Structural Engineering and Mechanics, *Vol. 62, No. 3 (2017) 291-295*
DOI: https://doi.org/10.12989/sem.2017.62.3.291

Flexural behaviour of reinforced concrete beams strengthened with NSM CFRP prestressed prisms

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(Received March 6, 2016, Revised October 23, 2016, Accepted December 22, 2016)

Abstract. The behaviour of reinforced concrete beams strengthened with near surface mounted (NSM) CFRP prestressed prisms was experimentally investigated. Five RC beams were tested under four point bending. All beams were made with dimensions of 300 mm in width, 2000 mm in length and 150 in depth. The effects of presstress level of CFRP prestressed prisms and prism material type were studied. The failure mode, load capacity, deflection, CFRP strain, steel strain and ductility of the tested beams were all analyzed. The results showed that the behavior of the reinforced concrete beams strengthened with NSM CFRP prestressed prisms showed a significant increase in the load-carrying capacity and the deformation capacity. The NSM CFRP prestressed prisms strengthening technique could be considered as an effective method for repairing RC structures.

Keywords: flexural behaviour; near surface mounted; CFRP; strengthened; beam

1. Introduction

Fiber reinforced polymer(FRP) materials have high potential for an effective strengthening of reinforced concrete (RC) structural elements, since they are lightweight, have high durability, exhibit high tensile strength and their availability are practically unlimited in size, geometry and dimensions. In the past, strengthening of reinforced concrete (RC) members by external bonded FRP materials is one of the most widely adopted solutions for retrofitting existing structures; most applications are related to shear and flexural reinforcement, confinement of columns and joints. In recent years, the increasingly widespread strengthening technique consists in using Near Surface Mounted (NSM) FRP bars or strips inserted in grooves cut in the concrete surface on the tension side.

Bilotta *et al*. (2016) assessed the performance and reliability of small-scale testing on near-surface mounted (NSM) FRP strengthening systems. Konthesingh *et al.* (2014) studied the effectiveness of strengthening unreinforced-masonry (URM) shear panels with near surface-mounted (NSM) fiber-reinforced polymer (FRP) strips. Benedetti *et al*. (2016) studied the influence of temperature on the curing process of the epoxy on bond behaviour of NSM-CFRP systems. Mostakhdemin Hosseini *et al.* (2016) assessed the effectiveness of the Near Surface Mounted (NSM) technique with prestressed CFRP (carbon fiber reinforced polymer) laminates for the flexural strengthening of reinforced concrete (RC) slabs of low strength concrete. Capozucca *et al.* (2015) investigated the response of RC beams with NSM circular CFRP rods through static and dynamic tests, analyzed the failure mechanisms of beams due to loss of strength and/or delamination. Bilotta *et al.* (2015) studied the efficiency of CFRP NSM strips and EBR plates for flexural strengthening of RC beams and loading pattern influence. Fernandes *et al.* (2015) studied the bond and flexural behavior of concrete elements strengthened with carbon fiber reinforced polymer (CFRP) laminate strips under fatigue loading conditions, applied according to the near-surface mounted (NSM) strengthening technique. Mostakhdemin Hosseini *et al.* (2014) investigated the effect of the prestressed Near Surface Mounted (NSM) Carbon Fiber Reinforced Polymer (CFRP) laminates on the behavior of reinforced concrete (RC) slabs. Sebastian *et al.* (2013) investigated the characterisation of load responses to failure of a RC frame and a NSM CFRP RC frame.

