BENDING BEHAVIOR TEST AND ASSESSMENT FOR FULL-SCALE PC BOX GIRDER REINFORCED BY PRESTRESSED CFRP PLATE

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ABSTRACT

This paper focuses on behavior of full scale prestressed concrete (PC) box girder with difference degrees of damage derived from service stage. According to typical structural damage, strengthening measures are proposed, including gluing steel plate, gluing prestressed CFRP plate and so on. In order to testify the effectiveness of reinforced method, bending behavior test are conducted for full scale PC box girder both before and after strengthening. After the test, the bending behaviors of test girder are comparatively analyzed, and the failure mechanism of test girder reinforced by prestressed CFRP plate is studied. What's more, the strengthening method of gluing prestressed CFRP plate is applied in in-situ prestressed concrete box girder bridge with obvious damage. The static and dynamic testing of this reinforced bridge shows the feasibility and effectiveness of gluing prestressed CFRP plate strengthening method. Studies in this paper provide reliable guidance for engineering application.

KEYWORDS

Strengthening, PC concrete box girder, prestressed CFRP plate, bending behaviour.

INTRODUCTION

With increasing service life, coupled with other factors like fire, earthquake, overload, design and construction defection, traffic accident and so on, many highway bridges cannot meet the service demand all over the world. Therefore, it is necessary to strengthen these bridges to recover structural performance and ensure service safety. In recent years, researchers have conducted a series of experiment studies and a lot of achievements were acquired (Wang *et al*. 2011, Nie *et al*. 2007, Zhuang 2005). The hot research topic includes structural behaviour study after strengthening, strengthening effectiveness, and constructional simplicity. The popular strengthening methods include bridge deck pavement strengthening method, enlarge cross section method, external tension prestress strengthening method, gluing steel plate strengthening method, change structural system method, adding longitudinal or transversal girder method and so on (Wang *et al*. 2010, Nie *et al*. 2011).

Bonding the carbon fiber strengthening plastic (CFRP) plate method is a strengthening method developed in recent years. CFRP is an excellent material for strengthening concrete structures, because its superior characters of high strength, low density, corrosion resistance, fatigue resistance and so on. CFRP is more and more used in strengthening project of civil engineering (Li *et al*. 2014). Normally, CFRP is glued to concrete surface by resin material to achieve composite effect to ensure the overall behaviour. Prestressed CFRP plate strengthening method combines the advantages of general CFRP plate and prestressing technique, which effectively improve the anti-cracking capacity, structural rigidity and deformation performance. This strengthening method makes full use of the high strength of CFRP plate, which helps save the strengthening material and cost.

In the bridge strengthening project, CFRP laminate or plate can be directly glued to the strengthening parts by epoxy adhesive material, which is easy to guarantee construction quality, avoid bolted work in gluing steel plate strengthening method. Compared with gluing plate strengthening method, CFRP plate strengthening technology has no damage for the original structure. Meanwhile, since the CFRP plate is a high tensile strength and low shear strength materials, it can be cut at the constructional site and the whole strengthening process is simple and convenient since no other constructional machine is needed. Although CFRP is an expensive material compared with traditional constructional material, its superior characters like corrosion resistance enable its application in serious environmental region and post maintenance work can be avoid after strengthening (Garden *et al*. 1998). Thus, CFRP strengthening method is a beneficial chose for bridge engineering.

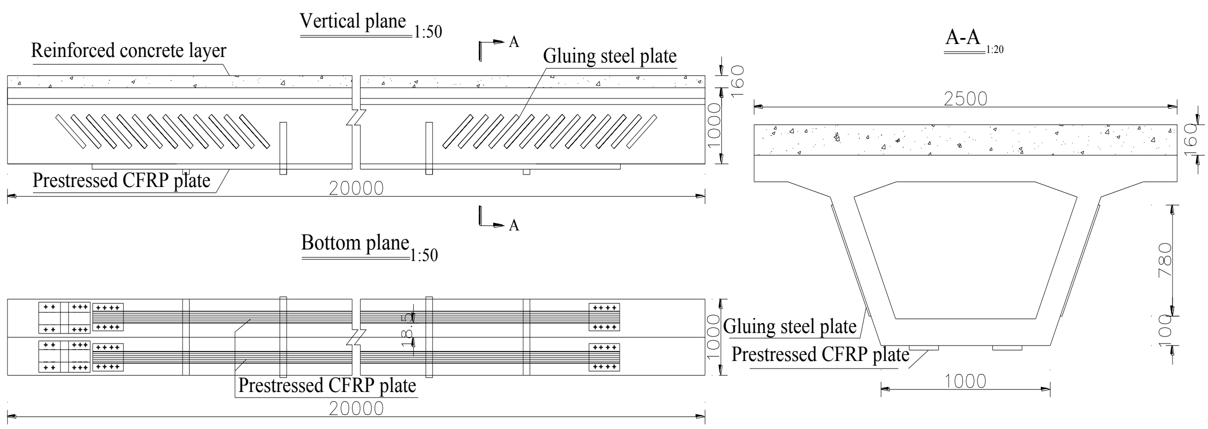
According to typical structure damages, strengthening measure of gluing steel plate and gluing prestressed CFRP plate are adopted. This paper is focus on bending behavior of full scale PC box girder before and after prestressed CFRP plate strengthening method. After the test, the bending behaviors of test girders are comparatively analyzed, and the failure mechanisms of test girders are studied. Based on test result, the strengthening method of gluing prestressed CFRP plate is applied in in-situ PC box girder bridge with obvious damage. The static and dynamic testing of this reinforced bridge shows the feasibility and effectiveness of gluing prestressed CFRP plate strengthening method.

