Article

Experimental Research on the Flexural Performance of RC Rectangular Beams Strengthened by Reverse-Arch Method

Tao Yu, Quansheng Sun ^{*}, Chunwei Li and Yancheng Liu

School of Civil Engineering, Northeast Forestry University, Harbin 150040, China; yutao.edu.cn@nefu.edu.cn (T.Y.); lichunwei@nefu.edu.cn (C.L.); yanchengliu@nefu.edu.cn (Y.L.)

* Correspondence: sunquansheng@nefu.edu.cn

Abstract: Carbon fiber-reinforced polymer (CFRP) reinforcement technology has been widely used in the reinforcement of reinforced concrete (RC) beams. At this stage, high prestressed CFRP board reinforcement is often used in actual reinforcement. However, most reinforced bridges are designed for a long time, and the design value of the protective layer is low, and it is impossible to achieve a large prestressed tension. Therefore, this paper proposes the reverse-arch method to paste the CFRP board and apply low prestress to strengthen the symmetrical RC beam. Through the three-point forward loading test, the cracking load, ultimate load, crack width, mid-span deflection, strain and failure mode of a reverse-arch method-pasted CFRP board-reinforced beam, a directly pasted CFRP board-reinforced beam and an unreinforced beam are compared. The results show that the load-bearing capacity and stiffness of the test beam can be improved by pasting CFRP plates with anti-arch method, but the ductility of the test beam is reduced. Compared with the unreinforced beam, the maximum cracking load and ultimate load are increased by 56% and 63% respectively. The reverse-arch method can produce low prestress, improve the stiffness and bearing capacity of members, and has a good prospect of engineering application.

Keywords: reverse-arch method; reinforced concrete beam; flexural performance; CFRP plate

Citation: Yu, T.; Sun, Q.; Li, C.; Liu, Y. Experimental Research on the Flexural Performance of RC Rectangular Beams Strengthened by Reverse-Arch Method. *Symmetry* **2021**, *13*, 1666. <https://doi.org/10.3390/sym13091666>

Academic Editor: Massimo Latour

Received: 18 August 2021

Accepted: 8 September 2021

Published: 9 September 2021

Publisher's Note: MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

The principle of CFRP [1] board reinforcement of concrete members is to use structural adhesive to stick CFRP material on the surface of concrete to form a new structural bearing system, so that the CFRP board participates in the force, so as to achieve the purpose of strengthening the concrete. The salient features of this reinforcement method are mainly manifested in two aspects: the CFRP's material properties and reinforcement methods. CFRP board has the advantages of low weight, high strength, good corrosion resistance, low thermal expansion coefficient, strong designability and good fatigue resistance, and has been widely used in the field of reinforcement [2,3]. Generally, there are three types of CFRP board reinforcement method [4]: direct external pasting reinforcement technology [5,6], surface embedding reinforcement technology [7,8], prestressed reinforcement technology [9,10]. In direct externally attached CFRP board reinforcement and surface-layer embedded CFRP board reinforcement, due to the existing load (self-weight and other additional external loads) of the structure before reinforcement, the strain of the CFRP plate will obviously lag behind the strain of the reinforced structure, making the CFRP board unable to fully demonstrate its excellent characteristics. The prestressed carbon fiber board can solve the above problems well. Therefore, applying prestress to the CFRP board is a hot topic in current research. There are two common methods for applying prestress at this stage. The first method is to stretch the CFRP plate directly on the reinforced beam itself through the anchoring system, and maintaining the prestress through permanent anchors [11]. The second method is to use a separate tensioning system—first, a special tensioning system is used to apply tension to the CFRP board to generate prestress, and

then the lifting system is used to paste the tensioned CFRP board to the bottom surface of the beam, and the tensioning system is removed after the colloid is cured.

The study found that the application of prestressed CFRP panels to the reinforcement of RC beams can effectively control the development of cracks and improve the bearing capacity of the reinforcement members. In the research into prestressed CFRP reinforcement, Khuram Rashid et al. [12] studied the flexural performance of reinforced concrete beams strengthened with carbon fiber sheets under different prestress levels. Xu Fuquan et al. [13] analyzed the flexural performance of reinforced concrete simply supported beams strengthened with prestressed carbon fiber plates and discussed the calculation method of prestressed CFRP strengthened beams. Kang Kan et al. [14] independently developed a CFRP plate tension anchor system and conducted a prestressed CFRP plate strengthening flexural performance test on six concrete beams. Deng Langni et al. [15] studied the calculation method of the flexural bearing capacity of the typical section of concrete beams strengthened with a prestressed CFRP plate. Based on the limit state of the flexural section, the calculation formulas for the flexural bearing capacity of the typical section under two failure modes were analyzed. Moshiri and Niloufar et al. [16] used prestressed CFRP composites to reinforce RC beams. They used the externally pasted groove method to delay the premature degumming of CFRP composites and compared them with conventional external pasting methods. The above two methods both require expensive CFRP tensioning equipment, and the construction is complicated. Using the reverse-arch method to attach CFRP board reinforcement can apply to prestress and effectively solve the secondary stress problem of concrete [17]. In terms of the basic theory of applying prestress by the reverse-arch method, Chen Daiguo et al. [18] used ANSYS® (ANSYS, Canonsburg, PA, USA) simulation calculation and analysis to strengthen the carbon fiber concrete beam with the reverse-arch method. They concluded that the carbon fiber reverse-arch method strengthened the concrete beam better than the traditional carbon fiber reinforcement. Zhao Qilin et al. [19] proposed a “reverse arch prestress technology” using a CFRP plate to reinforce steel structures. Through theoretical deduction, it is found that the bearing capacity of steel structures can be effectively improved under the strength design criteria. Liang Dong et al. [20] used the external prestress method to realize the inverted arch to prestress the carbon fiber cloth, strengthening the ordinary reinforced concrete beam. By deducing the calculation formula and calculating the example, the effectiveness of the reinforcement method was verified.

