Experimental study on static and fatigue properties of CFRP reinforced concrete beams

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Abstract. In order to solve the problem that steel corrosion seriously limits the service life of bridges, predecessors put forward the measure of using carbon fiber reinforced composite bar (CFRP) as stress bar. In order to study the static performance, fatigue performance and damage development of CFRP ribs, the static loading test of two mixed reinforced beams with different reinforcement ratios was carried out based on the static load test of pure reinforced concrete beams through three-point concentrated loading. The test results show that the CFRP rib beam works by the development process of balanced crack extension and fiber rupture; the deflection and strain of the test beam increase significantly in the initial stage of cyclic loading; as the number of load cycles increases, the crack growth rate becomes slower. And entering a relatively stable stage of development, and a large increase in the vicinity of the destruction; Under the same reinforcement ratio, the static load limit of composite reinforced beams is 0.95 times of that of pure reinforced concrete beams; the static load limit of 2FRP beams is 50% of that of 3FRP beams, but the fatigue life of 2FRP beams is 75 times of that of 3FRP beams. It can be seen that appropriate reinforcement ratio can effectively improve the service life of specimens. On the basis of the test, some suggestions on the design of CFRP reinforced concrete beams are put forward. The research results can be used for reference in the follow-up study.

1. Introduction

Due to the negative bending moment, the bridge supports a small crack when passing through the car. The carbonization of the concrete makes the pore water become acidic, destroying the passivation film of the steel bar, and infiltrating more harmful impurities such as oxygen and chloride salts. The rust is rusted, resulting in a decrease in load carrying capacity, further accelerating the expansion of the rust, and the gradual loss of the bond between the steel and the concrete, causing damage to the reinforced concrete structure in service. The problem of a decrease in the durability of the steel leading to a sharp increase in the cost of maintenance, reinforcement, and the like has been inevitable.

Carbon fibre reinforced composite material has the characteristics of high specific strength, corrosion resistance and durability, which fundamentally solves the problem of steel corrosion. However, the CFRP material remains elastic until it is destroyed, giving the building a risk of brittle failure without warning. Carbon fibre reinforced concrete beams consisting of corrosion-resistant FRP bars placed in the corner of section or lower row and corrosion-prone steel bars placed in the interior or upper row are widely used in bridges, highways and other bridges because of their large stiffness, good ductility and good corrosion resistance, which can greatly improve the service life of specimens[1].

At present, the research on CFRP by scholars at home and abroad mainly focuses on the mechanical properties of pre-stressed FRP structures, the flexural properties of CFRP reinforced concrete beams,
and the strengthening of damaged concrete beams by CFRP. However, there is little research on the fatigue resistance of CFRP reinforced concrete beams, and there is a lack of comparative analysis of crack changes, stiffness degradation and service life under static and dynamic loads. Therefore, this test is designed: CFRP reinforcement in different reinforcement ratios, through the static load and fatigue comparative test of specimen beams, the influence of CFRP longitudinal reinforcement ratio on static characteristics, fatigue resistance and crack development of composite reinforced beams is studied, and the appropriate reinforcement ratio is determined to maximize the use efficiency of specimens. This will not only enrich the mechanical properties of CFRP reinforced concrete structures, but also help to promote the application of CFRP reinforced concrete structures in bridge field.

2. Test survey

2.1. Specimen design

This test designed and produced five reinforced concrete beams with dimensions of 2000mm total length, 1600mm net span, 300mm beam height and 200mm width. Among them, 4 CFRP reinforced concrete beams, 1 pure reinforced concrete beam, and longitudinally compressed steel bars are all HRB400 hot-rolled ribbed steel bars with a diameter of 14mm. The stirrups are made of HPB300 hot-rolled round steel bars with a diameter of 8mm. The detailed dimensions and structure of the piece are shown in Figure 1. The main mechanical properties of the ribs are shown in Table 1.