TEST PROGRAM

Full-scale Test Girder

Test girders in this paper are 20m simple supported PC box girder removed from a real bridge. The in-situ inspection results show difference degrees of damage were existed in components of full-scale test girder. For example, lateral and longitudinal cracks were existed at bottom flanges near mid-span regions; many vertical, inclined and longitudinal cracks appeared in the webs; cracks were normally found in the concrete diaphragms; connecting steel plate are fractured; most of longitudinal concrete wet jointing were cracked, damaged and leaking. Strengthening measures were adopted by gluing steel plate and gluing prestressed CFRP plate for the test girder. Bending tests were conducted for simple supported full-scale test girders before and after strengthening, respectively.

For strengthening process, two prestressed CFRP plates were glued at bottom flange with distance of 400mm. The selected prestressed CFRP was 1.4mm thick and 100mm wide, with standard tensile capacity no less than 2400MPa, elastic modulus no less than 1.6×10^5 MPa and elongation rate no less than 1.7%. One end of CFRP plates were anchored by Q345 steel plates, which were attached at bottom flange by both adhesive glue and M20 bolts. Hydraulic jack were located at another end of CFRP plates, which is moveable, and CFRP plates were anchored by the same size Q345 steel plates after prestressed by hydraulic jack. The prestressed force for CFRP plates were 1560MPa, which was equal to 0.65 times the ultimate tensile standard strength. Effective initial prestressed force was 1326MPa and effective initial strain was 8288με, considering 15% prestressed force loss. Then, four Q235 steel plates were compressively attached at bottom of prestressed CFRP plate by both adhesive glue and M12 bolts (with 12mm diameter) along span length to enhance overall behaviour, shown in Figure 1. The compressive steel plates were 100mm in width and 6mm in thickness. In Figure 1, two compressive steel plates were 1955mm from mid-span section and the steel plates anchored both bottom flange and webs. Another two compressive steel plate were 4635mm far away from mid-span section, which anchored at the bottom flange by M12 bolts. Besides prestressed CFRP plate, the steel plate was glued at web within the field of 1.5 to 1.6m away from supporting section with distance of 300mm, and the steel plate was 45° from horizontal direction. The top flange is reinforced by 160mm concrete composite layer. There are two layers rebar arranged in this concrete composite layer and steel rebar are embedded at original to flange to enhance composite effect (GB 50367-2006). The test girder after strengthening is shown in Figure 1.

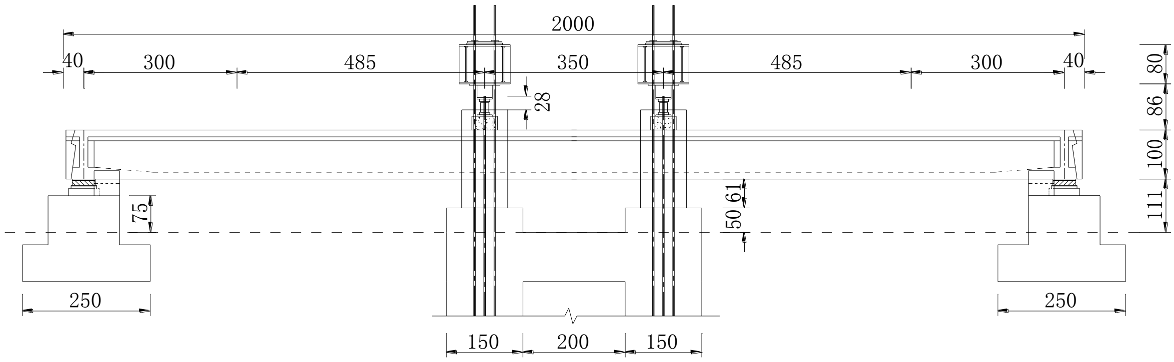


(a) Overall distribution (b) A-A cross section

Figure 1 Test girder strengthening by concrete composite layer, gluing steel plate and prestressed CFRP

