Research on Fatigue Test of Reinforced Concrete Beams Strengthened with CFRP Plates

Weifeng Li
Nanjing Vocational Institute of Transport Technology, Nanjing, 211188, China.

Abstract. To study the effect of different anchorages on the CFRP anchoring effect and fatigue, the loading test of the force-locking anchor system and the self-locking anchor system was carried out on the prefabricated beams with the same conditions to study the beams under different anchoring systems. After the fatigue test, the cracking situation, linear elasticity change, stiffness degradation, and failure mode were analyzed to analyze the fatigue life of the beam plate under different anchors, and it was concluded that the two anchoring systems had better performance without large overload. It has anti-fatigue performance and good reinforcement effect.

Key words: CFRP plate; anchoring system; beam bridge; fatigue test; failure mode.

1. Foreword
At present, long-span prestressed concrete bridges are becoming more and more popular, but as the age of the bridge increases, the performance of the prestressed concrete also declines. As the stiffness and deflection increase, the bearing capacity of the bridge decreases. To ensure the safe operation of the bridge after the load capacity of the bridge decreases, certain measures must be taken to reinforce the bridge structure. The traditional reinforcement method has the situation that the material is self-important, the elastic modulus is small, and the reinforcement effect is general, while the fiber-reinforced composite material (FRP) is more and more popular in the field of reinforcement because of its high strength, lightweight, high elastic modulus, corrosion resistance and other good properties, and prestressed carbon fiber reinforced composite materials (CFRP) can improve the performance of FRP materials and are widely used. As a non-metallic material, its anchoring effect is particularly important. In this paper, the fatigue effects of two different CFRP plate anchoring systems are analyzed and analyzed.

2. Production of trabecular specimens
To simulate the working state of the prestressed CFRP board reinforced the bridge under the load of the car, the corresponding indoor beam fatigue test was carried out. To ensure the typicality and comprehensiveness, this study selected two sets of prestressed CFRP plate anchoring systems, namely "force card anchoring system" and "self-locking anchoring system" for parallel research. Using an indoor trabecular test, make 3 pieces of reinforced concrete rectangular beams with proper size (fatigue
test after 2 pieces of reinforcement, 1 piece of bare beam loading test), and install two sets of prestressed CFRP plate anchoring system in the early stage. Pull the same prestress on 2 trabecular beams.

A total of 3 concrete test beams were cast in this project. The design strength of the test beam concrete is C40, the total length of the test piece is 6000mm, the net span is 5400mm, and the cross-sectional size is b×h=350mm×500mm. The top reinforcement is 3Φ16, the bottom reinforcement is 3Φ22, the side reinforcement is 8Φ12 erection steel bar, the stirrup is 1800mmΦ10@200mm in the middle of the span, and the rest is Φ10@100mm. To facilitate lifting and transportation, a lifting point is set at 1.0m from the beam end.

To accurately measure the strain of the steel bar under tension and compression during the test loading process, an optical fiber sensor is pasted on the steel bar in advance. According to "Standard for Test Methods of Mechanical Properties of General Concrete" (GB/T 50081-2002), the axial compressive strength of 150mm×150mm×150mm cubic test block was measured, as shown in Table 1.

The tensile strength of the concrete axis is calculated as follows:

\[
f_t = 0.395 f_{cu}^{0.55}
\]  

(1)

The elastic modulus of concrete is calculated as follows:

\[
E_c = 10^5 / (2.2 + 34.7 / f_{cu})
\]  

(2)

The measured data obtained the performance parameters of concrete and main tendons, and summarized to Table 1~ 2.

| parameter              | Axial compressive strength (MPa) | Axial tensile strength (MPa) | Elastic Modulus (GPa) |
|------------------------|----------------------------------|------------------------------|-----------------------|
| actual data            | 40.6                             | 3.03                         | 32.8                  |

| Main rib type/diameter | Yield Strength (MPa) | Ultimate strength (MPa) | Yield strain (µε) | Elastic Modulus (GPa) |
|------------------------|----------------------|-------------------------|-------------------|-----------------------|
| HRB400/22              | 420                  | 608                     | 2144              | 195                   |

One test beam is used for the rigid self-locking CFRP plate anchoring system (No. A). The tensile control stress of the CFRP plate is 1277MPa.