This paper proposes the reverse-arch method loaded with a CFRP plate. The jacking system is used near the middle of the beam span to make the beams arch upward. After inverting the arch, the CFRP plate is pasted on the bottom of the beam. After the colloid is cured, the jacking system is removed to generate prestress in the CFRP plate. The reverse-arch method of applying prestress avoids the use of professional anchors and reduces the cost. However, since the reverse-arch method of pasting CFRP is mostly in the theoretical stage, few experimental studies are available. In this paper, the reverse-arch method is used to reinforce concrete beams with CFRP. Compared with the non-reinforced beams and the rectangular beams reinforced with a CFRP plate, the flexural bearing capacity is studied. The development of deflection, strain, and cracks under load is studied.

2. Materials and Methods

2.1. Reverse-Arch Method Strengthening Reinforced Concrete Beam

The reverse-arch method is proposed compared to the traditional method of directly pasting CFRP plates to strengthen RC beams. Pasting the CFRP plate in the inverted arched state can effectively solve the secondary stress problem after the RC beam is reinforced. In this paper, the principle of applying prestress by the reverse-arch method is as follows: firstly, a rubber pad is placed at the contact point of the RC beam and the reaction beam. At the mid-span position of the test beam, a jack is used to cause reverse deflection in the beam, and then a CFRP plate is pasted on the bottom of the beam. The jack is removed

after the glue is cured. The CFRP plate and the original RC beam enter the working state simultaneously, as shown in Figure 1.

Figure 1. Reinforced arch method.

When the RC beam is inverted, the original compression zone of the RC beam becomes the tension zone. Due to the low reinforcement ratio in the original compression zone of RC beams, the initial compression area is easy to crack, so the inverted arch arc adopted in this paper is the critical condition for micro-crack occurrence in the RC beam [21]. Suppose that the inverted arch arc is too large. In that case, the RC beam's initial compression zone crack width will be too large, and the reinforced beam will fail prematurely when the compression zone concrete is loaded during the stress process, which will affect the concrete beam's bearing capacity.

Figure 2 shows the relationship between the anti-arch force value and the mid-span deflection. The dotted line in the figure is the limit value of the reverse arching force, and the cracking load of the structure under reverse bending is generally selected. The inverted arch force value can be selected at between 90% and 100% of the inverted arch force limit value. The ascending section in the figure is the process of applying anti-arch force, and its slope is the stiffness of the unreinforced structure. The descending section is a reverse arch unloading process, and its slope is the rigidity of the reinforced structure. The structure is reinforced with CFRP board by means of the reverse-arch method. When the anti-arching force value reaches the designated anti-arching force value, the load is held and the CFRP board is pasted. After the colloid is cured, the anti-arching force is slowly removed. The unloading curve of the structure is shown in Figure 1 as the unloading process curve of the reverse arch. Because the overall rigidity of the structure is significantly higher than that before the inverted arch reinforcement of the CFRP plate, when the inverted arch force is unloaded to 0 kN, the structure will have a pre-arch degree, and the CFRP plate will generate pre-stress or advanced strain during the inverted arch unloading process. It is easy to see that the magnitude of CFRP reverse arch prestress is obviously positively correlated with the value of reverse arch force in the structure.

Figure 2. Load–displacement curve of the mid-span during reinforcement by means of the reverse-arch method.

2.2. Test Beam Design

2.2.1. Reinforcement Design

A total of 3 simply supported beams with a rectangular cross-section are used. The concrete design strength grade is C30. All components are of uniform size and are of symmetrical structure. The total length is 3000 mm, the calculated span is 2700 mm, and the pure bending section is 900 mm. The section size is $b \times h = 150 \text{ mm} \times 300 \text{ mm}$. The main reinforcement of the test beam adopts two long $\Phi 18$ HRB400 threaded steel bars, and the longitudinal reinforcement ratio is 1.212%. The erecting reinforcement adopts two full-length $\Phi 8$ HPB300-grade threaded steel bars. The stirrups are made of $\Phi 8$ HPB300-grade smooth round steel bars, the form is double-limb stirrups. The specific longitudinal arrangement of stirrups is as follows: arrange 18 groups at a distance of 100 mm starting from half of the bending section; they are arranged symmetrically from the middle of the beam. In the middle of the shear bending section to the side of the fulcrum, seven groups are arranged every 80 mm. They are cured for 28 days after pouring is completed. The test beam size and reinforcement are shown in Figure 3, while the test beam size and reinforcement method are shown in Table 1.

Figure 3. Specimen size, interface, and reinforcement.

Table 1. The test beam size and reinforcement method.

Testing Specimens	Notation	Concrete Strength	Length (mm)	Section Dimensions (mm)	Paste Method
Concrete beam	R ₀	C30	300	30 × 15	/
Paste CFRP concrete beam	CFRP-R ₁	C30	300	30 × 15	Directly pasting
Paste CFRP concrete beam	CFRP-R ₂	C30	300	30 × 15	Reverse-arch method

(Annotation: “/” in the table means there is no corresponding parameter).

2.2.2. Material Performance

According to the requirements of the ordinary concrete mechanical properties test standards (GB/T 50081-2011) [22], the synchronous curing specimen test result shows that the concrete strength of the main beam is 32.4 MPa. The concrete compression test is shown in Figure 4.

Figure 4. Concrete compression test.

In the test, two kinds of steel were used—the primary reinforcement was HRB400, and the stirrup and erecting reinforcement was HPB300. According to the standard test method requirements for tensile testing of metallic materials (GB/T 228-2010) [23], the mechanical properties of the steel bars were measured and are listed in Table 2. Figure 5 shows the steel bar tensile testing machine.

Table 2. Mechanical properties of the steel bars in the RC beams.

Rebar Type	Yield Strength (MPa)	Tensile Strength (MPa)	Elastic Modulus (GPa)
HRB400	412.2	6610.8	202
HPB300	314.8	512.7	208

Figure 5. Steel tensile tests.

The CFRP plate used in this article was produced by Tianjin CABEN[®] Technology Group Co., Ltd. (Tianjin, China) with a specification of 2×100 mm. The density of the CFRP plate was $1.5\text{--}1.6$ g/cm³, and the volume content of carbon fiber was $\geq 65\%$. The carbon fiber tensile test is shown in Figure 6. The adhesive glue used was carbon fiber board matching glue (AB glue), with a glue sample preparation ratio: A:B = 2:1. It meets the technical requirements of Class I glue in the long-term performance appraisal standard of structural glue. The main performance indexes of CFRP plate and carbon board glue are shown in Table 3.