Test Setup

Four-point loading were adopted during the bending test. The test setup were mainly composed with four ant-pull piles, screw-thread steel rebar, steel diaphragms and hydraulic jack, shown in Figure 2. The test girders were all located in east-west direction, while the west side was fixing supporting section and the east side was movable supporting section. During the bending test, strain and deformation were recorded by TDS-602 machine. The strain measure points were mainly arranged at mid-span region in concrete, longitudinal rebar and CFRP plate. These measure points were arranged for testing plastic region length and the neutral axle location.



(a) Bending test

(b) In-situ bending test

Figure 2 Test setup

BENDING TEST WITH AND WITHOUT STRENGTHENING

Failure Mode

Before the test, the preloading was conducted for several times, in order to inspect the overall system workability and to eliminate the strain gauge mechanical hysteresis properties. During the bending test, initial loading increment can be appropriately greater, while this loading increase should be smaller and stable as steel rebar yielding to ascending to ultimate capacity. The bending test results are shown in Table 1 for test girder with and without strengthening, respectively. To clearly describe girder behavior with prestressed CFRP strengthening method, two failure modes were took into consideration, including preliminary failure mode and ultimate failure mode. The preliminary failure mode marks the failure of prestressed CFRP plate and test girder can carry capacity continuously after failure of CFRP plate. At this moment, test girder has small deflection and concrete strain of top flange is less than ultimate strain. Ultimate failure mode marks the full plastic ultimate state of test girder and unloading follows automatically. At this state, obvious deflection can be observed and concrete strain at compressive top flange attaining ultimate strain.

Table 1 Bending test result

Test girder	Cracking capacity (kN)	Yielding capacity (kN)	Ultimate capacity (kN)	Maximum deflection (mm)	Preliminary failure mode	Ultimate failure mode
Without strengthening	340	880	1047.4	295.1	Excessive deflection	
After strengthening	200	1022.8	1337.7	614.2	CFRP plate fracture	Excessive deflection

During bending test for full scale test girder without strengthening, no new crack was found in concrete when loading was less than 340kN. The test girder showed very well overall performance and the strain of main strengthening was much less than yield strain. When the load increased beyond 340kN, there was continuous sound and new vertical cracks were appeared. A big sound was heard as loading to 362.6kN, the concrete slag dropped out and crack width turned winder at bottom flange near middle span at 392kN. When the load reached 588kN, vertical crack extended to 1/2 height of the girder. The inclined cracks appeared in the web at 1/4 span section when loading to 784kN. As loading to 980kN, severe cracks with maximum crack width of 3mm were appeared at bottom flange and web. These cracks extended quickly and part of them extended to the top flange. When loading to 1048.6kN, the concrete strain at top flange did not reach ultimate strain, but there was 30cm deflection at middle span. This excessive deflection marked termination of bending test. At this moment, the bending test girder attained plastic ultimate limit state. There were lots of vertical cracks at middle span region and inclined cracks in web outside of pure bending region. The maximum width of these cracks reached to 3~4mm. The failure mode of test girder without strengthening is shown in the Figure 3.

(a) Vertical cracks near mid-span region   (b) Inclined cracks outside of pure bending region

Figure 3 Failure mode of full scale test girder without strengthening

Figure 4 shows the cracks distribution for test girder without strengthening. Learn from Figure 4, the crack distributions have two characters. Firstly, vertical bending crack in pure bending region were uniform and the spacing distance was about 30 to 40cm. Most vertical cracks extended to haunch and some cracks extended even to the top flange. Secondly, inclined cracks were mainly located in shear span region and some vertical cracks were appeared near loading point region. Most cracks extended to haunch with angle about 45°.

