

# Static Load Testing and Mechanical Property Interpretation of RC Beams Strengthened with CFRP Plates

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## Abstract

This paper explores the static behavior of reinforced concrete (RC) beams strengthened with prestressed CFRP plates through a combination of laboratory testing and finite element modeling. Three specimens were prepared: two strengthened beams employing different anchorage methods (rigid self-locking and force-card types) and one unstrengthened reference beam. The study focused on evaluating cracking load, ultimate bearing capacity, and deformation responses. The findings indicate that the use of prestressed CFRP plates markedly enhances beam performance. Specifically, the cracking load increased by about 60%, while the ultimate capacity improved by 32% and 50% for the respective anchorage systems. A high degree of deformation compatibility between the CFRP plates and concrete was observed. Strengthened beams displayed a denser crack pattern and better utilization of concrete strength, though accompanied by reduced ductility. The finite element simulations corroborated the experimental data and further highlighted the three distinct behavioral stages of the beams: elastic, cracking, and yielding. Overall, the research establishes a solid theoretical foundation for the application of prestressed CFRP plate reinforcement in engineering practice and demonstrates that the force-card anchorage system provides superior performance in stress transmission and failure mode control.

## Keywords

Prestressed CFRP Plates; Reinforced Concrete Beams; Static Behavior; Anchorage Methods; Structural Strengthening; Finite Element Modeling; Load-Bearing Enhancement; Crack Distribution.

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## 1. Introduction

Carbon Fibre Reinforced Composite (CFRP) panels have been widely used in the reinforcement of existing highway concrete bridges due to their excellent properties of light weight, high strength, fatigue and corrosion resistance. Among them, pre-stressed CFRP plate reinforcement is a typical "active reinforcement" technology, which can significantly improve the crack control ability and ultimate bearing capacity of the bridge during the use phase without interrupting the traffic by pre-tensioning the CFRP plate and applying the reverse bending moment to the bending zone, and it has little damage to the original structure, simple construction process, and low cost for the whole life cycle. Low cost. Compared with the traditional non-prestressed externally applied CFRP sheets, prestressing reinforcement can increase the utilisation rate of CFRP ultimate strength from 30% to 70%, which really realises the "ultimate utilisation" of material properties[1]. However, the service environment of bridges is complex, and the overloading of vehicles, variable cyclic loading, and the coupling of humidity, heat, and freezing significantly change the force path of the reinforced structure, and if the evolution mechanism is not clarified, the reinforcing effect may be degraded over time or

even fail prematurely. Therefore, the systematic study of the static and long-term performance evolution of CFRP-reinforced girders has become a key scientific issue for the rapid maintenance and toughness improvement of bridges.

In this paper, two newly proposed "rigid self-locking" and "force card" prestressed CFRP plate anchorage systems are adopted to strengthen 6 m foot RC girders, and static-amplitude fatigue coupling tests are carried out to establish a three-dimensional nonlinear structure that takes into account the overloading cycle, prestressing relaxation and environmental erosion[2]. A three-dimensional nonlinear finite element model considering overload cycling, prestress relaxation and environmental erosion is developed to systematically reveal the crack evolution and stiffness degradation of CFRP-reinforced girders under amplitude-variable cyclic loading, so as to provide theoretical and experimental bases for the design of CFRP-reinforced bridges in long-term performance[3].

## 2. Static Test

### 2.1 Test Preparation

A total of three reinforced concrete test beams were prepared in this study, and the specimen design parameters were as follows: the total length of the beams was 6000 mm, the net span was 5400 mm, and the rectangular cross-section size was 350 mm (width) × 500 mm (height). The designed strength grade of concrete is C40, and the longitudinal stress reinforcement is HRB400 grade steel. The reinforcement scheme is as follows: three 16mm diameter stress bars at the top of the beam, three 22mm diameter stress bars at the bottom of the beam, and eight 12mm diameter structural reinforcement bars at the side as the erection bars. The hoop reinforcement adopts 10mm diameter HPB300 reinforcement, which is arranged at a spacing of 200mm in the span of 1800mm, and the rest of the section is encrypted to a spacing of 100mm. The actual mechanical property parameters of concrete and reinforcement measured by the material property test are shown in Tables 1 and 2, which will be used as the basic parameters for the subsequent finite element analyses. The detailed dimensions and reinforcement configuration of the test beams are shown in Fig. 1. This reinforcement scheme fully considers the flexural and shear demands of the beams, and at the same time ensures the safety of the specimens during the test.

