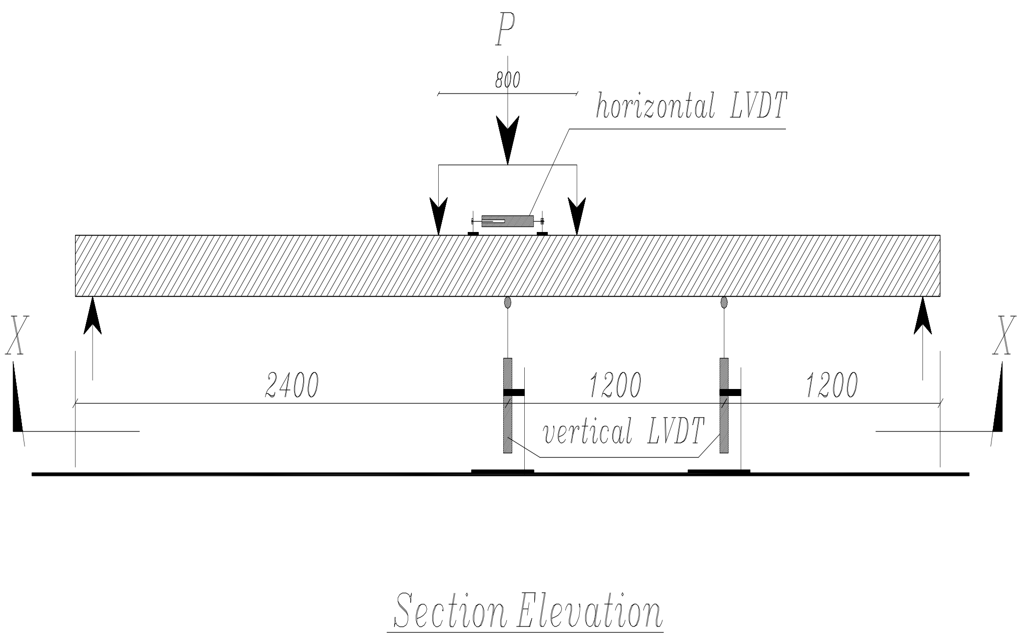


Figure 1a. Test set-up.



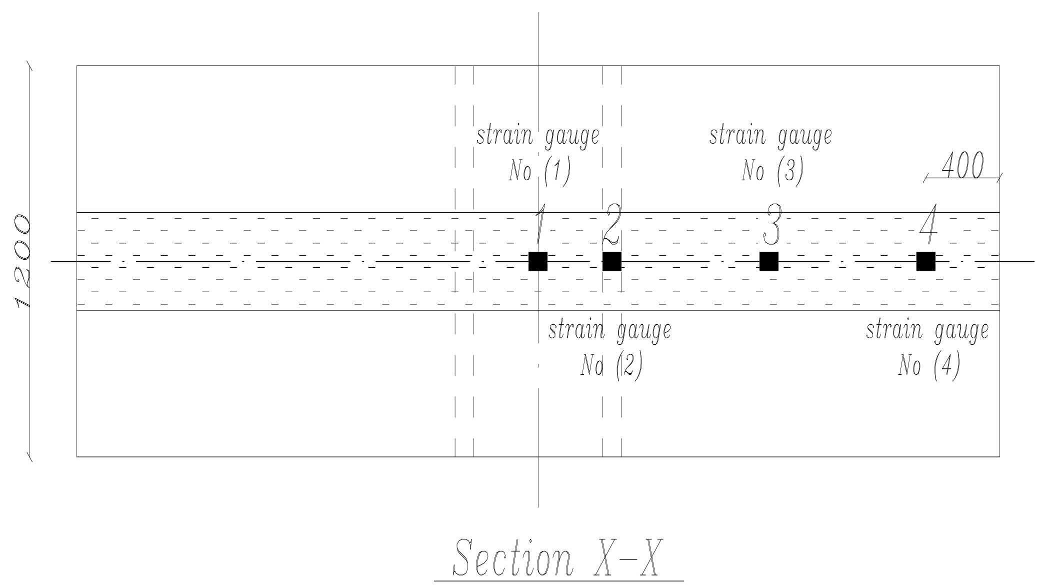


Figure 1b. Test set-up.

Table 1 Details of test specimens.