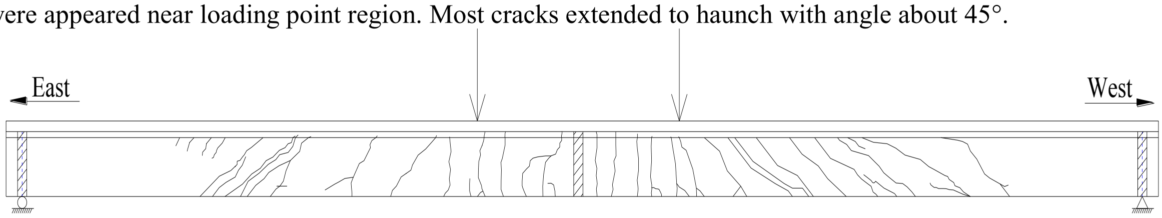


Figure 4 Cracks distribution for test girder without strengthening

In the bending process for test girder reinforced by gluing steel plate in web and prestressed CFRP plate in bottom flange, there was no new concrete crack developed when loading was less than 200kN and the test girder shew very well overall performance. New vertical crack appeared when loading beyond 200kN and continuous sound were heard as loading to 350kN. When loading to 416.5kN, vertical epoxy resin adhesive lay at north web near middle span region was cracked, and the original crack in test girder extended and turned wider. Prestressed CFRP plates at bottom flange were split when loading from 1078kN to 1205.4kN and the maximum width of concrete crack was 1.5mm. When loading from 1127kN to 1274kN, there was stripping between steel plate and concrete at web. The pre-stressed CFRP plate was fractured as loading to 1289.7kN and the test girder was unloading automatically when loading to 1317.4kN. As unloading to 1272.9KN, one CFRP plate burst apart with a loud sound and the test girder unloaded to 1225kN. The test girder was loaded again, another CFRP plate fractured at 1239.7kN and test girder unloaded to 1173.8kN automatically. Deflection of the test girder and width of the crack increased rapidly as the test girder was loaded once again. In this stage, both the bottom flange and webs had severe cracks. The widest crack was 2mm and vertical crack extended quickly to the top flange. The load did not increased and test girder unloaded automatically when loading to 1338.1kN. In this moment, the test girder approached ultimate bending plastic state in which the widest crack was 5mm and the deflection was 60cm. But the top flange was still not crushed. Figure 5 shows the failure characteristic of test girder.


(a) CFRP plate fracture

(b) Inclined crack in webs

Figure 5 Failure characteristic of test girder strengthened by prestressed CFRP and gluing steel plate

Figure 6 shows crack distributions on the north web. Learn from Figure 6, the cracks after test was much more intensive than test girder without strengthening. The cracks in Figure 6 were mainly concentrated in middle span region. There were mainly vertical intensive crack in pure bending section, most of which were extended to the top flange or even to the composite strengthening layer. There were mainly inclined crack with the angle of 45° in shear span region.

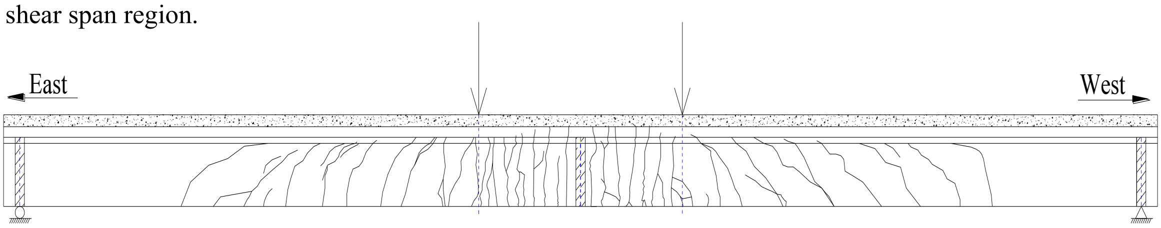


Figure 6 Crack distribution for test girder with strengthening

Test Result Analysis

(1) Test result analysis for PC box girder without strengthening

For the test girder without strengthening, the load and deformation curves at both mid-span and loading points are shown in Figure 7. Learn from Figure 7, the load-deformation curve in the mid span and loading point is basically identical with each other. The deformation increases continuously with the increase of loading, leading to concrete cracking, stiffness decreasing gradually and deformation growth rate increasing gradually. Learn from Figure 7, the bending process of the test girder can be divided into three stages. The first stage is elastic stage. In this stage, the deformation of each section increases linearly with loading, and the load is less than 340kN, which indicated no crack appearing and the girder deflection was less than 15mm. The second stage is elastic-plastic stage, corresponding to load between 340kN and 880kN. In the second stage, the load and deformation curves turned nonlinear and the stiffness of test girder declined, which indicated new cracks appeared in the test girder and both old and new cracks expanded continuously. The third stage is plastic stage, corresponding to load exceeded 880kN. In this stage, the growth of deflection increased, and the load-deformation curves tended to be horizontal. When the load reached 1047.4kN, the test girder was close to the limit state of plastic bending, and the maximum deflection is 300mm. Then the bending test was terminated due to the excessive deflection of test girder.

