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Static and Fatigue Properties of RC Beams Strengthened with Prestressed CFRP Plates

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Abstract: *In order to study the performance of bridges reinforced by prestressed CFRP plates under vehicle load, four reinforced concrete (RC) beams strengthened with prestressed CFRP plates and one unreinforced beam were designed. The reinforced beams adopted two typical prestressed anchor systems. The failure mode, bearing capacity, stiffness degradation and strain change law of the reinforced beam under static and variable amplitude fatigue cyclic loading were investigated through static bearing capacity test and fatigue performance test. A nonlinear finite element model of the test beam was established to simulate the static load test process. Research indicates: Compared with the unreinforced specimens, the cracking load of the RC specimens strengthened with the prestressed CFRP plate is increased by 60%, and the ultimate load is increased by 32% and 50%. The prestressed CFRP plate and the concrete at the bottom of the beam show good synergistic deformation performance. Under the action of variable amplitude fatigue load, the bending stiffness of the strengthened beam generally decreases linearly. The existence of prestress makes the stress distribution of the tension main bar more uniform and improves the fatigue resistance of the concrete beam. Therefore, the prestressed CFRP plate has a significant effect on strengthening reinforced concrete beams. The variable amplitude fatigue load is converted into equivalent constant amplitude fatigue load for life analysis. The fatigue life of the reinforced beam is 8 million times and 12 million times respectively. The safety performance of the two anchoring systems meets the normal use requirements of the structure.*

Keywords: *fatigue performance; fatigue test; finite element analysis; prestressed CFRP plates; reinforcement; fatigue life analysis*

1. Introduction

Carbon fiber reinforced polymer (CFRP) plate is widely used in the reinforcement and reconstruction of old highway concrete bridges because of its light weight, high strength, fatigue resistance and corrosion resistance [1-2]. Prestressed CFRP plate reinforcement technology is an active reinforcement method, which has advantages of simple technology, obvious reinforcement effect, less damage to the beam, better economy. Compared with traditional bonded non prestressed CFRP reinforcement method, it really realizes the maximum utilization of the superior performance of CFRP material [3]. In terms of bridge reinforcement components, the mechanical characteristics of the structure will change after its reinforcement. In order to ensure the effect of the structure reinforcement, it is very important to study the mechanism and law of the change.

In recent years, scholars at home and abroad have done a lot of research on the mechanical behavior of concrete beams strengthened with CFRP sheets under static and fatigue loads. For example, Sherif El Tawil et al. [4] established an analysis model to simulate the fatigue process of reinforced concrete structures strengthened with CFRP. The results show that the stress of steel and CFRP is continuously redistributed under fatigue load, which is similar to creep phenomenon. Garden HN et al. [5] found that applying prestress can effectively reduce the height of neutral axis, increase the height of concrete compression zone, and reduce the deformation of test beam. Garden HN et al. [5] found that applying prestress can effectively reduce the height of neutral axis, increase the height of concrete compression zone, and reduce the deformation of test beam. Based on the fatigue test of reinforced concrete beams strengthened with CFRP, Ru Haifeng [6] analyzed the deformation behavior of concrete flexural members strengthened with CFRP under high cycle repeated load. The results show that the stiffness of the strengthened beams decreases while the crack width increases under fatigue load. The fatigue stiffness formula of the reinforced concrete beams strengthened with CFRP is in good agreement with the experimental data. Lin Yudong [7] discussed the influence of different damage degree, initial prestress of CFRP plate and effective prestress of beam on the flexural performance of strengthened beam through static load test and nonlinear finite element analysis. The results show that the prestressed CFRP plate can effectively restrain the crack generation and development, reduce the crack width and component deflection, and significantly improve the flexural capacity of the strengthened beam. It is also found that the greater the damage degree of the beam before reinforcement, the earlier the CFRP plate will peel off, and the greater the reduction of the ultimate flexural capacity, and the CFRP plate will always peel off first and then fracture. In addition, Zhao Shaowei [8], Peng Hui [9], and Zhang Xiaobin [10] have also carried out the bending and fatigue tests of prestressed CFRP plates. For instance, some other scholars [11-14] have carried out beneficial exploration on the whole process analysis of static and fatigue damage of Prestressed CFRP reinforcement by using nonlinear finite element method.

The bridge structure needs to bear static load, vehicle moving load and vibration load which is often overload and not invariable. However, some studies mainly consider the influence of constant amplitude cyclic load, and few studies on the mechanical performance of reinforced structures under variable amplitude cyclic load. Based on this, two kinds of anchorage systems are used to reinforce the reinforced concrete beams with prestressed CFRP plates, and then the bending test and fatigue test are carried out to explore the fatigue performance of the strengthened members under variable amplitude fatigue cyclic load and evaluate the fatigue life of the members.

