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STRENGHTHENING OF THIN REINFORCED CONCRETE SLABS WITH CFRP LAMINATES

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ABSTRACT: Over the years, engineers and researchers have been working continuously to reduce the dead loads on buildings by reducing the sizes of structural elements. Slabs add significant dead load to buildings compared to other structural members. Accordingly, reducing the slab thickness can drastically reduce the dead loads of buildings. Such reduction in dead load will allow engineers to construct taller buildingswith long spans using relatively smaller columns and foundations. The aim of this paper is to study the flexural performance of thin reinforced concrete (RC) slabs cast with high strength concrete when externally strengthened with carbon fibre reinforced polymer (CFRP) laminates at their soffit. Two groups of slab specimens having a thickness of 75 mm were cast with a concrete compressive strength of 50 MPa and 100 MPa, respectively. The first group (C50) consists of three specimens strengthened in flexure with one and two layers of CFRP laminates. The second group (C100) consists of two slab specimens. The first slab is the control slab and the second specimen was strengthened with one layer of CFRP laminate. The test results of the first group with one and two layers of CFRP laminates indicated that the flexural strength have been increased by 69% and 126%, respectively over the control un-strengthened slab. However, for the second group, the flexural capacity of the strengthened slab was increased by 48% of that of the control specimen. The preliminary results from this study have shown that, the thin RC slabs can carry significantly higher loads in buildings if externally strengthened with CFRP laminates. It was also observed that as the concrete strength increases, the gain in flexural capacity of RC slabs from CFRP reinforcement decreases. Based on the results of this pilot study, the authors will expand the test matrix in a future study to examine the effect of several parameters including concrete compressive strength, reinforcement ratio, and number of CFRP layers on the performance of thin RC slabs.

1. Introduction

In the modern days, the construction materials field had grown in complexity and applications, so there are materials invented for almost all modern uses. One of the most critical technologies developed in the construction materials field is fiber-reinforced polymer (FRP) composite materials that are used to repair, strengthen and rehabilitate structures. There are many materials that could be used for these purposes and they vary with the type and extend of damage to the structural member. Structural damage can occur due to many reasons, such as fires, earthquakes, terrorist's attacks, change of occupancy, and wear and tear. Each type of damage should be analyzed and studied to assess the repairing material and strengthening method. One of the most common and widely used methods nowadays in strengthening reinforced concrete (RC) structural members such as slabs, beams, columns, and walls in shear and flexure, is by externally bonding FRP composite sheets and plates to concrete surfaces (Niu et al., 2006; Tamimi et al., 2011; Hawileh et al., 2014; El-Sayed et al., 2014; Hawileh et al., 2015). The old method of strengthening RC slabs and beams in flexure was by attaching steel plates to concrete surfaces (Borgerson, et al. 2011). Since the invention of the FRP strengthening systems, it had proven to have enormous potential and advantages over the steel alternative (Borgerson, et al. 2011).

FRP systems also demonstrated many advantages over the old method of steel plating (Rezazadeh, et al. 2014; ACI, 2008). These advantages can be summarized in the ease of FRP installation and insulation, high resistance to corrosion, strong structural bonding, high strength-to-weight ratio, and less labour intensive. As the range of applicability of this system started to widen, engineers and researchers have conducted various research studies on developing the optimum techniques of using this technology (Rezazadeh et al., 2014; ACI, 2008). It was found from these studies that bonding FRP sheets and plates to surfaces of RC members will increase their flexural and shear strengths significantly. There are many types of FRP composite materials in the construction materials market. Some of the most commonly used FRP types include carbon (CFRP), glass (GFRP), and aramid (AFRP) fibers (ACI, 2008; Bunsell, 1990).