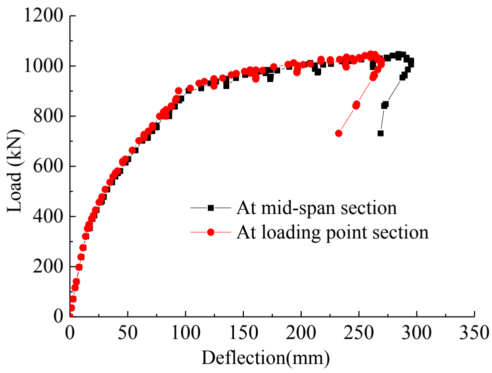
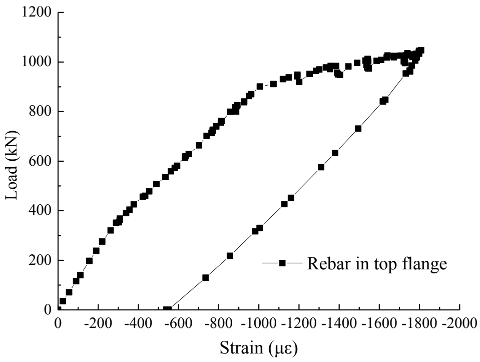
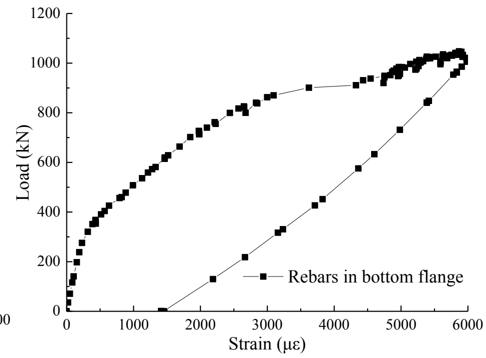


Figure 7 Load and deformation curves for test girder without strengthening

Figure 8 shows the load-strain curves of rebars in the top flange and bottom flange respectively. Learn from Figure 8, the strain has three symbols in the whole loading process, including new crack appeared in concrete, yield of rebar at bottom flange and failure of test girder. After the test, the cracking load, the yielding load and the ultimate load of the test girder were 340kN, 880kN and 1047.4kN respectively. There was no new crack in the test girder at the initial loading stage, and the strain of rebar was growing linearly. When the load reached about 300kN to 380kN, the concrete appeared new cracks, and the strain growth of rebar began to speed up. With the propagation of concrete cracks, the strain of rebar grew obviously. When the load reached 800~900kN, the rebar at bottom flange was gradually yielding, corresponding to the second typical point. As the continued increase of load, the strain growth rate of rebar still increased, corresponding to leap-growth of the strain in Figure 8. In this stage, the rebar at bottom flange showed obvious plastic characteristic. When loading to 1047.4kN, the test girder was close to the plastic bending limit state, and then the bending test was terminated.





(a) Rebar in top flange (b) Rebar in bottom flange

Figure 8 Load and strain curves at mid-span section

Figure 9 shows load and concrete strain curve at top flange at mid-span section. Learn from Figure 9, the concrete strain increased linearly with the increase of load under 340kN, and the test girder was in the elastic stage. With the loading continued, the concrete strain growth rate accelerated and the load-strain curve turned nonlinear. New cracks appeared continuously and the original cracks continued propagation. Then the load and concrete strain curve appeared mutation again, and the rebar at bottom flange was yielded. The concrete strain growth rate of the test girder turned greater, and the load - strain curve in Figure 9 reached horizontal stage. When loading to 1047.4kN, bending test was terminated. The residual strain was about 600με which can be seen from the Figure 9.

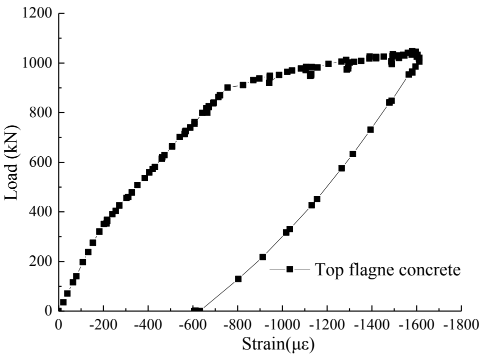


Figure 9 Load and concrete strain curve at top flange of mid-span section

(2) Test result analysis for PC box girder after strengthening

Figure 10 shows the load-displacement curves for reinforced test girder. Learn from Figure 10, the deflection curves at mid-span and at loading point were basically coincident. When loading less than 200kN, the load and displacement had linear relationship, which illustrated no new concrete crack appeared and the test girder was in elastic stage. The deflection in this stage was small, which was less than 8mm. When loading between 200kN and 1000kN, the test girder appeared new cracks, the stiffness decreased and the deflection increased. The relation between the load and displacement turned nonlinear, corresponding to elastic-plastic stage. During the loading process, both the old and new concrete cracks were propagated and the crack widths increased. When the load exceeded 1000kN, the prestressed CFRP plate was splited, and the displacement increased. When the load reached 1317.4kN, the curves in Figure 10 appeared sudden drop due to the successively fracture of the prestressed CFRP plate and the test girder was unloaded to about 1200kN automatically, which demonstrated the brittle failure of prestressed CFRP plate. Then, the displacement increased rapidly and the curves tended to be flat, although the load was still increasing. Learn from test result, the prestressed CFRP plate strengthening technique would not increase the bending capacity of the test girder, but it could enhance bending rigidity to a great extent. The load did not increased anymore when reaching 1338.1kN, which indicated attaining fully plastic state, and the maximum deflection reached 61.4cm.