Specimen	Type of CFRP	No. of laminates	CFRP Ratio (%)	Anchorage of laminates
S1	Control			
S2	Strips 50 x 1.2 mm.	1	0.061	No anchorage
S3		1	0.061	Epoxy anchor
S4		1	0.061	Steel plates
S5		2	0.122	No anchorage
S6	Sheets 305x0.38 mm.	1	0.04	No anchorage
S7		1	0.04	Steel bar
S8		2	0.08	No anchorage
S9		3	0.12	No anchorage

Different instrumentations were applied to the prestressed slabs to measure the deflection at different locations along the span and the compressive strain in the concrete. Strain gauges were also applied to CFRP to measure the tensile strain along the laminates.

2.1 Material Properties:

The concrete used for casting the slabs had average compressive cube strength of 25 and 36 MPa at time of release of the prestressing force and after 28 days, respectively. Four 7-wire low relaxation steel strands of 10 mm diameter were used to prestress each slab. The prestressing steel had tensile strength and modulus of 2027 MPa and 206 GPa, respectively. The strands were pretensioned to 75% of their ultimate tensile strength. The CFRP strips had a tensile strength and modulus of 2800 MPa and 165 GPa, respectively, while the CFRP sheets had a tensile strength and modulus of 715 MPa and 61 GPa, respectively. The epoxy used to bond the CFRP laminates to the concrete surface had tensile and bond strength of 30 and 4 MPa, respectively.

3 TEST RESULTS:

Four modes of failure were observed: rupture of the prestressing steel strands for control specimen, debonding of CFRP strips for specimens S2, S3, S4 and S5, rupture of CFRP sheets for specimens S6, S7, and S8 and crushing of concrete for specimen S9, as given in Table 2. For the specimens that failed due to debonding of the CFRP strips, the load-deflection of the strengthened slabs was linear up to cracking load and nonlinear after cracking up to failure as shown in Figure 2. The observed nonlinear behavior of the slabs after cracking is mainly attributed to the bond slip of the strips. For other specimens with CFRP sheets, the behavior after cracking was linear until failure, as shown in Figure 3. This is attributed to the linear behavior of the sheets. It can be also seen from the figure that after rupture of the CFRP sheets, the load-deflection behavior of the slab matches that of the control specimen.

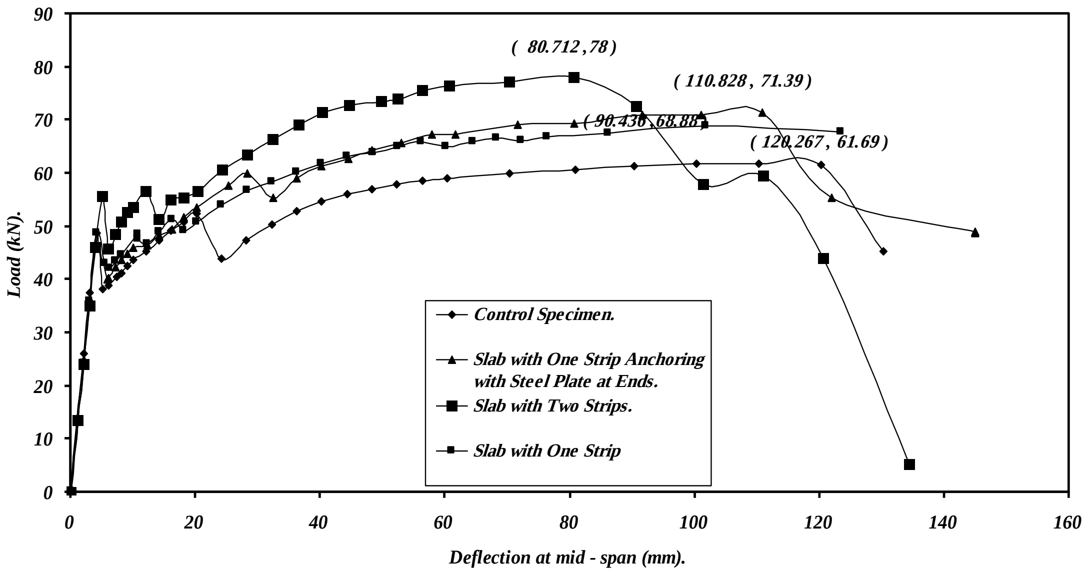


Figure 2 Load-deflection of slabs with CFRP strips.

