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Research article

Experimental study on large-scale compression members strengthened with circumferential prestressed CFRP plate

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ABSTRACT

There have been many research reports on the reinforcement of small-sized square columns with a cross-section of 200mm–300mm using prestressed carbon fiber-reinforced polymer (CFRP) materials, while there are few studies on piers in bridge and tower columns in cable-stayed bridges with a cross-section of several meters or even tens of meters. The horizontal pre-stressed steel tendons in the anchorage zone of tower columns in cable-stayed bridge replaced by prestressed CFRP sheets can not only facilitate construction and maintenance, but also have good fatigue resistance. The prestressed CFRP plate is used to reinforce the large-sized tower columns by using a specific device to tension the CFRP plate wrapped around the surface of the members. The tensioning device and test pedestal based on WSGG (wave-shaped-gear-grip) anchor clamping of CFRP plate have been developed in this paper, and the CFRP plate circumferential tensioning tests on the pedestal have been conducted. The test results are as follows: (1) the developed device can achieve circumferential tensioning of single-layer CFRP plate to 0.5ftk of the material, reaching a tensile force of 60kN, and generate effective restraint pressure on a 2-m long composite compression component; (2)The calculation formula for the constraint pressure generated by the circumferential prestressed CFRP sheet on the component has been derived and verified, and the maximum error between the calculated value and the experimental value is within 5%; (3) When iron sheet serves as the interface medium between CFRP plate and compression components, the prestress loss of the CFRP plate tensioned at one end is about 84% and 58%–60% when tensioned at both ends. It can be seen that the effective prestress of the CFRP plate with iron sheet as the interface medium is relatively small. Meanwhile, based on the distribution of compressive stress in the components and the effective pre tension value of CFRP plate, it can be seen that two end tensioning is better than one end tensioning; (4) The tensile stress of CFRP plate along the member is a cubic function when the tension force is 60kN, so it is deduced that the constrained compressive stress generated by CFRP plate on the member is a quadratic function distribution.

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1. Introduction

In recent decades, CFRP materials have rapidly become the research focus of engineers and researchers all over the world by virtue of their light weight, high strength, high elastic modulus and good fatigue and corrosion resistance [1–3], and have been used in the reinforcement and construction of civil engineering structures [4–7]. The earliest and most widely used non prestressed CFRP material is directly bonded for the reinforcement of flexural members [8]. However, the method of directly bonding CFRP materials cannot make full use of the high-strength performance of CFRP materials and improve the bending stiffness of full-scale beams is very limited. Research shows that due to the premature fall off of CFRP materials from reinforced members, The effective strengthening strength of CFRP is only about 20% of the ultimate strength of the material [9]. In order to improve the utilization rate of high-strength performance of CFRP materials, many researchers are committed to improving the bonding performance between CFRP materials and components, such as installing CFRP strips [10] or tendons in grooves cut on the concrete surface [11] or anchoring with anchors [12–15]. The use of anchors can indeed improve the bearing capacity and ductility of members [16–18], but it is difficult to improve the yield load and stiffness of members [19,20]. In order to improve the reinforcement efficiency, prestressed CFRP technology has become the research focus of researchers [21,22]. With the further research, the key difficulty of this technology lies in the reliability of the anchoring system and the simplicity of the tensioning system [23–25]. So far, the anchoring system includes: reinforced plate anchorage (flat steel plate [19] and wave-shaped-gear steel plate [26]), non-metallic anchorage [27,28], gradient anchorage [29], epoxy friction anchorage [30] and wedge anchorage [31]. The tensioning system can be divided into the following three categories: reverse arch method [32], auxiliary frame tensioning [33] and direct longitudinal [34] or transverse tensioning on members [35]. The reverse arch method cannot obtain accurate prestress value, and the auxiliary frame is bulky and not suitable for engineering application. Therefore, the tensioning method developed by researchers in recent years is also based on direct tensioning.

With the application of CFRP in the reinforcement of flexural members, many scholars also use this material for the reinforcement of compression members. Initially, the compression member was wrapped by direct bonding [36–38]. Similar to the reinforcement of flexural members, many scholars have found that the reinforcement effect of non-prestressed CFRP on compression members is limited through tests, but they have turned to the research on the reinforcement effect of Prestressed CFRP materials on compression members. The research shows that prestressed CFRP materials have obvious effect on the post-earthquake repair of full-scale columns in terms of bearing capacity and ductility, and can give full play to the high-strength performance of CFRP [39–41].