Figure 6. Tensile test of carbon fiber.

Table 3. Technical parameters of CFRP plate and carbon glue.

Material	Width (mm)	Thickness (mm)	Tensile Strength (mm)	Concrete Tensile Modulus (MPa)	Interlaminar Shear Strength (MPa)	Compressive Strength (MPa)	Elongation (%)
CFRP Plate	100	2	2617.8	1.9×10^5	54.1	/	1.7
CFRP plate glue	/	/	49.2	4543	/	108.4	1.64

(Annotation: “/” in the table means there is no corresponding parameter).

2.2.3. Test Plan and Measuring Point Layout

The experimental test plan of this article is shown in Figure 7. The test adopted Yangzhou Jingming static acquisition system, All sensors (pressure sensors, displacement gauges, strain gauges) were connected to the Yangzhou Jingming static acquisition instrument to achieve synchronous recording. The displacement meter adopted a linear variable differential transformer displacement meter (LVDTs[®]). The crack observation used the Haichuang Hi-Tech[®] crack observation instrument. The sensor used a 300 kN sensor, while a 300 kN screw hydraulic jack is used for loading.

The test used the load control index to load; before reaching the cracking load, 30% of the cracking load was taken as the first-class load. When the specimen cracked and before the yield load was reached, 5% of the yield load was taken as the first-class load. After reaching the yield load value, the displacement control index was used for loading, taking 20% of the total displacement that occurred when the yield load was reached as the first-class load. The test was conducted until the specimen was damaged, the concrete in the upper compression zone of the specimen was crushed and the test was terminated.

Figure 7. Experimental test plan.

In the text, the R_0 beam was not reinforced. The CFRP- R_1 beam was a rectangular beam strengthened by directly pasting a carbon fiber plate onto it. The CFRP- R_2 beam was a rectangular beam reinforced with a carbon fiber board pasted using the reverse-arch method. The length, width, and thickness of the carbon fiber sheet were 2400, 100, and 2 mm, respectively. In order to facilitate the observation of the test phenomenon and the distribution of cracks during the test, the two sides of the beam were painted, and the test beam was divided into a standard grid of 50 mm $\times$ 50 mm. The supported beam arranged the test conditions. During the test, according to the standard for test methods of concrete structures (GB/T50 152-2012) [24], the three-point downward loading method was adopted, and the distribution beam was used, and the length of the distribution beam was 1500 mm. The left side of the support method was the fixed-pin pedestal, with the sliding support on the right; the supporting mode of the distribution beam was consistent with that of the test beam. The pressure sensor was arranged in the middle of the RC beam. The field loading is shown in Figure 8.

Figure 8. R_0 beam loading equipment.

To measure the strain of concrete, steel bars, and CFRP panels, resistance strain gauges were used to measure the strain of each material on the steel bar, CFRP plate, and concrete. The strain gauge parameters are shown in Table 4. Additionally, the strain gauges were organized symmetrically. Six 5 $\times$ 3 mm strain gauges were pasted on the primary reinforcement at the bottom of the beam. Six 5 $\times$ 3 mm strain gauges were pasted on the pure bending section of the CFRP plate. Five strain gauges with dimensions of 100 $\times$ 3 mm were pasted on the side of the test beam in the middle. We used the acquisition instrument

to record data in real-time to analyze the strain changes of the test beam during the test. Displacement sensors were arranged at the fulcrums on both sides of the test beam, the mid-span, and the positions of the two loading points. The strain gauge, displacement sensor and pressure sensor all used the same acquisition system. The strain gauges were measured using a 1/4 way bridge with temperature compensation, and the displacement and pressure transducers were both measured using a full bridge. In order to reduce measurement data errors, the temperature in the test room was consistent to ensure a stable test environment and reduce external interference. The strain and deflection arrangement of the test beam is shown in Figure 9.

Table 4. Strain gauge parameters.

Size (mm)	Specs	Appropriate Temperature (°C)	Resistance Values (Ω)	Sensitivity Coefficient (%)	Mechanical Hysteresis ($\mu\text{m/m}$)	Maximum Strain Limit ($\mu\text{m/m}$)	Supply Voltage (V)
5 × 3	BX120-100AA	−30–70	120 ± 1	2.1 ± 2	1.2	20,000	3–10
100 × 3	BX120-1AA	−30–70	120 ± 1	2.1 ± 2	1.2	20,000	3–10

Figure 9. Deflection and strain arrangement of test beam.

3. Results and Discussions

3.1. Test Results and Analysis of R_0 Beam's Flexural Bearing Capacity

First, the test beam is preloaded, and the load is 8 kN. At this time, the sensor values are all normal. After preloading, the formal loading is performed. Before the load reaches the yield load, the load-mid-span deflection of the original beam shows a linear trend. When the load reaches 16 kN, cracks appear in the pure bending section of the original beam, and the deflection of the test beam at this time is 0.78 mm. With the increase in the load, the cracks in the pure bending section gradually increase, and the distribution is more uniform; the crack spacing is about 10 cm. When the load reaches 111 kN, the steel bar in the pure bending section yields, and the mid-span deflection is about 11.7 mm at this time.

After the steel bar yields, the mid-span deflection increases faster, the cracks become wider, and there are multiple oblique cracks in the bending-shear zone. When the mid-span deflection reaches 24.9 mm, transverse cracks appear on the upper edge of the original beam mid-span, plastic hinges begin to form gradually, the crack height does not increase, but the crack width continues to increase. When the mid-span deflection reaches about 42.8 mm, the main crack near the mid-span penetrates up and down, the concrete in the

compression zone is wholly crushed, and the test ends. The loading failure of the R_0 beam is shown in Figure 10.

Figure 10. R_0 beam failure mode.

The R_0 beam mid-span deflection-load curve is shown in Figure 11.

Figure 11. R_0 beam mid-span load-deflection curve.