FRP prestressed prisms are bars of small cross section made with high-strength concrete or epoxy mortar and concentrically pretensioned by a single FRP bar. Previous research reported that using FRP prestressed prisms as reinforcement can delay cracking of the beam,decrease deflection, and reduce crack width (Nawy and Chen 1998, Svecova and Razaqpiir 2000, Banthia *et al*. 2003). Liang *et al.* (2016) tested the behaviour of concrete beams reinforced with various reinforcement, including ordinary steel bars, CFRP bars and CFRP prestressed concrete prisms(PCP). Liang *et al.* (2016) tested concrete slabs reinforced with CFRP prestressed concrete prisms (PCP) on the flexural behavior. Liang *et al.* (2016) studied mechanical properties

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http://www.techno-press.org/?journal=sem&subpage=8
ISSN: 1225-4568 (Print), 1598-6217 (Online)

Table 1 Mechanical properties of rebars

Reinforcement	Diameter	Yield strength	Ultimate strength	Elasticity modulus
	d/mm	f_y/MPa	f_u/ MPa	E_s/ MPa
Steel bar	8	290	440	2.1×10^5
Steel bar	10	290	435	2.1×10^5
Steel bar	14	365	540	2.0×10^5
CFRP bar	7	------	2200	1.6×10^5

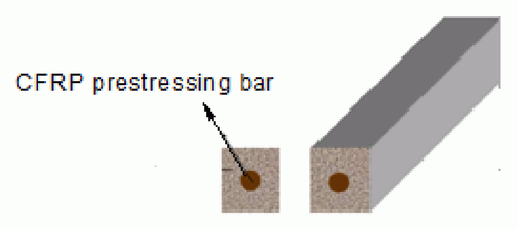


Fig. 1 Typical CFRP prestressed prism

of concrete beams reinforced with CFRP prestressed prisms under reverse cyclic loading.

In this study, the effectiveness of the NSM technique with CFRP prestressed prisms for the flexural strengthening of reinforced concrete beams is assessed. The failure mode, cracking patterns, load carrying capacity, deflection, CFRP strain, ductility of RC beams strengthened with NSM CFRP prestressed prisms was studied.

2. Experimental programme

2.1 Materials

In this test, five concrete beams were designed in accordance with Chinese Code GB50608 (2010). CFRP rebar with diameters of 7 mm was adopted, HPB235 plain rebar with diameters of 8 mm and 10 mm was used for the transverse stirrups and compression reinforcement, respectively; and HRB335 ribbed rebar with diameters of 14 mm was used for the tension reinforcement. Table 1 lists the mechanical properties of the rebars adopted in the beams.

A typical geometry of the prestressed prism that was used in this experimental investigation is shown in Fig. 1. The prisms had a 60×40 mm in cross section, were made of reactive powder concrete (RPC) with a compressive strength of 154 MPa and a tensile strength of 17.4 MPa, expect for the prisms used in one beam, which was made of epoxy mortar with a compressive strength of 75 MPa and a tensile strength of 20 MPa. Prims were concentrically prestressed by a single CFRP rebar. The jacking stresses varied from 880 MPa to 1320 MPa, which are equal to 0.40 to 0.60, respectively, of the guaranteed tensile strength. All beams were cast with normal-strength concrete with a compressive strength of 34.9 MPa and a tensile strength of 2.1 MPa.

2.2 Beam specimens

Table 2 Reinforcement details of all tested beams

Beam number	Prestress (kN)	Prism type	Compressive reinforcement	Stirrup	
				Mid span	Shear span
JBL	——	reactive powder concrete			
PC0	0	reactive powder concrete			
PC1	35	reactive powder concrete	2ϕ 10	ϕ8 @150	ϕ8@60
PC2	43	reactive powder concrete			
HP	35	epoxy mortar			

The experimental program is composed of five reinforced concrete (RC) beams. One of the RC beams was kept unstrengthened, and other beams were flexurally strengthened with NSM CFRP prestressed prisms.The beam dimensions and reinforcement details are shown in Fig. 2. The beam had a rectangular cross section of 150×300 mm, 2.0 m total length, 1.8 m clear span and a shear span of 0.7 m. The longitudinal steel reinforcement is consisted of 3 bars of 14 mm diameter in the tension zone and 2 bars of 10 mm diameter in the compression zone. Steel stirrups of 8 mm diameter spaced at 60 mm in shear span and spaced at 150 mm in flexural span are adopted for transversal steel reinforcement. The general information of the tested beams is represented in Table 2.