At present, U-shaped or well-shaped horizontal prestressed steel tendons are usually used in the tower column anchorage zone of cable-stayed bridges to balance the strong tension of stay cables [42–44]. The construction of the horizontal prestressed tendon is complex, and it needs to reserve holes, threading, tensioning and grouting in the anchorage zone. In addition, the poor fatigue performance of the horizontal prestressed tendon under high stress state will lead to sudden fracture, which is difficult to maintain and repair. The CFRP cloth or sheet tensioned on the surface of the tower column can replace the horizontal prestressed steel tendon in the anchorage zone of the tower column, which can solve the problems of complex construction and difficult maintenance and repair. However, CFRP cloth is easy to be tensioned unevenly and difficult to impregnate. The most important thing is that its pre-tension force is limited, which is more suitable for small-size components. CFRP sheet is factory pultruded, with the advantages of uniform carbon wire distribution, high strength and good durability [45,46]. The most important thing is that CFRP sheet can be tensioned at the same time in multiple layers, and the tensioning tonnage is large. Therefore, CFRP sheet is more suitable to replace the horizontal prestressed steel tendon in the tower column anchorage zone.

At present, the research on Prestressed CFRP materials for strengthening compression members is focused on small-scale columns such as 200mm × 200 m and 300mm × 300 m [47,48], However, there are few reports on large-scale compression components such as piers in bridge and tower columns in cable-stayed bridge, with cross-sectional dimensions usually ranging from a few meters to several tens of meters. The following key problems need to be solved in the reinforcement or construction of large-scale compression members with prestressed CFRP materials: (1) the tensioning process of large tonnage pretension can be established; (2) Considering the longer interface friction, the effective prestressing force that can be formed by prestressed CFRP materials.

In order to preliminarily explore the effectiveness of using prestressed CFRP plate to reinforce large-sized tower columns, based on the typical cross-section of the tower columns, this paper developed a tensioning device and test bench based on WSGG anchors to clamp CFRP plate. CFRP plate circumferential tension tests were conducted on the bench to verify the tensioning process of prestressed

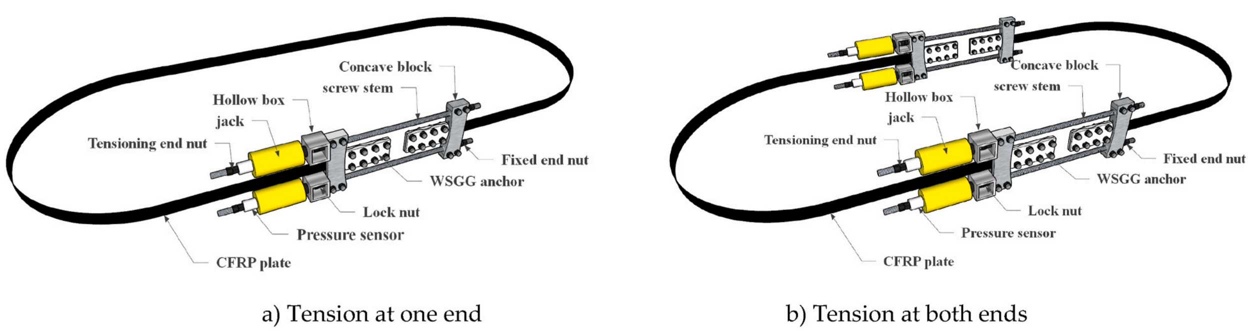


Fig. 1. Schematic diagram of circumferential tensioning device.

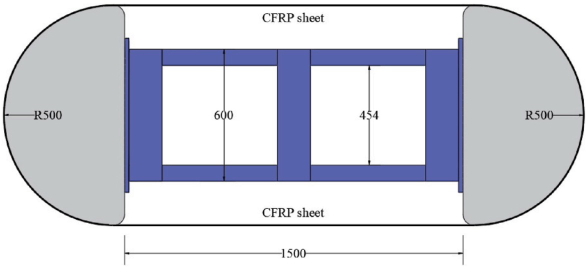


Fig. 2. Dimensions of test platform.

CFRP plate for large-size compression members and explore the effective pre-tension force of CFRP plate and the distribution law of restrained compressive stress on compression members by circumferential pre-stressed CFRP plates.

2. Experimental details

2.1. Circumferential tensioning device

The circumferential tensioning device, as shown in Fig. 1, is mainly composed of two concave blocks, two tensioning screw stems and supporting nuts, two WSGG (wave-shaped-gear-grip) anchors holding CFRP plate, two hollow frames, two pressure sensors, and two through-center jacks. It is connected through a U-shaped arrangement of CFRP plate. This device can achieve tension at one end or both ends.

The circumferential tensioning device directly applies prestress by jack, and can reach a higher level of prestress with the change of Jack tensioning tonnage and the number of layers of CFRP plate, which can provide hoop restraint for large-scale compression members. In addition, in order to accurately control the tension value during construction tensioning, the circumferential tensioning device considers the tension reading during tensioning, and two supporting pressure sensors are installed at each jack.