![Figure 1. Dimensions of specimen.](image)

In order to reduce the brittleness of the test piece, medium-strength concrete should be used, and the pouring quality ratio is cement: water: sand: gravel = 0.43:1:1.97:2.13 C40 concrete. Three cubic compressive strength standard test blocks are reserved during pouring, and the test pieces are cured in the same indoor environment. The average axial compressive strength measured by the standard test procedure before the test piece is loaded is 53.96 MPa.

| The name          | CFRP tendons | reinforced |
|-------------------|--------------|------------|
| Diameter (mm)     | 14           | HRB400Φ14  | HPB300Φ8 |
| Cross section (mm²)| 154          | 154        | 226       |
| Severe (g/m)      | 261          | 1210       | 395       |
| Tensile strength (MPa) | 1800~2000   | 360        | 270       |
| Ultimate shear strength (MPa) | >150        | 570        | --        |
| Elastic modulus (G Pa) | 140~155     | 210        | 210       |

2.2. Test Equipment and Loading Scheme

PWS-500 electro-hydraulic servo dynamic and static test system is used for loading; the test beam is fixed at both ends and loaded at three equal points; Level at the support and loading point, the load across the middle line is realized by the thick steel plate underlying the actuator. The layout of loading device and concrete measuring point is shown in Figure 2. The concrete strain gauge is BX120-60AA, and the steel strain gauge is BX120-5AA.
Static loading tests were carried out on BS0F, BS2F and BS3F to test the initial mechanical properties of the specimens, so as to obtain the static ultimate loads of CFRP beams with different reinforcement ratios and determine the fatigue loading peaks of the specimens BM2F and BM3F. The loading procedure of fatigue test is as follows: firstly, the preloading test with load value of 1 KN gap is carried out, secondly, two initial static tests of stiffness test of specimens are carried out, and finally, the loading procedure is entered into the stage of fatigue cyclic loading test, as shown in Figure 3.

![Figure 2. Arrangement for data acquisition.](image1)

![Figure 3. Fatigue Test Loading Program.](image2)

The Standard for Testing Methods of Concrete Structures stipulates that the fatigue loading frequency should not be greater than 80% of the natural frequencies of structural members or load frames, and should not be less than 130% of the natural frequencies. Literature [5] points out that when the fatigue loading frequency is close to the natural frequencies of specimens, resonance will occur, which will affect the collection of test data. The test load is controlled by test force, and the sinusoidal fluctuating fatigue load is applied by the actuator at the bisection point of the beam. The loading frequency is 3 Hz and the stress ratio is 0.7. In order to prevent the bearing from jumping, the minimum fatigue load is one tenth of the maximum fatigue load. When loaded to the set number of cycles (0, 100, 500, 1000, 5000, 10000), static loading tests are carried out to test the stiffness changes of components during the test. Static loading failure tests are carried out when the fatigue failure characteristics of the specimens occur to determine the residual bearing capacity and stiffness of the beams after fatigue.

### Table 2. Main test results.

| Member number | Specimen failure mode | Upper and lower limits of fatigue load/ KN | Fatigue load amplitude/ KN | Static failure load/ KN | Static cracking load / KN | Fatigue life(second) | Failure pattern |
|---------------|-----------------------|------------------------------------------|---------------------------|------------------------|--------------------------|---------------------|----------------|
| BS0F          | Static test static failure | --- | --- | 147.38 | 34.00 | --- | C |
| BS2F          | Static test static failure | --- | --- | 134.37 | 23.29 | --- | P |
| BM2F          | Static failure after fatigue loading | 9.5 | 95 | 84.7 | 216.23 | 18.58 | 27420 | P+F |
| BS3F          | Static test static failure | --- | --- | 267.85 | 25.23 | --- | P+2F |
| BM3F          | Static failure after fatigue loading | 19.6 | 196 | 196 | / | 26.15 | 370 | P+2F |

Note: 1. In the specimen number, B stands for test beam; S is for the beam that did the static load failure test; M stands for test beam used for fatigue loading; The last two represent the number of CFRP bars at the bottom of the specimen. 2. “/” means no data collected. “---” represents an untested process.

### 2.3. Measurement content

The test mainly measures the mid-span displacement, the steel strain, the CFRP strain, and the concrete strain in the compression zone. The strain data is automatically collected by the DH3817 dynamic and static strain test system, and the crack initiation and propagation (crack length, width and development trend) are observed and recorded during the loading process.
3. Test phenomenon

Table 2 shows the main test results of each specimen. According to the test results, the failure modes of the specimens with mixed reinforcement are concrete crushing (C), CFRP bar tension (P) and CFRP bar shearing (F).

3.1. Static test

When the specimen BS0F is loaded into 10KN, the concrete is cracked and loaded into the 115KN tensile steel. After the loading, the deflection of the specimen increases sharply with the load slowly increasing, and the bearing capacity of the beam is significantly reduced. When the specimen is loaded to 147.38KN, the specimen is destroyed. The initial crack initiation of beam BS3F was about 40kN, followed by the sound of fibre fracture, the height of the compression zone is gradually decreased, and finally showed the shear of CFRP bars in one corner, and the failure pattern of the rest tensile fracture. Later, it was found that the transverse stress of beam was caused by the deviation of loading steel plate. The BS2F beam showing brittle failure of mid-span CFRP bars is shown in Figure 4.