2. Static test and finite element analysis

2.1 Basic information of the test

Five concrete test beams are designed in this experiment. The total length of the test beam is 6000 mm, the clear span is 5400 mm, the section size is 350 mm×500 mm, the design strength grade of concrete is C40, and the main reinforcement is HRB400. As shown in Figure 1, the top reinforcement of the test beam is 3Φ16, the bottom reinforcement is 3Φ22, the side reinforcement is 8Φ12 and the stirrup is 1800mmΦ10@200mm while the rest part is Φ10@100mm. The measured material properties of concrete and reinforcement are shown in Table 1 to 2.

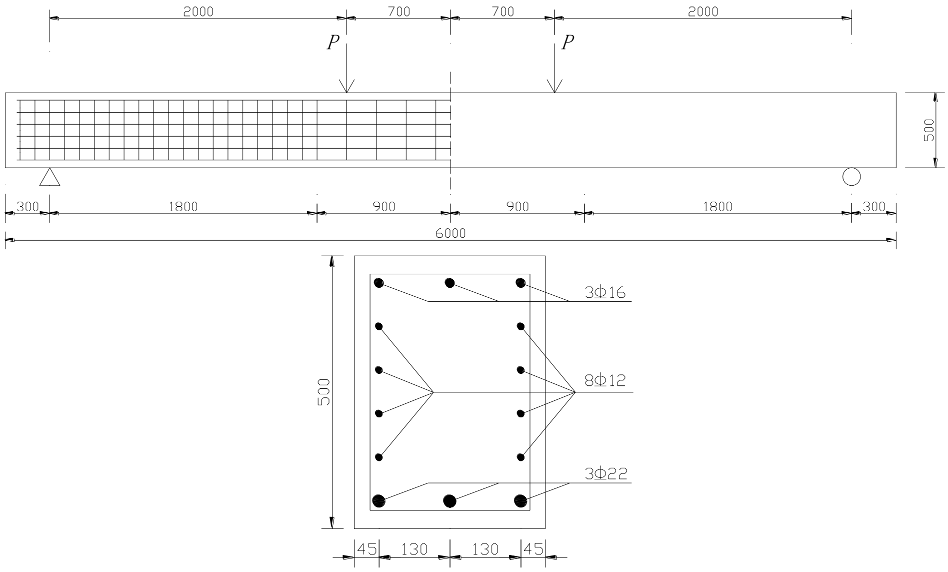

Figure 1: Dimension and section reinforcement drawing of test beam (mm)

Table 1: Properties of concrete

strength grade	compressive strength (MPa)	tensile strength (MPa)	elastic modulus (GPa)
C40	40.6	3.03	32.8

Table 2: Properties of steel

Type	yield strength (MPa)	ultimate strength (MPa)	elastic modulus(GPa)
HRB400	420	608	195

The prestressed CFRP plate with width of 50 mm, thickness of 3 mm and length of 5200 mm is anchored at the bottom of each test beam whose elastic modulus is 237GPa, the tensile strength is 2800mpa, the linear expansion coefficient is 3.2×10^{-5}, the Poisson's ratio is 0.17, and the tensile control

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stress is 1277 MPa. Two different anchorage systems of Prestressed CFRP plates, namely "rigid self-locking anchorage system" and "force card anchorage system" are used for comparison. The anchorage length of both sides of the CFRP plate is 200 mm respectively. Before the test, the CFRP plate has been tensioned and anchored on the corresponding test beam. The specimen number and purpose are shown in Table 3.

Table 3: Number and purpose of test piece

specimen number	anchorage system	test purpose
L0	unreinforced	bearing capacity test of bare beam
A1	self-locking system	fatigue test
A2	self-locking system	static test
B1	Lika system	fatigue test
B2	Lika system	static test

The two ends of the test beam are simply supported using four point bending loading method. The MTS (hydraulic servo system) actuator was used in the structural laboratory of Jiangsu Academy of Transportation Sciences Co., Ltd. For l0 specimen without reinforcement, the load values of each stage before and after crack occurrence are 5kn and 10kN respectively while for A2 and B2 reinforced specimens, the load values of each stage before and after cracks are 10kN and 20KN respectively. After the specimens yield, the displacement loading method is adopted, and the loading speed is 5 mm/min.

