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Performance of Concrete Beam Strengthened with Prestressed Sprial Steel Wires

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Abstract

In view of the defects and limitations of the existing reinforcement methods, it is necessary to put forward a reinforcement method with better interfacial bond performance, more convenient construction and economical reinforcement. A new reinforcement technique with prestressed spiral steel wires was presented, and one control beam, three strengthened beams under monotonic loading were tested. Under the same initial prestressing level, the amount of reinforcement and different groove sizes, the flexural capacity, load-deflection relationship, crack and deformation of reinforced concrete beams were systematically investigated. Results show that the reinforcement technique can significantly improve the first-crack load, steel-yielding load, ultimate load of the beams, and improve the service performance of the strengthened beams. The high performance of the spiral steel wires is allowed for better utilization. The conclusions obtained in the study are of important reference value to direct the similar engineering practice.

Keywords: Concrete beams, Spiral finned steel wires, Near surface mounted, Reinforcement technique

1. Introduction

Due to various natural factors and human error, the structural bearing capacity is gradually reduced, and corresponding maintenance and reinforcement measures should be taken to meet the requirements for use. Although the present concrete reinforcement methods can improve the structural capacity to a certain extent, fiber reinforced polymer (FRP) reinforcement technology is the most widely used, but both traditional reinforcement methods and FRP reinforcement techniques have their own limitations [1].

Traditional reinforcement technology has some defects, such as large construction space, long construction period, large self-weight, limited use conditions and poor corrosion resistance, while FRP has such characteristics as high cost, brittle failure, and low shear strength. Both external paste and embedded FRP are prone to bonding failure, and special anchors are needed when FRP is used as prestressed tendon.

In view of the defects of the above reinforcement technology and the reinforcement material itself, it is of practical significance to put forward a new reinforcement material and the corresponding reinforcement technology. So, the purpose of this study is to put forward a new reinforcement method and verify the feasibility through the experimental study, the performance of the reinforcement material and the construction technology.

2. State of the Art

Over the past years, some scholars have studied the bonding properties, fire resistance performance, high temperature properties and seismic performance of FRP reinforced concrete (RC) beams [2-4]. Nigro et al. provided a conceptual approach to fire safety checks for bending moment resistance of FRP-RC members and suggested a simplified design method for sagging bending moment resistance of FRP-RC slabs in fire situations with reference to thermo-mechanical analysis [2]. Najafabadi et al. investigated the mechanical properties of glass and carbon FRP bars with epoxy resin matrices embedded in concrete under an extensive range of elevated temperatures and embedded FRP bars with various bar diameters [3]. Lin and Zhang modelled several FRP-reinforced concrete beams by using a recently developed a two-node layered composite beam element and investigated the effect of different surfaces of FRP reinforcing bars on the structural response of FRP-reinforced concrete beams with bond-slip effect [4].

The performance of near-surface mounted (NSM) FRP concrete columns and the nonlinear analysis method, bending behavior and fatigue performance of NSM FRP concrete beams were also studied by some experts [5-8]. For example, Al-Saadi et al. reviewed current research status of the concrete members retrofitted by NSM FRP system under monotonic and fatigue loading, they also summarized the fatigue properties of FRP composites and concrete, steel and FRP materials [5]. These studies have shown that the reinforcement technology NSM FRP has the bonding failure, the strain of non-prestressed FRP is delayed, and the crack resistance performance of the strengthened beam is not improved, so the prestress of FRP is needed to improve the above defects [6-8].

For the punching behaviour of concrete column-slab connections reinforced with non-prestressed and prestressed CFRP plates, the flexural bearing capacity, the crack width prediction and the shear reaction analysis, the bonding performance and the shear performance of pre-stressed CFRP concrete beams, Abdullah and Bailey built a three-