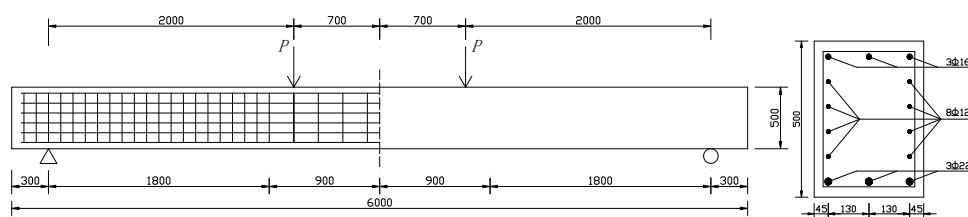


Fig. 1 Dimension and section reinforcement drawing of test beam(mm)

Table 1. Properties of Concrete

Strength grade	Compressive strength (MPa)	Tensile strength (MPa)	Modulus of elasticity (GPa)
C40	40.8	3.05	32.5

Table 2. Properties of Steel

Type Yield	Strength (MPa)	Ultimate strength (MPa)	Modulus of elasticity (GPa)
HRB400	420	610	200

### 2.2 Anchoring Process

In this study, two different pre-stressed CFRP plate anchorage systems were used to reinforce the test beams. The specific reinforcement scheme is as follows: at the bottom centre of each test beam, a

prestressed CFRP plate with specifications of 50 mm (width) × 3 mm (thickness) × 5200 mm (length) is installed, which is tested to have the following mechanical parameters: modulus of elasticity of 248 GPa, ultimate tensile strength of 3,500 MPa, coefficient of linear expansion of  $3.2 \times 10^{-5}$ , and Poisson's ratio of 0.17. The following mechanical parameters are adopted uniformly for the tests. In the test, a uniform tensioning control stress of 1600MPa was adopted, and two different anchoring methods, namely "rigid self-locking anchorage system" and "force card anchorage system", were used for comparative study[2].

As for the anchoring process, 200mm of anchorage length was reserved at each end of the CFRP plates, and professional tensioning equipment was used to complete the prestressing and anchoring operations before the test. To ensure the comparability of the test data, all the reinforced specimens were treated according to the same construction process and quality standards. The main difference between the two anchorage systems is that the rigid self-locking system adopts a hydraulic graded tensioning process and maintains the prestressing force through a mechanical self-locking device, while the force card system adopts a unique mechanical locking technology, which provides a better stress-retaining performance. Specific grouping of specimens is detailed in Table 3.

**Table 3.** Number and Purpose of Test Piece

Specimen number	Anchorage system	Test application
L1	Unreinforced	Bare Beam Load Capacity Test
A2	Self-locking system	Static test
B2	LIKA system	Static test

### 2.3 Loading Settings

In terms of the loading device arrangement, the test beam adopts the form of simple support at both ends, and the two loading points are symmetrically arranged in the mid-span area of the test specimen, with the centre spacing strictly controlled at 1400mm. The load application adopts the MTS hydraulic servo loading system certified by the Ministry of Transportation and Communications Class A Laboratory, which has the functions of high-precision loading control and real-time data acquisition, and ensures the precise control of the test process.

