Experimental study on axially compressed square RC stub columns strengthened with prestressed CFRP strips

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Abstract. Five square reinforced concrete (RC) stub columns were fabricated and experimental tested under an axial compression load in order to study the effectiveness of strengthening by using prestressed carbon fiber reinforced polymer (CFRP) strips. The specimens tested included one un-strengthened and four strengthened. Three specimens were strengthened by using prestressed strips, and the other one strengthened by using non-prestressed was used to compare. The prestress of the strip was achieved by tensed using a special device before it was pasted to the column. The experimental data such as the failure modes, load-displacement curves and strain distribution of CFRP strips were obtained. The effects of prestress magnitude of CFRP strips on the ultimate bearing capacity and deformation capacity of the specimens were analyzed. The results show that the prestress of CFRP strips can effectively increase the ultimate capacity and delay the crack occurrence of the specimens. And ultimate strain, plastic deformation of the specimens were also improved with increase of prestress magnitude of strip.

Key words: prestressed CFRP, square RC column, axial compression test, ultimate bearing capacity.

1. Introduction
Carbon fiber reinforced polymer is widely used to strengthen concrete, wood and steel structures because of high strength, light weight, good corrosion resistance and easy cutting [1-4]. One of methods commonly used to strengthen RC column is to adhere circumferentially CFRP strips, which can improve bearing capacity of structural member and does not change significantly its axial stiffness [5~10]. However, the load on the column is required to be removed ahead of schedule [11] because the strips do not work until the concrete of column expends laterally under compression. In many conditions, it is challenge, even impossible to remove the load on the column to be strengthened. If the strip is tensed before adhering to column, it can restrain the concrete of column even the concrete does not expend [12-13]. Therefore, strengthen by using prestressed strip is unnecessary to remove the load on the column.

It is found there are two types of methods to pre-stretch the strips in past research works. One is tensing the strip firstly and then spinning column to wind the strip around the column by a machine tool [12]. This method is appropriate in laboratory because the pretension force of the strip results in an additional torque of the column and a special machine tool is requisite. The other is using a special anchor device connecting with the ends of strip and the pretension can be achieved by manually screw
driving the bolts of the device (Yamakawa et al [14], 2001). Zhou et al [15] (2012) and Cheng et al [16] (2011) improved the anchor device in order to delay fracture of the strip adjacent to the anchor. However, it is challenge to pre-tension the strip accurately and the distribution of prestress is inhomogeneous. Moreover, the anchor device is not reusable, is easy rust because it is made of metal. We proposed a pre-tension device which can control the prestress precisely and is reusable [17]. The strengthen procedure using the device is elaborated in Section 2.1.

In order to validate the strengthen procedure proposed and investigate the effectiveness of prestressed CFRP strips, five square RC stub columns were fabricated and experimental tested under an axial compression load in this paper. The specimens tested included one un-strengthened and four strengthened. Three specimens were strengthened by using prestressed strips, and the other one strengthened by using non-prestressed was used to compare. The experimental data such as the failure modes, load-displacement curves and strain distribution of CFRP strips were obtained. The effects of prestress magnitude of CFRP strips on the ultimate bearing capacity and deformation capacity of the specimens were analyzed.

2. Experimental program

2.1. Test specimens

Five identical square RC columns were designed and fabricated. The geometric dimensions and configuration of reinforcement are shown in Fig. 1. A chamfer with a radius of 25mm is set to reduce the stress concentration of CFRP strips. Four specimens were strengthened by using strips. The specimen numbers and test parameters are listed in Table 1.

![Figure 1. Dimensions and reinforcement drawing of specimens](image)

| Number   | Strengthening | Prestress of strip /% |
|----------|---------------|-----------------------|
| SC       | No            | —                     |
| SC-S(0)  | Yes           | 0                     |
| SC-S(0.1)| Yes           | 10                    |
| SC-S(0.2)| Yes           | 20                    |
| SC-S(0.25)| Yes        | 25                    |

Columns were strengthened by CFRP strips with a spacing of 75 mm. The strips were prestressed by a pre-tension device developed by our research group. The steel rod wrapped around the CFRP was
supported by the force-transmitting rod, and then the upper and lower bolts were tightened to achieve the purpose of pulling CFRP strips. The principle is using a force-transmitting rod to form a balancing system between CFRP strips and the device. The pre-tension device can be disassembled after the rubber was anchored.