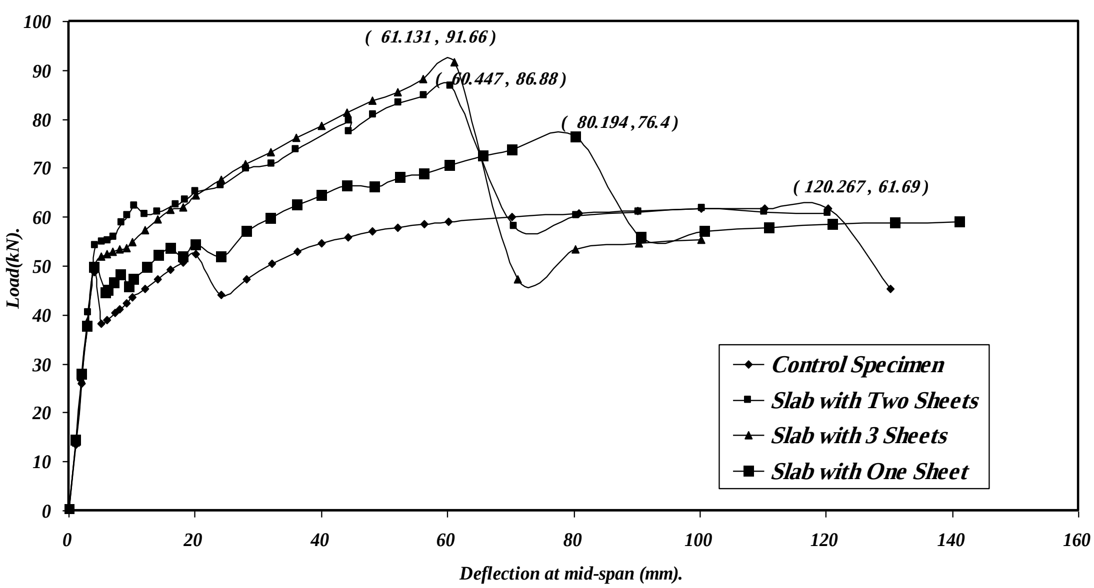


Figure 3 Load-deflection of slabs with CFRP sheets.

The test results indicate that the used anchorages of the CFRP strips could not prevent the bond failure. The effect of the anchorages on the failure load of the prestressed specimens was not significant. The ultimate load for the strengthened slabs using one strip with and without anchorages ranged from 68.8 to 71.4 kN, compared to 61.7 kN for the control specimen. The strengthened slab with two strips, failed at 78.0 kN. The bond failure mode was not observed for slabs with CFRP sheets as shown in Figure 4a and Figure 4b . Due to the large contact area between the prestressed slabs and the CFRP sheets.

Failure of the slabs with one and two CFRP sheets was due to rupture of the sheets at a load level ranging from 71.4 to 86.9 kN, while the slab with three sheets failed by crushing of the concrete at a load level of 91.7 kN. This indicates that the tensile strength of the sheets was fully utilized. The flexural capacity of the slab S5 with two strips was less than that of S8 with two sheets despite in the fact that S5 had a higher CFRP reinforcement ratio than S8. This is explained by the better bond characteristics of CFRP sheets compared to that of the strips due to the larger bonded area of the sheets. This led to a change in the failure mode from debonding of the strips to rupture of the sheets.

The cracking and failure loads, number of cracks in the constant moment zone, as well as failure modes of the slabs are shown in Table 2.

Table 2 Test Results.

Speci-men	P_{cr} (kN)	P_{ult} (kN)	Net tensile strain	Stabilized crack load	Number of cracks(1)	Mode of failure
S1	48.7	61.7	N/a(2)	52.0	2	RS(3)
S2	49.7	68.8	N/a	61.0	3	B(4)
S3	48.5	68.9	N/a	59.8	3	B
S4	52.0	71.4	N/a	59.0	3	B
S5	53.7	78.0	N/a	59.9	3	B
S6	52.1	76.4	0.012	66.0	6	RC(5)
S7	52.5	76.4	N/a	65.5	6	RC
S8	54.1	86.9	0.011	69.0	5	RS & RC(6)
S9	55.0	91.7	0.013	73.8	6	C(7)

1 Cracks in the constant moment zone
2 Not available
3 Rupture of steel strands
4 Bond failure of CFRP laminates
5 Rupture of CFRP laminates
6 Rupture of one steel strand occurred at a load level of 79.0 kN followed by rupture of CFRP laminates at 86.9 kN.

7 Crushing of concrete

3.2 Serviceability of slabs:

It can be seen from Table 2 that increasing the CFRP reinforcement ratio increased the cracking load (see S2 and S5, also S6, S7 and S8). The cracking load increases from 48.7 kN for the control specimen up to 55.0 kN for the strengthened slabs. This coincides with the findings of Bouhicha et al. (2003) of tested concrete beams strengthened by plate bonding. He concluded that the stress intensity factor is reduced at the crack tip for strengthed beams; moreover, he concluded that the crack width was reduced by 30 to 40 %.