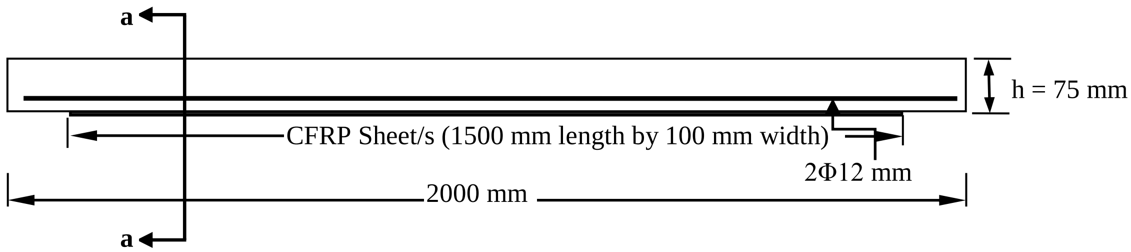
On the structural engineering side, flexural members (slabs and beams) can use the extra capacity provided by the external FRP reinforcement to reduce their cross-section (depth).One important structural element that this research deals with is slabs. Slabs are flexural members that are used for flooring and roofing purposes. They act like beams in transferring and reacting to loads and are the largest elements in any structure. Accordingly, slabs add significant dead load to buildings compared to other structural members. Thus, reducing the slab thickness can drastically reduce the dead weight of buildings. The slab thickness can be reduced without affecting its flexural capacity by using high strength concrete and/or adding flexural reinforcement. In addition, when slabs are designed with high strength concrete, the Whitney block depth (a) will decrease, leading to an increase in the couple lever moment arm. Thus, the flexural capacity of RC slabs increases with the increase in the concrete compressive strength.

The aim of this paper is to study the flexural performance of thin RC slabs cast with high strength concrete when externally strengthened with CFRP laminates at their soffit. This study can be applied to newly built slabs to reduce their thickness, or to the existing slabs to enhance their load carrying capacity if the intended use of the structure is changed. The general trend of strengthening such elements is attaching the FRP system to the soffit of the slab with epoxy resin adhesives. In this case, the FRP system will act as secondary flexural reinforcement to help the main longitudinal steel reinforcement in increasing the flexural capacity. The parameters varied and studied in this experimental investigation are the concrete compressive strength and the number of CFRP layers.

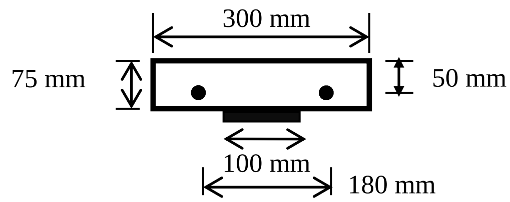
2. Experimental Program

2.1. Specimen Detail

The experimental program consisted of two groups of specimens cast with highconcrete compressive strengths of 50 (C50) and 100 MPa (C100), respectively. The first group (C50) consisted of three specimens, one control (C50-C) and two strengthened in flexure with one (C50-1L) and two layers (C50-2L) of CFRP composite sheets, respectively. The second group (C100) consisted of two slab specimens, one control (C100-NF) and the other strengthened with one layer (C100-IL) of CFRP composite sheets. The CFRP sheets were attached to the soffit of the slab specimens with epoxy adhesives. The length, span length, width, and height of the cast specimens are 2000, 1700, 300,and 75 mm, respectively. The slabs were reinforced with two 12 mm diameter steel bars located at a depth of 50 mm from the top compression fibre. Figure 1 shows details of the control and strengthened slab specimens. The slabs were strengthened with 100 mm wide unidirectional MapeWrap CFRP sheets (Mape, 2013) that had a nominal thickness of 0.165, mm and bonded to the soffit of the slab specimens with epoxy adhesives. The thickness of each CFRP ply of the cured laminate is 0.767 mm, as reported by the manufacturer (MapeWrap, 2013).



a) Front view of the strengthened slab specimens



b) Cross-section of a typicalstrengthened slab (Section a-a)

c) Fig. 1– Detailing of RC slabspecimens

2.2. Material Properties

Coupon tests were carried out to examine the mechanical properties of the steel reinforcement. The averages of the experimentally measured modulus of elasticity, yield strength, and tensile strength were found to be 205 GPa, 501 MPa and 560 MPa, respectively. In addition, standard concrete cylinders were tested after 28 days to obtain the concrete compressive strength concrete. The averages of the measured concrete strength for the two groups of specimens were found to be 52 and 103 MPa, respectively. The CFRP cured laminates had an elastic modulus, tensile strength, and elongation at rupture of 55 GPa, 876 MPa, and 1.6%, respectively (MapeWrap, 2013).