The circumferential overlap length of the CFRP strips is 180mm, which meets the requirements of the specification. And the overlapping positions of the CFRP strips are mutually staggered. In order to prevent the upper and lower end of columns from being damaged in advance during test, two-layer CFRP strips with a width of 100 mm were attached to the ends of column, as shown in Fig. 2a. The prestress level is controlled by the strain measured on the CFRP strips near the tension end. As shown in Fig. 2b.

![Diagram of CFRP strips and pretensing device](image)

**Figure 2.** Diagram of CFRP strips and pretensing device

### 2.2. Material properties

The concrete C30 was used. The longitudinal rebar was HRB335 and Φ 18 mm. The stirrups were made of HPB300 and had a diameter of 8mm. SKO brand CFRP weight 300 g/m² was used to strengthen the specimens. The width and thickness of the strip was 100 mm and 0.167 mm. The tested mechanical properties of concrete, steel rebars and CFRP are shown in Table 2.

| Materials  | $f_c$ / MPa | $f_y$ / MPa | $E$ / MPa |
|------------|-------------|-------------|-----------|
| Concrete   | —           | 33.4        | $3.12 \times 10^4$ |
| Rebar      | 587         | 587         | $2.0 \times 10^5$ |
| Stirrup    | 410         | 410         | $2.0 \times 10^5$ |
| CFRP       | 3870        | —           | $2.45 \times 10^5$ |

### 2.3. Loading and measurement scheme

The tests were carried out using a pressure testing machine with a capacity of 5000 kN. Before loading formally, the specimen was preload to 20% of the predicted ultimate capacity in order to ensure the meters work properly and loading position geometric alignment. When the test began formally, the load was applied with an increment of 10% of the ultimate load and each level of load was held for 2.5 minutes. The displacement controlling scheme was employed when the load reached 80% of the ultimate
load. Then a loading speed of 0.05 mm/min was applied until the load dropped to 85% of the ultimate carrying capacity.

Vertical load, vertical deformation and strains of CFRP strips were measured during testing. A pressure transducer was located on the top of the specimen to measure the load. Vertical deformation was achieved by using two linear variable differential transformers (LVDTs) placed on the loading plate of the machine. Four strain gauges were arranged uniformly on each CFRP strip. Longitudinal and hoop strain gauges were also pasted on the mid-span of the specimen to catch the strains of concrete. The arrangement of the strain gauges and LVDTs are shown in Fig. 3.

Figure 3. Arrangement of strain gauges and LVDTs

3. Failure modes and observations

3.1. RC column
The specimen was elastic and there was no significant phenomenon in the initial loading stage. The load increased linearly. When the load reached about 70% of the peak load, vertical cracks began to appear in the concrete at the upper end of the column. As the load increased, cracks extended obliquely downward, especially at the corner of the column. When the peak load was coming, cracks in the corner expanded and vertical cracks appeared in the middle of the column. After peak load, the concrete at the end of column fell off and the load decreased rapidly. The test stops when the load dropped to 85% of the peak load. The damaged RC column is shown in Fig. 4a.

3.2. Column strengthened with non-prestressed strips
The column strengthened with non-prestressed CFRP strips showed no obvious damage when the load was small. The lateral deformation of concrete was small and the strain of CFRP strips increased slowly. When loaded to about 75% of the peak load, the concrete between CFRP strips at the upper end of column began to produce vertical cracks. As the load increased, cracks extended downward from the upper end of column, and the concrete gradually cracked and bulged at the corner of the middle column. After loaded to the peak load, the concrete on the top half of column with no CFRP strips collapsed. When the load dropped to 85% of the peak load, the test was stopped. The CFRP strips were not torn, as shown in Fig. 4b.

