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Tests of concrete slabs reinforced with CFRP prestressed prisms

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Abstract. This paper reports the testing of concrete slabs reinforced with CFRP prestressed concrete prisms(PCP) on the flexural behavior. Four concrete slabs were tested, a reference slab reinforced with steel bars, and three slabs reinforced with CFRP prestressed concrete prisms (PCP). All slabs were made with dimensions of 600mm in width, 2200mm in length and 150 in depth. All concrete slabs reinforced with CFRP prestressed concrete prisms(PCP) exhibited CFRP bar rupture failure mode. It was shown that the application of the CFRP prestressed prisms can limit service load deflections and crack width, the increased level of prestress in the CFRP prestressed prism positively affected the maximum crack width. The deflection of concrete slabs reinforced with CFRP prestressed prisms decreased as prestress in the CFRP prestressed prism increased..

Keywords: test; slabs; CFRP; deflection; crack width

1. Introduction

The use of fiber reinforced polymers (FRP) in concrete structures has increased rapidly in the last 20 years due to their excellent corrosion resistance, high tensile strength, and good nonmagnetization properties.

Over the last couple of decades, several investigations were conducted to study the performance of FRP reinforced concrete structures in shear and flexure.

Zhang *et al.* (2014) studied the flexural defections of concrete beam reinforced with basalt FRP bars and proposed a modified equation of the flexural rigidity to calculate the deflection of the FRP-RC beams.Mahroug *et al.* (2014) reported the testing of four continuously supported concrete slabs reinforced with carbon fibre reinforced polymer (CFRP) bars. Ashour and Kara (2014) studied the size effect on shear strength of concrete beams reinforced with longitudinal carbon fiber rein- forced polymer (CFRP) bars and without vertical shear reinforcement. Oller *et al.*

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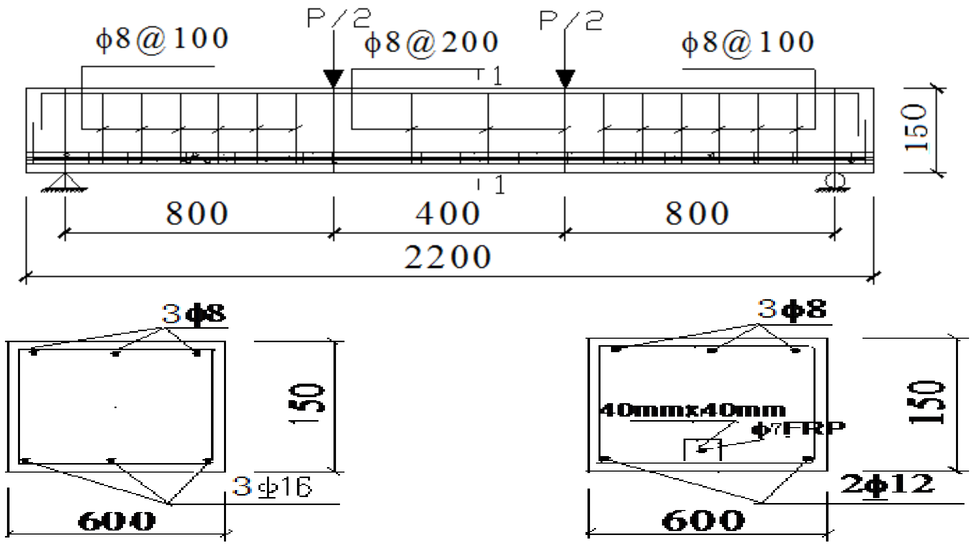
(2015) presented a mechanical model for the prediction of the shear strength of FRP RC beams that takes into ac-count its particularities. Ferreira *et al.* (2015) studieded shear strain influence in the service res- ponse of FRP reinforced concrete beams. Pawłowsk and Szumigała (2015) studied the flexural behaviour of a series of simply supported Basalt fiber reinforced polymer (BFRP) bars RC beams under short-term static loads. Adam *et al.* (2015) studied the flexural behavior of concrete beams reinforced with locally produced glass fiber reinforced polymers (GFRP) bars.Tomlinson *et al.* (2015) evaluated the flexural and shear performances of concrete beams reinforcedwith basalt fiber-reinforced polymer (BFRP) rebar and stirrups. Razavi *et al.* (2015) investigated the load-deflection analysis of the Carbon Fiber Reinforced Polymer (CFRP) strengthened reinforced con-crete (RC) slab using Recurrent Neural Network (RNN). Said *et al.* (2016) the shear behavior of concrete beams reinforced with lab produced glass fiber reinforced polymers (GFRP) bars and sti-rrups.Ferrier *et al.* (2016) studied shear behaviour of a new type of high-performance lightweight beam with improved performance over conventional reinforced concrete (RC) by adding fibre-reinforced polymer (FRP) reinforcing rebar to ultra-high-performance concrete with microfibre reinforcement (UHPC-SFR). Elgabbas *et al.* (2016) introduced and discussed the cracking behavior, deflection, and failure modes of basalt-fiber-reinforced polymer bars in concrete beams.