The R_0 beam's center deflection–load curve is mainly divided into three working stages: the elastic stage, crack development stage, and plastic stage. The elastic stage is from the beginning of loading to the appearance of the first crack in the original beam. At the beginning of the test, the load is small, and the original beam is in an elastic working state. As the load increases, the concrete strain in the tension zone increases. When it reaches the concrete cracking strain, the concrete in the pure bending section begins to crack, and the elastic phase ends. The crack development stage is from the first crack in the original beam before the tensile steel bar yields. After the test beam cracked, as the load increased, new cracks continued to appear, and the cracks extended upward, and the width continued to increase. The plastic stage is from the yield of the steel bar to the failure of the test beam. When the tensile steel bar yielded, the mid-span deflection of the test beam increased sharply, the cracks developed rapidly, and the width of the cracks continued to increase. At this time, the load no longer increased significantly. Many oblique cracks also appeared in the bending-shear zone. With the continuous increase in the loading displacement, the concrete in the compression zone is gradually crushed, and finally, a fracture surface is formed.

3.2. Strengthening Beam Test Results and Analysis

3.2.1. Main Damage Phenomenon and Process

(1) CFRP- R_1 beam

In RC beams strengthened by directly pasting CFRP plates, the RC beam first presented upward cracks in the purely curved section during the loading process. As the load increased, the cracks in the purely curved section developed upward and were evenly distributed; oblique cracks also appeared in the bending-shear zone. At this time, the carbon fiber board made a slight noise, but no damage was observed. As the load continued to increase, the RC beam made the sound of concrete cracking. As the load further increased, accompanied by a loud noise, the carbon fiber board was peeled off at one end, and a layer of concrete was attached to the inside of the CFRP plate. The crack width of the RC beam increased significantly. At this time, the load was loaded to 175 kN, and the mid-span deflection was 12.6 mm. The failure mode of the CFRP- R_1 beam is shown in Figure 12.

Figure 12. CFRP- R_1 destruction mode.

(2) CFRP- R_2 beam

Figure 13 shows the load-middle-span displacement curve in the loading and unloading process of pasting the CFRP board using the inverted arch method. The limit value of reverse arching force is 16 kN. When the actual anti-arch force value is 15.5 kN, the CFRP board is pasted, and the jack is slowly removed after the structural adhesive is cured. When the unloading force value is 0 kN, the whole process of pasting the CFRP board by the inverted arch method ends. It can be seen in Figure 13 that the reinforced beam has a pre-camber, and the CFRP plate is pre-stressed during the unloading process.

Figure 13. Load-displacement curve of the mid-span during reinforcement by the reverse-arch method.

At the beginning of the test, the load of the test beam gradually increased. During the loading process, the carbon fiber board made a slight noise, but no damage was seen.

For the beams strengthened with the reverse-arch method pasted with CFRP plate, no apparent changes were observed on the concrete surface at the beginning of the test. As the test beam bears a more significant load, the carbon fiber board makes a slight noise, but no damage is seen. As the load continues to increase, there is a slight cracking sound in the test beam, and the cracks are evenly distributed on the beam side through the crack observer. When the load reaches 140 kN, the cracks are visible and develop upwards. At this time, the CFRP plate is intact. When the load exceeds the limit load of the RC beams strengthened by directly pasting carbon fiber plates, the reverse-arch method-pasted CFRP plate to strengthen the beams presents no significant change. The load is increased to 188 kN, and with a bang, carbon fiber peels at one end, and the inner layer of concrete attached to the carbon fiber is revealed. At this time, the crack width increases significantly. The mid-span deflection is 12.8 mm. The failure mode of the RC beam strengthened by the reverse-arch method and pasted with CFRP plate is shown in Figure 14.

Figure 14. CFRP-R₂ Failure Mode.

3.2.2. Deflection Analysis

It can be seen from Figure 15, the ultimate load of the R₀ beam is 111 kN, and the mid-span deflection is 11.7 mm. When the ordinary CFRP plate reinforces the RC beam, the flexural bearing capacity is significantly improved. After being reinforced with ordinary carbon fiber boards, the load-bearing capacity reached 175 kN, which is 52% higher than that of unreinforced beams. The mid-span deflection is 12.6 mm. The flexural load-bearing capacity of the beams strengthened by the reverse-arch method and pasted with carbon fiber board reaches 188 kN, which is 63% higher than that of the unreinforced beams. The mid-span deflection is 12.8 mm. The cracking load, yield load, and ultimate load of each test beam are shown in Table 5.

Figure 15. Test beam mid-span load-deflection curve.

Table 5. Characteristics and load of test beam.

Test Beam	Cracking Load (kN)	Cracking Displacement (mm)	Yield Load (kN)	Yield Displacement (mm)	Ultimate Load (kN)	Ultimate Displacement (mm)	Improved Carrying Capacity (%)
R ₀	16	0.78	111	11.70	115	26.00	/
CFRP-R ₁	20	0.59	175	12.60	175	12.60	52
CFRP-R ₂	25	0.49	188	12.80	188	12.80	63

The test results show that the CFRP plate can improve the load-bearing capacity of the beam. Under different reinforcement methods, the development trend of the load–deflection curves is the same. Under the same load, the R₀ beam displacement increases faster, indicating that the CFRP plate strengthens the beam with minor deformation and greater stiffness. The load–deflection curve of the concrete increases linearly before cracking. After the concrete cracks, the load–deflection curve grows faster, indicating that the stiffness of the beam decreases. After the CFRP-R₂ beam is prestressed, precompression stress is established in the tension zone of the beam, which delays the cracking of the concrete and improves the rigidity of the beam.

Since this test did not adopt a better end anchoring method, the reinforced specimens all yielded failure due to the peeling of the CFRP end. Therefore, there is no good measurement of the load–displacement change law and the ultimate flexural load during the plastic deformation of the structure during the plastic deformation of the structure by the direct bonding CFRP reinforcement and the reverse-arch method-pasted CFRP reinforcement. However, the existing experimental data clearly demonstrated that the CFRP reverse-arch method has changed the mechanical performance of the structure, which has achieved the purpose of the experiment.