The number of cracks in the constant moment zone increased from two for the control specimen up to six for slabs with CFRP sheets. The number of cracks in the constant moment zone was only three for slabs with CFRP strips. This is attributed to occurrence of bond slip of the strips during loading of the slabs.

The load at the stabilized crack pattern increased from 52.0 kN for the control specimen up to a load level ranging from 59.0 to 61.0 kN for slabs strengthened with CFRP strips and a load level ranging from 65.5 to 73.8 kN for slabs with CFRP sheets, as shown in Table 2. The load at the stabilized crack is higher for specimens with CFRP sheets compared to the specimens with strips due to the better bond characteristics for the sheets.

The deflection of the strengthened slabs after cracking was less than that of the control specimen. This gives better performance if the slabs were designed as partially prestressed, i.e. allowing for cracks under service loading condition.

From the behavior of the slabs under service loading conditions, it can be concluded that the performance of the strengthened slabs was better compared to the control specimen. This is especially true for slabs strengthened with CFRP sheets. This conclusion coincides with the findings of Hassan and Rizkalla (2002), where bridge decks strengthened by CFRP sheets had better behavior than specimens with CFRP strips.

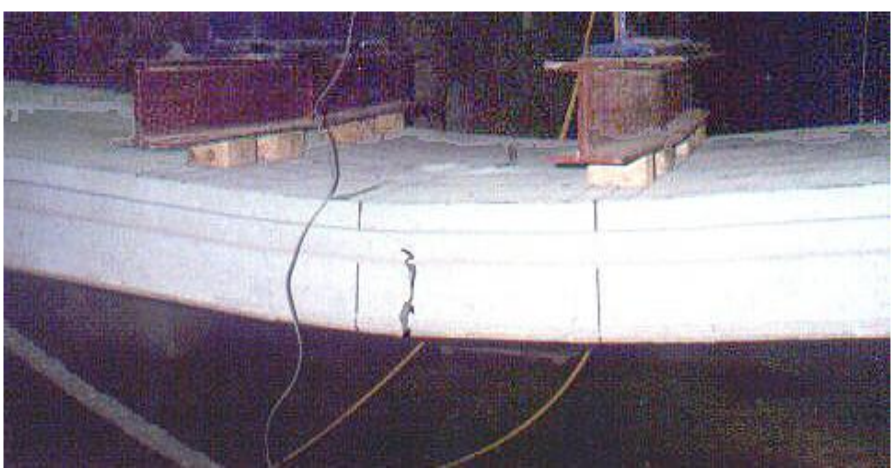


Figure. 4a Failure modes of slabs strengthened with CFRP strips.

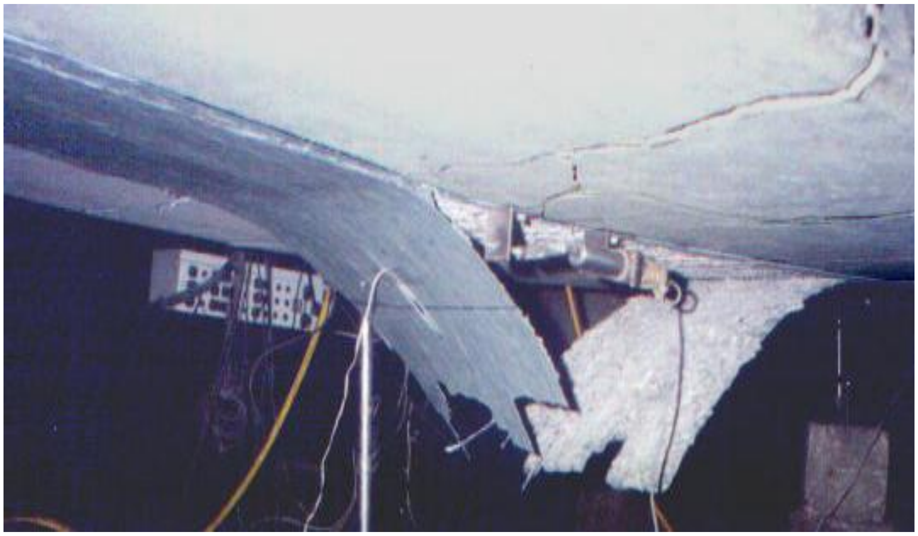


Figure. 4b Failure Modes of slabs strengthened with CFRP Sheets.

