Study on short-term prestress loss of bridge reinforced with large diameter carbon fiber bars

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Abstract. At present, the technology of strengthening bridge with prestressed CFRP bars is gradually rising, so it is necessary to study the law of prestress loss. In order to evaluate the short-term prestress loss of prestressed concrete beams was studied by combining laboratory tests with practical reinforcement projects. The anchorage loss, concrete elastic compression loss of CFRP bars were obtained by measuring the prestressed loss data of CFRP bars used to strengthen retired old beams and corresponding theoretical calculation. Then, combined with the corresponding loss data of 6 prestressed CFRP bars in the actual strengthening project of Wenzhou Lijing Middle Bridge, the experimental investigation was carried out. The results show that the prestress loss of CFRP bars is between 4%~8%, and develops rapidly in the early stage, among which the anchorage loss accounts for 45.90%. The anchorage retraction value is about 1.33mm, and the elastic compression loss of concrete is basically negligible.

1. Introduction
Under the action of natural environment, material deterioration, construction defect, vehicle overload and other factors, the reinforced concrete bridge will have different degrees of damage and disease, and even collapse accident[1]. By 2018, there were more than 600,000 bridges in service for more than 10 years, and more than 300,000 bridges for more than 15 years[2]. A large number of bridges need to be strengthened. At present, the prestressed CFRP reinforcement technology of bridge has a good application prospect because of its low cost, large increase in flexural capacity and convenient construction.

The prestressed reinforcement of reinforced concrete bridges with CFRP bars can significantly improve the mechanical performance of bridges[1]. However, the prestress loss of CFRP bars should be paid attention to. At present, some scholars have carried out research work in this field. Wang Zuohu etc[3] pointed out that the prestress loss composition of CFRP bars is basically similar to that of steel strand, and the elastic modulus of CFRP bars has a very important effect on the prestress loss. On the composition of the loss of prestress, Xu Feng⁴ suggested that the relaxation of CFRP bars and the long-term deformation of steel supports are the main factors causing the long-term loss of prestress. Meng
Lvxiang etc. [5] work out the results of the prestressed relaxation loss of CFRP bars show that the relaxation loss rate of the prestressed CFRP bars holding 1000MPa and diameter of 8mm is only 2.56% in 1000h. In addition, many scholars have conducted corresponding researches on the prestress loss of CFRP plates and CFRP cloth, among which Xu Xiao and Ai Jun [6] through the experiment of strengthening concrete beams with prestressed CFRP cloth, concluded that the prestress loss of CFRP cloth developed faster in the early stage, and the rate gradually decreased with the passage of time, and the prestress value gradually tended to be stable. And Deng Lani, Zhao Simin and so on [7] have evaluated the prestress loss rate of prestressed CFRP plates and concluded that the estimated value of the prestress loss rate of the steel structure strengthened by prestressed CFRP plates should be 15% of the tensioning control value. As for the prestress loss rate of concrete beams strengthened by prestressed CFRP plates, Deng Lani et al. [8] suggest that the estimated value of the prestress loss of the prestressed CFRP reinforced concrete structure should be 10%-15% of the tensioning control stress. At present, the experimental research on the prestress loss of bridges strengthened by CFRP bars is mainly carried out in the laboratory, and the relevant measured data in the engineering practice is still relatively lacking, especially the prestress loss of large-diameter CFRP bars serving the engineering practice is still to be studied.

In this paper, the total prestress loss rate $\sigma_{\text{total}}$, the anchorage loss $\sigma_1$, and the concrete’s elastic compression loss $\sigma_2$ of the 12.7mm diameter CFRP reinforcement bridge are tracked and measured through the model test of the decommissioned old beam and the actual engineering measurement. The relevant data of the above losses are obtained, which can provide a reference for the design of the bridge strengthened by prestressed CFRP bars.

2. Measured loss of prestress

The prestress loss of bridges strengthened by CFRP bars includes three short-term losses, including anchorage loss $\sigma_1$, concrete elastic compression loss $\sigma_2$ and friction loss $\sigma_3$ [9][10]. In this paper, the prestress loss of bridges strengthened by CFRP bars is measured comprehensively through model experiment and practical engineering of decommissioned old beams.

2.1. Model experiment of decommissioned old beams

The model test of retired old beams is mainly used to observe the short-term loss of prestressed CFRP bars strengthened bridges and its variation rule with time, and to evaluate the size of anchorage loss $\sigma_1$, concrete compression loss $\sigma_2$, and to give the suggested value to guide the engineering practice.