The test mainly measures the displacement of beam bottom, the strain of tension and compression reinforcement, cracking load, ultimate load and crack development. The load value during the test loading process is automatically read and recorded by MTS loading system; The displacement values are automatically collected by the dynamic and static test system located in the middle of the beam and at the loading point to accurately obtain the deflection changes of the pure bending section; The displacement at the support is measured by dial indicator; the concrete beam, main reinforcement and CFRP plate are pre pasted with optical fiber sensors, and the strain data is collected by data acquisition instrument.

2.2 Nonlinear finite element analysis

In order to verify the test results, the finite element software ANSYS is used to analyze the whole process of the static test model of concrete beams strengthened with CFRP plates. Solid65 element is used to simulate the concrete beam, shell181 element is used to simulate the CFRP plate, and link8 element is used to simulate the steel bar. The multi linear isotropic strengthening elasto-plastic model is used for the concrete constitutive relationship, the ideal elasto-plastic model is used for the ordinary steel bar constitutive relationship, and the linear elasto-plastic constitutive relationship is used for the CFRP plate. The bond slip between steel bar and concrete is not considered. The concrete beam is meshed by mapping method. The element length is 50 mm, and the three-dimensional hexahedral element is obtained. The size of CFRP plate element and reinforcement element is also 50 mm. CP command is used to couple the degree of freedom of the joints in the end anchorage zone of CFRP plate element and the corresponding concrete element joints at the bottom of the box girder, so as to achieve the effect of rigid connection. The prestress is applied by cooling method, and the tension process is simulated by simulating the stress produced by the temperature grading change of the slab. The prestress loss is 6% of 77MPa, the permanent prestress load of 1200Mpa is applied, and the corresponding temperature change value of prestress is obtained. The finite element model is shown in Figure 2.

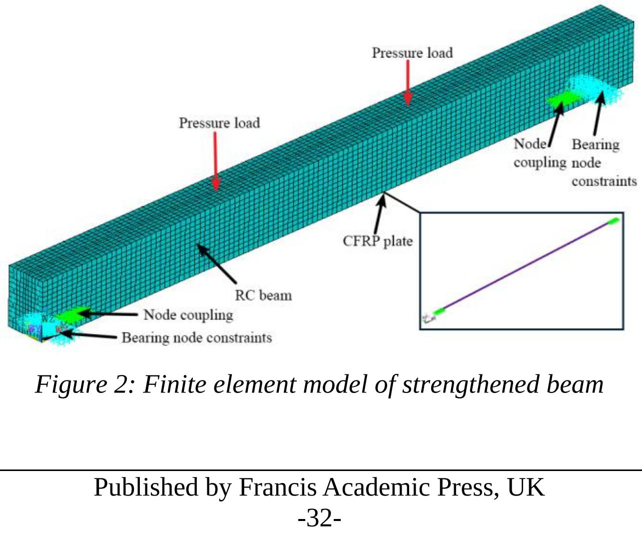

Figure 2: Finite element model of strengthened beam

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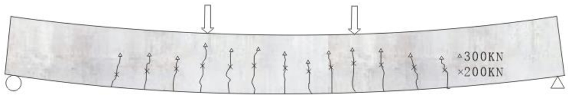
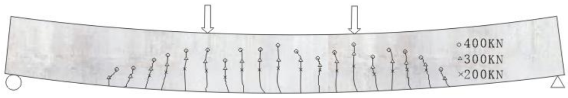
2.3 Results and discussion

2.3.1 Crack development and failure mode

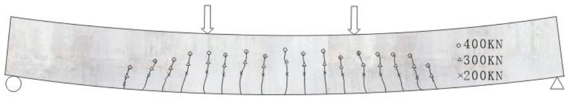
During the loading process, the crack development of each test beam was observed in real time. The number of cracks increased rapidly and the crack spacing decreased gradually. In the limit state, the crack distribution is more uniform, and the crack spacing at the bottom of the test beam is basically the same. The crack development of specimens l0, A2 and B2 is shown in Fig. 3. After reinforcement, the crack development of specimens is more intensive, indicating that the prestressed CFRP plate can make the concrete material performance play more fully.