2.3. Testing and Loading

A four-point bending test arrangement was used to test all specimens as shown in Fig. 2. This testing arrangement was chosen to simulate the common loading case on slabs, which is uniformly distributed loading. The slabs were tested under a displacement control mode of 2 mm/min using a Universal Testing Machine (UTM) that has a capacity of 2000kN.

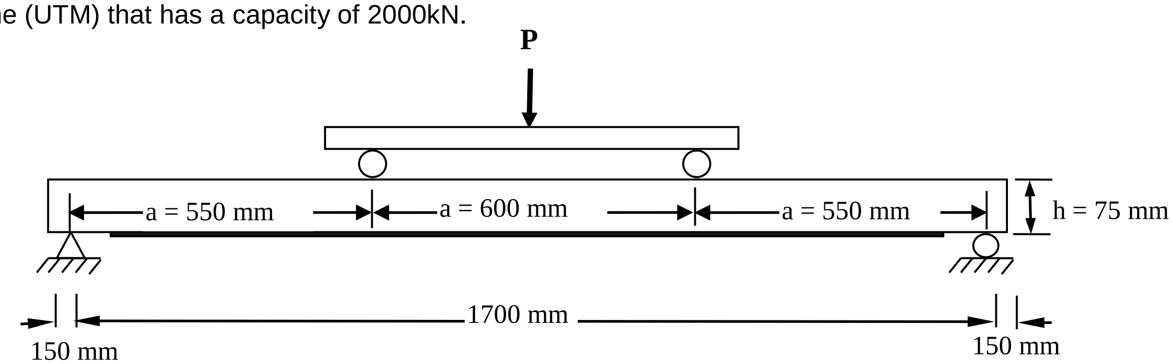


Fig. 2 -Loading set-up

3. Results and Discussion

3.1. Load versus midspan deflection response curves

Figures 3 and 4 show the load versus midspan deflection response curves of the C50 and C100 specimens, respectively. It is clearly indicated from Figs. 3 and 4 that as the CFRP flexural reinforcement ratio increases, the flexural capacity of the tested specimens increase. However, the ductility of the beam specimens decreases with the increase in the number of CFRP layers. The ultimate load-carrying capacity (P_u) of the tested specimens are shown in Table1. Table 1 also shows the percent increase in the load-carrying capacity of the strengthened specimens over that of the control slab specimens. As indicated in Table 1 the flexural strength of the strengthened specimens of the C50 group with one and two layers of CFRP laminates has been increased by 69% and 126%, respectively over the control un-strengthened slab specimen. However, for the C100 group of specimens, the flexural capacity of the strengthened specimen was increased by only 48% over that of the control slab specimen. Thus, it could be concluded that thin RC slabs can carry significantly higher loads in buildings if externally strengthened with CFRP laminates. It was also observed that as the concrete strength increases, the gain in flexural capacity of RC slabs from CFRP reinforcement decreases.