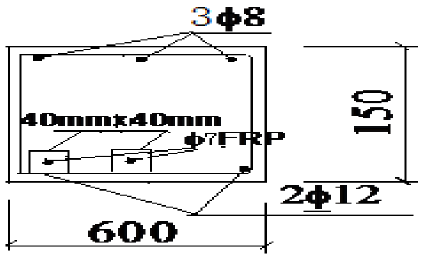
However, the low modulus of elasticity of the FRP materials and their non-yielding characteristics results in large deflection and wide cracks in FRP reinforced concrete members. The solution for this problem is usually sought by increasing the reinforcement ratio in the section. By choosing this solution, the high tensile capacity of the FRP bars, which is one of their most important advantages, cannot be properly utilized in design. Considering the relatively high cost of these materials, it would also be economically unattractive.

The feasibility of using FRP prestressed concrete prisms (PCP) as reinforcement have been used for crack control and deflection control. Using PCP as reinforcement for concrete beams introduces compressive stresses to the tensile zone of concrete beam. Hence, at first cracking of the beam, only hairline cracks appear. This behavior is significantly different from FRP reinforced concrete, and even from steel reinforced concrete to some extent. There is sufficient bond between the CFRP bar and the high strength concrete of the prism, the concrete prisms and surrounding beam concrete. The bond between the prisms and the beam remained apparently intact until the failure of the beam.

It is believed, as previous experiences have shown (Hanson 1969, and Bishara *et al*. 1971, Chen and Nawy 1994, Nawy and Chen 1998, Svecova and Razaqpiir 2000, Banthia *et al*. 2003) that using PCP as reinforcement can delay cracking of the beam, decrease deflection, and reduce crack width under the service load. Hanson (1969) investigated the effect of using prestressed concrete prisms as reinforcement for crack control in T-beams. Bishara *et al*. (1971) investigated flexural rigidity,crack formation and development, moment redistribution, and plastic hinge rotation of PCP reinforced beams. The research concluded that the use of PCP as part of the reinforcement in the intermediate support regions of continuous beams was beneficial since it considerably improved the serviceability criteria without reducing the moment redistribution capacity. Chen and Nawy (1994) reported the flexural behaviour of thirteen rectangular simply supported high strength concrete beams reinforced with PCP. Nawy and Chen (1998) also investigated the flexural behaviour of four continu-ous concrete T-beams reinforced with steel PCP. Svecova and Razaqpur (2000) investigatedthe flexural behaviour of concrete beams reinforced with CFRP prestressed prisms. Banthi *et al.* (2003) investigated the use of GFRP prestressed straps as ties for steel free bridge decks. It was also concluded that the use of GFRP



(a) Slab BB (b) Slab PB1, PB2



(c) Slab PB3

Fig. 1 Typical dimensions and geometry of tested slabs

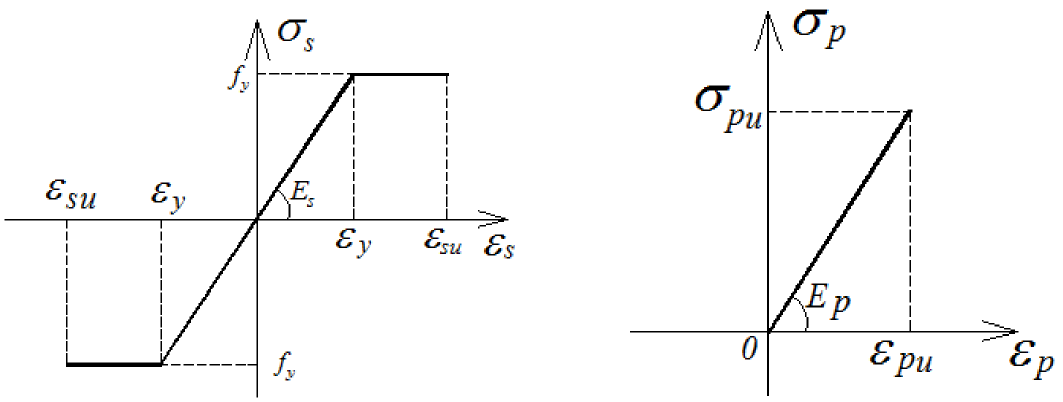
Fig. 2 The precast slabs

prestressed straps was feasible for lateral confinement of steel free deck slabs.