3.2. Fatigue test

It can be seen from the experimental phenomena that the fatigue damage process of CFRP reinforced concrete beams characterized by FRP rib failure can be divided into three stages: In the first stage, some of the larger shear fibres suffered fatigue damage, but the shear properties of the fibre bundles did not change significantly, and the deflection of the hybrid reinforcement beams did not change significantly. In the second stage, with the continuous action of fatigue load, some CFRP tendons suffer serious fatigue damage or even fracture, the shear resistance of FRP tendons deteriorates, and the deflection of test beams increases significantly. In the third stage, most of the fibres are cut off, so the specimens are not suitable for further service.

Because the upper limit of fatigue load has exceeded the cracking load of the specimens, the beam BM2F has cracked in the first static loading process. When loaded to the upper limit load, five first bending and shearing cracks were produced in the lower span of 30 cm. The longest crack extends to about 30 mm from the top of the beam, and the maximum crack width is about 0.2 mm. When the cyclic loading is 400 times, there is no new crack except the existing crack propagation. The first crack on the side of the beam has extended to the top of the specimen, but no through crack has been formed. When the fatigue load is 30 000 times, the strain of FRP under tension has exceeded the measuring range. It is predicted that the excessive slip of FRP bars and concrete results in the fatigue failure of the specimen BM2F. The failure pattern is shown in Fig. 5-a. The ultimate failure value of late static load is 215.13KN.

The typical failure modes of beam BM3F are shown in Fig. 5-b. The main crack of BM3F in the initial static loading section grows rapidly to the G2 strain gauge, and the surface crack extends to the top of the specimen at 130.2KN. The sound of fibre fracture is accompanied by the fatigue loading. The width of the main crack changes rapidly when the fatigue life is between 80% and 90%, and the secondary crack tends to close gradually, with 380 times of fatigue failure.
From the above test results, it can be seen that the reinforcement ratio in tension zone has a great influence on the ultimate load and fatigue life of composite beams. The static load limit of BS3F increases from 133.39 KN to 266.95 KN, and the fatigue life decreases sharply from 27425 times to 372 times, which is only 1.36% of BS2F. It can be seen that the mechanical properties of CFRP reinforced concrete beams are very sensitive to the structure of specimens.

4. Formatting the text
As shown in Figure 6, under the action of static load, the test pieces BS2F and BS3F have the characteristics of high rigidity and large brittleness compared with the test piece BS0F, which makes the cracks sprout early, the width is larger, the extension is faster, and the position is higher. Shortly after the cracking load, the crack development is relatively complete. Concurrently, the CFRP tendon has higher tensile strength than the steel bar, which can better restrain the crack growth of the lower part of the concrete. Therefore, the BS2F and BS3F have fewer cracking points. For reinforced concrete beams, the cracks cannot be observed with the naked eye. During the whole process of loading, new cracks appear continuously and the width of cracks is small, and the distribution of cracks is relatively uniform.

The fatigue failure mode of the test beam shows a significant difference due to the different reinforcement ratios, as shown in Figure 7. The beam BM3F presents the destruction of over-reinforced beam. The unbalanced specimen in the compression zone after concrete crushing results in the displacement of loading point to the out-of-plane. Finally, the beam exhibits rapid and complete fatigue failure under 372 cyclic loads. Two FRP bars are cut off at the initiation of initial crack and one is pulled off. Beam BM2F reinforcement is more suitable and can work well with concrete. The crack width at the initiation of the first crack increases steadily with the increase of the number of cycles. When the bonding force between FRP and concrete is constant, the larger concentrated stress makes the deformation of the FRP reinforcement with smaller elongation exceed the limit and leads to local fatigue failure.

For CFRP reinforced concrete beams, both static load and fatigue fracture occur at the initiation of cracks at the bottom of beams at the first loading. When approaching fatigue failure, the cracks stop growing and close gradually, and eventually fatigue failure occurs at the main crack. Compared with pure reinforced concrete beams, cracks near the middle span are fine and dense, CFRP The crack width
of reinforcement beams is large and distributes in the whole net span interval. The reason is that the bond between FRP bars and concrete is worse than that of steel bars. The less tension the reinforcement at the end of the reinforcement can provide, the more easily cracks will occur and the more unfavourable to the use of the project. It is necessary to consider the use of fibre reinforced concrete to reduce its influence on the later use.