2.2. Circumferential tensioning procedures

The steps of circumferential CFRP plate tensioning process are as follows.

1) CFRP plate installation: install WSGG anchors at both ends of the CFRP plate, and then install the concave blocks at the front end of the WSGG anchors.
2) Gluing: apply epoxy resin adhesive to the bonding surface of CFRP plate and the bonding part of components.
3) Installation of tensioning device: surround the installed CFRP plate on the outer surface of the component, install the prestressed tensioning cage, including inserting the upper and lower tensioning screws in parallel on the concave blocks, and tightening the fixed end nut at one end; At the other end, screw in the lock nut first, and then insert the hollow frame, so that the lock nut is located in the hollow frame. After this operation, insert the jack and pressure sensor, and finally screw on the tensioning end nut to form the prestressed tensioning cage as a whole.
4) Correction: Adjust the distance between adjacent concave blocks to ensure the same distance. Adjust the horizontal height of the CFRP plate placed on the surface of the component, so that the CFRP plates around it are at the same horizontal height.
5) Tensioning: multiple jacks are lifted through the diverter valve. During the tensioning process, the pre-stressed tensioning of CFRP plate is completed by mutual checking between the sensor reading and the elongation of CFRP plate.
6) Anchoring: pre-stress locking is realized by tightening the lock nut in the hollow frame to the outer surface of the concave blocks.

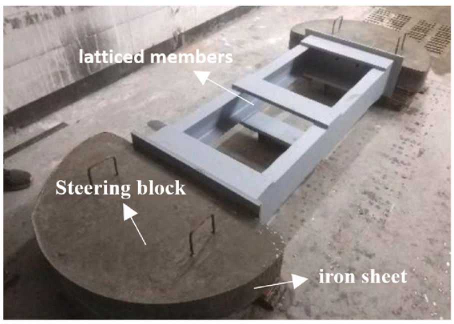


Fig. 3. Photos of test platform.

a) Tension at both ends b) tension at one end

Fig. 4. Photos of test scheme.

Table 1
Scheme of circumferential tension test.

Scheme No	Friction medium	Tensioning mode
Scheme I	Iron sheet	one end
Scheme II	Iron sheet	both ends

7) Remove: after the lock nut in the hollow frame is tightened and stuck, screw out the nut at the tensioning end, and take out the pressure sensor, Jack and hollow frame from the prestressed tensioning end.

2.3. Test platform and scheme

The circumferential prestressed CFRP plate is the CFRP plate surrounded on the outer surface of the component. Both ends of the CFRP plate are installed in a special device integrated with anchorage and tensioning, and the jack is used to apply pre-tension to the CFRP plate. The principle of reinforcement is as follows: the CFRP plate is tightened inward under tension, and a restrained compressive stress is generated on the surface of the member. This compressive stress can balance or offset the tensile stress generated by the component under other loads, or improve the material strength of the concrete material by compressing it in three directions, so as to achieve the reinforcement effect of the member strengthened with circumferential prestressed CFRP sheet. Therefore, the effect of reinforcement depends on the pre-tension of CFRP plate.In order to study the effect of circumferential CFRP plates on the reinforcement of members with curved outer surface, a test platform as shown in Figs. 2 and 3 is designed: two semi cylindrical with a diameter of 1 m and channel steel composite members. Test the interface medium of the component and two tensioning methods (one end tensioning and two ends tensioning, as shown in Fig. 4), as shown in Table 1. And each scheme is tested three times.

2.4. Material properties

The test scheme is tension at both ends and tension at one end of the circumferential CFRP plate (as shown in Fig. 5). The CFRP plate used is 50mm $\times$ 1.2mm in a single layer, and its mechanical properties are shown in Table 2. The CFRP plate is clamped with WSGG anchors, and the maximum control stress of CFRP plate tensioning is 0.5ftk (see Fig. 6).