The loss of prestress retired old beam model test adopts hollow slab beam which has been in operation for 25 years, the strength grade of concrete is C50, at the bottom of the beam layout an 12.7 mm in diameter, 10m in length of the prestressed CFRP bars, the tensile strength of CFRP reinforcement design value is 2200 MPa, control stress is 950 MPa (44% of design value). The control forces of 120 kN. The prestress loss of prestressed CFRP bars is monitored by a core-through force transducer installed between the connecting screw and the retaining nut (as shown in Fig. 1). Considering that there is no friction when the pre stressing is applied, so the friction loss $\sigma_3$ of CFRP bars are not considered in this test.

Figure 1 Arrangement of prestressing bars and force sensors
The layout of decommissioned old beams and prestressed CFRP bars are shown in Fig. 1. The prestressed bars are tensioned by jacks. Upon the completion of the CFRP tendons tensioning, tighten the retaining nut, then read the force value of the force transducer $F_1$, and then relax jack, at this point, on both sides under the action of prestressed anchorage, the gaps between the connected component squeezed tight, pre-stressed happen trace retraction (assuming the retraction value for $a$), at this time again read the value of the force transducer $F_2$ to record the difference between the two data And then to calculate the CFRP reinforcement anchorage loss $\sigma_1$.

2.2. Actual engineering survey

The measurement of the actual project is mainly used to verify the accuracy of the loss assessment values and their variation with time obtained from the model test of decommissioned old beams.

Lijing Middle bridge was completed in 2007 (see Figure 2-4) and reinforced with prestressed CFRP bars in 2020. The bridge is a 3*16m hollow slab girder bridge with a width of 11m, and each span contains 10 hollow slab girders. The east first span is reinforced with prestressed CFRP bars, as shown in Figure 5. Two CFRP bars with a diameter of 12.7mm and a length of 12m are arranged longitudinally for each beam, and the tension control stress is 950MPa. In the transverse bridge, five CFRP bars with a diameter of 12.7mm and a length of 9.5m are arranged perpendicularly to the beam axis and the tension control stress is 790MPa.
In this reinforcement project, force transducer are used to monitor the total prestress loss of prestressed CFRP bars. In the longitudinal reinforcement direction, 6 force transducer are placed on 6 CFRP bars as shown in Fig. 3. The reading steps of force sensor data are the same as the model test of decommissioned old beams. After completing reading the value of force transducer $F_2$, need to increase the step tests on concrete elastic compression loss $\sigma_2$, in a beam is one of the CFRP reinforced prestressed tensioning finished, and then the another of the same beam CFRP bars are tensioned, after the completion of the tensioning of this CFRP bar, to read again the force transducer value $F_3$, and then to calculate the elastic compression of concrete loss parts $\sigma_2$.

3. Prestress loss analysis

3.1. Total prestress of CFRP bars $\sigma_{\text{total}}$

The analysis of the total loss of prestress was carried out through decommissioned beams with a long observation period. See Figure 5-6 for details of the variation of the total loss with time.

![Figure 4 Side view of bridge reinforcement](image)

![Figure 5 Changes of residual prestress over time](image)
It can be seen from the above two charts that the prestress loss develops rapidly in the early stage, and the completion degree of the prestress loss reaches more than 95% in the first 7 days. In the later stage, the residual prestress fluctuates around 900MPa, but does not always decline, and the prestress loss rate stays between 5%-6% in the end.

3.2. Anchorage loss of CFRP bars \( \sigma_{\text{at}} \)

The calculation formula of anchorage loss \( \sigma_{\text{at}} \) of prestressed CFRP bars is mainly referenced the calculation method of anchorage loss of steel bar/steel strand\(^{[11]} \) as follows

\[
\sigma_{\text{at}} = \frac{a}{l} E_c
\]

Where:
- \( a \) — Anchorage system deformation and CFRP bar shrinkage;
- \( l \) — Total length of CFRP bars;
- \( E_c \) — The elastic modulus of CFRP bars is 160GPa\(^{[12]} \).