The test adopts a graded loading system, and different loading parameters are set according to the differences in specimen types: for the unreinforced comparison specimen L1, a load increment of 5kN per stage is adopted before the crack appears, and adjusted to 10kN per stage after the crack appears; for the reinforced specimens A2 and B2, a load increment of 10kN per stage is adopted before the crack appears, and increased to 20kN per stage after the crack appears; when the specimen enters into the yield stage, it is uniformly converted into displacement control system, and the load is applied by the MTS hydraulic servo loading system. After the specimens entered the yielding stage, the system was converted to displacement control mode with a constant loading rate of 5mm/min to ensure the safety of the test process and reliability of the data. The deformation monitoring system consists of a high-precision displacement meter arranged in the mid-span cross-section, a displacement sensor at the loading point and a mechanical percentile meter at the support, which collects displacement data in real time through the dynamic and static testing system, and focuses on monitoring the development of deflection in the purely curved section; the strain monitoring system adopts optical fibre sensors to measure the surface strain of concrete, strain gauges to monitor the deformation of the stressed steel reinforcement, and a special strain sensor to record the change in strain of the CFRP plate. The strain monitoring system uses optical fibre sensors to measure the concrete surface strain, strain gauges to monitor the deformation of the reinforcing bars, and special strain sensors to record the change of the CFRP plate strain, and all the strain data are synchronously recorded by the multi-channel data collector; the crack observation system is equipped with a high-

definition digital camera to record the process of crack development, and a professional crack observer to quantitatively measure the width of the cracks, and adopt the artificial marking method to trace the path of the cracks[4].

### **3. Nonlinear Finite Element Analysis**

#### **3.1 Reliability Studies**

This study establishes a refined numerical model of concrete beams reinforced with CFRP plates based on ANSYS finite element analysis platform, and simulates and analyses the whole process of static test[5]. In the finite element modelling process, differentiated unit types and constitutive models are adopted for different material components: Solid65 solid unit is used to simulate the concrete material, considering its cracking and crushing behaviours, and multilinear isotropic reinforced elastic-plastic constitutive relationship is chosen; Shell181 shell unit is chosen to characterize the mechanical properties of the CFRP plate, and linear-elastic constitutive model is adopted; the reinforcement material is simulated by Link8 rod unit[6]. Link8 rod unit is used to simulate the steel reinforcement material, and the ideal elastic-plastic constitutive relationship is applied. All the material parameters are taken from the measured data of the previous material performance tests to ensure the reliability of the model parameters.

#### **3.2 Grid Division Strategy**

In terms of meshing strategy, the concrete beams are discretised using the mapping division method, and the standard cell size is set to 50 mm to generate a regular 3D hexahedral cell mesh. 50 mm cell size is also adopted for the CFRP plate and reinforcement cells to ensure the coordination of the mesh of each component. The rebar modelling adopts the solid cut-off method, and the bond-slip effect between the rebar and concrete is not considered for the time being. In the boundary condition setting, the corresponding node constraints are applied at the position of the support: the fixed hinge support constrains the degrees of freedom in the three directions of UX, UY and UZ, and the sliding hinge support constrains the degrees of freedom in the two directions of UY and UZ. In order to accurately simulate the actual working conditions, the influence of the beam self-weight is considered in the model, and the concentrated load is equivalently converted into surface load applied in the loading area to avoid the phenomenon of stress concentration.

#### **3.3 Interface Connection Simulation**

Aiming at the key technical challenge of simulating the connection between CFRP plate and concrete interface, this study proposes an improved modelling method. Different from the simple bonding method of the traditional GLUE command, this model is based on the actual force characteristics of the prestressed CFRP plate, and adopts the node degree of freedom coupling (CP command) method to rigidly connect the nodes of the anchorage zone at the end of the CFRP plate with the corresponding concrete nodes, so as to more realistically reflect the mechanical behaviours of the two working in concert. The prestressing force application adopts the temperature stress simulation method, which equivalently simulates the tensioning process through the graded cooling process, and finally achieves an effective prestressing force application of 1500 MPa by considering the 6% prestressing force loss. The modelling method effectively overcomes the problem of interface connection distortion in traditional simulation and significantly improves the analysis accuracy[7]. Fig. 2 demonstrates the overall finite element model established, including the detailed meshing and boundary condition settings, which lays a good model foundation for subsequent parametric analysis and result verification.

