Ultimate strength prediction for reinforced concrete slabs externally strengthened by fiber reinforced polymer (FRP)

Abstract

This paper presents the potential use of externally bonded fiber reinforced polymer (FPR) systems to upgrade reinforced concrete slabs deficient in flexural strength. A total of five slabs, each having 500 mm width, 125 mm thickness, and 1530 mm length, were cast and tested to failure under four-point bending. Two slabs were reinforced with three number of 10 mm tor steel bars at the tension side that corresponds to 0.38% steel reinforcement ratio. One slab was used as a control whilst the other slab was strengthened with fiber reinforced polymer (FRP). Other three slabs were reinforced with four numbers of 6 mm mild steel bars at the tension side that corresponds to 0.18% steel reinforcement ratio. One slab was used as a control specimen while the other two slabs were strengthened with different arrangement of fiber reinforced polymer (FRP). In the experimental stage, the influences of FRP on the slabs were analyzed by studying their behaviour at failure.

Keywords: Flexural, Reinforced concrete slabs, Strengthening, Fiber reinforced polymer (FRP)

1. Introduction

Strengthening of reinforced concrete (RC) structures is often required due to design stage errors, construction stage errors, inadequate maintenance, over loading at service stage, accidental damages and reduction of capacity due to aging and environmental effect. Some sort of a upgrading is required for those structures to overcome the problem. A large number of strengthening techniques are available in the world and are being used worldwide to overcome such problems. Some of the commonly used strengthening techniques are section enlargement, steel plate bonding, sprayed concrete, jacketing method, external post tensioning, Fiber Reinforced Polymer (FRP) bonding. Although these techniques can effectively increase the element's load carrying capacity, they are often susceptible to corrosion damage, which results in failure of the strengthening system. According to Tamer EM and Khaled S (2008), among those, the application of Fiber Reinforced Polymer (FRP) is a non-corrosive innovative strengthening system, which has the potential for extending service lives of RC structures and reducing maintenance costs.

Fiber Reinforced Polymer (FRP) can be used for the strengthening or retrofitting of existing concrete structures to resist higher design loads, correct deterioration-related damage. According to Tarek HA and Yousef AS (2001), repair with externally bonded FRP reinforcement is a highly practical strengthening system, because of ease and speed of installation, efficiency of the structural repair and corrosion resistance of the materials. The application of FRP creates minimal modification to the geometry, aesthetics and utility of the structure. Several studies on the behaviour of reinforced concrete slabs strengthened with FRP composite sheets provided valuable information regarding the strength, deformation, ductility and long-term performance of the FRP strengthening systems. Accoring to Sujeeva S (2002), the advantages of using FRP include lightweight, ease of installation, minimal labour costs, higher strength-to-weight ratio, higher stiffness-to-weight ratio, higher corrosion resistance and durability.

This paper presents the potential use of externally bonded fiber reinforced polymer (FPR) systems to upgrade reinforced concrete slabs deficient in flexural strength. This aims a confirmation to the effectiveness of using FRP in repair and rehabilitation of reinforced concrete slabs.

2. Experimental study

Experimental investigation was carried out on five slab specimens reinforced with tor steel bars (f_y = 460 N/mm^2), mild steel bars (f_y = 250 N/mm^2) and different arrangement of fiber reinforced polymer (FRP). The specimens were tested under four point bending.

2.1 Slab specimens

In the Experimental program five slabs of length 1530mm, and a cross-section of 500mm width × 125mm depth were cast with two types of steel bars. The clear span was 1350 mm. Three slabs were singly reinforced at tension side by four numbers of 6 mm mild steel bars and the other two slabs were singly reinforced at tension side by three numbers of 10 mm tor steel bars with a concrete clear cover of 25 mm. This corresponded to a steel reinforcement ratio of about 0.18% and 0.38% respectively. For the strengthened slabs, Carbon Fiber Reinforced Polymer (CFRP) strips having a width of 200 mm and a thickness of 1 mm was bonded to the tension face of the slab with two different arrangements (TS1 & TS2), which corresponded to a CFRP reinforcement ratio of about 0.32% and 0.64%. Figure 1 shows a schematic of a typical test specimen with loading arrangement.