2.3 Testing

Beam deflection was measured using linear variable displacement transducers (LVDTs) placed along the beam. Strain gauges were also utilized to measure strains in NSM CFRP reinforcement, internal steel reinforcement and concrete. All specimens were tested under a static four-point load test as shown in Fig. 3. A servo-controlled hydraulic jack with a capacity of 500 kN was used to apply the load to the test beam through a steel spreader beam.

The load was applied in displacement control mode at a rate of 0.5 mm/min, and all data were collected by a data acquisition system. The test set-up is shown in Fig. 3.

3. Results and discussion

3.1 Failure modes and cracking patterns

Three types of failure modes occurred in the test: (a) concrete crushing after steel reinforcement yielded. (Beam JBL); (b) compression failure of concrete beams without rupture of CFRP bar (Beam PC0, Beam PC1, Beam PC2); (c) compression failure of concrete beams with rupture of CFRP bar (Beam HP).

Fig. 4 shows the final crack pattern of the tested reinforced concrete (RC) beams. For beam JBL, the

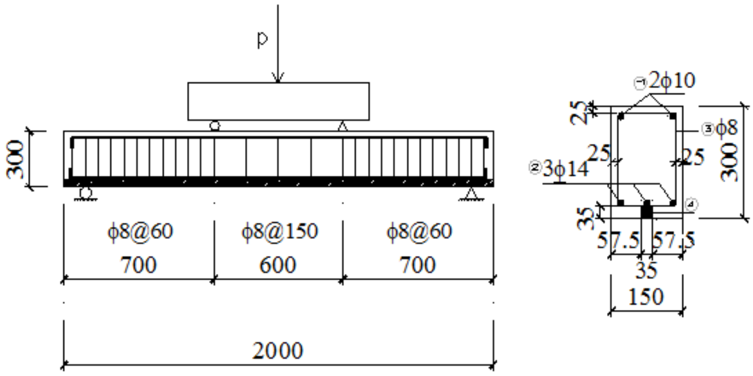


Fig. 2 Tested beam details

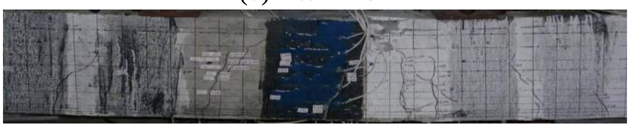
Fig. 3 Test setup

(a) Beam JBL

(b) Beam PC0

(c) Beam PC1

(d) Beam PC2



(e) Beam HP

Fig. 4 Crack patterns of the tested beams

reference beam, exhibited typical flexural behaviors of RC beams during the test. The cracking load was 27 kN and the longitudinal tensile reinforcing steel bars yielded at 143 kN. It failed due to the crushing of the compressed concrete with a maximum crack width of 0.41 mm and a maximum mid-span deflection of 17.48 mm. For beam PC0, the cracking load was 35 kN and the longitudinal tensile reinforcing steel bars yielded at 149 kN. When the concrete cracked, the crack width was 0.018 mm. With the increase of the load, the crack width increased and the crack extended. The flexural-shear cracks then appeared as the load increasing, accompanied by a slight but sharp sound.

When the beam failed, its load was 176 kN. For Beam PC1, PC2, the crack patterns were similar, which mostly were flexural crack together with small flexural-shear cracks. When the beam failed, the sound of gradual rupture of the CFRP could be heard. For Beam HP, the first flexural crack which width was 0.025 mm appears in the mid-span when the load was 36 kN. And the longitudinal tensile reinforcing steel bars yielded at 200 kN. It failed due to the crushing of the compressed concrete of concrete beams with rupture of CFRP bar.