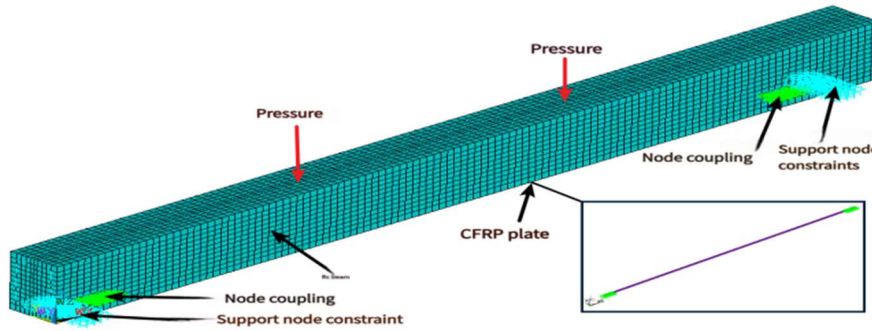


Fig. 2 Finite Element Model of Strengthened Beam

## 4. Analysis of Test Results

### 4.1 Crack Development And Damage Patterns

During the test loading process, the crack development patterns of various specimens were systematically observed and recorded in real time. By comparing and analysing the crack development patterns of unreinforced specimen L1 and reinforced specimens A2 and B2, obvious differential characteristics can be clearly observed. For the unreinforced specimen L1, the initial cracks appeared to be sparsely distributed with a large crack spacing, while specimens A2 and B2 reinforced with pre-stressed CFRP plates showed significantly different crack development patterns, with denser distribution of cracks and significantly reduced spacing. This phenomenon is visualised in the comparison of Fig. 3(a)-(c).

In-depth analysis of the crack development process can be found that, with the continuous increase of the load, all the specimens show a trend of rapid growth in the number of cracks, and the crack spacing shows a regular change of gradually decreasing. When the specimen reaches the limit state, the crack distribution tends to be homogenised, especially in the bottom region of the specimen, and the crack spacing is basically the same. This homogenised crack distribution characteristic indicates that the reinforcing effect of the prestressed CFRP sheet effectively improves the stress performance of the concrete material, so that its strength potential can be more fully exploited[8].

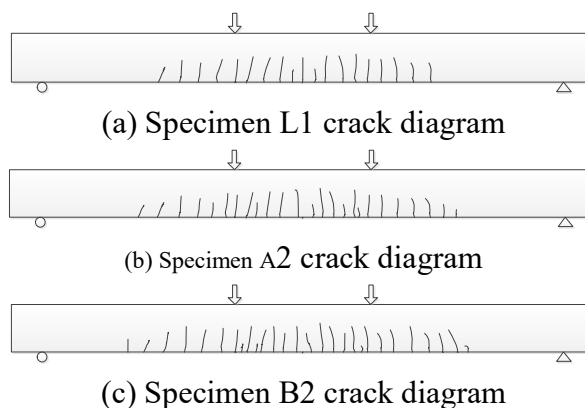
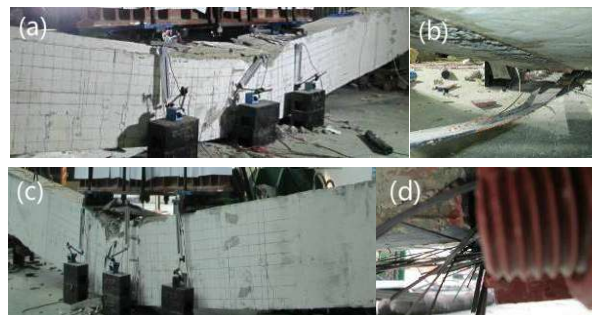