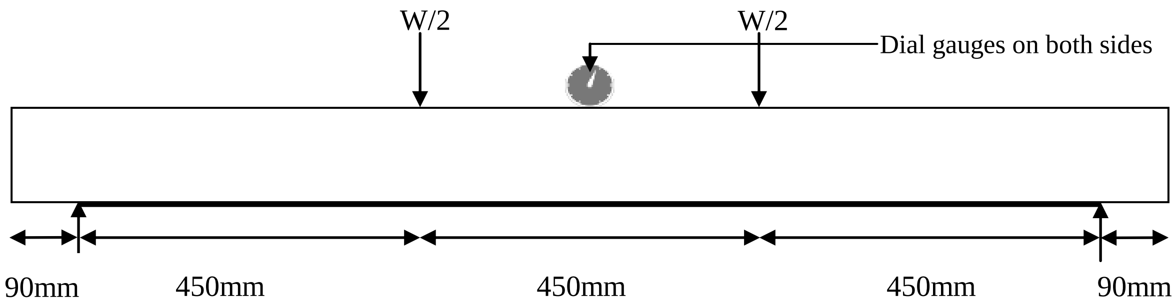

Figure 1: Slab loading pattern

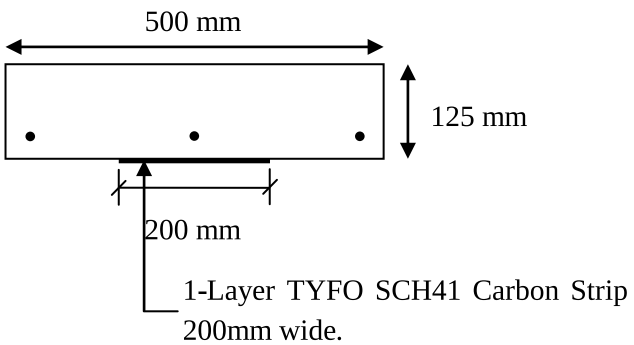

Figure 2: T10 – TS1 Cross section

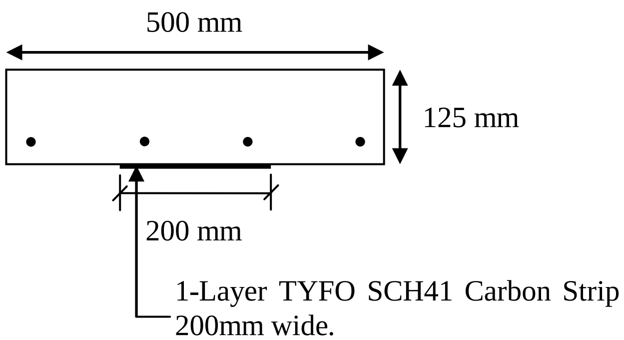

Figure 3: R6 – TS1 Cross section

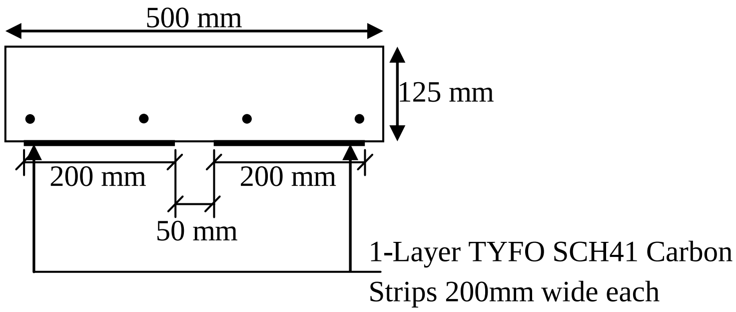

Figure 4: R6 – TS2 – Cross section

2.2 Test matrix

The test matrix is given in Table 1. A total of five slabs were used in the present study. Two slabs were used as control specimens whilst the other three slabs were strengthened with CFRP strips as follows. As the first arrangement, one CFRP strip bonded to centre of tension face of the slabs, had 10 mm tor steel bars and 6 mm mild steel bars. As the second arrangement, two strips of CFRP bonded to tension face of the slab, had 6 mm mild steel bars.