(a) Crack diagram of specimen L0



(b) Crack diagram of specimen A2



(c) Crack diagram of specimen B2

Figure 3: Crack development of test beam

The failure mode of specimen l0 is ductile failure, and specimens A2 and B2 have entered the yield stage, and show certain ductility. As shown in Fig. 4 (a) and Fig. 4 (b), when specimen A2 fails, the CFRP plate does not break. The reason for failure is that the strain in the CFRP plate increases rapidly after entering the yield stage, and finally slips out of the anchorage, and specimen A2 immediately fails. Also seen from Fig. 4 (c) and Fig. 4 (d) that specimen B2 has entered the yield stage when failure occurs, and the stress in the prestressed CFRP plate increases rapidly, which eventually leads to the CFRP plate being broken. The failure of CFRP plate was comminuted after fracture, and the phenomenon of CFRP plate sliding out of anchorage did not occur.

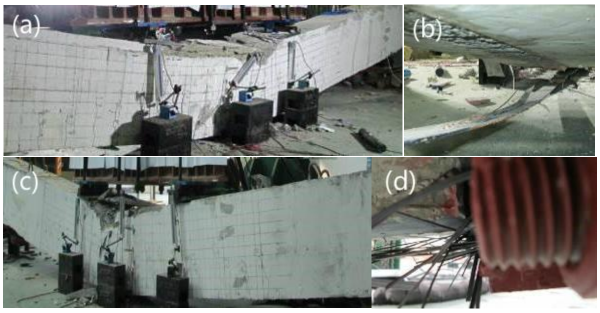


Figure 4: Failure modes of A2 and B2 specimens

Comparing the failure modes of A2 and B2, it can be found that the anchorage performance of the force card anchorage system is better than that of the rigid self-locking anchorage system. Although the rigid self-locking anchorage system has the phenomenon of Prestressed CFRP plate sliding out of the anchorage, the specimen has entered the yield stage when the sliding out occurs. For the actual bridge structure, such a large deformation will not occur in the normal use stage. Therefore, for the actual structure, the safety of the rigid self-locking anchorage system can meet the requirements of normal use.

2.3.2 Load displacement curve

Table 4: Characteristic load of test beams

Test beam	Cracking load/kN	ultimate load/kN
L0	50	340
A2	80	450
B2	80	510

The characteristic load results of the test beam are shown in Table 4, in which the load value is the total load value applied on the beam.

It can be seen from table 4 that the cracking load of specimen l0 is 50kN, and that of specimen A2 and B2 is 80KN. The cracking load of members strengthened with prestressed CFRP plate increases by 60%. The ultimate bearing capacity of specimen l0 is 340 KN, the ultimate bearing capacity of specimen A2 and B2 are 450kn and 510 KN respectively. After reinforcement, the bearing capacity of specimen is increased by 32% and 50% respectively, and the reinforcement effect is obvious.

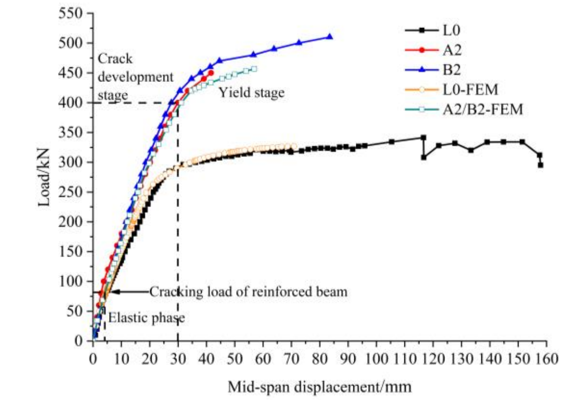


Figure 5: Load-mid span displacement curves

It can be seen from Figure 5 that test results are in good agreement with finite element calculation results at each stage, indicating that the established nonlinear finite element model can predict the bending behavior of the strengthened beam before the failure of Prestressed CFRP plate.

The stress process of strengthened beam can be divided into three stages ① Elastic stage (0~80kN):Before the cracks appear, the strengthened beam is in elastic state, the load mid span displacement curve is approximately a straight line, and the structural stiffness is basically unchanged. ②Fracture development stage (80~400kN):With the increase of load, the number of cracks increases, and the slope of load displacement curve after cracking slightly slows down, but it is basically consistent with the elastic stage.③Yield stage (above 400kN):The tensile reinforcement was immediately broken and the specimen was destroyed.

2.3.3 Stress-strain change

Strain curves of concrete at the bottom of beam and CFRP slab at the same position of specimen l0, A2, B2 and finite element model midspan are shown in Fig. 6.