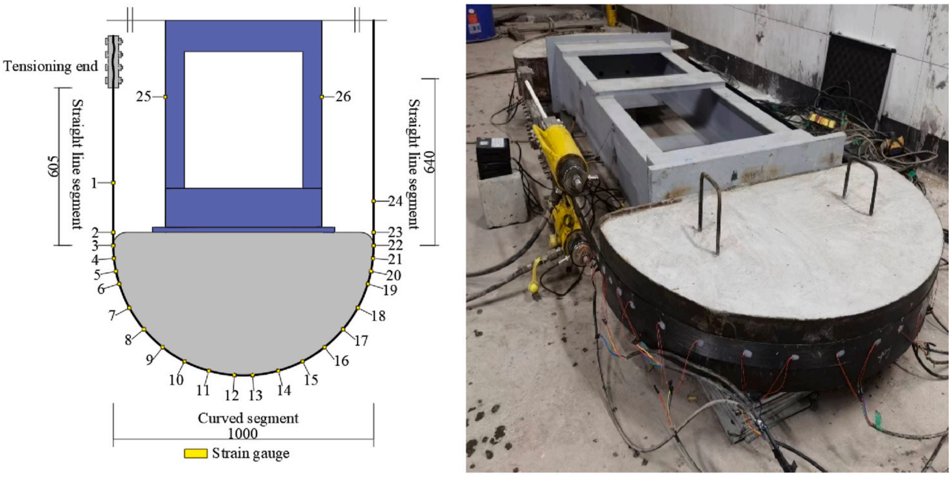
3. Results and discussion

3.1. Strengthening principle and constraint stress analysis of circumferentially prestressed CFRP plate

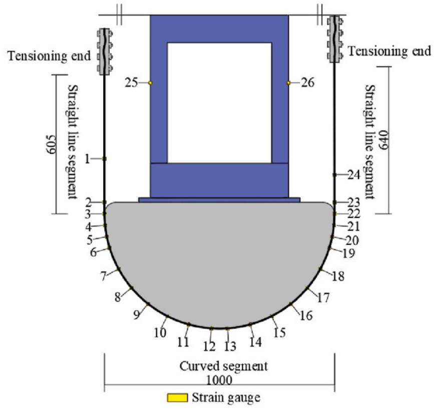
According to the different assumptions of CFRP plate and contact body, the distribution of compressive stress on the surface of CFRP plate and member is different. According to the literature analysis, the following two assumptions are suitable for the relationship between CFRP plate and members: rigid body assumption and elastic assumption: (1) assuming that the contact between CFRP plate and member surface is rigid contact, the pressure of CFRP sheets on member surface is uniformly distributed. (2) It is assumed that the contact between the CFRP plate and the surface of the member is Hertz elastic contact, and the stress between the two contact surfaces is ellipsoidal distribution, that is, quadratic function distribution. Based on the above two kinds of stress distribution and stress balance, the constraint compressive stress and constraint pressure of CFRP plate on the member are analyzed respectively, as follows.

3.1.1. Constrained compressive stress is uniformly distributed

Take a bending segment of CFRP plate for force analysis, as shown in Figure 6. Since the compressive stress is uniformly distributed, it is known that the friction force is also uniformly distributed, so the friction force balances itself in the vertical direction, it can be



a) Tension at one end



b) Tension at both ends

Fig. 5. Arrangement of strain gauges.

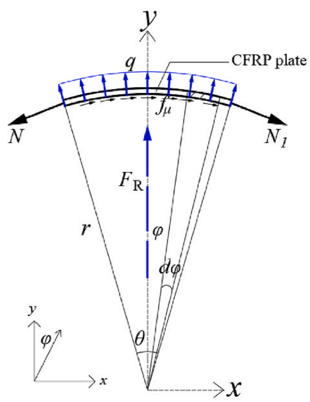


Fig. 6. Schematic diagram of stress analysis when normal compressive stress is uniformly distributed.

Table 2
Mechanical properties of CFRP plate.

Serial number	Test items	detection result
1	ftk	2425 MPa
2	modulus of elasticity	1.65 × 105MPa
3	elongation	1.71%

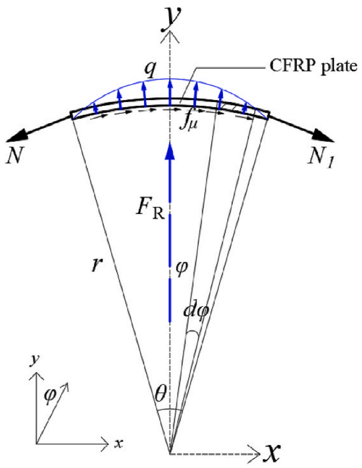


Fig. 7. Schematic diagram of force analysis when normal compressive stress is quadratic function distribution.

deduced according to $\sum Y = 0$:

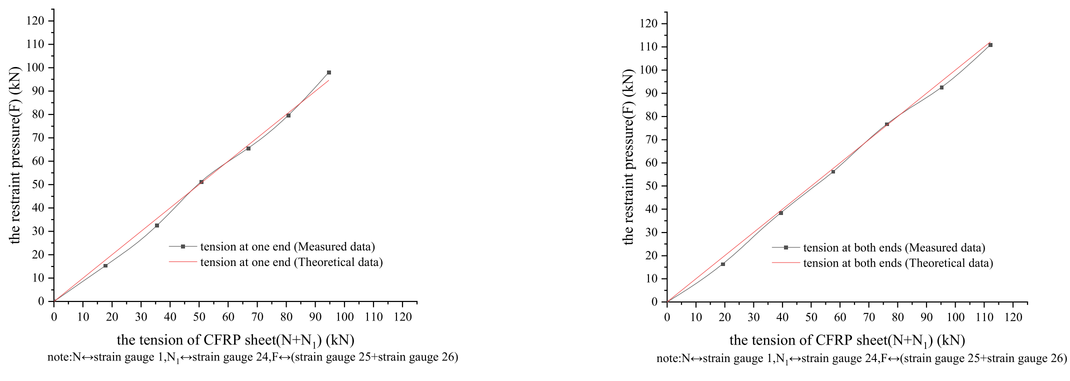
$$N \cdot sin\frac{\theta}{2} + N_1 \cdot sin\frac{\theta}{2} = 2\int_0^{\frac{\theta}{2}} (qb_c r d\varphi) cos\ \varphi \tag{1}$$

After simplification:

$$q = \frac{N + N_1}{2b_c r} \tag{2}$$

Since the compressive stress q and friction force f_μ are symmetrical, the force balance can deduce the pressure F of the component on the CFRP plate:

$$F = F_R = (N + N_1) sin\frac{\theta}{2} \tag{3}$$



a) Tension at one end   b) Tension at both ends

Fig. 8. curve of tension (F) of circumferential CFRP plate and restraint pressure (N+ N_1) of member.

3.1.2. Constrained compressive stress is a quadratic function distribution

Take a bending segment of CFRP plate for force analysis, as shown in Fig. 7 q is the quadratic function distribution. Since Y-axis is the axis of symmetry, it can be assumed that the quadratic function expression is $y = Ax^2 + C$ $(A < 0)$

According to the boundary condition:

when x = 0, $y = q = c$;

when $x = \pm r \cdot sin\frac{\theta}{2}, y = 0$;

Obtain: $A = \frac{-q}{r^2\ sin^2\frac{\theta}{2}}$, then quadratic parabolic equation:

$$q(x) = \frac{-q}{r^2 \cdot sin^2\frac{\theta}{2}}x^2 + q \tag{4}$$

Can be converted to:

$$q(\varphi) = \frac{-q}{r^2 \cdot sin^2\frac{\theta}{2}}(r \cdot sin\ \varphi)^2 + q \tag{5}$$

According to the vertical force balance

$$N \cdot sin\frac{\theta}{2} + N_1 \cdot sin\frac{\theta}{2} = 2\int_0^{\frac{\theta}{2}} \left(\frac{-q\ sin^2\ \varphi}{sin^2\frac{\theta}{2}} + q \right) b_c r d\varphi\ cos\ \varphi \tag{6}$$

Compressive stress after simplification q:

$$q = \frac{3(N + N_1)}{4b_c r} \tag{7}$$

Then

$$q(\varphi) = \frac{3(N + N_1)}{4b_c r} \cdot \left(1 - \frac{sin^2\ \varphi}{sin^2\frac{\theta}{2}} \right) \tag{8}$$

Since the compressive stress q and friction force f_μ are symmetrical, the force balance can deduce the pressure F of the component on the CFRP plate:

$$F = F_R = (N + N_1)sin\frac{\theta}{2} \tag{9}$$

Where:

N/N1 - tension value at one end of CFRP plate (kN);

F - pressure of CFRP sheet on member (kN);

FR - pressure of member on CFRP plate (kN);

fμ—Friction stress between CFRP plate and member (MPa);

q-compression stress of member on CFRP plate (MPa);

bc-width of CFRP plate (mm);