3.3. Columns strengthened with prestressed CFRP strips
The columns strengthened with prestressed CFRP strips had a common failure mode during the axial compression test. At the initial stage, the strain of CFRP strips increased slowly, and the lateral deformation of concrete was not changed due to the active restraint of prestressed CFRP strips. When
the load reached about 80% of the peak load, vertical cracks appeared at the upper end of columns where with no CFRP strips wrapped. The crack extends from the upper end to the middle of columns as the load increased, accompanied by a 'click' of colloidal cracking. When loading to about 85% of the peak load, the lateral deformation of columns grow faster, and the strain of prestressed CFRP strips at the top of columns increased rapidly, especially the strain of CFRP strips around cracks increased sharply.

The concrete on the top half of columns was obviously cracked as the load increased, and some local parts began to bulge. When loaded to the peak load, the concrete on the top half of columns was crushed. As the displacement increased, the concrete detached from the corner of columns, and cracks in the middle of columns extended downward through CFRP strips. And CFRP strips were partially cracked and columns were destroyed, as shown in Fig. 4c, Fig. 4d and Fig. 4e.

![Figures 4. Failure mode of specimens](image)

### 4. Test results and discussion

#### 4.1. Carrying capacity

The axial bearing capacity of the specimens are listed in Table 3. It can be found that the carrying capacity of the columns strengthened had a great increase than RC column. The carrying capacities of the specimens SC-S(0) and SC-S(0.1) were close because the strips had a stress loss. Another reason may be that CFRP strips winding positions just overlapped with stirrups, which reduced the strengthening effect. The strengthening effect of the strip with 20% pre-tension was significantly improved. However, when the prestress level was increased from 0.2 to 0.25, the peak load changed small. This is because the failure modes of columns were characterized by collapse of CFRP strips after they reaching a certain initial stress, and the carrying capacity was determined by the CFRP strength.

| NO.     | Prestress level /% | Peak load /kN | Ratio of increase / % |
|---------|--------------------|---------------|-----------------------|
| SC      | —                  | 2989.3        | —                     |
| SC-S(0) | 0                  | 3316.7        | 10.95                 |
| SC-S(0.1)| 10                | 3379.2        | 13.04                 |
| SC-S(0.2)| 20                | 3577.1        | 19.66                 |
| SC-S(0.25)| 25               | 3614.1        | 20.90                 |

Fig. 5 shows the load-displacement curves of the specimens. As can be seen from the figure, the prestressed CFRP strip delayed the occurrence of cracks because of the 'active constraint' they provided. As the prestress level increasing, the crack propagation became slower, the peak load appeared later, and the ultimate strain of columns increased. It indicated that the plastic deformation ability of columns strengthened with prestressed CFRP strips can be effectively improved.
4.2. Strain of CFRP strips

Fig. 6 shows the curves of the load vs. strain of strips. Take the first broken CFRP strip on each column to be compared. It can be found that these strained points were in the upper part of columns. The reason is that the pressure machine applied a vertical load from the bottom.

In the initial stage of loading, the concrete was still elastic, the strain of non-prestressed CFRP strips increases slowly, and the strain of prestressed strips remain nearly constant. When the load exceeded 1000kN, the concrete entered the plastic stage, the lateral deformation gradually became larger, and the strain of CFRP increased. When concrete cracked, the strain growth rate of the prestressed CFRP strip was slower than that of the non-prestressed strip. After the peak load, the strain of prestressed CFRP strip increased sharply, and its increase rate of different prestress levels was basically same. At the same time, it was also found that the higher the prestress level, the larger CFRP strain when the column was broken. The utilization rate of CFRP was 87.5% when the prestress level was 0.25.

![Figure 5. Curves of load - deformation](image1)

![Figure 6. Curves of load - strain of CFRP strips](image2)

5. Conclusion

(1) The strengthening procedure for RC column using prestressed CFRP strips is exercisable and valid.

(2) Pre-tension of CFRP strip can improve the carrying capacity of the strengthened column and delay the occurrence of concrete crack. The ultimate strain and ultimate strength of column increase with prestress of the CFRP strip.

(3) High strength of CFRP is more easily applied in the prestressed strengthening works. The material utilization rate of CFRP is obviously improved with the pre-tension.

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