3.2 Load carrying capacity of the tested beams

Table 3 provides the summary of the results of the tested beams in terms of cracking load (P_{cr}), yielding load (P_y), ultimate load (P_u). Based on Table 5, the cracking load, yielding load and ultimate load of beam PC0 strengthened with non-prestressed NSM CFRP prism are 29.6%, 4.2%, 7.9% higher than those of the reference beam JBL, respectively. The cracking load of beam PC1, PC2, HP (strengthened with NSM CFRP prestressed prisms) are 51.9%, 51.2%, 33.3% higher than that of the reference beam JBL, respectively. The yielding load of beam PC1,

Table 3 Summary of the results in terms of loads

Beam ID	P_{cr} (kN)	$\frac{P_{cr,SB}-P_{cr,JBL}}{P_{cr,JBL}}$ (%)	P_y (kN)	$\frac{P_{y,SB}-P_{y,JBL}}{P_{y,JBL}}$ (%)	P_u (kN)	$\frac{P_{u,SB}-P_{u,JBL}}{P_{u,JBL}}$ (%)
JBL	27	—	143	–	163	—
PC0	35	29.6	149	4.2	176	7.9
PC1	41	51.9	159	11.2	177	8.6
PC2	41	51.9	187	30.8	196	20.3
HP	36	33.3	200	39.9	235	44.2

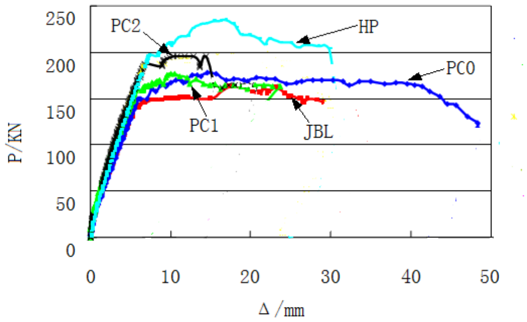


Fig. 5 Load-deflection curves for the test beams

PC2, HP (strengthened with NSM CFRP prestressed prisms) are 11.2%, 30.8%, 39.9% higher than that of the reference beam JBL, respectively. The ultimate load of beam PC1, PC2, HP (strengthened with NSM CFRP prestressed prisms) are 8.6%, 20.3%, 44.2% higher than that of the reference beam JBL, respectively. This indicates that the load-carrying behavior of the beam can be improved significantly by using the NSM CFRP prestressed prisms. The yielding load and ultimate load of the tested beams in the same prisms material has increased with the increase of the prestress level in the CFRP prestress prisms. And it is obvious that the load capacity of the strengthened beams in the same prestress level of the CFRP prestress prisms depended on the prisms material. The cracking load of beam PC1 (strengthened with NSM CFRP prestressed prisms, which was made of reactive powder concrete (RPC)) are higher than that of the beam HP (strengthened with NSM CFRP prestressed prisms, which was made of epoxy mortar). The yielding load and ultimate load of beam HP (strengthened with NSM CFRP prestressed prisms, which was made of epoxy mortar) are higher than that of the beam PC1 (strengthened with NSM CFRP prestressed prisms, which was made of reactive powder concrete (RPC)).

3.3 Load-deflection response

Fig. 5 shows the load-deflection curves for beams strengthened with NSM CFRP prestressed prisms. It can be seen that in general the load-deflection curves present an approximate tri-linear response defined by elastic stage, crack propagation stage and ultimate stages. In the first stage, before concrete cracking, the deflection increased linearly as the applied load increased. At this stage, a bit differences in the initial flexural stiffness were observed for the test beams. This shows that using NSM CFRP prestressed prisms had a little effect on the stiffness in the elastic stage. In the second stage, from concrete cracking to steel yielding, the initial stiffness change and the cracks developed constantly as the load increased. The curve exhibited the NSM CFRP prestressed prisms increased the stiffness, cracking load and yielding load. But the shape of load-deflection curves of the specimen was similar. The last stage started from the steel yielding to the failure occurred. In this stage, the deflection increased at a higher rate than in the previous stage, and the load remained relatively stable. During this stage, the crack width of the test beams can be limited by the NSM CFRP prestressed prims. And the deflection can be controlled by the NSM CFRP prestressed prims. In general, the behavior of the reinforced concrete beams strengthened with NSM CFRP prestressed prisms showed a significant increase in the load-carrying capacity and the deformation capacity compared to the reinforced concrete beams. Using NSM CFRP prestressed prisms resulted in a reduction of the crack width and the deflection.