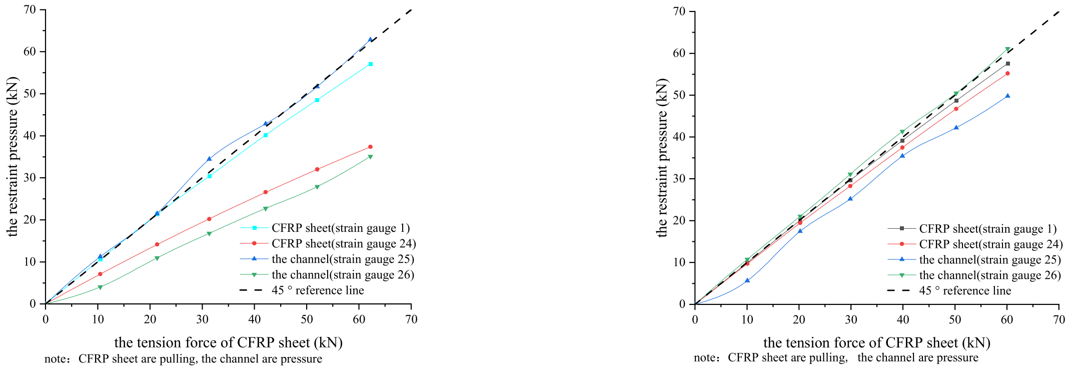
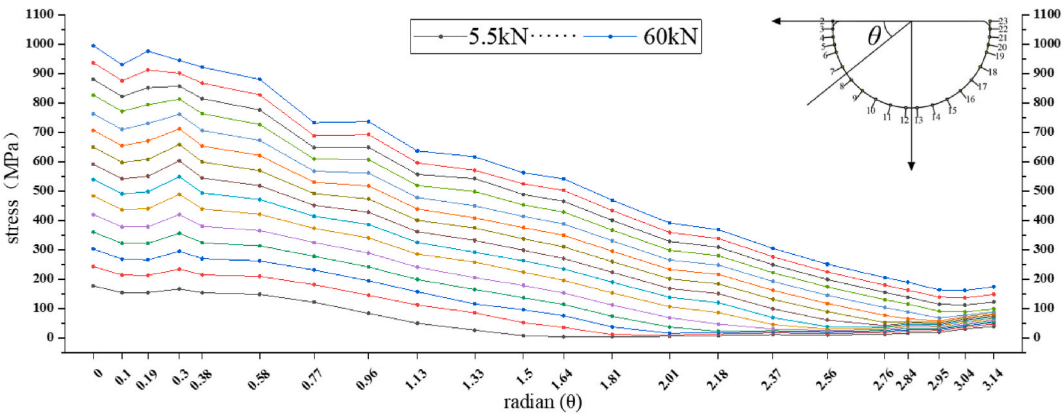


Fig. 9. The curve of the tensioning force of CFRP plate and the restraint pressure of member.

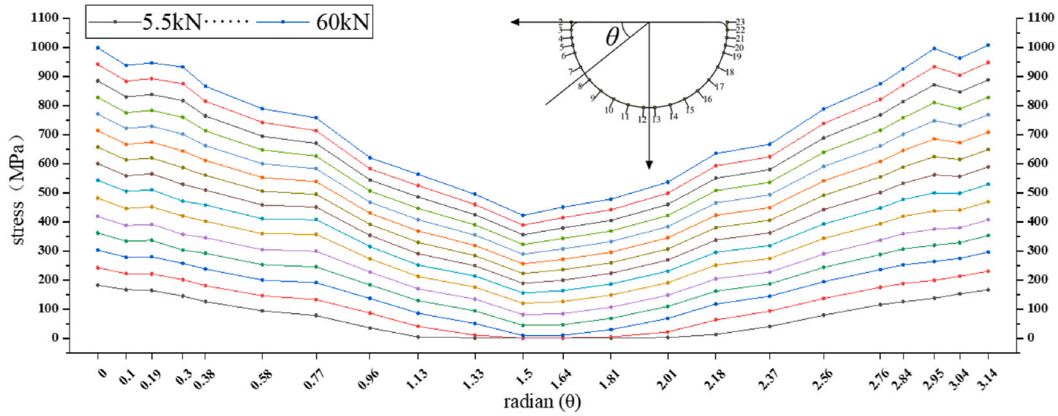
Table 3
Prestress loss of CFRP plate under 60kN in each test scheme.

Test times	Interface medium	the prestress loss rate at 60kN	
		Tension at one end	Tension at both ends
1	Iron sheet	83.54%	58.14%
2	Iron sheet	84.07%	58.51%
3	Iron sheet	83.92%	60.16%

Note: The prestress loss in the table refers to instantaneous loss.



a) Tension at one end



b) Tension at both ends

Fig. 10. Stress diagram of CFRP curve section in iron sheet medium.

r-radius of bending segment (mm);
θ- radian of bending segment, $0 \le \theta \le \pi$;
φ- angle between normal stress and y-axis
dφ- included angle of micro curve segment.

Through the analysis, it can be seen that although the normal stress of CFRP plate on the member is different under different distribution conditions, the pressure F on the member is the same, and the constraint pressure is only related to the tension value and tension angle on both sides of CFRP plate.