It can be seen from Figure 13 that regardless of whether the reverse-arch method is used, when the influence of the end anchoring on the reinforced structure is ignored, the ductility of the reinforced beam is significantly reduced after the CFRP plate is reinforced. At the same time, it can be found that when the amount of CFRP remains unchanged, the reverse-arch method does not significantly affect the stiffness and ductility of the reinforced beam. Comparing with other similar experiments [25], it can be seen that the effect of CFRP is similar to that of steel bars. When CFRP plates are used to reinforce suitable reinforcement beams, increasing the amount of CFRP will reduce the ductility of the structure. On the contrary, the ductility of the structure will increase. Therefore, in practical applications, an appropriate amount of CFRP should be selected to ensure the ductility of the structure.

3.2.3. Strain Analysis

(1) Analysis of High Strain of Concrete Along Beam

The strain test data along the beam height under different loading cases are shown in Figures 16–18.

It can be seen from Figures 16–18 that the strain development law of all beams is the same. At the same time, it can be found that before the structure yields, as the load increases, the neutral axis of the section moves up slightly. The reason for this is that the concrete in the tension zone continues to withdraw from work. This complies with the change law of the neutral axis of the structure from a normal use state to the ultimate load state. It shows that when the structure yields, the limit state method can be used to calculate the section force.

Comparing the three test beams, it can be seen that the R₀ beam has the highest neutral axis, the CFRP-R₁ beam is second, and the CFRP-R₂ beam is the lowest, indicating that the reverse-arch method of pasting CFRP plate has a significant effect. The reverse-arch method is pasted with a CFRP plate for reinforcement, which reduces the neutral axis position, increases the height of the concrete compression zone, reduces the beam deformation,

and improves the flexural bearing capacity as a whole. Under yield load, the neutral axis position is 3 cm lower than that of the original beam.

Figure 16. Strain along with the beam height in the mid-span of R_0 beam.

Figure 17. Strain along with the beam height in the mid-span of CFRP- R_1 beam.

Figure 18. Strain along with the beam height in the mid-span of CFRP- R_2 beam.

(2) Strain analysis of the steel bar, concrete, and CFRP plate

The strains of each test beam's steel bars, concrete, and CFRP plate are shown in Figures 19–21.

Figure 19. Comparison of R_0 beam load and strain of steel bar and concrete.

Figure 20. Comparison of CFRP- R_1 beam load and strain of steel bar, concrete, and CFRP plate.

Figure 21. Comparison of CFRP- R_2 beam load and strain of steel bar, concrete, and CFRP plate.

It can be seen from Figure 19 that at the beginning of the test, due to the cohesion between the concrete and the steel bar, the strain of the steel bar and the concrete is not very different before the concrete cracks. After the concrete cracks, the strain of the concrete and the strain of the steel bars gradually separate. Under the same load, the tensile strain of concrete is greater than that of steel bars because the tensile capacity of steel bars is much larger than that of concrete. The concrete on the upper part of the reference beam is in the compression zone, so the compressive strain of the concrete increases negatively when it is loaded.

It can be seen from Figure 20 that the strain of the CFRP plate is greater than the strain of concrete and steel bars. Before the CFRP plate is peeled from the concrete, the carbon fiber board bears most of the tensile stress at the bottom of the beam, which effectively slows down the deformation of the beam. The carbon fiber board can bear a large part of the tensile stress while deforming, sharing the tensile stress of concrete and steel bars. When the CFRP plate is peeled from the concrete, the steel bar yields, and the beam reaches its limit.

It can be seen from Figure 21 that the strains of the CFRP plate, concrete, and steel bars are not very different in the CFRP-R₂ beam at the initial stage of load application. In the late loading stage, compared with the CFRP-R₁ beam, the tensile strain of the CFRP plate is close to that of the steel bar. This explains why the prestressed carbon fiber board strengthens the RC beam to strengthen the synergy of concrete, steel, and CFRP plate. It is more effective in reducing beam deformation. The prestress effect of the reverse-arch method to strengthen the beam is more prominent. The CFRP plate shares more load and significantly improves the stiffness of the beam after cracking.

3.2.4. Crack Analysis

The crack distribution of each test beam is shown in Figures 22–24.

Figure 22. R₀ beam crack distribution.

Figure 23. CFRP-R₁ beam crack distribution.

Figure 24. CFRP-R₂ beam crack distribution.

(1) R₀ beam

The R₀ beam demonstrates the first crack in the concrete tension zone of the pure bending section. With the continuous increase in the load, the cracks develop upward, and new cracks appear in other positions of the pure bend section, the cracks are evenly distributed, and the spacing is about 10 cm. When the maximum width of the crack reaches 0.2 mm, the crack length can extend to about 200 mm. After that, the cracks develop slowly. When the crack length reaches 250 mm, the crack no longer develops upwards and tends to be stable. When the load continues to increase when the crack width reaches 0.5 mm, the steel bar begins to yield, and the crack width develops faster. As the displacement load increases, the cracks extend upwards, new cracks appear in the bending-shear section, and the concrete falls off. Lateral cracks appear in the compression zone on the upper edge of the concrete until the concrete is completely crushed. R₀ beam crack distribution map is shown in Figure 22.

(2) CFRP-R₁ beam

The first crack appeared in the test beam when the load of the ordinary CFRP plate reinforced beam reached 20 kN. As the load increases, cracks gradually increase. Before the steel bar yields, the crack width develops linearly. When the steel bar yielded, the carbon fiber board peeled off on the test beam, and the crack width reached 0.42 mm. CFRP-R₁ beam crack distribution map is shown in Figure 23.

(3) CFRP-R₂ beam

The reverse-arch method strengthens the beam. When the load is 25 kN, the first crack appears in the test beam's pure bending section, and the crack's width is 0.01 mm. As the load increases, cracks with different widths and lengths appear. New cracks constantly appeared in the mid-span and bending-shear section of the test beam, and the crack spacing was about 10 cm. When the load reached 188 kN, the carbon fiber board peeled off on the test beam, the crack width sharply widened, and the test was terminated. CFRP-R₂ beam crack distribution map is shown in Figure 24.