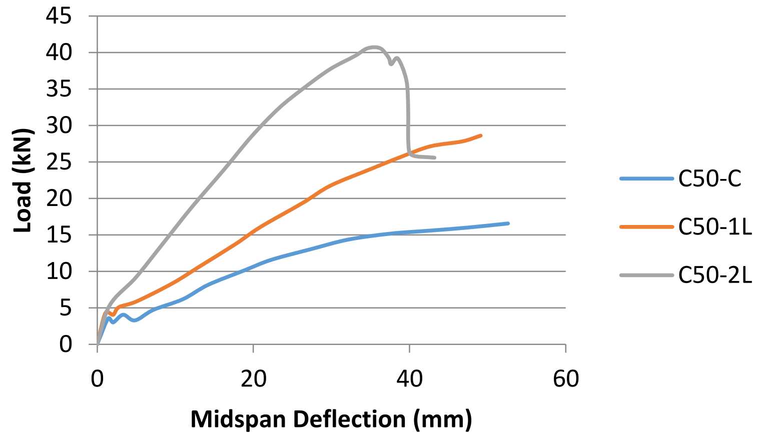


Fig. 3 - Load versus midspan deflection response curves of the C50 specimens

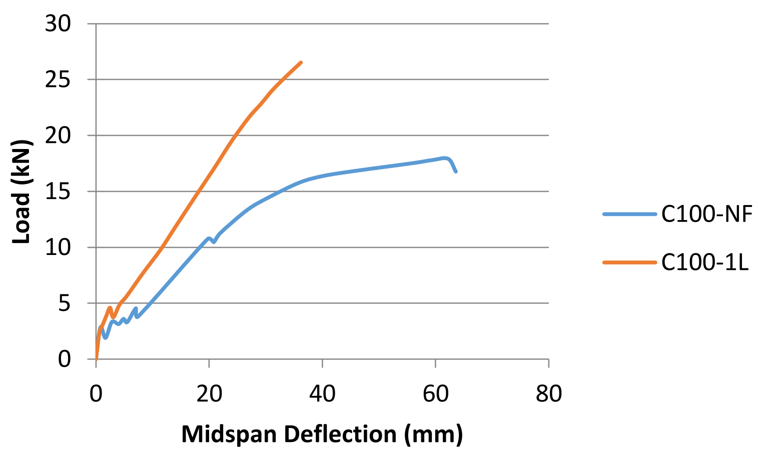


Fig. 4 - Load versus midspan deflection response curves of the C100 specimens

Table 1 - Summary of test results

Beam Designation	***P_u* (kN)**	**% Increase over control**
C50-C	18.24	-
C50-1L	30.84	69
C50-2L	41.25	126
C100-NF	24.12	-
C100-1L	35.72	48

3.2. Failure mode

Figure 5 shows the failure modes of the tested slab specimens. It is clearly observed from Fig. 5a and 5b that the control slab specimens (C50-C and C100-NF) failed as expected in a ductile tension control mode. Failure was initiated with concrete cracking in the tension zone between the two loading supports, followed by yielding of the steel reinforcement, and progressed by concrete crushing in the top concrete compression fibers. The strengthened specimens wit
h one layer of CFRP laminates (C50-1L and C100-1L) failed by debonding of the CFRP sheets from the adjacent concrete surfaces as shown in Fig. 5b and 5e. Failure of these two specimens was initiated with flexural cracks in the maximum bending moment zone of the slab, which ultimately resulted in deboning of the CFRP laminates from the adjacent concrete surface. Finally, the strengthened slab with two layers of CFRP laminates (C50-2L) failed by yielding of the flexural reinforcement followed by concrete crushing close to the loading support as shown in Fig. 5c.

(a) C50-C

(b) C50-IL

(c) C50-2L

(d) C100-NF

(e) C100-1L

Fig. 5 - Tested specimens at failure

4. Conclusion

The test results from this pilot study indicates that thin reinforced concrete slabs can be designed to carry the required moment capacity if externally strengthened with CFRP laminates. It is also observed that strengthening of thin RC slabs with CFRP laminates is very effective in enhancing its load-capacity. In particular, the load-carrying capacity of the C50 group with one and two layers of CFRP laminates has been increased by 69% and 126%, respectively over the control slab specimen. It is also observed that as the concrete compressive strength increases, the percent increase in the flexural capacity is reduced. This occurred due to the shift of the neutral axis upward that lead to concrete crushing at the onset of yielding of the steel reinforcement. In fact, the percent increase of the load-carrying capacity of the C100-1L over that of the control unstrengthened slab was only 48%.

It can also be concluded that the concept adopted in this pilot study is very efficient in reducing the slab thickness. The authors will expand the scope of this study in a future experimental investigation to examine the effect of concrete compressive strength, flexural reinforcement ratio, and number of CFRP layers on the performance of thin slab specimens.

5. Acknowledgements

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