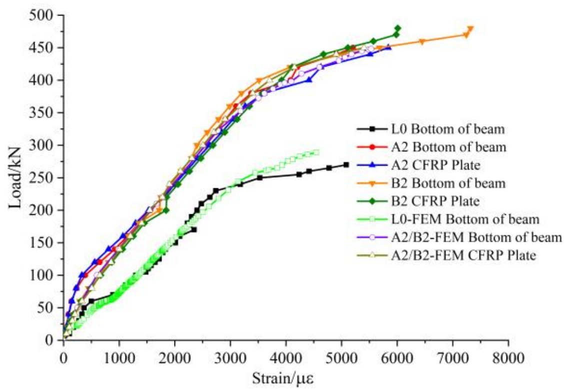


Figure 6: Load-strain curves

It can be seen from Figure 6 that under the same load, the strain of concrete at the bottom of A2 and B2 beams is obviously smaller than that of concrete at the bottom of l0 beams. Hence, the prestressed CFRP plate can significantly restrain the strain development of the concrete beam bottom when it is used to strengthen the reinforced concrete beam.

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3. Fatigue test of strengthened beams

3.1 Test overview

As shown in Figure 7, in the fatigue performance test, the loading point position, main test content and data acquisition method of the beam are basically consistent with the static test, and the four point bending loading method is also adopted. During the test, the changes of the beam were observed carefully, and the typical failure modes such as cracking, crack development, steel yield and CFRP plate rupture were recorded in time.

Figure 7: Loading diagram of test beam

According to the static load test results, combined with the actual load in the bridge structure, the fatigue loading is carried out in three stages, and the fatigue load ratio is 0.3. The specific load value and fatigue times are shown in Table 5,

In the first stage, the corresponding load is small and the beam is in the initial cracking state, which mainly simulates the response of the specimen under small load while the second stage is the moderate load and in the third stage, the load is large, which mainly simulates the response of the structure under overload.

Table 5: Fatigue load

stage	Upper / lower limit of load /kN	Cycle times / 10000 times	Type of simulation action type
I	80/24	50	small load action
II	160/48	50	medium load action
III	280/84	direct destruction	overload effect

In the test, in order to investigate the mechanical properties and bending capacity of the strengthened beam after a certain number of cyclic loading under different stress amplitude, the initial static load test was carried out before the fatigue test, and the fatigue loading was stopped when the fatigue times were 100000 times, 300000 times, 500000 times, 600000 times, 800000 times and 1000000 times, and the static load test was carried out. The maximum load applied in the static load test was each order the upper limit of fatigue load of the section.

3.2 Results and discussion

3.2.1 Crack development and failure mode

After the first static load test, a small number of micro cracks appear in the concrete beam. In the subsequent static load test, the number of cracks in the beam increases a little, and the change of crack width is not obvious. The second stage is the increase of width and height of the beam crack. In each subsequent static load test, new cracks appear, and the increase of crack width is not obvious. The third stage is increase in width and height of the beam crack. There are many cracks in the pure bending section and the bending shear section.

It is found that the cracks are closed after unloading in each static load test, which indicates that the prestressed CFRP plate can effectively close the cracks at the bottom of the beam. According to the research of reference, the cracks of unreinforced beams generally only occur in the area with large bending moment in the middle of the span, and the cracks appear earlier. Once they appear, they expand faster, the number of cracks is small, and the width develops larger. In this test, after the prestressed CFRP plate reinforcement, the pure bending crack of the specimen is more intensive, and there are many cracks in the bending shear section, with large number and small width.

For specimen A1, when the fatigue load reaches 1.3 million times, the load value applied on specimen A1 decreases rapidly, which indicates that the stiffness of specimen A1 is decaying rapidly. When the

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fatigue loading reaches 1.31 million times, the specimen A1 is damaged and accompanied by a loud noise. As shown in Figure 8, when specimen A1 fails, one main tensile bar and one distributed bar break, the specimen breaks into two sections, and the CFRP plate slides out of the anchorage and peels off from the lower part of the specimen.

Figure 8: Failure mode of specimen A1

When the fatigue loading reaches 1.43 million times, the specimen B1 is damaged, accompanied by a loud noise. As shown in Fig. 9, when the failure occurs, three tensile bars and two distributed bars in specimen B1 break, the specimen breaks into two sections, and the CFRP plate presents crushing failure.