From the perspective of the entire loading process, the development trend of cracks in the test beams is the same. As the load increases, the cracks develop gradually, and the cracks of each test beam develop relatively smoothly during the test. The cracks of the CFRP-R₁ and CFRP-R₂ strengthened beams develop slowly. Under the same load, the crack width is significantly reduced compared to the R₀ beam. The use of the reverse-arch method to strengthen the beam can effectively delay the appearance of cracks so that the development of the original cracks is also slower. The crack spacing is smaller, and the stiffness of the test beam is also improved.

As shown in Figure 25, the test beam load–maximum crack width curve shows that the direct bonding of carbon fiber reinforcement and the reverse-arch method of pasting carbon fiber board reinforcement can significantly inhibit the development of cracks in the test beam. Directly pasting the carbon fiber board to strengthen the beam does not significantly increase the cracking load of the beam. Still, it can effectively inhibit the development of

cracks and effectively improve the load-bearing capacity of the beam. The reverse-arch method-pasted carbon fiber board reinforcement can effectively inhibit the development of cracks and increase the cracking load of the beam. Under the same load, the length of cracks in the beams reinforced by the reverse-arch method with CFRP plate is shorter than that in the beam reinforced with carbon fiber board directly, and the appearance time is later. When the test beam reached yield, the crack width of the beam strengthened by directly pasting the carbon fiber board was reduced by 11.9%. Compared with the original beam, the crack width is reduced by 26% when the reverse-arch method is used to paste the CFRP plate.

Figure 25. Load and maximum crack width curves of the test beam.

4. Analysis of Reinforced Structure Cracking and Bearing Capacity

4.1. Carrying Capacity

We reinforced concrete beams with fiber composite materials to calculate the flexural bearing capacity of the regular section. The reader can refer to the calculation method of ordinary reinforced concrete beams in “Code for Design of Reinforcement of Concrete Structures” (GB 50367-2013) [26]. When fiber composite materials are used to strengthen beams, the following basic assumptions should be met: (1) the relationship between stress and strain of fiber composite material is linear, and its tensile stress σ_f is equal to the product of tensile strain ε_f and elastic modulus E_f ; (2) when considering the influence of the secondary force, the hysteresis strain of the fiber composite material should be determined according to the initial force condition before the reinforcement of the component; (3) before reaching the ultimate state of flexural bearing capacity, no bond peeling failure will occur between the reinforcement material and the concrete.

When the beam is in the ultimate state, the non-prestressed tensile steel bar in the body yields, and the concrete at the edge of the section compression zone reaches the ultimate compressive strain. The stress diagram of the member’s normal section compression zone can be simplified into an equivalent stress diagram. In the limit state of the beam, the height of the compression zone of each test beam is small, and the effect of the reinforcement in the compression zone of the beam is ignored in the calculation. Figure 26 shows the total bearing capacity of the regular section of the externally prestressed concrete beam with a rectangular section.

According to the force diagram in Figure 24, the calculation formula for the bearing capacity of the front section of the flexural member after reinforcement is:

$$M = \alpha_1 f_{c0} b x \left(h - \frac{x}{2} \right) + f'_{y0} A'_{s0} (h - a'_s) - f_{y0} A_{s0} (h - h_0) \quad (1)$$

$$\alpha_1 f_{c0} b x = f_{y0} A_{s0} + f_t A_{fe} - f'_{y0} A'_s \quad (2)$$

Figure 26. The calculation diagram of the bending bearing capacity of the regular section of the test beam.

From the geometric conditions:

$$x = \frac{0.8 \varepsilon_{cu}}{\varepsilon_{cu} + \varepsilon_{ff} + \varepsilon_{f0}} h \quad (3)$$

where M is the design value of the bending moment after reinforcement of the member ($\text{kN}\cdot\text{m}$); α_1 is the equivalent rectangular stress diagram coefficient, which is taken according to the current national standard “Code for Design of Concrete Structures” (GB 50010-2011) [27]; f_{c0} is the design value of the axial compressive strength of concrete (N/mm^2); b is the section width (mm); x is the height of the compression zone of the equivalent rectangular stress graph (mm); a'_s is the distance from the edge of the compression zone to the point of action of the resultant force of the compression reinforcement (mm); A'_{s0} and A_{s0} are the cross-sectional area of the compression steel bar and the cross-sectional area of the tension steel bar (mm^2), respectively; f'_{y0} and f_{y0} are the design values of compressive strength and tensile strength of steel bars (N/mm^2), respectively; f_f is the design value of CFRP tensile strength (N/mm^2); and ε_{ff} is the actual tensile strain of CFRP.

For prestressed CFRP plate reinforced beams, due to the large ultimate strain of carbon fiber, the height of the concrete compression zone is small at this time, and the shape of the stress diagram of the compression zone has little effect on the ultimate bearing capacity. Therefore, it can be simplified to an equivalent rectangular stress diagram. In the limit state of the beam, the height of the compression zone is small, and the effect of the reinforcement in the compression zone of the beam is ignored in the calculation. From the equilibrium equation for the cross-section, it is obtained that:

$$M = f_{y0} A_{s0} \left(h - \frac{x}{2} \right) + \sigma_f A_f \left(h - \frac{x}{2} \right) \quad (4)$$

$$\alpha_1 f_{c0} b x = f_{y0} A_{s0} + \sigma_f A_f \quad (5)$$

where M is the flexural bearing capacity of the standard section; A_f is the cross-sectional area of the CFRP plate; σ_f is the tensile stress of the carbon fiber board; and h is the distance between the center of the CFRP plate and the compressed edge of the concrete.

4.2. Cracking Load

The cracking load is calculated using the nominal tensile stress method—that is, when the tensile edge stress of concrete σ_{ct} exceeds the ultimate tensile strength of the concrete, the concrete cracks, and the bending moment that the structure bears at this time is the

cracking moment M_{cr} . The schematic diagram of the cracking load calculation of the CFRP plate-strengthened beam is shown in Figure 27.

Figure 27. Schematic diagram of the calculation.