Table 1: Test Matrix

Specimen	*Longitudinal Reinforcement*	*No. of CFRP strips*	*CFRP Reinforcement Ratio (%)*
T10 – Control	*3 T10 @ 225mm*	--	--
T10 – TS1	*3 T10 @ 225mm*	1	*0.32*
R6 – Control	*4 R6 @ 175mm*	--	--
R 6 – TS1	*4 R6 @ 175mm*	1	*0.32*
R 6 – TS2	*4 R6 @ 175mm*	2	*0.64*

2.3 Material properties

All the slabs were cast with normal weight concrete with a maximum aggregate size of 18 mm. The concrete had an average compressive strength of 38 N/mm^2 and modulus of elasticity of 29 kN/mm^2 at the time of testing. A concrete cover of 25 mm was used for the main reinforcement. The characteristic strength of tor and mild steel reinforcement was 460MPa and 250MPa, respectively. The CFRP strip was TYFO SCH41 Carbon Strip. Properties of CFRP composite strips and the Epoxy are given in Table 2 and Table 3.

Table 2: Specifications of CFRP

Typical dry fiber properties	
Tensile Strength	*3.79 GPa*
Tensile Modulus	*230 GPa*
Ultimate Elongation	*1.7%*
Density	*1.74 g/cm3*
Weight per sq.yd.	*644 g/m2*

Table 3: Specifications of Epoxy Material

Properties	*Typical Test Values*
UTS	*72.4 MPa*
Tensile Modulus	*3.18GPa*
Elongation Percentage	*5.0%*
Flexural Strength	*123.4 MPa*
Flexural Modulus	*3.12 GPa*

2.4 Test set-up and instrumentation

All slabs were tested under four-point bending with an effective span of 1350 mm as shown in Figure 1. Load was applied monotonically at the mid-span of the slab using a hydraulic jack and a proving ring having a capacity of 100 kN. A spreader plate was used to transfer the load to the slab through two loading points placed at the ends of the middle third of the slab span. The slab was supported on two steel rods, 1350 mm apart on centre. Two dial gauges were placed on the mid-points of both longitudinal directions on the top surface, mid span of the slab to measure the deflection while a calibrated load cell was used to record the load. Two strain gauges, each of 30 mm length, were bonded to the surface of the CFRP strip at the mid-span and concrete at the top face at the mid-span of the slab. Figure 5 shows a photograph of the test arrangement.