In this study, the flexural behavior of several CFRP prestressed prisms reinforced concrete slabs is tested.

Table 1 Reinforcement details of all tested slabs

Slab number	Tension reinforcement	Prestress (kN)	Compressive reinforcement	Stirrup	
				Mid-span	Shear span
BB	3ϕ16	——			
PB1	1PCPs+2ϕ12	35	3Φ8	ϕ8@200	ϕ8@100
PB2	1PCPs+2ϕ12	43			
PB3	2PCPs+1ϕ12	35			



(a) Stress-strain curves of steel reinforcement (b) Stress-strain curves of CFRP reinforcement

Fig. 3 Stress-strain curves

2. Experimental programme

2.1 Test specimens

Four slabs, including three concrete slabs reinforced with CFRP prestressed prisms and one concrete slab reinforced with steel bars which was tested as a reference slab, were constructed and tested in flexure. All slabs tested were made with dimensions of 600mm in width, 2200mm in length and 150mm in depth. All the slabs had a equal clear spans of 2m, a diameter of 8mm of steel bar as stirrups and as compression reinforcement. Figs. 1, 2 shows the loading arrangement of the slabs and the precast slabs, receptively.

The tested slabs were cast by ready mix concrete with a 48.8MPa compressive strength and a tensile strength of 2.8 MPa after 28 days. High-strength concrete with a compressive strength of 154 MPa and a tensile strength of 17.4 MPa was used to cast the prisms.Six cubes (150mm) and three cubes (150mm) were made and tested immediately after testingof each slab to provide the cube compressive strength and splitting tensile strength,respectively. After 24 h, the cubes were demoulded and cured in a fog room (20±2°C, 95% relative humidity) for 28 days. All longitudinal reinforcement details of all slabs are presented in Table 1. The slab BB was reinforced with three steel bars of 16mm diameter, which had a yield strength of 468 MPa and a ultimate strength of 615MPa. The slab PB1, PB2 were reinforced with two steel bars and one CFRP prestressed prisms. The slab PB3 were reinforced with one steel bars of 12mm diameter and two CFRP prestressed prisms. The steel bars of 12mm diameter, which had a yield strengthof 360 MPa and a

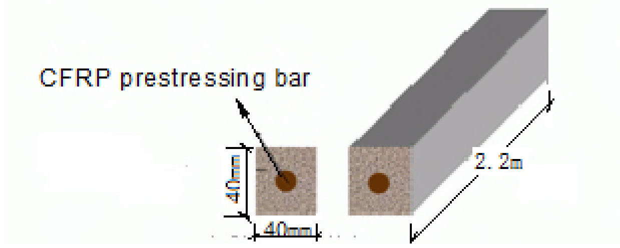


Fig. 4 Typical CFRP prestressed concrete prism(PCP)

ultimate strength of 550 MPa. Fig. 3 illustrates the stress-strain curves for steel and CFRP reinforcement.

Fig. 4 illustrates a typical geometry of a prestressed concrete prism(PCP) that was used in this experimental investigation. Each prisms was concentrically prestressed by an 7mm diameter single CFRP bar. The prisms were 40×40mm in cross section. According to themanufacturer, the ultimate tensile strength of this bar was 2200 MPa with modulus of elasticity of 155 GPa. The jacking stresses varied from 880Mpa to 1320 MPa, which are equal to 0.40 to 0.60, respectively, of the guaranteed tensile strength. The effective prestressing stresses was varied from 792 Mpa to 1188Mpa at the time of casting slabs,which shows a 10% loss of prestress due to elastic shortening, relaxation, creep, and shringage.

2.2 Instrumentation and test setup

Fig. 5 shows the test setup for the slabs. The load was applied by a servo-hydraulic testing machine. The load from the actuator was converted to two-point loads at 0.4m from the center support using a steel spreader beam. The load was applied monotonically until failure. The load was applied by using a displacement rate of 0.01mm/s, and the automatic data acquisition system recorded data every 10 seconds.