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dimensional finite element model to predict the punching behaviour of concrete column-slab connections which incorporate bonded non-prestressed and prestressed CFRP plates to the tension surface of the slab [9]. Peng and Xue proposed a simple design method for the flexural capacity of prestressed and non-prestressed FRP reinforced concrete beams [10]. Atutis et al. focused on crack width prediction and shear response analysis of the prestressed concrete (PC) beams [11]. Kara et al. estimated the curvature, deflection and moment capacity of the reinforced concrete beams and predicted the moment-curvature relationship [12]. Abdullah et al. studied the adhesion of non-prestressed and prestressed carbon fiber reinforced polymer plates to concrete column-to-board joints. They found that the development of the critical diagonal crack was the main reason for the reduction in the ultimate capacity of the strengthened slabs [13]. Moustapha and Thomas experimentally evaluated the impact of CFRP amount and strip spacing on the shear behavior of PC beams and evaluated the Fiber-Reinforced Polymer shear capacity of PC beams [14-15]. Si-Larbi et al. carried out experimental on many large-scale beams strengthened by well-known reinforcement techniques, such as externally bonded CFRP plate and the NSM technique, which were compared to the proposed new strengthening material through four-point bending tests [16]. These studies have shown that the reinforcement technology prestressed FRP can improve reinforcement performance and have good reinforcement effect, especially good crack resistance performance [17-18]. But the prestressed FRP needs special anchor, and the FRP has a low shear strength and high cost in raw material. So the reinforcement technology of NSM prestressed spiral steel wire was proposed in this study. The experimental research was carried out to analyze the flexural capacity and bearing capacity of NSM prestressed spiral steel wire. The flexural relationship, crack and deformation of reinforced concrete beams were summarized, and the direction of further research was proposed.

The rest of this study is organized as follows. Section 3 describes the test method and samples preparation. Section 4 gives the results analysis and discussion, and finally, the conclusions are summarized in Section 5.

3. Methodology

3.1 Experimental materials

The sprial steel wire was made of high-quality carbon steel by special spiral model and formed screw longitudinal ribs of high-strength steel wire through the electromagnetic induction and tempering. Its diameter was 7.00 mm and the tensile strength was 1.57 GPa, marked as: prestressed steel wire 7.00-1570-WLR-H-GB/T5223-2002. The mechanical properties of the sprial steel wire are shown in Table 1.

The grade of concrete strength was C30, and the average value of cube compressive strength was 27.7 MPa. The mechanical properties of steel bar are shown in Table 2.

Table 1. Mechanical performance of the spiral steel wire.

Nominal diameter (mm)	Tensile strength (GPa)	Yield strength (GPa)	Elastic modulus (GPa)	Elongation (%)
7.00	1.57	1.38	205	3.5

The structural adhesive used in this test is JGN epoxy structural adhesive produced by Dalian Institute of Chemical Physics, China. The adhesive has high tensile properties, good impact resistance, and fatigue resistance. The technical indicators of JGN epoxy structural adhesive meet the requirements of “Design Code for Concrete Structure Reinforcement” (China GB50367-2006) [19]. The test results are shown in Table 3.

Table 2. Mechanical properties of the steel bar.

Steel types	Yield strength (MPa)	Ultimate strength (MPa)	Elastic modulus (GPa)	Elongation (%)
Ø8	325	490	2.10	23
Ø14	378	556	2.00	54

Table 3. Test results of JGN adhesive.

Project title	Detection conditions (°C)	Performance index (MPa)	Test results (MPa)	Evaluation results
Axis tensile strength	25±2	≥33	40.1	qualified
Tensile elastic modulus	25±2	≥3600	3800	qualified
Elongation	25±2	≥1.5	2.4	qualified
Compress strength	25±2	≥90	98.8	qualified
Bend strength	25±2	≥45	66.9	qualified
Shear strength Steel-steel	25±2	≥21	21.4	qualified
Bond strength Steel-concrete	25±2	≥2.5	3.6	qualified

3.2 Specimen configuration

The beams were designed as a simple rectangular support with a cross section of 150 mm × 300 mm and a beam length of 2400 mm. The calculated span was 2100 mm. The longitudinal steel reinforcements were 2ø14 and the erection bars were 2ø8. The stirrups at 1/3 of the beam across were provided by using 8 mm smooth stirrups spaced at 150 mm, and shear reinforcement at 1/3 of the supports were placed at a spacing of 100 mm. The net cover of longitudinal steel reinforcements a_s =30 mm, and that of the erection bars a_s' =25 mm, then the effective height of the concrete beams h_0 =270 mm. Open groove shape of the strengthened beams is rectangular, and the groove size was 10 mm × 20 mm, 15 mm × 20 mm, 20 mm × 20 mm, respectively.

The reinforcement scheme is shown in Table 4, and the groove sizes and reinforcement drawing is shown in Fig. 1.

3.3 Test loading device

The test loading was carried out under a static monotonic loading according to “Standard Methods for Testing of Concrete Structures” (China GB50152-92) [20]. Servo press of 500 kN was used in this test. The loading was divided into three stages, including preload, standard load and failure load. The size and speed of loading were controlled by the computer. The content of the measurement includes the mid-span deflection, the strain of steel bar, and sprial finned steel wires, the crack load, yield load, ultimate load and so on. The practical loading for the test is shown in Fig. 2.