Fig. 3 Crack Development of Test Beam

Through the systematic observation and analysis of the damage modes of the test beams, the damage characteristics of the different specimens can be clearly distinguished: the unreinforced specimen L1 showed typical ductile damage characteristics, and its damage process was accompanied by significant plastic deformation; whereas the pre-stressed CFRP plate reinforced specimens A2 and B2 maintained a certain degree of ductility although they both entered the yielding stage at the time of damage, in which the damage mechanism of specimen A2 The damage mechanism of specimen A2 is that the rapid growth of CFRP plate strain in the yielding stage leads to its ultimate failure by

slipping from the anchorage system (as shown in Fig. 4a and b), whereas specimen B2 shows a different damage mode, i.e., the nonlinear rapid growth of prestressing CFRP plate stress in the yielding stage ultimately triggers the brittle fracture of the material (as shown in Fig. 4c and d), and the CFRP plate shows a crushed damage morphology after the fracture[9]. It is worth noting that the CFRP plate of specimen B2 did not slip from the anchorage during the whole damage process, and this phenomenon contrasts with the damage characteristics of specimen A2, which fully reflects the significant influence of different anchorage systems on the damage mode of the structure, and also indicates that the Rikka anchorage system has an obvious advantage in the stress transfer efficiency, and it can more effectively play the high-strength performance of the CFRP material, while the rigid self-locking system has an obvious advantage in the stress transfer efficiency, and can more effectively play the high-strength performance of the CFRP material. It also shows that the rigid self-locking system has a significant advantage in stress transfer efficiency and can more effectively exert the high strength of CFRP material, while the rigid self-locking system may fail under extreme deformation conditions with interfacial slip. These differences in damage characteristics not only verify the effectiveness of the pre-stressed CFRP plate reinforcement technology, but also provide an important experimental basis for the optimisation of the anchorage system selection in the engineering practice.



**Fig. 4** Failure Modes of A2 and B2 Specimens

Comparing the damage modes of specimens 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 occurred the phenomenon that the prestressed CFRP plate slipped out of the anchorage, the specimen had already entered into the yield stage when the phenomenon of slipping out occurred, and for the actual bridge structure, such a large deformation would not occur in the normal use stage. Therefore, the safety of the rigid self-locking anchorage system can meet the normal use requirements for the actual structure[10].

#### 4.2 Load-Mid-Span Displacement Curve

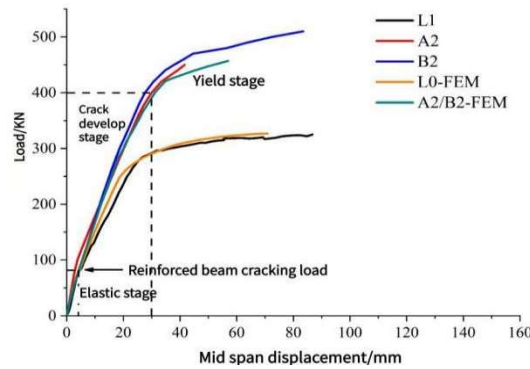
The results of the characteristic loads of the test beams are shown in Table 4, where the load values are the total load values applied to the beams.

**Table 4.** Characteristic Load of Test Beams

Test beam number	Cracking load/kN	Ultimate load/kN
L1	50	340
A2	80	450
B2	80	510

As can be seen from Table 4, the cracking load of specimen L1 is 50kN, and the cracking load of specimens A2 and B2 are both 80kN, and the cracking load of the members is increased by 60% after

reinforcement with pre-stressed CFRP plates. The final load capacity of specimen L1 was 340kN, and the final load capacities of specimens A2 and B2 were 450kN and 510kN, respectively, and the load capacities of the reinforced specimens were increased by 32% and 50%, respectively, with obvious reinforcement effect. The load-mid-span displacement curves of the reinforced beams obtained from the tests are compared with the finite element simulation results as shown in Fig. 5.