To measure the slab deflection, three linear variable displacement transducers (LVDTs) were placed under the load points and at midspan of the beam. In addition, two LVDTs were placed at both ends of the slabs to measure the possible of tilting. Electrical resistance strain gauges were used to measure the strain in the tension and compression reinforcement. Strain gauges were also used to monitor strain in concrete. Reinforcement strains were measured for each bar at the midspan; concrete strains were measured at the top compression surface at midspan.

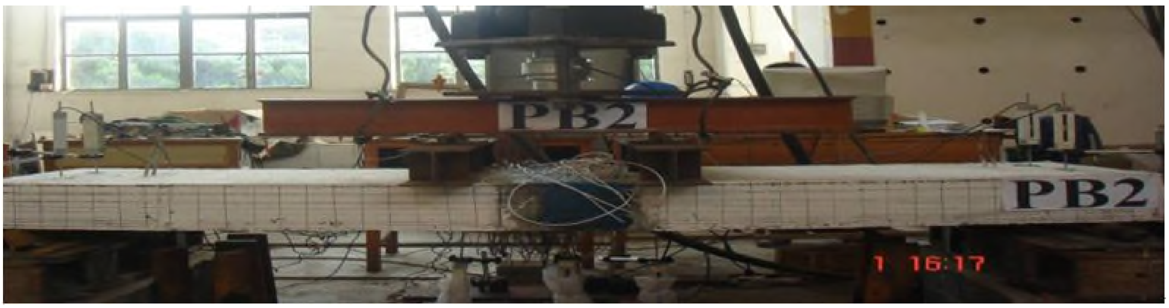
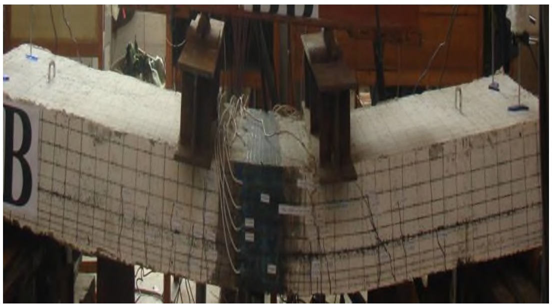
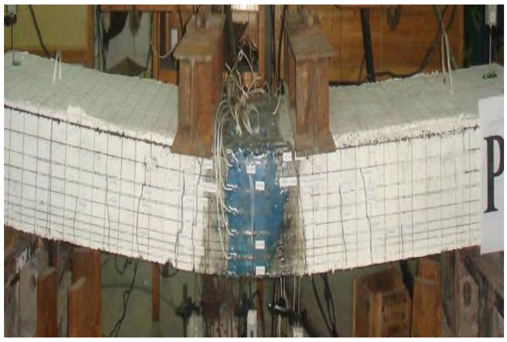