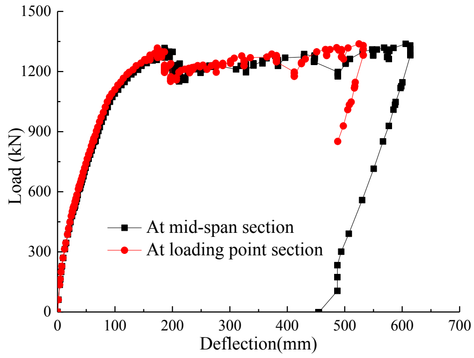
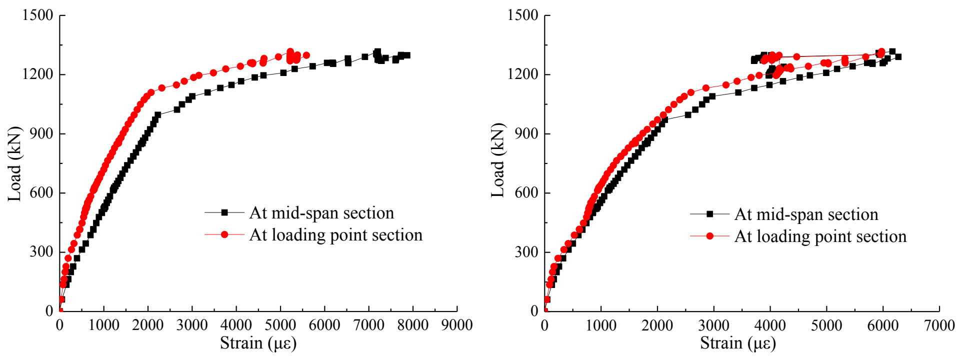


Figure 10 Load and deformation curves for test girder after strengthening

When the prestressed CFRP plate was close to collapse, the relative displacement between the prestressed CFRP plates and concrete was less than 0.1mm, which could be neglected. Figure 11 (a) and (b) show the curves between load and strain of the prestressed CFRP plate at the mid-span section and the loading point section, respectively. Learn from Figure 11, the strain increasing rate of prestressed CFRP plate was increased gradually with the continuous decrease of test girder stiffness. There are two obvious mutation points in Figure 11 at about 200kN and 1000kN respectively, corresponded to new concrete cracking development and the rebar yielding at bottom flange. After that, the strain increase of prestressed CFRP plate was not stable, because the prestressed carbon fiber plate splitting continuously after 1000kN. When the load reached about 1300kN, the prestressed CFRP plate in the south broke partly, leading to the sudden drop of strain curve in Figure 11 (b). When load fell to about 1200kN and then loading again to 1239.6kN, prestressed CFRP plate in the south side broke off. Learn from test result, prestressed CFRP plate occurred brittle failure. The strain of prestressed CFRP plate at south side was relatively uniform, and the strain differences at the mid span and the loading point were not obvious. However, for prestressed CFRP plate at north side, the strain in the mid span was significantly higher than that in the loading point.



(a) Prestressed CFRP plate at north side (b) Prestressed CFRP plate at south side

Figure11 Load and prestressed CFRP plate strain curves

(3) Comparative analysis

Learn from the bending test results, critical cracking capacity of test girder with strengthening was smaller than that of test girder without strengthening. Cracks existed in original girder, so concrete tensile stress was relatively small for unreinforced test girder, resulting in lagging development of new concrete cracks. For strengthened test girder, test girder was repaired by the crack grouting treatment, but concrete cracks would appear again in relatively early time of bending process. The yielding capacity of the reinforced test girder was greater than that of test girder without strengthening. This testified pasting CFRP plate strengthening method improved the bending rigidity of test girder. What's more, the strengthening method also improved the ultimate capacity of the test girder by 28%, which was mainly contributed from the 16cm composite strengthening layer for top flange.

Table 2 gives mid-span deflections of the test girders under different load levels. In Table 2, 200kN is the cracking capacity of the prestressed CFRP plate, 880kN is the yield capacity of the un-reinforced test girder and 1047.4kN is the ultimate capacity of the un-reinforced test girder. Experimental results showed that under different load levels, the pasting prestressed CFRP plate strengthening method can result improvement of ω_0/ω_1 ratio, which indicate the improvement of bending rigidity.