One test beam is used for the Nanjing Rica CFRP plate anchoring system (No. B). The tensile control stress of the CFRP plate is 1277MPa.

| Specimen number | Longitudinal reinforcement | CFRP plate (mm²) | Initial tensile stress (Mpa) | Anchor system |
|-----------------|---------------------------|------------------|-----------------------------|---------------|
| A               | 3Φ22                      | 150              | 1277                         | Self-locking system |
| B               | 3Φ22                      | 150              | 1277                         | lika System    |
| L               | 3Φ22                      | --               | --                           | --            |
3. Fatigue test method

In addition to the static load, the actual bridge structure also has to withstand moving loads such as vehicles and vibration loads. To simulate the actual stress state of the reinforced structure, this study conducted a fatigue performance test on the RC beam reinforced with prestressed CFRP plates.

The test loading system uses MTS actuators with a maximum dynamic and static load of 1000kN. The specimen has a net span of 5400 mm and is simply supported at both ends. The four-point bending loading method is adopted, and the two loading points are located in the middle of the specimen, 1400 mm apart.

The main test contents during the test are added load, displacement, strain, and others.

Load value: The load value during the test loading process is automatically read and recorded by the MTS loading system.

Displacement: Displacement meters are set at the mid-span of the beam and the loading point respectively. The displacement value is collected by the dynamic and static test system to obtain the displacement change of the pure bending section accurately and quickly. The displacement at the support can be measured with a dial indicator and read manually.

Strain: The concrete beam, main ribs, and CFRP board are pre-pasted with optical fiber sensors, and the deformation of each material can be obtained in real-time through the optical fiber demodulator.

During the test, it is necessary to carefully observe the changes of the beam body (such as cracking, crack development, steel bar yield, CFRP plate breakage, etc.), record the corresponding load value, and take a photo record of the typical shape. The tester must wear a safety helmet during the test to ensure the safety of the site before observing or performing other operations.

According to the static load test results, combined with the actual load appearing in the bridge structure, the specimen is fatigue loaded in three stages, the fatigue load ratio is taken as 0.3, the specific load value and the number of fatigue are shown in Table 4.4, the loading frequency is 4Hz. In the first stage, the corresponding load is small, and the beam is in the initial cracking state, which mainly simulates the reaction of the specimen under small load; in the second stage, the load is moderate, mainly simulates the reaction of the specimen under moderate load; in the third stage, the load is large, Mainly to simulate the reaction of the structure under overload.

| stage | Load upper limit kN | Load lower limit kN | Cycles K | use                  |
|-------|---------------------|---------------------|----------|----------------------|
| I     | 80                  | 24                  | 500      | Small load           |
| II    | 160                 | 48                  | 500      | Medium load          |
| III   | 280                 | 84                  | Until destruction | Overload effect       |

![Figure 1. Displacement meter](image1)

![Figure 2. Dynamic and static test system](image2)
To investigate the mechanical properties and flexural capacity of the reinforced beam after a certain number of cyclic loadings under different stress amplitudes, the initial static load test was conducted before the fatigue test. The fatigue times were 100,000, 300,000, and 500,000 At times, 600,000 times, 800,000 times, and 1 million times, the fatigue loading is stopped, and the static load test is carried out. The maximum value of the load applied during the static load test is the upper limit of the fatigue load at each stage.

4. Main test phenomena and crack development

Stage I: After the initial static load test, a small amount of fine cracks appeared in the concrete beam. In the subsequent static load test, the number of beam cracks increased slightly, and the crack width did not change significantly.

Stage II: The crack width and height of the beam body have increased. In each subsequent static load test, new cracks were generated, and the crack width did not increase significantly.

Stage III: The crack width and height of the beam have increased. Cracks in the pure bending section of the test piece are relatively densely developed, and there are many cracks in the bending and shearing section.

After each static load test is unloaded, the cracks of the test piece are closed, indicating that the application of prestressed CFRP plates at the bottom of the beam can effectively close the cracks at the bottom of the beam. According to the literature (Liu Muyu, Li Kaibing. Experimental study on fatigue performance of concrete beams reinforced with carbon fiber cloth [J]. It only occurs in the area with a large bending moment in the middle of the span, and the cracks appear earlier. Once they appear to expand faster, the number of cracks is less and the width develops more. In this test, after being reinforced with prestressed CFRP plates, the cracks in the pure bending section of the test piece are relatively densely developed, and there are many cracks in the bending and shearing section, with a large number of cracks and a small width. It shows that under the fatigue load, the prestressed CFRP plate is applied to the bottom of the beam, so that the performance of the reinforced concrete beam material is fully exerted.