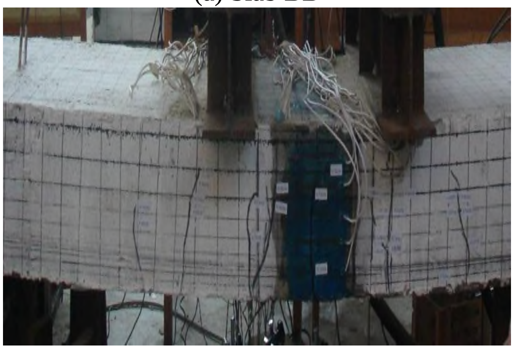
Fig. 5 Test setup



(a) Slab BB



(b) Slab PB1



(c) Slab PB2

(d) Slab PB3

Fig. 6 Failure modes of Slabs

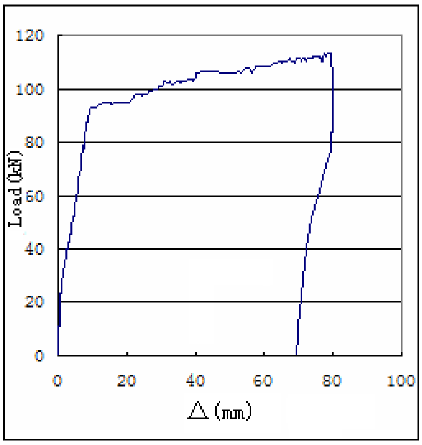
3. Experimental results

3.1 Failure modes

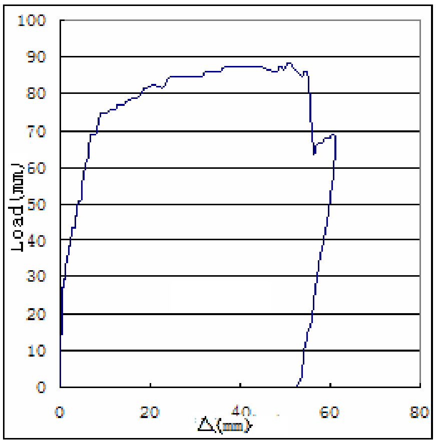
Two different failure modes were observed in the experimental tests as shown in Fig. 6: (a) concrete crushing after steel reinforcement yielded(Slab BB, Fig. 6(a)); (b) CFRP bar rupture ((Slab PB1 (Fig. 6(b)), Slab PB2 (Fig. 6(c)), Slab PB3 (Fig. 6(d))).

For slab BB, the first observed crack was at load equal to 27kN, which width was 0.05mm. Up to 94kN, the new cracks appeared in the mid-man of slab, and the crack width was 1.5mm. A total of eleven cracks appeared while the slab was broken. For slab PB1, the first flexural crack which width was 0.04mm appeared in the mid-span when the load was 30kN.The second crack appeared when the load reached 78kN. As the load increased, the crack appeared repeatedly. When the slab was failure, there are six flexural cracks and five flexural-shear cracks. For slab PB2, the first flexural crack which width was 0.025mm appeared in the mid-span when the load was 30kN. When the load reached 78kN, the second crack appeared. When the slab was failure, there are seven flexural cracks and five flexural-shear cracks. For slab PB3, the first flexural crack which width was 0.04mm appeared in the mid-span when the load was 33kN. When the load reached 38kN, the second crack which width was 0.055mm appeared. When the slab was failure, the amount of cracks was the same as slab PB1.