3.3 Ductility:

The ductility of the strengthened slabs was evaluated according to the recommendations of the ACI Committee 440 (2002). The committee states

> *"To maintain a sufficient degree of ductility, the strain level in the steel at the ultimate limit state should be checked. Adequate ductility is achieved in the strain at the point of concrete crushing or failure of the FRP, including delamination or debonding, is at least 0.005, according to the definition of a tension-controlled section".*

The minimum net tensile strains of the slabs are reported in Table 2. It can be seen that ductility of the strengthened slabs is maintained and the net tensile strains at slab failure are well above 0.005. The maximum deflection of the strengthened slabs measured at the maximum load ranged from L/38 to L/80, compared to L/40 for the control slab, where L is the span of the specimen. This excessive deflection will give enough warning before failure. It can be also concluded that increasing the CFRP reinforcement ratio decreased the ductility of the slabs.

4.Analytical study:

The slabs were analyzed using strain compatibility approach accounting for the non-linear behavior of concrete and steel. The stress-strain relationship of the concrete in compression was assumed to be parabolic. Complete bond was assumed between the steel and concrete. CFRP was modeled using a linear stress-strain approach and complete bond between the concrete and CFRP. Moment-curvature relationship of the concrete section was calculated. Deflection of the slabs was calculated using integration of the curvature along the spans. The predicted deflection of the control slab is overestimated, as shown in Figure 5, due to the fact that tension stiffening was ignored in the analysis. The predicted deflection of the slab (S2) with one CFRP strip without an anchorage was underestimated, as shown in Figure 6, due to the bond slip of the CFRP, which was not accounted for in the analytical model. The slip of the strips started at low load levels and increased with increasing applied load. Predicted deflection of slabs (S3 and S4) with one CFRP strip anchored at the ends was in good agreement with the observed values.

The predicted cracking load ranged from 47.3 to 47.8 kN due to the slight increase in the transformed section properties of the slabs. This is different from the measured values, where an increase of up to 13% was observed in the cracking load. This could be due to the reduction in the stress intensity at the crack tip in the strengthened slabs.

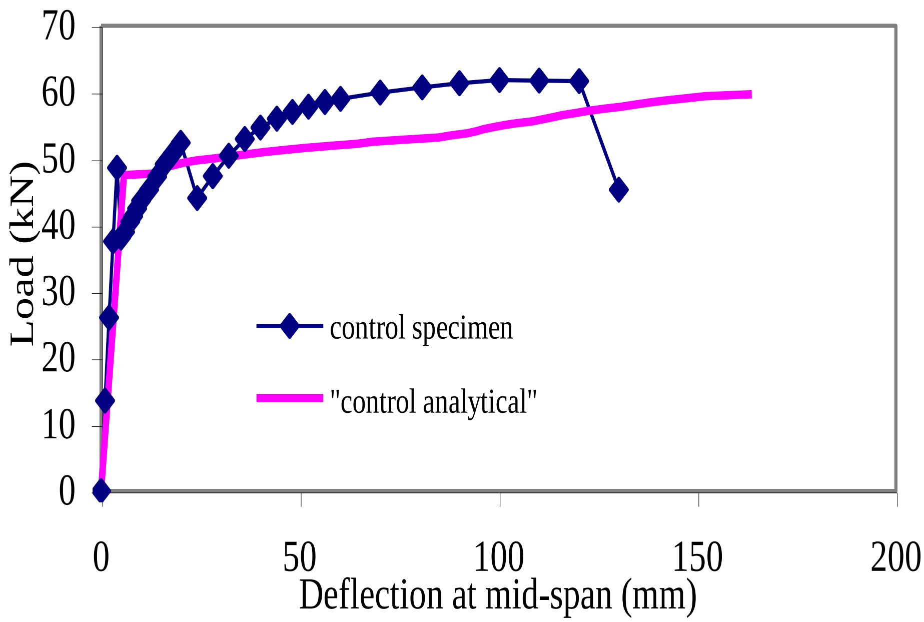


Figure 5 Load-deflection of the control slab.