5. Linear elasticity change

Figure 4.1 shows the load-span mid-displacement curve of the specimens A1 and B1 after the initial static load test and after 500,000, 1 million, and 1.2 million fatigue loads. (B) The graphs represent the load-span displacement curves of specimens A1 and B1, respectively. It can be seen from Figure 3 that after different times of fatigue loading, the specimen still maintains a good linear elastic state.

![Figure 3. Load-span displacement curve](image-url)
6. Stiffness degradation
The stiffness of the test piece in the four-point bending test can be calculated by the following formula:

\[
B = \frac{\Delta F}{\Delta f} \left[ \frac{(L-L_f)^3}{24} + \frac{(2L-L_f)(L-L_f)}{16} L_f \right]
\]  

(3)

In the formula, B represents the bending stiffness of the specimen; F is the load on the specimen; f is the mid-span displacement of the specimen; mm, the span of the specimen; mm, the distance between the two loading points.

Figure 4 shows the degradation curves of stiffness performance of specimens A1 and B1 under fatigue load. It can be seen from Figure 9.16 that with the increase of the number of fatigue, the bending stiffness of the test piece generally decreases linearly, which is caused by the accumulation of fatigue damage. However, when specimen A1 undergoes a static load test after 300,000 fatigue loads and 800,000 fatigue loads, its bending stiffness is greater than that obtained during the previous static load test, and specimen B1 after 300,000 fatigue loads. This anomaly also happened. The reason for this phenomenon is that under fatigue load, the number of cracks in the reinforced test piece increases, and the crack width decreases, thereby resulting in a more uniform stress distribution on the test piece. Wu Zhishen, National University of Ibaraki, Japan, also observed such phenomena in the relevant tests on beams reinforced with prestressed PBO sheets.

It can be concluded that the stress distribution of the prestressed CFRP plate strengthened beams under fatigue load is more uniform.

7. Strain change
Figure 5 shows the strain curve of the concrete at the bottom of the mid-span beam under different fatigue loads. (a) is the strain curve of the specimen A1, and (b) is the strain curve of the specimen B1...

It can be seen from Figure 6.1 that when the applied load is small, the strain change curves of the concrete at the bottom of each beam after different fatigue times are relatively close, but generally, the strain at the bottom of the mid-span beam increases as the number of fatigue increases. The general trend is caused by cumulative fatigue damage.

Figure 6 shows the strain change curve of the CFRP plate at the bottom of the mid-beam of the test piece after different fatigue loads. curve. It can be seen from the figure that the strain change curves obtained when the fatigue load times are less than 1 million times are similar, but generally, as the fatigue times increase, the strain on the CFRP plate tends to increase. It is worth noting that, from Figure (a), it can be seen that after 1.2 million fatigue loads, the strain of the CFRP plate under the same load is less than the strain obtained after 500,000 and 1 million fatigue loads. It can be inferred from the final
failure form of the test piece that the cause of this phenomenon is the weak slip phenomenon from the rigid self-locking anchor at the end of the CFRP plate under overload during the third stage of fatigue loading. It can be seen from Figure (b) that the strain on the CFRP plate has an increasing trend with the increase of the number of fatigue loads. From this, it can be seen that the work performance of the force card anchoring system under fatigue load is good, and the CFRP plate does not appear sliding out of anchors and other phenomena.

Figure 7 shows the strain change curve of the main tension bar of the test specimen after undergoing different fatigue loads. Among them, (a) is the strain curve of specimen A1, and (b) is the strain curve of specimen B1. It can be seen from Figure 7 that as the number of fatigue loads increases, the strain at the mid-span of the tensile main tendons increases under the same load. It can be seen from Figure (a) that when the number of fatigue is less than 1 million, the strain values obtained under the same load are not much different, but after 1.2 million fatigue loads, the strain of the steel bar at the mid-span under the same load increases significantly, which It is because, in the third stage of fatigue loading, the end of the CFRP plate is weakly slipped from the rigid self-locking anchor, which causes a large increase in the strain in the main reinforcement. It can be seen from Figure (b) that after 1.2 million fatigue loadings, the strain of the main reinforcement at the mid-span cross-section of specimen B1 has a slight increase from the previous stage, and the increase is smaller than that in specimen A1. It can be inferred that the work performance of the force card anchoring system during fatigue loading is better than that of the rigid self-locking anchoring system.