Table 2 Stiffness analysis for the test girders

Load (kN)	Deflection at mid-span (mm)		ω_0/ω_1
	Without strengthening (ω_0)	With strengthening (ω_1)	
200	8.14	6.37	1.28
880	98.32	68.94	1.43
1047.4	284.18	90.93	3.13

Table 3 gives deflections of the test girders at yielding and ultimate states. Learn from Table 3, test girder without strengthening has relatively reasonable steel rebar ratio and good ductility. For the test beam after strengthening, the ductility decreased obviously because of strengthened by prestressed CFRP plate. Prestressed CFRP plate would achieve ultimate strain and fracture in earlier bending process, and test girder shew fine ductility thereafter. According to the test result, the value of $\omega_p/\ \omega_y$ for strengthened test girder reached 2.2, which satisfying the requirement of structural ductility.

Table 3 Ductility analysis of the test girders

Test girder	Yield deflection ω_y (mm)	Ultimate state deflection ω_{pu} (mm)	$\omega_p/\ \omega_y$
Without strengthening	98.32	295.05	3.00
With strengthening	87.74	194.42	2.22

IN-SITU APPLICATION AND TESTING

Engineering Background

Baolan Railway Interchange Bridge, which is a prestressed concrete box girder, on the southern section of freeway around Ningxia city was taken as an engineering example to testify the effectiveness of prestressed CFRP reinforcement method. To determine the specific reinforcement measures, in-situ inspection was conducted. Table 4 shows typical damage in the bridge.

Table 4 Typical damages of 20m PC box girder

Position	Damage
Bottom plate	Transverse and longitudinal cracking, which are sandwiched with mud partially.
Web	Diagonal cracking, vertical cracking, longitudinal cracking
Wet joint	Cracking and seepage in multiple wet joints
Transverse connection	Water erosion and concrete cracking in the middle cross beam, fracture of steel plate connection
Girder inside	Water accumulation
Strand	Hole damage and bellows exposure appeared in web and bottom flange
Stirrup	Stirrups are erosion in the bottom plate at mid-span of multiple box girders

According to the inspection result, the specific strengthening measures were determined. Firstly, prestressed CFRP plate was tensioned at the bottom plate to decrease the rebar stress at bottom plate. Three prestressed CFRP plates were tensioned in the exterior girder while two prestressed CFRP plates were tensioned in interior girder. Secondly, strengthening rebars were added in negative moment at pier top to ensure continuous system and increase safety factor. Thirdly, steel plate was pasted on webs within the range of 1.5m to 6.5m away from supporting section, in order to decrease rebar stress at the supporting section and to prevent development of inclined concrete cracking in web. Fourthly, the existing bridge deck pavement was milled and then 16cm thick C45 waterproof concrete layer was paved as well as 8cm thick asphalt concrete surfacing course, to improve flexural rigidity and capacity of the bridge. Double-layer reinforcing mesh was arranged in the bridge deck, improving transverse integrality of the bridge deck and structural transverse stress condition. The bridge after strengthening is shown in Figure 12.

(a) Right half of bridge (b) Strengthening at bottom plate and web

Figure 12 In-situ bridge after strengthening

Load Testing

In order to testify structural safety under service stage, both static and dynamic load tests were conducted for this reinforced bridge from November 22nd to November 23rd in 2014. Analysis and evaluation were conducted on the strengthening effect. The four axles truck was adopted in static load test, and the axle spacing was 1.95m+2.90m +1.3m. The front two axles were single axle with two tires and the center distance of two tires was 2.03m while the outside distance was 2.25m. The rear two axles were single axles with four tires and the outside distance was 2.46m. The empty car was 14t weigh while the loaded car after weighted was 58.9t in total. From the front axles to the rear axle, the four axle loads were 5t, 9t, 25.4t, 21.5t respectively. In order to ensure the effectiveness of the loading, the static load test were carry out under the most unfavorable load condition, including 0.4L section and the mid-span section.

Through dynamic load test, it were acquired the dynamic effects of bridge (such as dynamic strain and dynamic deflection) and dynamic response with known load weight under the certain driving speed and traffic lane. Two exterior lanes were selected as dynamic loading lanes, respectively. Each drive pattern should consider different driving speeds, and record the dynamic response of the measuring point under the corresponding conditions. Different driving speeds were considered, including 5km/h, 20km/h, 40km/h, 60km/h and 80km/h.