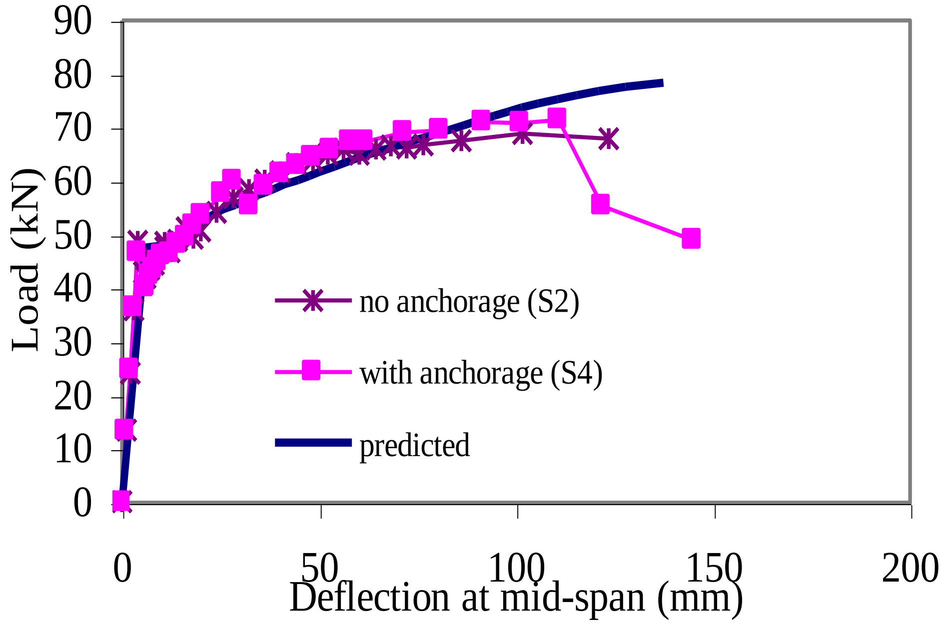


Figure 6 Load-deflection of the slabs with one CFRP strip.

Table 3 shows the predicted cracking and ultimate loads as well as the predicted failure mode of the slabs. For slabs strengthened by CFRP strips, the bond failure mode was not predicted since it was assumed full bond between the laminates and the concrete. Therefore, the predicted ultimate loads were higher than the observed values by 9 to 32%.

It can be also seen that the predicted and observed failure modes of the slabs with CFRP sheets (S6, S7, and S8) are the same due to rupture of the laminates. The predicted ultimate loads were in good agreement with the measured values. The predicted failure mode of slab S9 was due to rupture of the laminates, while the observed mode was due to crushing of concrete. This suggests that the assumed tensile strength and modulus of the sheet reported by the manufacturer are conservative and its actual tensile strength is higher than 715 MPa.

Table 3 Predicted test results.

Speci men	Predicted values			$P_{cr(exp)}$/ $P_{cr(pred.)}$	$P_{ult(exp)}$/ $P_{ult(pred.)}$
	P_{cr} (kN)	P_{ult} (kN)	Mode of failure		
S1	47.3	59.7	RS(1)	1.03	1.03
S2	47.5	78.5	RC(2)	1.05	0.88
S3	47.5	78.5	RC	1.02	0.88
S4	47.5	78.5	RC	1.09	0.91
S5	47.6	114.9	RC	1.13	0.68
S6	47.5	67.3	RC	1.10	1.13
S7	47.5	67.3	RC	1.11	1.06
S8	47.6	81.8	RC	1.14	1.06
S9	47.8	94.5	RC	1.15	0.97

1 Rupture of steel strands
2 Rupture of CFRP laminates

5.CONCLUSIONS:

Nine hollow core prestressed concrete slabs were strengthened in flexure using CFRP laminates. Two types of the laminates were used; CFRP strips of 1.2 mm thickness and CFRP sheets of 0.38 mm. The following conclusions could be drawn as follows:

1. The cracking load of the strengthened slabs increased by up to 13%. This could be due to reduction of the stress intensity factor in the strengthened slab.
2. Use of CFRP sheets is more efficient than CFRP strips due to the better bond characteristics of the sheets. The ultimate loads increased by values up to 26 and 49%, for slabs with strips and sheets, respectively.
3. Adding end anchorages for the CFRP strips could not prevent the bond failure; however, it delayed the failure of the slabs.
4. The number of cracks and the loads, at which the cracks, were stabilized increased for slabs with CFRP sheets due to its good bond behavior.
5. Ductility of the strengthened slabs satisfies the limits provided by ACI Committee 440, which specifies a minimum value of 0.005 net tensile strain at failure.
6. The deflection of the slabs with CFRP could be predicted reasonably well; however, modeling of the bond between the laminates and the concrete should be further investigated.

6.REFERENCES

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