3.4 Strain in CFRP bars and tensile steel reinforcements

Fig. 6 shows the relationship between the applied load and the CFRP strain or steel strain. According to the load-strain curves of the tested beams have a common configuration formed by the three phases: (1) before concrete cracking, where the CFRP strain variation is almost null; (2) between concrete cracking and the steel reinforcement yielding, the strain increased as the load increased; (3) between the steel reinforcement yielding and the ultimate load, the CFRP strain increased at a higher rate, but the load remained relatively stable. The load-CFRP strain curves present an approximate non-linear response. And the utilization of the NSM CFRP prestressed prisms with higher prestress level was fully developed.

3.5 Ductility

Ductility is the ability of the structures to sustain large deformations without a decrease in load resistance and it is necessary for reinforced concrete beams to provide early warning of failure. Ductility has generally been measured by a ratio called the ductility factor or index ($u = \frac{\Delta_u}{\Delta_y}$) corresponding to a deformation (such as curvature, deflection, rotation) at failure (Δ_u) divided by the

Table 4 Deflection and ductility coefficient of the beams

Beam ID		JBL	PC0	PC1	PC2	HP
Yield	Δ_y (mm)	5.63	6.23	5.68	6.75	7.24
Peak	Δ_u (mm)	17.48	14.59	13.01	14.50	16.75
Ductility coefficient μ		3.10	2.34	2.29	2.15	2.31

corresponding value at yielding (Δ_y). The experimentally measured values of ductility coefficient were listed in Table 4.The value of ductility coefficient ranged from 2.15 to 2.34 for the beams strengthened with NSM CFRP prestressed prisms.

As can be seen in Table 3, the increasing prestress level of CFRP prestressed prisms, which were made of reactive powder concrete (RPC), could decreased the ductility of the strengthened beams. The ductility coefficient of beam HP (strengthened with NSM CFRP prestressed prisms,which was made of epoxy mortar) are higher than that of the beam PC2 (strengthened with NSM CFRP prestressed prisms, which was made of reactive powder concrete (RPC)).

4. Conclusions

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

• Failure of the reinforced concrete beams strengthened with NSM CFRP prestressed prisms occurred by crushing of the compressed concrete without rupture of CFRP bar, or crushing of the compressed concrete with rupture of CFRP bar.

• Regardless the prestress level of the CFRP prestressed prisms, the NSM technique with CFRP prestressed prisms is highly effective for the flexural strengthening of RC beams.

• The behavior of the reinforced concrete beams strengthened with NSM CFRP prestressed prisms showed a significant increase in the load-carrying capacity and the deformation capacity.

• Using NSM CFRP prestressed prisms resulted in a reduction of the crack width and the deflection.

• Because of its efficiency, the NSM CFRP prestressed prisms strengthening technique could be considered as an effective method for repairing RC structures.

Acknowledgments

This work was supported by the Chinese National Natural Science Foundation (No. 51368001), the Natural Science Foundation of Jiangxi Province for Distinguished Young Scholars (No.20162BCB23051),the Technology Support Project of Jiangxi Province (20161BBH80045),the Open Project Program of Jiangxi Engineering Research Center of Process and Equipment for New Energy, East China Institute of Technology (No.JXNE-2014-08) and the Opening Project of Guangxi Key Laboratory of Disaster Prevention and Structural Safety (No. 2013ZDK01), which are gratefully acknowledged.

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