Figure 8. Schematic diagram of failure crack propagation.

5. Analysis of Stiffness Change
The mid-span deflection load variation of the test beam is shown in Figure 8. It can be seen from the graph that the tension is borne by the concrete in the tension zone for a short period of time from the beginning of the experiment, the load is about 10KN, and part of the tension is shared by the stress bars, which makes the initial stiffness of all specimens similar; However, due to the yield stage of steel bars and the linear elastic material of FRP bars, the beam BS0F has a plastic development stage, while the beam BS2F and BS3F have a direct brittle fracture after the secondary stiffness [6] stage after the concrete crack develops to a stable growth stage. Compared with BS2F, beam BS3F has larger static stiffness, stronger deformation resistance and higher bearing capacity, but its ductility is insufficient, brittle damage is serious, which does not meet the design requirements of ductility performance of structure, and is not conducive to structural health testing.

Comparing BS2F with BM2F, when the reinforcement ratio of cross section is suitable, the compressive steel bars will bear part of the tension and play a plastic buffer role near the static load limit. Cyclic loading of specimens will magnify the effect of this effect and make full use of the fibre reinforcement, which also conforms to the safety rules for use. However, the structure of BS2F and BM2F is identical, but after fatigue loading, the static failure limit value of the specimen BM2F is 1.61 times that of the specimen BS2F, which is due to the excessive grinding of CFRP bars when the specimen BS2F is bonded with strain gauges.

From Figure 8, it can be seen that the stiffness degradation of test beams can be divided into three stages: the first stage is the dispersion cracking of concrete, which is accompanied by the random fracture of fibres, and the material stiffness decreases rapidly in this stage; the second stage is the fracture of fibres, which is more difficult to destroy than the matrix, so the material stiffness in this stage is more difficult to destroy fibres. In the third stage, the accelerated coupling of various damage forms leads to the sudden fracture of the material. In this stage, the stiffness of the material decreases rapidly, that is, brittle failure.

6. Energy consumption
The ductility of the member under repeated loading can change the deformability of the specimen under the condition that the bearing capacity does not change significantly after entering the failure stage. This is also a key indicator of safety prediction before structural failure. The greater the ductility of the components, the stronger its energy dissipation consumption [7].

When the serving beam is subjected to external loads, part of the applied energy is stored in the material in the form of strain energy (elastic strain energy and inelastic strain energy), and the other part is consumed in the form of friction and internal damping. The results show that the damage of the material is related to the inelastic strain energy in the strain energy. When the inelastic strain energy accumulates to the limit that the material can withstand, the specimen will fail fatigue. The energy dissipation capacity of the specimen can be determined by the area of the hysteretic curve. As shown in Figure 9, the single cycle energy dissipation capacity of the specimen BM3F is significantly greater than that of the specimen BM2F because of its high load-carrying capacity, which leads to the rapid accumulation of damage in the internal material of the specimen and the significant reduction of its
fatigue life. But in the whole life cycle, the total energy consumption of beam BM2F is larger than that of beam BM3F, but the change of single load amplitude is small. The strain in material can be recovered in time, which greatly prolongs its fatigue life.

![Hysteretic curve of specimen.](image)

**Figure 9.** Hysteretic curve of specimen.

7. Conclusions
In the fatigue test of concrete beams with mixed reinforcement, the failure modes are mainly controlled by FRP bars. The failure modes are fatigue tension and shear of FRP bars. The insufficient bond between FRP bars and concrete is one of the main reasons for the failure. The development of deflection of test beams and the strain increment of steel bar and concrete at the same position increase remarkably at the initial stage of fatigue cycle; with the increase of the number of fatigue load cycles, the growth rate slows down to a relatively stable stage of development; and a considerable increase occurs near failure.

The ductility and fatigue life of the specimens can be increased by properly adjusting the ratio of FRP bars to steel bars, so as to meet the requirements of structural safety and quality inspection and the optimal utilization rate. The static load and fatigue failure of the test beam are all broken from the first crack. During the service period, after the main crack appears, appropriate reinforcement measures can be taken to reduce the loss.

Considering the brittleness of fatigue failure, appropriate safety margin should be reserved, and the specimen can be used as the criterion of fatigue failure when it enters the stage of fatigue failure. According to the test results, it is suggested that the fatigue failure of the specimens should be judged immediately when one of the following characteristics occurs: all cracks except the main crack appear closure phenomenon; after the stable stage, the deflection of the specimens and the strain of steel bar and concrete begin to increase considerably.

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