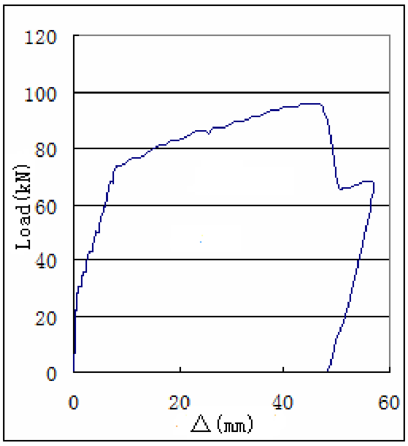
3.2 Load - deflection response



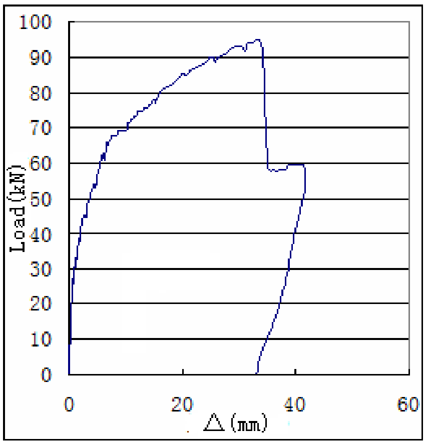
(a) Slab BB



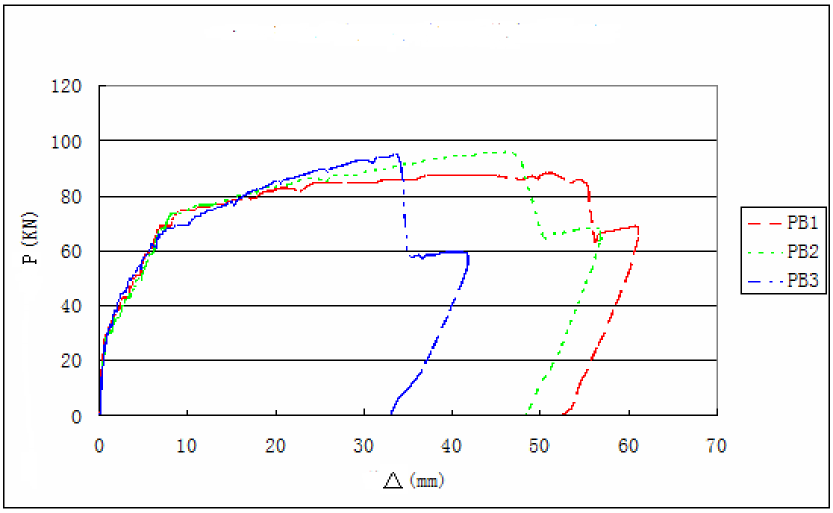
(b) Slab PB1



(c) Slab PB2



(d) Slab PB3



(e) Slab PB1, PB2, PB3

Fig. 7 Mid-span deflection of slabs

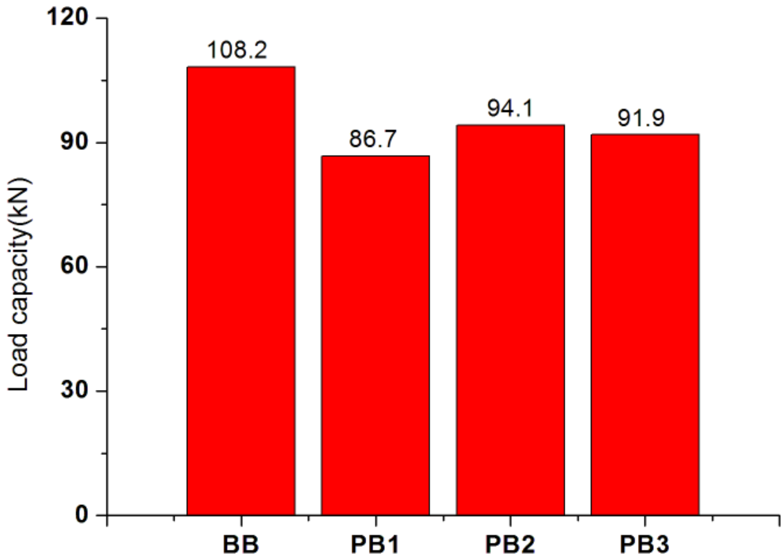


Fig. 8 Experimental load capacity of slabs

The load versus mid-span deflection curves of all slabs are shown in Fig. 7. At initial stages of loading, the deflection increased with the increase of load, all tested slabs were un-cracked and the load-deflection behavior was linear. As the load increased, the concrete cracked, the mid-span deflection varied non-linearly up to a certain load (i.e., the yield load), and after that point, the mid-span deflection increased dramatically and reached a maximum, yet, the load increased slowly. Beyond the ultimate load point, the deflection started increasing inappreciably and the load decreased sharply. Comparing slab PB1, slab PB2 and slab PB3, due to the prestress in the reinforcing prisms, the cracking of the slab did not noticeably affect the load deflection curve. The significant change in stiffness was caused in both cases by the cracking of the prisms. Before yielding, the cracking load, yield load and deflection of that were not very different. After the yield load point, the bearing capacity and deflection increased with the increase of the prestress and amount of CFRP prestressed concrete prisms. It was obvious that improving prestress should slightly improve the ultimate bearing capacity, reduce the deflection of concrete slabs reinforced with CFRP prestressed prisms. To increase the amount of CFRP prestressed concrete prisms also can improve the ultimate bearing capacity and significantly reduce deflection, but decrease ductility.

3.3 Load capacity

Failure loads of the tested slabs are shown in Fig. 8. It is shown that the flexural capacity of the concrete slabs reinforced with CFRP prestressed prisms increased slightly as the level of prestress increased. Comparing slab PB1, the ultimate load of slab PB2 was increased 8.5%. And at the same level of prestress, the flexural capacity of the concrete slabs reinforced with CFRP prestressed prisms increased slightly with the increase of amount of CFRP prestressed concrete prisms. Comparing slab PB1, the ultimate load was increased 5.9% for slab PB3. The ultimate strength of slab BB, PB1, PB2, PB3 was 98.5, 84.5kN, 86.3kN, 81.3 kN, respectively, which