Table 4. Reinforcement scheme of test.

Beam	Open groove shape	Groove width (mm)	Groove depth (mm)	Number	Tension control (MPa)
RB	—	—	—	—	—
BPS2-10	Rectangle	10	20	2	981.25
BPS2-15	Rectangle	15		2	
BPS2-20	Rectangle	20		2	

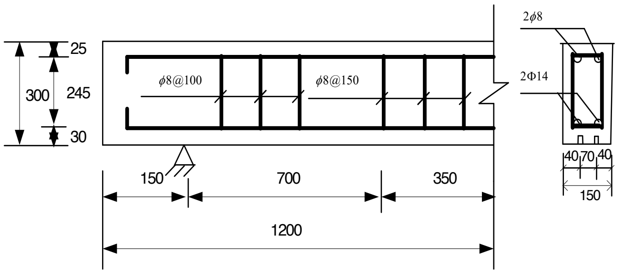


Fig. 1. Groove sizes and reinforcement drawing.

Fig. 2. Practical loading for specimens.

4. Results Analysis and Discussion

4.1 Bearing capacity analysis

The significant loads of the beams are shown in Table 5, including the crack load, the yield load, and the ultimate load. From Table 5, we can see that the significant loads of the strengthened beams are improved observably compared to the control beam. BPS2-15 was the most obvious one, and the increments were 641%, 154%, and 97.93%, respectively. The characteristic values of the strengthened beams increased with groove width increasing, but the bearing capacity of the strengthened beam reduced and shear compression failure wolud occur under the oversized groove.

Table 5. Significant values for load.

Beam	Crack load (kN)	Improve (%)	Yield load (kN)	Improve (%)	Ultimate Load (kN)	Improve (%)
RB	10.0	—	55	—	99.6	—
BPS2-20	68.8	580	110	100	172.3	72.9
BPS2-15	74.1	641	140	154	197.2	97.9
BPS2-10	69.8	598	120	118	190.2	90.9

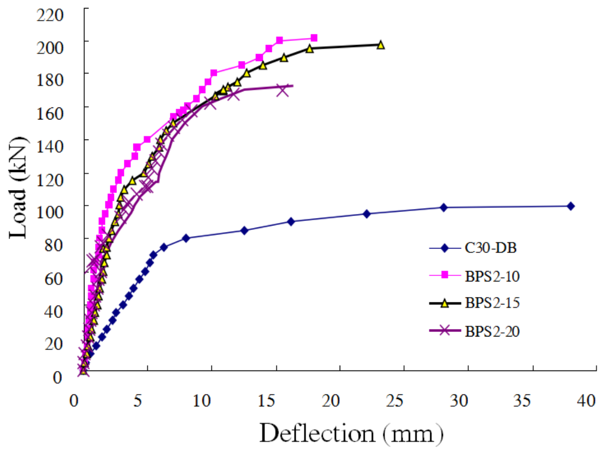
4.2 Load-deflection analysis

The actual measurement of the load-deflection curve is shown in Fig. 3.

It can be seen from Fig. 3 that the development process of all the curves is basically similar, and there are two turning points: the cracking point and the yield point of the steel bar. The deflection of the strengthened beam is significantly reduced compared to the control beam. In addition, the load-deflection curve is a linear change, and the deflection changes relatively little before the concrete cracks. The deflection of the strengthened beam has little effect on the size of the groove.

From the concrete crack to the yielding stage of the steel, the load-deflection curve is close to a straight line. As the size of the groove increases, the deformation trend becomes smaller, but the effect is not obvious. From the yield stage to the damage stage, the curve exhibites a nonlinear change. As the groove size increases, the amount of deformation increases rapidly. In summary, BPS2-15 is an ideal reinforcement method in this test.

Fig. 3. Load-deflection curve of specimens.



4.3 Strain analysis of sprial finned steel wire and steel

The graph of Load-reinforcement strain is shown in Fig. 4. In which *S* represents bars and *H* represents sprial finned steel wires. From the curves, we can see that the stress-strain curve of steel is similar to spiral rib steel wires in each stage basically.