Let the bending section coefficient of the tensile edge of the section before the structure crack be W_c . The area of the cross-section of the component before cracking is A_c , the effective prestress is N_{pe} , the distance between the prestressing force point and the cross-section centroid axis before cracking is e_p , the elastic modulus of concrete is E_c , and the ultimate tensile strain ϵ_{cr} of concrete is taken as 0.0001. From the following formula:

$$\sigma_{ct} = \frac{M_{cr}}{W_c} - \left(\frac{N_{pe}}{A_c} + \frac{N_{pe}e_p}{W_c} \right) = E_c \epsilon_{cr} \quad (6)$$

The cracking load and ultimate bearing capacity of the two CFRP-R₁ and CFRP-R₂ reinforced beams according to the above formula is calculated, and the calculated results are compared with the test values. See Table 6 for details. According to the calculation of the cracking load and bearing capacity of the CFRP board by directly pasting the CFRP board and the inverted arching method, the calculation results are in good agreement with the test results.

Table 6. Comparison of test value and formula calculation value.

Test Piece	Test Value of Cracking Load (kN)	The Calculated Value of Cracking Load (kN)	Error (%)	Test Value of Flexural Capacity (kN)	The Calculated Value of Flexural Capacity (kN)	Error (%)
R0	16	16.2	1.23	115	117	1.71
CFRP-R ₁	20	20.7	3.38	176	178	1.12
CFRP-R ₂	25	24.3	−2.88	188	185	−1.62

5. Conclusions

This paper studies the CFRP board reverse-arch method to strengthen the beam, and compares this method with directly pasting the CFRP board to strengthen the beam and an unreinforced beam. The cracking load, ultimate load, beam stiffness and crack development of the test beam are analyzed in detail. Through the bending test of the test beam, the following conclusions can be drawn:

- (1) Through the analysis of the test data, it can be seen that the cracking load and ultimate load are improved compared with the reinforcement of the CFRP plate by the reverse-arch method and the reinforcement by the direct adhesion of the CFRP plate. The RC beam can effectively increase the cracking load of the beam body. Compared

with the original beam, the cracking load of the reverse-arch method of attaching the CFRP plate and the direct pasting of the CFRP plate is increased by 25% and 56%, respectively;

- (2) The reverse-arch method of pasting the CFRP plate to strengthen the test beam obtained the inverted arch deformation during the early loading stage, which produced the prestress effect. As a result, the test beam and the pasted CFRP plate are under the same force at the beginning of loading, avoiding the secondary stress of the CFRP plate, thereby improving the ultimate load-bearing capacity of the beam. Compared with the original beam, the inverse arch method-pasted CFRP plate reinforcement can increase the ultimate load-carrying capacity by 63%;
- (3) The reverse-arch method-pasted CFRP plate reinforcement can effectively improve the rigidity of the beam. When the applied load is less than the cracking load, the deflection growth rate provided by the inverse arch method of pasting the CFRP plate is similar to that of directly pasting the CFRP plate. When the loading load exceeds the cracking load, the increased rate of the deflection of the test beam is more gentle when the reverse-arch method of pasting the CFRP plate is compared with directly pasting the CFRP plate. Compared with the original beam, the deflection growth rate provided by the reverse-arch method of pasting the CFRP plate and the direct pasting of the CFRP plate is smaller in the whole test process;
- (4) The reverse-arch method-pasted CFRP plate reinforcement can effectively limit the development of cracks. Under the same load, the length of cracks in the beams reinforced by the reverse-arch method with CFRP plate is shorter than that of the beam reinforced with carbon fiber board directly, and the appearance time is later. When the test beam reaches yield, the crack width of the beam strengthened by directly pasting the CFRP plate is reduced by 11.9% compared with the original beam. The reverse-arch method pastes the CFRP plate to strengthen the original beam. When the test beam yields, the crack width is reduced by 26%;
- (5) The calculation of the flexural bearing capacity of the CFRP board reinforced by the inverted arch method is in good agreement with the test results.

When the beam is reinforced by the inverted arch method, the inverted arching force value cannot exceed the inverted arching force limit value to avoid the impact of the upper edge concrete cracking on the load-bearing capacity of the beam. Because the end of the reinforced beam was not properly anchored in this test, the CFRP plate was peeled off during the bending process of the structure. The strength of the CFRP plate was not fully exerted and the ductility of the reinforced beam was reduced. Therefore, the end of the reinforced beam should be effectively anchored. Directly pasting the CFRP board for reinforcement can greatly improve the rigidity and load-bearing capacity of the beam. Compared with directly pasting the CFRP board for reinforcement, inverted arch pasting of the CFRP board not only has the advantages of directly pasting the CFRP board, but also can effectively increase the beam's cracking load, and cause the structure to produce a certain degree of pre-arching, and the CFRP board produces a certain prestress. Therefore, the inverted arch method of pasting CFRP board reinforcement can be popularized and applied.

Author Contributions: Conceptualization, T.Y., Q.S.; formal analysis, analysis and writing, T.Y.; writing—review, Q.S., C.L.; methodology, Y.L. All authors have read and agreed to the published version of the manuscript.

Funding: The research in this paper was supported by the Science and Technology Project of the Department of Transportation of Heilongjiang Province (2020HLJ018), the Science and Technology Project of the Department of Transportation of Heilongjiang Province (2020HLJ059) and the project of Jilin Province transportation innovation and development support (Science and Technology) (2020-1-9).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The research in this paper was supported by the Science and Technology Project of the Department of Transportation of Heilongjiang Province (2020HLJ018), the Science and Technology Project of the Department of Transportation of Heilongjiang Province (2020HLJ059) and the project of Jilin Province transportation innovation and development support (Science and Technology) (2020-1-9).

Conflicts of Interest: The authors declare no conflict of interest.