Each static and dynamic load condition was repeated for twice. Checking coefficient can be calculated by the ratio of testing value to calculated value, which is a significant parameter to evaluate structural safety. The average deflection and strain were taken for analysis. The checking coefficients for all the static deflection measure points were around 1.1, while the checking coefficients for all the dynamic deflection measure points were between 0.36 and 0.77. Learn from the deflection measurement results, the static loading test resulted in greater effect under static loading, and the average checking coefficients for every measuring point were about 1.1, which belong to acceptable limits. However, the effect under the dynamic load was smaller, and the average checking coefficients were about 0.6. Thus it can be seen that the structural stiffness meets the requirements.

For strain analysis, it were measured the strain from the static load test, strain from dynamic load test and the theoretical calculated strain. There were totally 21 measuring points in static load test. After static load test, checking coefficients of five measure points were varied from 0.24 to 0.37, and check coefficients of sixteen strain measuring points were between 0.43 and 0.77. So the average check coefficient for all the measuring points was 0.59 and the standard deviation was 0.196. In dynamic load test, there were totally 21 measuring points. After dynamic test, checking coefficients of nineteen measuring points were between 0.4 and 0.91. So the average value for all the dynamic measuring points was 0.64 and the standard deviation was 0.3. To sum up, structural stress condition satisfies the requirements.

According to the comparison of static and dynamic load test, the difference between the static test data and dynamic test data was small, and speed had little influence on the dynamic strain under each dynamic loading condition. In this test, comparative analysis was conducted for concrete strain checking coefficient at bottom flange and strain checking coefficient at prestressed CFRP plate under both static and dynamic load test. Checking coefficients of most measuring points were between 0.5 and 1.0, which testified the structural stress condition satisfied the requirements.

Learn from static and dynamic loading test, structural stiffness and strength of Ningxia Baolan Railway separating interchange were improved effectively after prestressed CFRP and gluing steel plate strengthening. The reinforcement effectiveness was obvious and the expected strengthening aims were achieved. The prestressed concrete box girder bridge after reinforcement can operate safely in the service stage.

CONCLUSION

This paper has carried out bending experimental study for prestressed concrete small box girder with and without strengthening. According to analysis of the test results, it can arrive at the following conclusions:

- the 16cm concrete composite layer reinforced at top flange is the main influence factor for improving ultimate capacity. Strengthening technique in this paper can significantly increase the yield capacity and ultimate capacity. The yielding load increases by 16% and the ultimate load increases by 28%.
- prestressed CFRP plate strengthening technique can make full use of material properties of CFRP plate as well as postpone the crack development. Prestressed CFRP plate strengthening technique increases the rigidity of test girder.
- the results show the test girder strengthened by prestressed CFRP plate strengthening technique has enough energy dissipation capability as well as good deformation capacity.
- for the prestressed CFRP plate strengthening technique, the combined surface between the CFRP plate and concrete has good work performance. There is no relative slip and the structural integrality work performance is good.
- prestressed CFRP plate reinforcement method is applied for in-situ Baolan Railway Interchange Bridge. After prestressed CFRP plate strengthening, the structural stiffness and strength can be effectively increased, and the stress and deflection condition is good. So the strengthening effectiveness is obvious and the expected strengthening goal has been achieved, which can meet the requirements of the service stage.

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REFERENCE

Garden H. N., Hollaway L. C. and Thorne A. M. (1998). "The strengthening and deformation behaviour of reinforced concrete beams upgraded using prestressed composite plates", *Materials and Structures,* 31(4), 247-258.

GB 50367-2013 (2013). Code for design of strengthening Concrete structures.

Li M., Zhu F. and Zhao Y. (2014). "Study on fatigue crack propagation of CFRP reinforced bridge based on fracture mechanics", *China Journal of Highway and Transport*, 27(11), 63-68.

Nie J., Zhao J. and Tang L. (2007). "Application of steel plate and concrete composite to strengthening of reinforced concrete girder". *Bridge Construction*, (3), 76-79.

Nie J., Zhu L., Ren M. and et al. (2001). "Application of steel and concrete composite structures in rehabilitation of passageways in Beijing". *Building Structure*, 31(9): 56-57.

Wang C., Yuan Z., Guo X., Gao S. and Ren T. (2010). "Flexural behavior experiment of reinforced concrete T-beams with steel plate-concrete composite strengthening". *Journal of Traffic and Transportation Engineering,* 10(6), 32-40.

Wang C., Yuan Z., Gao S., Guo X. and Feng L. (2011). "Flexural behavior test of rectangular reinforced concrete beams of steel plate-concrete composite strengthening". *China Journal of Highway and Transport*, 24(5), 65-73.

Zhuang J. (2005). "Test and analysis for concrete beam strengthened by prestressed CFRP technology". *Master thesis*. Tsinghua University.