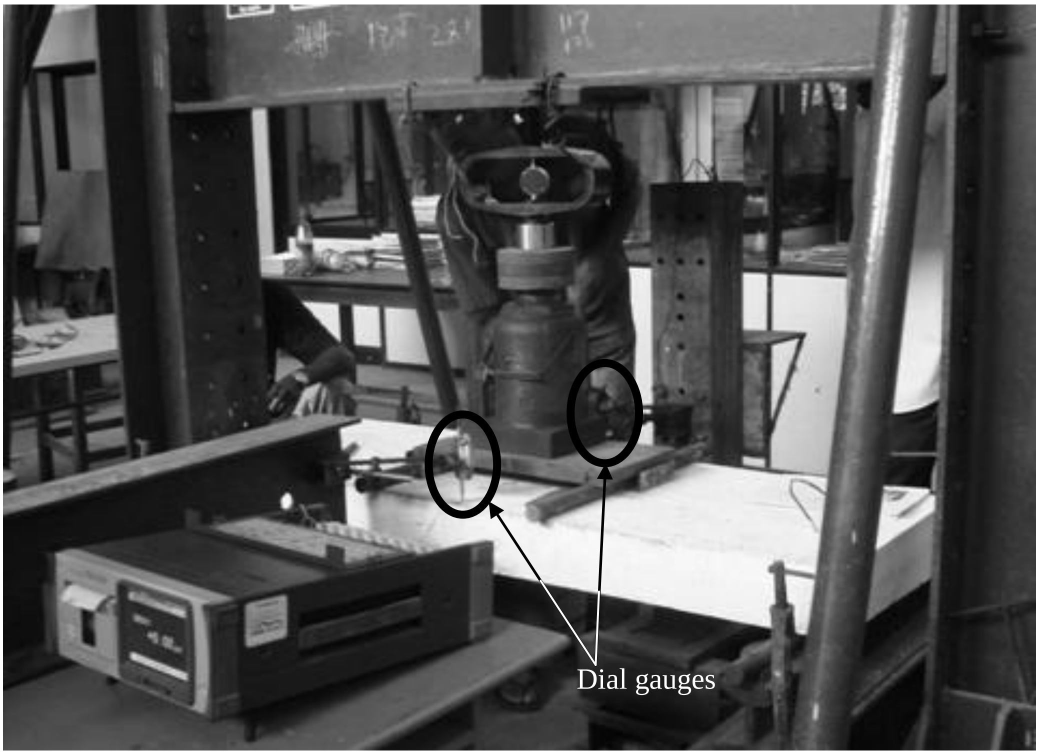

Figure 5: Test arrangement

2.5 Test results and discussions

2.5.1 Mode of failure

The control slabs exhibited a conventional ductile flexural mode of failure in which the slabs failed by crushing of concrete. Specimens T10 – TS1, R6 – TS1 and R6 – TS2 strengthened with CFRP failed prematurely without warning by debonding of CFRP laminates.

2.5.2 Load–CFRP strain relationship

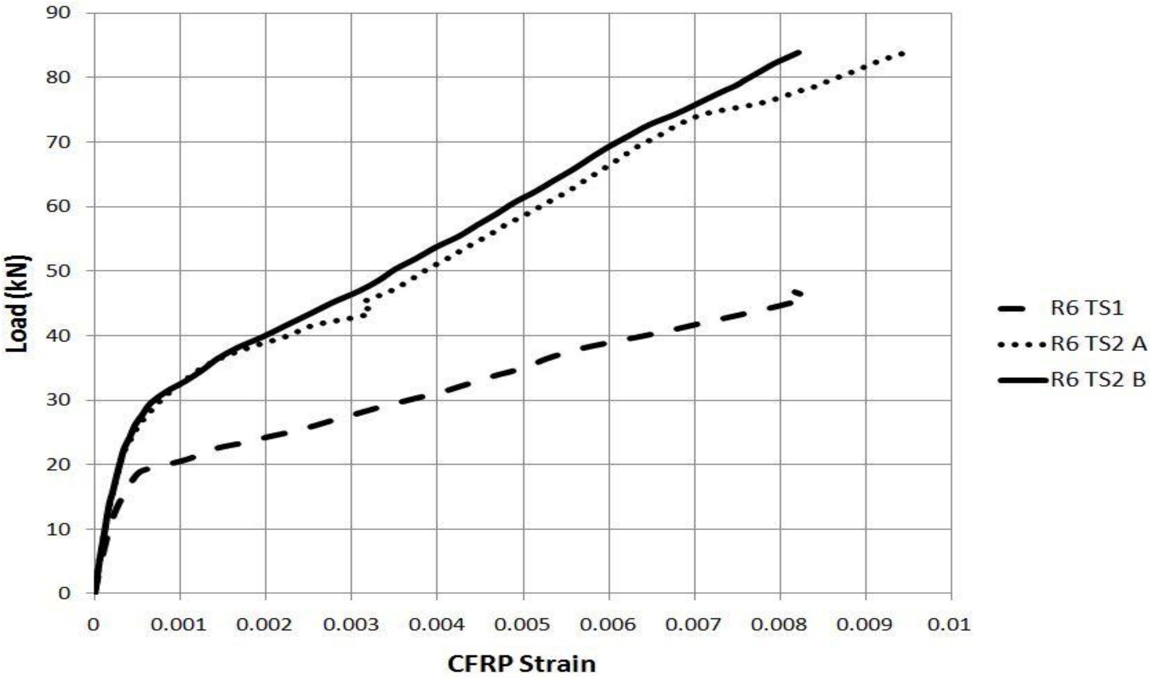

Figure 6: Load versus CFRP strain at mid-span relationship.

The load versus CFRP strain at mid-span section relationships are shown in Figure 6. The load versus mid-span CFRP strain relationships for specimens R6-TS2-A and R6-TS2-B were identical. All the values were less than it ultimate CFRP strain value of 0.017.Therefore there were no CFRP material failure occurrence.

2.5.3 Load–deflection relationship

The load versus mid-span deflection relationships for all specimens is shown in Figure 7 while Table 4 summarizes the structural test results and increments of the load carrying capacity of strengthen slabs.