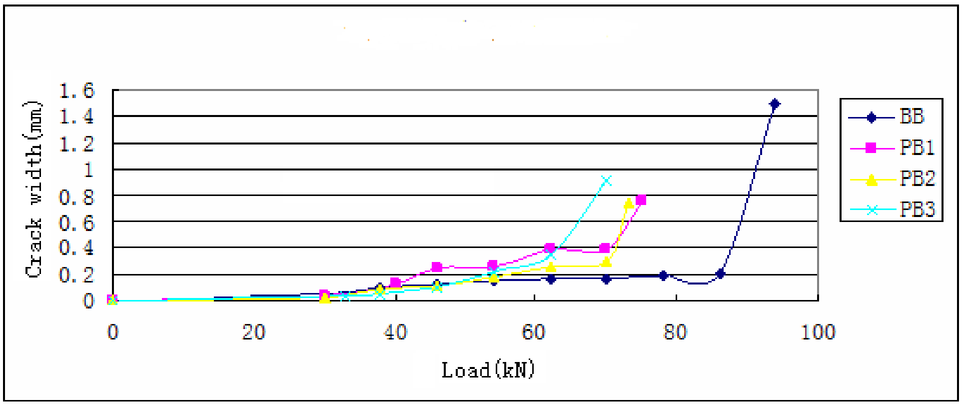


Fig. 9 Mid-span crack width curves of the tested slabs

was calculated by ACI (Svecova and Razaqpur 2000). It is shown that using the ACI suggested value underestimated the capacity of the concrete slabs.

3.4 Crack width

Fig. 9 presents the mid-span crack width curves of the tested slabs. It was evident that the crack width of concrete slabs reinforced with CFRP prestressed prisms was smaller than that of the conventional steel reinforced slab at initial stages of loading. The crack width versus load graphs in Fig. 9 showed the positive effect of prestress in the prism on crack width. The cracks of concrete slabs reinforced with CFRP prestressed prisms were hairline before prism cracking, and they widen after the prism cracking.When the concrete slabs reinforced with CFRP prestressed prisms, the crack width decreased as the prestress in the prism increased, Hence, clearly the increased level of prestress in the prism positively affected the maximum crack width. Comparing the conventional steel reinforced slab (i.e., slab BB), at initial stages of loading, the concrete slabs reinforced with CFRP prestressed prisms cracked later, the cracks developed slowly. At service load, the crack width was smaller, the total number of cracks was slightly larger, the average crack spacing was smaller.

3.5 Ductility

Table 2 provides the summary of the results of the tested slabs in terms of cracking load (P_{cr}), yielding load (P_y),ultimate load (P_u), cracking deflection (Δ_{cr}), yielding deflection (Δ_y) and ultimate deflection(Δ_u). The ductility of concrete slabs is defined as the deformation capacity from the yield point to the peak load point(or the 85% of the peak load),and the displacement ductility coefficient could be defined as $u = \frac{\Delta_u}{\Delta_y}$,where Δ_u stands for the peak displacement, Δ_y stands for the yield displacement when the steel reinforcement yielded. The displacement ductility coefficients were shown in Table 2. It is shown that compared with the ordinary concrete slab, the slabs reinforced with prestressed concrete prisms have lower ductility, the ductility coefficient of slab PB1, PB2, PB3 is 85.7%, 79.2%,53.2% of slab BB, respectively. The ductility performance

Table 2 Deflection, load and ductility coefficient of the slabs

Slab		BB	PB1	PB2	PB3
Crack	Δ_{cr}(mm)	0.9	1.1	0.9	0.9
	P_{cr} (kN)	27	30	30	33
Yield	Δ_y(mm)	9.7	8.6	7.22	8.5
	P_y (kN)	92	75	75	67
Peak	Δ_u(mm)	75.0	56.2	50.3	35.0
	P_u (kN)	108.2	86.7	94.1	91.9
Ductility coefficient μ		7.7	6.6	6.1	4.1

basically remains unchanged as the level of prestress increased, therefore, the prestress has little effect on the ductility of concrete slabs reinforced with CFRP prestressed prisms. In all the slabs, the ductility coefficient of slab PB3 is the least, it shown that the increasing amount of CFRP prestressed prisms could decreased the ductility of the slabs. So it must increase the amount of steel bar as the increasing amount of CFRP prestressed prisms.

4. Conclusions

Based on the experimental results, the following conclusions can be drawn:

• The concrete slabs reinforced with CFRP prestressed prisms illustrated narrow cracks and small deflections, owing to the higher elastic modulus of CFRP prestressed prisms compared with CFRP bar.

• The application of a reasonable amount of prestress to the CFRP prestressed prisms can limit service load deflections and crack width of concrete slabs reinforced with CFRP prestressed prisms to acceptable levels.

• Flexural cracks of concrete slabs reinforced with CFRP prestressed prisms are hairline before CFRP prestressed prism cracking, and they widen after the CFRP prestressed prism cracking. When the concrete slabs reinforced with CFRP prestressed prisms, the crack width decreased as the prestress in the CFRP prestressed prism increased, Hence, clearly the increased level of prestress in the CFRP prestressed prism positively affected the maximum crack width.