3.2. Verification of theoretical calculation formula of constraint pressure

Compare the pressure value calculated by the above derived formula for the circumferential tensioning of CFRP plate on the component with the test data, as shown in Fig. 8. From the figure, it can be seen that the measured pressure curve of the reinforced component is in high agreement with the theoretical calculation curve, and the maximum error is within 5%. It verifies the correctness

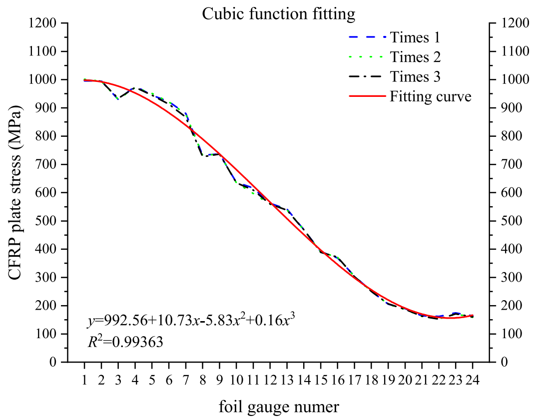
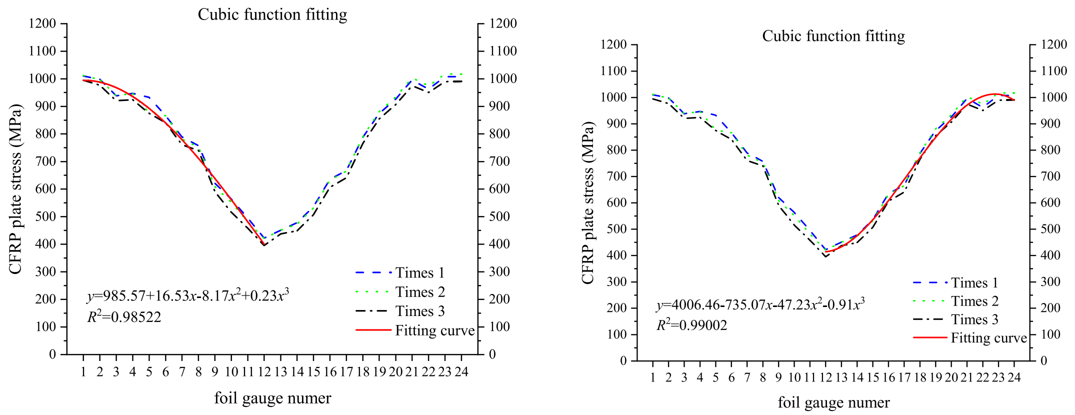


Fig. 11. Stress curve and fitting line of CFRP plate tensioned at one end.



a) Left fit b) Right fit

Fig. 12. Stress curve and fitting line of CFRP plate tensioned at both ends.

of the theoretical derivation formula. Through the theoretical formula, the value of CFRP plate tension and the circumferential winding angle of CFRP plate t can be designed according to the constraint pressure on the component.

3.3. Verification of theoretical calculation formula of constraint pressure

As shown in Fig. 9a), under tension at one end, the stress on the near pull side of CFRP plate and channel steel of lattice composite structure at the tension side is greater than that on the other side. As shown in Fig. 9 b), under the tension at both ends, that is, the CFRP plate on both sides are tensioned at the same time, and the stress of CFRP plate and channel steel on both sides is roughly the same.

From the stress of the member and the effective pre-tension value of CFRP plate established, it can be seen that the tension mode at both ends is better than that at one end for the circumferential tension of CFRP plate, and the compressive stress distribution of the strengthened member is more uniform.

According to the calculation, the effective prestress loss at 60kN are shown in Table 3 (the difference in stress between the tensioning end and the fixed end when tensioning at one end, and the difference in stress between the tensioning end and the arc top when tensioning at both ends).

Fig. 10a) is the stress variation diagram of the curved CFRP plate under various loads when one end is tensioned and interface medium is iron sheet. It can be seen that the interface medium between the CFRP plate and the outer surface of the arc is iron sheet, and the stress curve of CFRP plate along the curved surface decreases significantly. The maximum stresses obtained from three tests at point 1, i.e. the tensioning end, are 995.45MPa, 1000.89 MPa and 998.25 MPa respectively, and the maximum stresses obtained from three tests at point 24, i.e. the fixed end, are 163.85 MPa, 159.47 MPa and 160.55 MPa respectively. According to the calculation formula of friction prestress loss rate of tension at one end, the prestress loss rates from tension end to fixed end are 83.54%, 84.07% and 83.92% respectively under the maximum tension of 60kN, as shown in Table 3.

Fig. 10b) is the stress variation diagram of the curved CFRP plate under all levels of load when both ends are tensioned and interface medium is iron sheet. It can be seen that the interface medium between CFRP plate and the outer surface of the arc is iron sheet, and the stress curve of CFRP plate along the arc also decreases significantly. When the tension at both ends is close, the lowest point of stress appears at 12 points, that is, near the symmetry line of the arc curve. The maximum stresses obtained from the three tests at point 1, i.e. the tensioning end, are 1010.21 MPa, 1011.86 MPa and 994.46 MPa, respectively. The maximum stresses obtained from the three tests at point 24, i.e. the other tensioning end, are 1007.00 MPa, 1016.98 MPa and 990.74 MPa, respectively. The three maximum stresses at point 12 are 422.24 MPa, 420.83 MPa and 395.42 MPa, respectively. According to the calculation formula of prestress loss rate of tension at both ends, the prestress loss rate of tension at both ends is 58.14%, 58.51% and 60.16% respectively under the maximum tension of 60kN, as shown in Table 3.