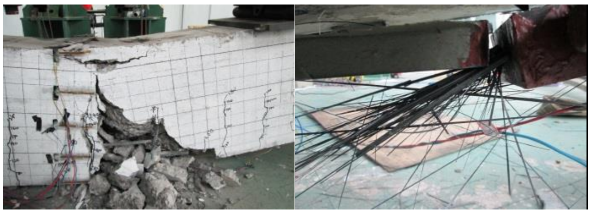
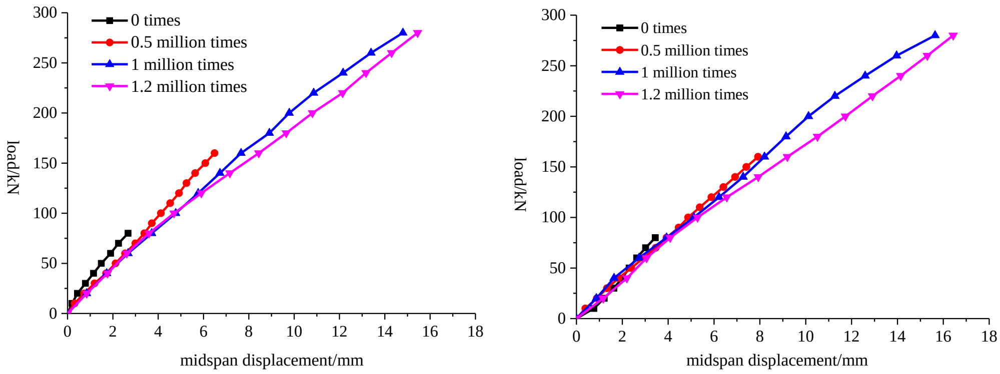


Figure 9: Failure mode of specimen B1

3.2.2 Stiffness degradation

As shown in Fig 10 (a) and 10 (b), the load midspan displacement curves of specimens A1 and B1 after the initial static load test and after 500000, 1 million and 1.2 million fatigue tests. With the increase of the number of repeated fatigue loads, the midspan displacement of the test beam under the same static load increases continuously, and the stiffness of the beam decays continuously. At the initial stage of fatigue loading, the residual deflection of the beam develops rapidly. When the fatigue load is further increased by 1 million cycles, the deflection of the strengthened beam develops rapidly, and the stiffness of the strengthened beam decays obviously.



(a) Specimen A1 *(b) Specimen B1*

Figure 10: Load-mid span displacement curves of reinforced beams

The stiffness of the specimen in the four point bending test can be calculated by the following formula:

$$B=\frac{\Delta F}{\Delta f}\left[\frac{\left(L-L_f\right)^3}{24}+\frac{\left(2L-L_f\right)\left(L-L_f\right)}{16}L_f\right] \tag{1}$$

B is the bending stiffness of the specimen; F is the load of the specimen; F is the midspan displacement of the specimen; L = 5400 mm; L = 1400 mm is the distance between two loading points.

According to formula (1), the stiffness performance degradation curve of A1 and B1 under fatigue

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load which is shown in Figure 11. With the increase of fatigue times, the bending stiffness of the two specimens decreases linearly, which is due to the accumulation of fatigue damage.

However, it can be seen from the figure that the bending stiffness of specimen A1 is greater than that obtained in the previous static load test after 300000 times of fatigue loading and 800000 times of fatigue loading, and this abnormal phenomenon also occurs in specimen B1 after 300000 times of fatigue loading. The reason is that under the action of fatigue load, the number of cracks increases and the crack width decreases, resulting in more uniform stress distribution on the specimen. This kind of phenomenon was also observed by Wu Zhishen of national Ibaraki University in Japan in the relevant tests of beams strengthened with prestressed PbO sheets.