The median \( a \) plays a crucial role in the anchorage loss \( \sigma_{\text{at}} \), which is now calculated through the data obtained from the decommissioned old beam tests, \( \Delta F_1 = 2.7 \, kN, \sigma_{\text{at}} = 21.31 \, MPa, a = 1.33 \, mm. \)

Now, it is compared with the data obtained from the actual reinforcement project of Wenzhou Lijing Middle Bridge to verify its accuracy. The specific values are shown in Table 1.

| Prestressed CFRP bar number | \( \Delta F_1 \)/kN | \( \sigma_{\text{at}} \)/MPa | \( a \)/mm |
|----------------------------|-----------------|-----------------|---------|
| 1                          | 2.3             | 18.16           | 1.135   |
| 2                          | 1.4             | 11.05           | 0.69    |
| 3                          | 1.6             | 12.63           | 0.789   |
| 4                          | 2.4             | 18.94           | 1.18    |
| 5                          | 3.6             | 28.42           | 1.78    |
| 6                          | 1.1             | 8.68            | 0.54    |
| On average                 | 2.07            | 16.31           | 1.02    |
| Test of decommissioned beams | 2.7            | 21.31           | 1.33    |

As can be seen from the above table, in the reinforcement project of Wenzhou Lijing Middle Bridge, the prestressed anchorage loss values of each CFRP bar are slightly different, which is caused by the different degree of tightening of the retaining nut by the construction personnel after the completion of
prestressing in actual operation. The deviation between the average values and the test values of the retired old beams is within a reasonable range. The engineering design value of anchor system deformation and CFRP reinforcement shrinkage $\alpha$ is suggested to be 1.1mm.

3.3. concrete elastic compression loss $\sigma_{12}$

Since only one prestressed bar was tensioned in the test of decommissioned old beams, there is no elastic compression loss of concrete with CFRP bars. Only theoretical calculation is carried out here, and the calculation method is referred to the literature\cite{13}. It is as the following formula:

$$\sigma_{12} = \alpha_{EP} \sum \Delta \sigma_{pc}$$  \hspace{1cm} (2)

Where, $\alpha_{EP}$—the ratio of the elastic modulus of prestressed CFRP bars to the elastic modulus of concrete;

$\Delta \sigma_{pc}$—The normal stress of concrete generated by the post-tension prestressed CFRP bars is calculated at the center of gravity of the prestressed CFRP bars whose sections are tensioned.

Among them, the cross-sectional area of hollow slab beam is taken as 0.43$m^2$, the concrete grade is C50, the concrete elastic modulus is taken as $3.45 \times 10^4$MPa, and the elastic modulus of CFRP bars is taken as 160GPa\cite{8}, then it can be calculated.$\sigma_{12} = 1.295$MPa

Now, the data $\Delta F_z$ collected in the reinforcement project of Wenzhou Lijing Middle Bridge is used to check the theoretical calculation results to realize the evaluation. Table 2 below compares the theoretical calculation values with the collected data.

| Prestressed CFRP bar number | $\Delta F_z$/kN | $\sigma_{12}$/MPa |
|----------------------------|-----------------|------------------|
| 1                          | 0.0             | 0.0              |
| 3                          | 0.3             | 2.37             |
| 5                          | 0.1             | 0.79             |
| On average,                | 0.133           | 1.05             |
| Theoretical value          | 0.164           | 1.295            |

Theoretical calculated value and actual reinforcement project in the table although there are some differences between the data collected, but the difference is not large, prestressed CFRP reinforced concrete elastic compression loss between 1‰ to 3‰, almost negligible, the actual data from the reinforcement project in sizes, because the effect of temperature and vehicle load, but the deviation is still within a reasonable range.

4. conclusion

At present, the technology of strengthening bridge with prestressed CFRP bars is gradually rising, and the research on the law of prestress loss is becoming more and more important. Based on the practical reinforcement project of prestressed CFRP bars and the model test of decommissioned beams with prestressed loss, this paper makes a detailed analysis of the proportion of each short-term loss, the size of the total loss rate and the time distribution of prestressed loss in the total prestressed loss of CFRP bars and draws the following conclusions:

1. The total prestress loss rate of external prestressing reinforcement of CFRP bars for old Bridges with service time of more than 10 years is about approximately is applied 4%~8%, and most of the loss is completed within 7 days after the prestressing.

2. In the external prestressing of prestressed CFRP bars for the reinforcement of old Bridges, the prestressing short-term loss mainly comes from the anchorage loss of CFRP bars. The elastic compression loss of concrete is very small and can be almost ignored, among which the anchorage loss accounts for about 45.90%. 
In the future, we hope to increase the observation of the prestress loss of CFRP bars for a long time to observe the regularity.

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