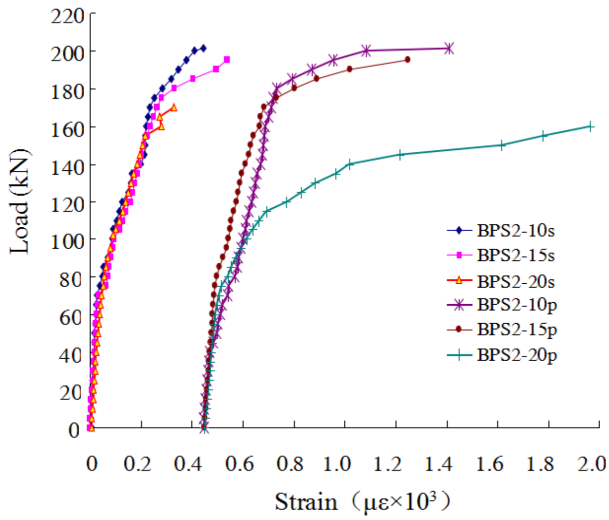
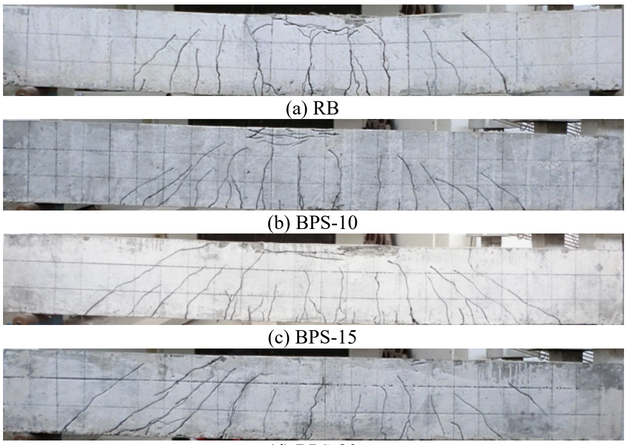


Fig. 4. Load-midpoint strain covers of specimens.

As shown in Fig. 4, at the concrete cracks and the steel-yielding stage, the initial prestress will make the strain of sprial finned steel wire ahead. Under the same load, the steel strain of prestressed reinforced concrete beam is less than that of the control beam, indicating that prestressed sprial finned steel wire can delay the steel strain. After the steel-yielding stage, the strain of sprial finned steel wire decreases slowly with the groove size increasing.

4.4 Crack distribution situation

Fig.5 is the situation of crack distribution. Compared with the control beam, the developing process of the crack of the strengthened beams is shown in Fig.5.



(a) RB

(b) BPS-10

(c) BPS-15

(d) BPS-20

Fig. 5. Cracks distribution.

Compared with the control beam, the crack width of the strengthened beams decreased obviously, but the amount of the major crack was bigger and the crack spacing decreased with the groove size increasing. When the groove size (BPS2-20) was large enough, the overall performance of the strengthened beams reduced, and the bearing capacity of the strengthened beams and the development of crack would be affected.

It can be seen from Fig. 5, the new reinforcement method can effectively prevent the development of cracks and significantly reduce the width of cracks. Therefore the bending rigidity of the strengthened beams will improve.

5. Conclusions

Based on the test about four reinforced concrete beams NSM prestressed sprial finned steel wire, the flexural capacity, load-deflection relation, cracks and deformation of reinforced concrete beams with prestressed NSM sprial finned steel wire were analyzed, and the main results are as follows:

(1) Compared with the control beam, the crack load, yield load and ultimate load of the strengthened beam were significantly improved. Among them, BPS2-15 was the most obvious, with increments of 641%, 154%, and 97.93%, respectively. The results show that the crack load of the strengthened beam is improved obviously, and the improvement on the ultimate load is less. Sprial finned steel wire has good comprehensive properties with strong bond property, good toughness, elastic modulus, tensile strength and shear strength, which make up for the deficiency of FRP fiber material.

(2) The crack load of the strengthened beams increased with the increase of the groove width, but the bearing capacity of the strengthened beam will be reduced and shear compression failure may occur under the oversized groove. The NSM prestressed sprial finned steel wire construction technology is simple, so it is a kind of reinforcement method with remarkable effect.

(3) The reinforced concrete beam strengthened with prestressed NSM sprial finned steel wire can effectively reduce the deflection and crack width of the strengthened beam, improve stiffness of the strengthened and prolong the service life of the strengthened beam.

There are still some problems to be further improved and developed. Due to the limitation of time and conditions, only a small number of test beams were studied, a large amount of experimental researches and numerical simulations are required. Short-term static load test of the reinforced concrete beam is mainly carried out, the research work under long-term load, fatigue load and seismic load are still needed.

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