![Figure 5. Curve of concrete strain change at the bottom of mid-span beam](image1)

![Figure 6. Strain change curve of CFRP plate at the bottom of mid-span beam](image2)
8. Destruction mode

For specimen A, when the fatigue load reaches 1.3 million times, it can be seen from the MTS loading system that the load value applied to specimen A decreases rapidly, which indicates that the rigidity of specimen A is rapidly declining. When the fatigue loading reached 1.13 million times, with a loud noise, the specimen A broke. Figure 9.20 shows the failure mode of specimen A. It can be seen from Figure 8. that when the test piece A1 fails, a tensile main bar and a distributed steel bar break, the test piece is broken into two sections, and the CFRP plate slides out of the anchor and peels off from the lower part of the test piece. After the damage, the CFRP plate still maintains a strip state. It can be seen from the figure that when the end of the CFRP plate slides out of the rigid self-locking anchor, the tooth marks of the wedge-shaped steel clips in the anchor friction with the CFRP plate The traces left.

It can be judged from the comprehensive analysis of the failure shape of the test piece and the deformation and strain of the test piece. The final failure of the test piece is due to the fatigue load further increased after 1 million times of fatigue. The rigid self-locking anchor system has the phenomenon of anchor relaxation, the same load The deformation of the lower test piece increases, increasing the stress amplitude on the steel bar, which eventually leads to fatigue fracture of the steel bar, and then the CFRP plate is pulled out of the rigid self-locking anchor, and the test piece immediately fails.

When the fatigue loading reached 1.43 million times, the specimen B1 was destroyed, and the failure was accompanied by a loud noise. Figure 10 shows the failure mode of the test piece B1. It can be seen from Figure7.2 that when failure occurs, three tensile bars and two distributed bars in specimen B1 break, the specimen is broken into two sections, the CFRP plate shows crushing failure, and the force card anchoring system remains in working condition.

It can be seen from the above failure modes that during the fatigue loading stage, the Rica anchoring system maintains a good working state, and the anchoring system still maintains a good working performance until the final fatigue failure occurs. The final failure of specimen B is due to the accumulation of fatigue damage of the steel bars under the fatigue load, which eventually causes fatigue fracture.

Figure 8. Specimen B failure mode
9. Fatigue life analysis
The fatigue loading times of specimens A1 and B1 were 1.3 million and 1.43 million, respectively, and the number of fatigue loading was less than 2 million. This is due to the large amplitude of stress applied in the third stage of fatigue loading. It can be seen from the reaction under overload that the overload has a great influence on the fatigue life of the specimen.

According to the strain value of the main tension bar at each stage of the mid-span section of the test piece in Figure 7.13, the stress amplitude of the steel bar at each stage can be obtained. The literature is selected (Zhang Ke, Ye Lieping, Yue Qingrui. Fatigue life of concrete beams strengthened with prestressed carbon fiber cloth Analysis [J]. Industrial Building, 2008, 38(7): 107-112.) The formula when the stress is 0.3, namely:

\[
\lg N_f = 34.31736 - 12.56013 \lg \Delta \sigma_m
\]  

(4)

In the "Code for Design of Concrete Structures", the limit of fatigue stress amplitude for HRB400 steel bar at a load ratio of 0.3 is 145MPa, and the number of fatigue under the standard stress amplitude is conservatively defined as 2 million times. According to the theory of cumulative fatigue damage, the change Amplitude fatigue load is converted into equivalent constant amplitude fatigue load, that is, using the formula:

\[
\sum \frac{n_i}{N_i} = \frac{n_m}{N_m}
\]  

(5)

Converting the variable-amplitude fatigue load used in this test into a constant-amplitude fatigue load with a reinforcement stress amplitude of 145 MPa, and calculating the number of fatigue times, we can get: nAm=8 million times>>2 million times, nBm=12 million times >> 2 million times.

10. Conclusion
This shows that the test structure fully meets the requirements of the specification. The reason why the variable amplitude fatigue load is used in the test is mainly to take into account that the load suffered by the actual structure is not constant, and the vehicle is often overloaded.

It can be seen from the fatigue load test that the prestressed CFRP plate reinforced with rigid self-locking anchor system and force card anchor system has good fatigue resistance, and the pre-stressed rigid self-locking anchor system and force card anchor system Reinforced RC beams with stress CFRP plates all meet the relevant regulations for concrete structural members in the code, and the reinforced beams are more uniformly stressed under fatigue loads. At the same time, it can be seen that overloading has a great impact on the fatigue life of structural members. During the operation of the actual bridge structure, overloaded vehicles must be strictly controlled.

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