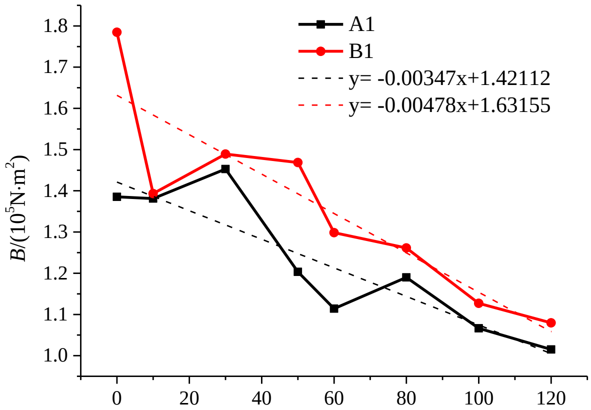


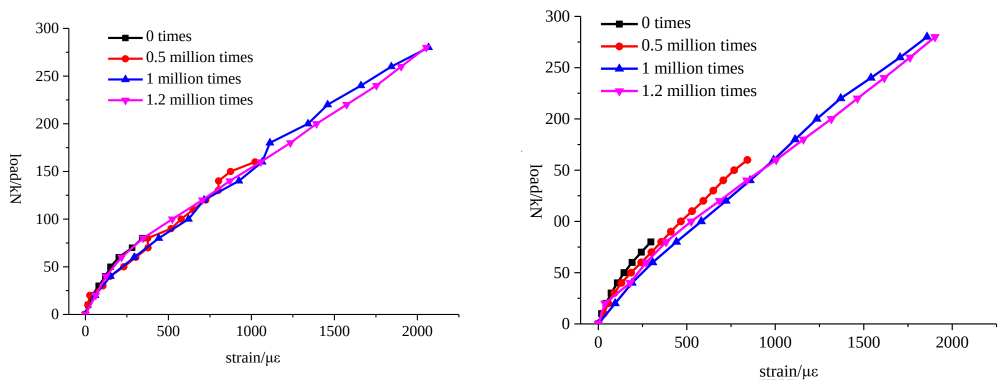
Figure 11: Stiffness performance degradation curve

The relationship between bending stiffness and fatigue loading times was fitted

$$y_{A1} = -0.00347x + 1.42112$$
$$y_{B1} = -0.00478x + 1.63155 \quad (2)$$

3.2.3 Strain change

As shown in FIG. 12, 13 and 14, the strain curves of the concrete at the bottom of the midspan beam, the CFRP plate at the bottom of the midspan beam and the main tensile reinforcement in the midspan of the specimens A1 and B1 after different fatigue loads.



(a) Specimen A1 *(b) Specimen B1*

Figure 12: Concrete strain curve at the bottom of mid-span beam

It can be seen from Fig. 12 that when the applied load is small, the strain curves of the concrete at the bottom of each beam after different fatigue times are relatively close, but on the whole, with the increase of fatigue times, the strain of the concrete at the bottom of the mid span beam tends to increase, which is caused by the cumulative fatigue damage.

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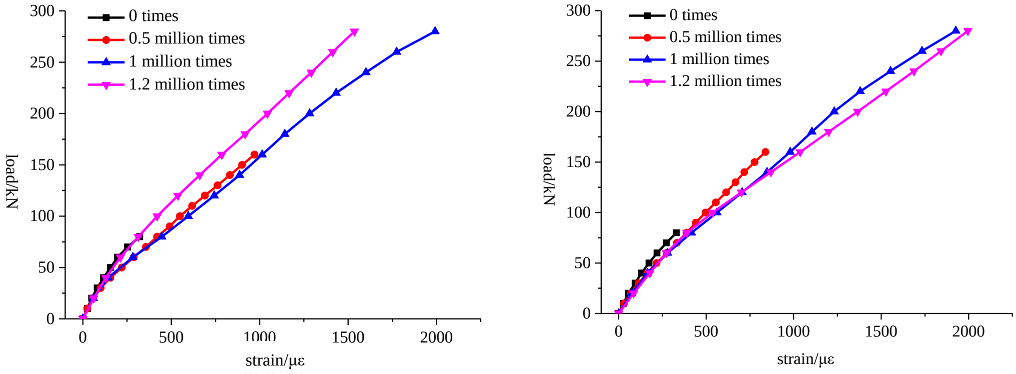
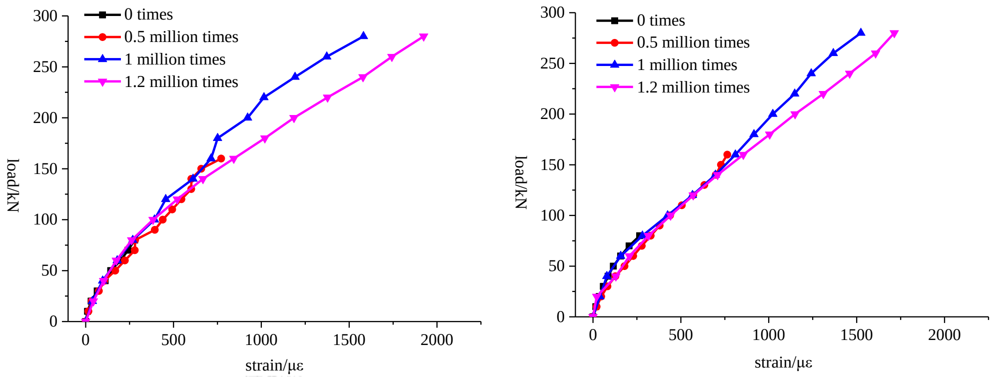