References

- Goodhew, P.J.; Clarke, A.J.; Bailey, J.E. *A Review of the Fabrication and Properties of Carbon Fibers*; Elsevier: Amsterdam, The Netherlands, 1975; Volume 17. [\[CrossRef\]](#)
- Jumaat, M.Z.; Rahman, M.M.; Rahman, M.A. Review on bonding techniques of CFRP in strengthening concrete structures. *Int. J. Phys. Sci.* **2011**, *6*, 3567–3575. [\[CrossRef\]](#)
- Amran, Y.H.M.; Alyousef, R.; Rashid, R.S.M.; Alabduljabbar, H.; Hung, C.-C. Properties and applications of FRP in strengthening RC structures: A review. *Structures* **2018**, *16*. [\[CrossRef\]](#)
- Wang, H.; Xian, G. Shear capacity of RC beams strengthened with flax fiber sheets grafted with nano-TiO₂. *Materials* **2020**, *13*, 1430. [\[CrossRef\]](#) [\[PubMed\]](#)
- Boothby, T.E.; Bakis, C.E. Durability of externally bonded fiber-reinforced polymer (FRP) composite systems. In *Strengthening and Rehabilitation of Civil Infrastructures Using Fibre-Reinforced Polymer (FRP) Composites*; Elsevier: Amsterdam, The Netherlands, 2008. [\[CrossRef\]](#)
- Eva, O.; Mireia, P.; Antonio, M. Contribution of externally bonded FRP shear reinforcement to the shear strength of RC beams. *Compos. Part B* **2019**, *164*. [\[CrossRef\]](#)
- Azam, R. CFRP grid embedded in mortar for strengthening of shear-critical RC beams. *Mag. Concr. Res.* **2018**. [\[CrossRef\]](#)
- Deng, L.; Luo, R.; Qian, X.; Ma, J.; Huang, X. Experimental study on intelligent carbon fiber slab embedded reinforced concrete beam with rectangular section. *Build. Struct.* **2019**, *49*, 92–97.
- Aslam, M.; Shafiq, P.; Jumaat, M.Z.; Shah, S.N.R. Strengthening of RC beams using prestressed fiber reinforced polymers—A review. *Constr. Build. Mater.* **2015**, *82*, 235–256. [\[CrossRef\]](#)
- Wang, H.-L.; Jin, W.-L.; Cleland, D.J.; Zhang, A.-H. Strengthening an in-service reinforcement concrete bridge with prestressed CFRP bar. *J. Zhejiang Univ. Sci. A* **2009**, *10*, 635–644. [\[CrossRef\]](#)
- Mohee, F.M.; Al-Mayah, A.; Plumtree, A. Development of a novel prestressing anchor for CFRP plates: Experimental investigations. *Compos. Struct.* **2017**, *176*, 20–32. [\[CrossRef\]](#)
- Rashid, K.; Li, X.; Deng, J.; Xie, Y.; Wang, Y.; Chen, S. Experimental and analytical study on the flexural performance of CFRP-strengthened RC beams at various prestressing levels. *Compos. Struct.* **2019**, *227*. [\[CrossRef\]](#)
- Xu, F.; Li, D.; Zhao, J.; Huang, J. Experimental research on reinforced concrete beams strengthened by prestressing CFRP plate. *Build. Struct.* **2010**, *40*, 372–375.
- Kang, K.; Zhang, P.; Deng, L. Experimental research on flexural behavior of reinforced RC beams strengthened with prestressed CFRP plates anchored at both ends. *J. Lanzhou Univ. Technol.* **2011**, *37*, 110–115.
- Deng, L.; Chen, H.; Zhang, P. Study on calculation methods for flexural capacity of normal section of concrete beams strengthened with prestressed CFRP plates. *Build. Sci.* **2009**, *25*, 74–77.
- Moshiri, N.; Czaderski, C.; Mostofinejad, D.; Hosseini, A.; Sanginabadi, K.; Breveglieri, M.; Motavalli, M. Flexural strengthening of RC slabs with nonprestressed and prestressed CFRP strips using the EBROG method. *Compos. Part B* **2020**, *201*. [\[CrossRef\]](#)
- Xiao, X. *Study on the Flexural Behavior of RC Beams Strengthened With Prestressed CFRP under Secondary Load*; Hunan University: Changsha, China, 2016.
- Chen, D.G.; Yao, Y.; Deng, Y.J. Simulation calculation analysis of RC beam strengthened with carbon-fiber by reverse-arch method. *Adv. Mater. Res.* **2011**, *1269*. [\[CrossRef\]](#)
- Zhao, Q.; Wang, J.; Jin, G.; Sun, B. Analysis on the “reverse-arch prestressed technique” and the improved bearing capacity for steel structure strengthened by carbon-fibre. *Steel Constr.* **2002**, *51*–54.
- Liang, D.; Sun, J.; Li, Y. Theoretical analysis of Pre-CFRP reinforcement based on anti-arch deflection. *J. Univ. Jinan Sci. Technol.* **2014**, *28*, 316–320.
- Lin, Q.; Wang, L. Experimental study on concrete beams strengthened with CFRP using reverse arch method. *Build. Struct.* **2020**, *50*, 86–89.
- Ministry of Housing and Urban-Rural Development of the People’s Republic of China. *Standards for the Test of Mechanical Properties of Ordinary Concrete (GB/T 50081-2011)*; China Architecture & Building Press: Beijing, China, 2011.
- Ministry of Housing and Urban-Rural Development of the People’s Republic of China. *Standard Test Method for Tensile Testing of Metallic Materials (GB/T 228-2010)*; China Architecture & Building Press: Beijing, China, 2010.
- Ministry of Housing and Urban-Rural Development of the People’s Republic of China. *Standard for Test Methods of Concrete Structures GB/T50 152-2012*; China Construction Industry Press: Beijing, China, 2012.

-
25. Pan, Y.; Hu, W.; Guo, R.; Ren, Y. Experimental study on flexural performance of RC beams strengthened with CFRP grid-PCM. *J. Build. Struct.* **2020**, *41*, 119–128.
 26. Ministry of Housing and Urban-Rural Development of the People's Republic of China. *Design Code for Reinforcement of Concrete structures: GB 50367-2013*; China Construction Industry Press: Beijing, China, 2014.
 27. Ministry of Housing and Urban-Rural Development of the People's Republic of China. *Design Code for Concrete Structures: GB 50010-2010*; China Construction Industry Press: Beijing, China, 2011.