• The deflection of concrete slabs reinforced with CFRP prestressed prisms decreased as prestress in the CFRP prestressed prism increased.

• The CFRP bar rupture was the dominant mode of failure for concrete slabs reinforced with CFRP prestressed prisms.

Acknowledgments

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References

Adam, M.A., Said, M., Mahmoud, A.A. and Shanour, A.S. (2015), "Analytical and experimental flexural behavior of concrete beams reinforced with glass fiber reinforced polymers bars", *Constr. Build. Mater.*, **84**(1), 354-366.

Ashour, A.F. and Kara, I.F. (2014), "Size effect on shear strength of FRP reinforced concrete beams", *Compos. B.*, **60**, 614-620

Banthia, V., Mufti, A.A., Svecova, D. and Bakht, B. (2003), "Transverse confinement of deck slabs by concrete straps", *Proceedings of the 6th International Symposium on Fiber-Reinforced Polymer Reinforcement for Concrete Structures*, **6,** 945-954.

Bishara, A., Mason, G.E., and Almeida, F.N. (1971), "Continuous beams with prestressed reinforcement", *ASCE Struct. J.*, **87**, 2261-2275.

Chen, B. and Nawy, E.G. (1994), "Structural behavior evaluation of high strength concrete beams reinforced with prestressed prisms using fiber optic sensors", *ACI Struct. J.*, **91**(6), 708-718.

Elgabbas, F., Vincent, P., Ahmed, E.A. and Benmokrane, B. (2016), "Experimental testing of basalt-fiber-reinforced polymer bars in concrete beams", *Compos. B.*, **91**(15), 205-218.

Ferreira, D., Oller, E., Barris, C. and Torres, L. (2015), "Shear strain influence in the service response of FRP reinforced concrete beams", *Compos. Struct.*, **121**, 142-153.

Ferrier, E., Confrere, A., Michel, L., Chanvillard, G. and Bernardi, S. (2016), "Shear behaviour of new beams made of UHPC concrete and FRP rebar", *Compos. B.*, **90**(1), 1-13.

Hanson, N.W. (1969), "Prestressed concrete prisms as reinforcement for crack control", *PCI J.*, **14**(5), 14-31.

Mahroug, M.E.M., Ashour, A.F. and Lam, D. (2014), "Tests of continuous concrete slabs reinforced with carbon fibre reinforced polymer bars", *Compos. B.*, **66**, 348-357.

Mirza, J.F., Zia, P. and Bhargava, J.R. (1971), "Static and fatigue strengths of beams containing prestressed concrete tension elements", *Highway Res. Record*, **354**, 54-60.

Nawy, E.G. and Chen. B. (1998), "Deformational behavior of high performance concrete continuous composite beams reinforced with prestressed prisms and instrumented with bragg grating fiber optic sensors", *ACI Struct. J.*, **95**(1), 51-60.

Oller, E., Marí, A., Bairán, J.M. and Cladera, A. (2015), "Shear design of reinforced concrete beams with FRP longitudinal and transverse reinforcement", *Compos. B.*, **74**(1), 104-122.

Pawłowsk, D. and Szumigała, M. (2015), "Flexural behaviour of full-scale basalt FRP RC beams-experimental and numerical studies", *Procedia Eng.*, **108**, 518-525.

Razavi, S.V., Jumaat, M.Z., EI-Shafie, A.H. and Ronagh, H.R. (2015), "Load-deflection analysis prediction of CFRP strengthened RC slab using RNN", *Adv. Concrete Constr.*, 3(2), 91-102.

Said, M., Adam, M., Mahmoud, A. and Shanour, A. (2016), "Experimental and analytical shear evaluation of concrete beams reinforced with glass fiber reinforced polymers bars", *Constr. Build. Mater.*, **102**(1), 574-591.

Svecova, D. and Razaqpur, A.G. (2000), "Flexural behavior of concrete beams reinforced with Carbon Fiber-Reinforced Polymer (CFRP) prestressed prisms", *ACI Struct. J.*, **97**(5), 731-738.

Tomlinson, D. and Fam, A. (2015), "Performance of concrete beams reinforced with Basalt FRP for flexure and shear", *J. Compos. Constr.*, **19**(2), 162-168.

Zhang, L., Sun, Y. and Xiong, W. (2015), "Experimental study on the flexural deflections of concrete beam reinforced with Basalt FRP bars", *Mater. Struct.*, **48**(10), 3279-3293.

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