(a) Specimen A1 *(b) Specimen B1*

Figure 13: Strain curve of CFRP plate at the bottom of mid-span beam

It can be seen from Fig. 13 that when the fatigue loading times are less than 1 million, the strain curves obtained are similar, but on the whole, with the increase of fatigue times, the strain on the CFRP plate tends to increase. It is worth noting that it can be seen from figure (a) that after 1.2 million fatigue loads, the strain of CFRP plate under the same load is less than that after 500000 and 1 million fatigue loads. Combined with the ultimate failure mode of the specimen, it can be inferred that the reason for this phenomenon is that in the third stage of fatigue loading, the end of CFRP plate slips out slightly from the rigid self-locking anchorage under overload. Also, it can be seen from figure (b) that the strain on the CFRP plate increases with the increase of the number of fatigue loads. It can be seen that the working performance of the force card anchorage system under fatigue load is good, and there is no phenomenon such as the CFRP plate sliding out of the anchorage.



(a) Specimen A1 *(b) Specimen B1*

Figure 14: Strain change curve of main bar under tension in mid-span

It can be seen from Figure 14 that with the increase of fatigue load times, the strain at the midspan section of tensile main reinforcement under the same load has an increasing trend. It can be seen from figure (a) that when the fatigue number is less than 1 million times, the strain values obtained under the same load are similar, but after 1.2 million times of fatigue load, the strain of the steel bar at the middle section of the span increases greatly. This is due to the slight sliding out of the rigid self-locking anchorage at the end of the CFRP plate under the overload action in the third stage of fatigue load, which leads to the tension in the main reinforcement there has been a substantial increase in the response to the crisis. It can be seen from figure (b) that after 1.2 million times of fatigue loading, the strain of the main tensile reinforcement at the midspan section of specimen B1 increases slightly compared with the previous stage, and the increase rate is less than that in specimen A1. It can be concluded that the performance of the force card anchorage system is better than that of the rigid self-locking anchorage system during fatigue loading.

4. Fatigue life analysis of strengthened beams

This test and related research show that the fatigue failure of concrete beams strengthened with CFRP is generally marked by the fatigue fracture of the main reinforcement, and the stress amplitude of the main reinforcement determines the fatigue life of the beams strengthened with CFRP sheets, which can

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be used as the basis for the fatigue life prediction of reinforced concrete members.

The fatigue loading times of A1 and B1 are 1.3 million and 1.43 million respectively, and the fatigue loading times are less than 2 million. This is due to the large stress amplitude in the third stage of fatigue loading, which mainly simulates the response of the specimen under overload. From the strain values of the main tensile reinforcement at the midspan section of the specimen in Figure 9.19, the stress amplitude of the reinforcement at each stage can be obtained. The formula in reference when the stress is 0.3 is selected, that is:

$$\lg N_f = 34.31736 - 12.56013\lg\Delta\sigma_m \quad (3)$$

In the code for design of concrete structures, the limit of fatigue stress amplitude of HRB400 steel bar is 145mpa under the load ratio of 0.3, and the fatigue times under the stress amplitude of the code is conservatively defined as 2 million times. According to the fatigue cumulative damage theory, the variable amplitude fatigue load can be converted into the equivalent constant amplitude fatigue load. The results show that the fatigue life of A1 is 8 million times, more than 2 million times, and that of B1 is 12 million times which is more than 2 million times. It can be seen that the test structure fully meets the requirements of the specification.

5. Conclusion

In this paper, the static and fatigue properties of reinforced members under static and variable amplitude fatigue cyclic loading are studied by using the method of experimental study and numerical simulation.

(1) The static test and finite element analysis show that the crack load of RC Beam Strengthened with prestressed CFRP plate can be effectively improved, the crack development of beam body is more intensive after reinforcement, and the performance of concrete material is more fully played. After reinforcement, the bearing capacity of the specimen is significantly improved, but the ductility of the specimen is decreased.

(2) The fatigue test shows that the stress distribution of RC Beams Strengthened with prestressed CFRP plates is more uniform under variable amplitude fatigue load. The reinforced beams anchored by rigid self-locking system and force card system have good anti fatigue performance, and meet the relevant provisions of the code for concrete structural members. At the same time, it can be seen that overload has a great impact on the fatigue life of structural members. In the actual operation process of bridge structure, overload vehicles should be strictly controlled.

(3) According to the fatigue cumulative damage theory, the fatigue life of the beam strengthened by the self-locking anchorage system is 8 million times, and the fatigue life of the beam strengthened by the force card anchorage system is 12 million times. When the two anchorage systems reach fatigue failure, the tensile reinforcement at the bottom of the beam has already yielded, which indicates that their safety performance meets the requirements of the normal use of the structure.

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