Table 4: Test results

Specimen	*Experimental Values*		*Mode of failure*	*Increment of the load carrying capacity (%)*
	P_u (kN)	*Δ_u (mm)*		
T10-CS	*29.17*	*5.68*	*Concrete crushing*	---
T10-TS1	*82.16*	*13.95*	*CFRP debonding*	*[(82.16-29.17)/29.17]×100 = 181.66*
R6-CS	*18.24*	*1.30*	*Concrete Crushing*	---
R6-TS1	*48.56*	*8.90*	*CFRP debonding*	*[(48.56-18.24)/18.24]×100 = 166.22*
R6-TS2	*85.61*	*8.66*	*CFRP debonding*	*[(85.61-18.24)/18.24]×100 = 369.30*

P_y and P_u refer to yield and ultimate loads, respectively. Δy and Δu refer to mid-span deflections at yield and ultimate loads, respectively.

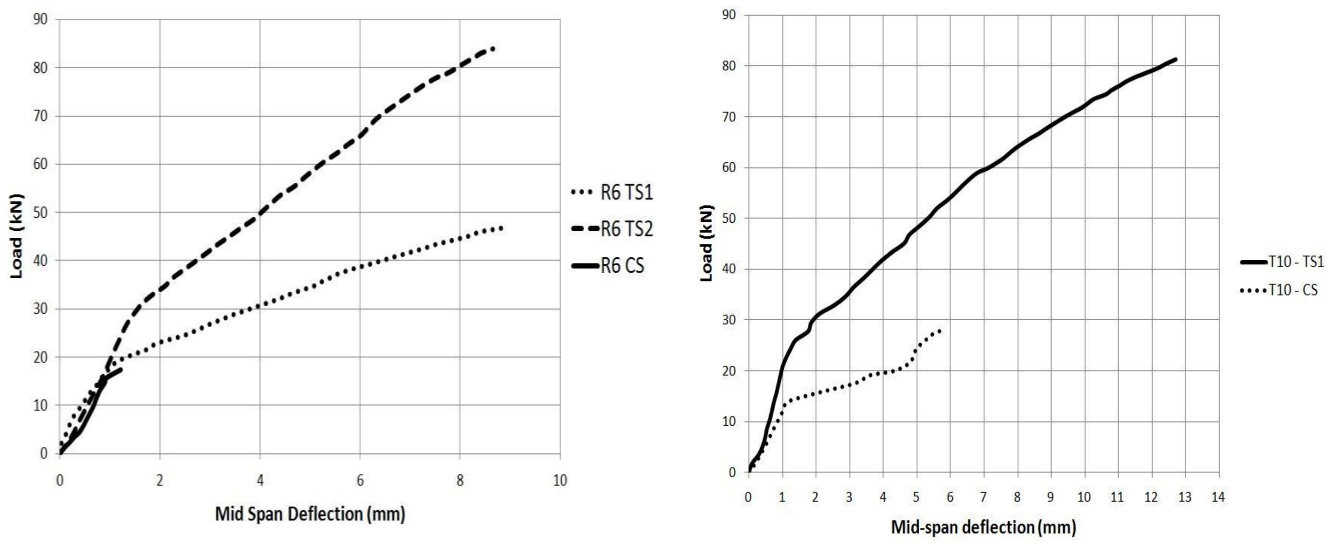

Figure 7: Load versus mid-span deflection relationship.

CFRP bonding improves the ductility of the slabs effectively. The ultimate load of specimen T10-TS1 was about 181.7% higher than that of control. Specimen T10-TS1 failed by intermediate crack induced debonding of the CFRP strip. The strengthening with CFRP greatly increased the load carrying capacity of the slabs.

The ultimate load of specimen R6-TS1, which was strengthened with with one strip of CFRP along with span, was about 166.2% higher than that of control specimen R6-CS. The ultimate load of specimen R6-TS2, which was strengthened with two strips of CFRP along with span, was about 369.3% higher than that of control specimen R6-CS.

The slabs strengthened with higher percentage of CFRP had higher ultimate load carrying capacity relative to those of the control.

3. Conclusion

A simple and efficient, experimental procedure to predict the nominal moment capacity of RC slabs strengthened with external CFRP laminates was presented. The experimental results of a series of slab strengthened with a different number of layers of CFRP were also presented. From the results obtained following conclusions can be drawn:

- The experimental study indicated that the strengthened specimens' failure mode was Intermediate crack induced debonding failure due to stress concentration.

- CFRP bonding improves the ductility of the slabs.

- The test results indicated that a significant gain in flexural strength can be achieved by bonding CFRP laminates to the tension face of RC slabs.

- The use of CFRP laminates as an external reinforcement to strengthen and upgrade concrete structural members proved to be efficient.

References

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