To sum up, the tension at both ends is better than that at one end in terms of uniform stress and effective prestress value. The iron sheet is selected as the interface medium between CFRP plate and reinforced member, and the friction coefficient is large. Therefore, the prestress loss of tension at one end is about 84%, and the prestress loss of tension at both ends is 58%–60%. Therefore, it is necessary to find the interface medium with small friction coefficient to improve the effective prestress.

3.4. Distribution law of normal compressive stress

According to the previous analysis in this paper, there are two kinds of distribution of compressive stress applied by circumferential prestressed CFRP plate to the reinforced member, namely, uniform distribution and quadratic function distribution.

As shown in Fig. 11, the stress curve of CFRP plate when one end is tensioned and the tension force is 60kN. The stress curves of CFRP plate along the curve segment from three tests basically coincide. The data of the three test curves are fitted. As shown in Fig. 11, when the fitting is a cubic function, its correlation coefficient$R^2 = 0.99$, and the slope equation of the cubic function curve is a quadratic function. According to the mechanical relationship between friction and normal stress, the distribution of confined compressive stress of CFRP plate on members is a quadratic function.

Fig. 12 shows the stress curve of CFRP plate when tensioning at both ends and the tension force is 60kN. Like the tension at one end, the stress curves of the CFRP plate in the three tests of tension at both ends basically coincide, and Fig. 12a) shows that the test data on the left side is fitted as a cubic function with its correlation coefficient.$R^2 = 0.99$; Fig. 12b) shows the cubic function fitting of the test data on the right, and its correlation coefficient.$R^2 = 0.99$. It can also be deduced that the confined compressive stress distribution of CFRP plate on members is a quadratic function.

From the test data, data fitting and the analysis of the normal stress in this paper, it can be seen that the normal stress distribution of the prestressed CFRP plate on the reinforced member is more consistent with a quadratic function after either one end tension or two end tension circumferentially.

4. Conclusions

This paper reports an experimental study on large-scale compression members strengthened with circumferential prestressed CFRP plate using specific devices. The following conclusions can be drawn based on the limited experimental results and discussion.

1) The test shows that the developed tensioning device and pedestal based on hinged anchor clamping CFRP plate can realize the circumferential tensioning of CFRP plate, which is easy to construct, simple to operate.
2) The test and theoretical analysis show that the compression member is strengthened by the restraint pressure generated by pre-stressed CFRP plate after circumferentially tensioned, and the magnitude of the restraint pressure is related to the tension value and the center angle of the arc.
3) The test results show that when CFRP plate are tensioned at one end or both ends in a circumferential direction, the tension method at both ends is better than that at one end and the compressive stress distribution of the strengthened members is more uniform, according to the force of the member and the effective pre tension value established by CFRP plate.
4) The iron sheet is selected as the interface medium between CFRP plate and reinforced member, and the friction coefficient is large. Therefore, the prestress loss of tension at one end is about 84%, and the prestress loss of tension at both ends is 58%–60%.
5) The test and data fitting show that when the CFRP plate is tensioned in the circumferential direction at one or both ends, the tensile stress of the CFRP plate is distributed as a cubic function along the arc, and the normal compressive stress distribution of the CFRP plate on the reinforced member is more consistent with the quadratic function.
6) It is found that reducing the friction between CFRP plate and reinforced members can improve the uniformity of restraint pressure, and it is necessary to continue the research work in this area.
7) The conclusions in this paper only apply to the reinforcement of compression members with curved cross-sections by circumferential tensioned pre-stressed CFRP plates.
8) The contribution of this paper is to verify the feasibility of circumferential tension CFRP reinforcement of compression components based on WSGG anchors, laying the foundation for further research on multi-layer CFRP plates with simultaneous circumferential tension.

Additional information

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Xiaoying Chen: Validation, Project administration, Conceptualization. **Gang Yang:** Writing – original draft, Formal analysis, Data curation. **Jing Zhuo:** Writing – review & editing, Investigation. **Yonghui Zhang:** Software, Methodology, Funding acquisition. **Changrui Ren:** Supervision. **Longsheng Qi:** Writing – review & editing, Investigation. **Hanchen Du:** Resources. **Changming Bu:** Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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