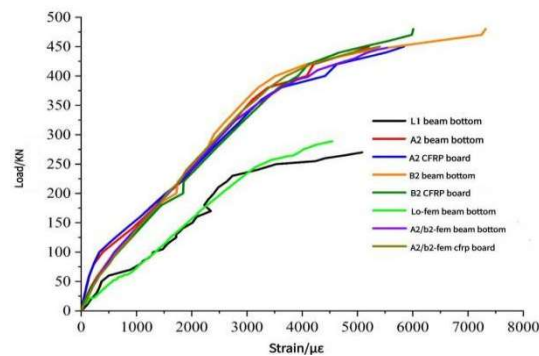
**Fig. 5** Load-Mid Span Displacement Curves

As can be seen from Fig. 5, the test results agree well with the finite element calculation results at all stages, indicating that the established nonlinear finite element model can predict the flexural behaviour of the reinforced beams before the failure of the prestressed CFRP plates. The stressing process of the reinforced beams can be divided into three stages: ① elastic stage (0~80kN): before the crack appears, the reinforced beams are stressed in an elastic state, and the load-mid-span displacement curves are approximately straight lines, and the structural stiffness is basically unchanged. ② Crack development stage (80~400kN): visible cracks appeared, the number of cracks increased with the increase of load, the slope of the load-displacement curve slightly slowed down after cracking, but basically consistent with the elastic stage. Compared with the unreinforced beam L1, the stiffnesses of A2 and B2 are almost unchanged, indicating that the presence of prestressed CFRP plates can effectively inhibit the beam deflection, avoid excessive stiffness discount due to crack development, and significantly improve the flexural load capacity of the reinforced beam[11]. ③ Yield stage (greater than 400kN): continue to load, the load growth slows down while the displacement continues to increase, and eventually the CFRP plate strain grows rapidly and slides out of the anchorage or rupture occurs, the tensile reinforcement bar is immediately pulled off, and the specimen is damaged. It can also be seen that the ductility of the reinforced specimen is reduced compared to the unreinforced beam L1.

### 4.3 Adaptive Change

The strain variation curves of the concrete at the bottom of the beam at the mid-span position of specimens L1, A2, B2 and the finite element model and the CFRP plate at the same position are shown in Fig. 6.

As can be seen from Fig. 6, under the same load, the concrete strains at the bottom of the beams of specimens A2 and B2 are significantly smaller than those at the bottom of the beam of specimen L1. It can be seen that when the prestressed CFRP plate is used for flexural reinforcement of reinforced concrete beams, it can significantly restrain the development of concrete strain at the bottom of the beam[12]; comparing the concrete strain at the bottom of the beams at the mid-span position of the test specimens A2 and B2 with the strain of the CFRP plate at the same position, it can be seen that the two are very close to each other, which indicates that the prestressed CFRP plate and the concrete at the bottom of the beams show good performance of collaborative deformation.



**Fig. 6** Load-Strain Curves

## 5. Conclusion

In this study, the static performance of reinforced concrete beams reinforced with prestressed CFRP plates is systematically investigated through static tests and finite element simulations, and the effects of different anchorage systems on the reinforcement effect are discussed. The results show that the prestressed CFRP plate reinforcement technique can significantly increase the cracking load and ultimate load capacity of the beams, while effectively improving the crack distribution and the utilisation of concrete strength. Although the ductility of the strengthened girders was reduced, their performance in the normal service stage still met the project requirements. In the test, the force card type anchorage system demonstrated better stress transfer efficiency and damage mode than the rigid self-locking anchorage system, which provides an important basis for the selection of anchorage system in engineering practice. The finite element simulation results are in good agreement with the test data, which verifies the reliability of the model and lays a theoretical foundation for the subsequent research. The results of this study not only enrich the theoretical system of prestressed CFRP plate reinforcement technology, but also provide a scientific basis for practical engineering applications. Future research can further explore the performance evolution of reinforced beams under long-term service environment, in order to optimise the design method and enhance the durability of the reinforcement technology.

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