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Repair of flange damage steel-concrete composite girders using CFRP sheets

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Abstract. Damaged steel-concrete composite girders can be repaired and retrofitted by epoxy-bonded carbon fiber-reinforced polymer (CFRP) sheets to the critical areas of tension flanges. This paper presents the results of a study on the behavior of damaged steel-concrete composite girders repaired with CFRP sheets under static loading. A total of seven composite girders made of I20A steel sections and 80mm-thick by 900mm-wide concrete slabs were prepared and tested. CFRP sheets and prestressed CFRP sheets were used to repair the specimens. The specimens lost the cross-sectional area of their tension flanges with 30%, 50% and 100%. The results showed that CFRP sheets had no significant effect on the yield loads of strengthened composite girders, but had significant effect on the ultimate loads. The yield loads, elastic stiffness, and ultimate bearing capacities of strengthened composite girders had been changed as a result of prestressed CFRP sheets, the utilization ratio of CFRP sheets could be effectively improved by applying prestress to CFRP sheets. Both the yield loads and ultimate bearing capacities had been changed as a result of steel beam's flange damage level and CFRP sheets could cover the girders' shortage of bearing capacity with 30% and 50% flange damage, respectively.

Keywords: damaged composite girders; carbon fiber-reinforced polymer; prestressing; strengthening

1. Introduction

Steel-concrete composite girder is a common structural system due to its material efficiency by using the steel section in tension and the concrete deck in compression. It is commonly used in bridges owing to its efficient use of materials, high stiffness and high load carrying capacity. However, many existing bridges require upgrading due to the increasing traffic volume. In many research reports, it is recommended that a repaired and retrofitted method should be considered before a decision is made to replace a bridge. Strengthening existing composite girders is cheaper and easier than replacing the girders and it also doesn't influence the use of the girders. Previous researches have shown that carbon fiber-reinforced polymers（CFRP）possess excellent

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mechanical and physical properties that make them be excellent candidates to repair and retrofit the steel-concrete composite girders bridges. CFRP sheets have many advantages including lightweight, high strength and corrosion resistance. And they can be epoxy-bonded to the tension face of the damaged members to restore or enhance the ultimate bearing capacities of composite girders. During the past decade, there have been many studies on the repair and retrofit of steel beam and steel-concrete composite girders with epoxy-bonded fiber-reinforced polymers（FRP） materials. However, very few studies have presented the use of epoxy-bonded plates or sheets and prestressed epoxy-bonded plates or sheets to strengthen steel beams that have a tension flange defect, such as a notch. In this paper, the tension flanges of steel beams were partly sawn at mid-span of composite girders. CFRP sheets and prestressed CFRP sheets were adhesively bonded to the lower side of the flange of steel beams to restore the bearing capacities and the elastic stiffness. The effects of the number of layers, prestressed CFRP sheets, and the flange damage levels were investigated.

2. Previous work

Experimental investigations were carried out to study the structural behavior of reinforced concrete beams or steel beams strengthened using CFRP laminates (Colombi and Poggi 2006, Schnerch and Sami 2008, Xue *et al*. 2010, Obaidat *et al*. 2011, Fayyadh and Razak 2012, Wu *et al*. 2012, Bocciarelli *et al*. 2013, Bocciarelli and Colombi 2013, Boukhezar *et al*. 2013, Hui *et al*. 2014, Colombi *et al*. 2014, Panjehpour *et al*. 2014). However, in the document literature, the experimental investigations on steel-concrete composite girders or damaged steel girders strengthened using advanced composite laminates were limited. Sen and Liby (1994) proposed a total of six 6.10 m-long span composite girders made of W203×11 steel beam and a 711 mm-wide by 115 mm-thick concrete slab. And all of the girders were strengthened by CFRP sheets. The test results showed that CFRP laminates could quite improve the ultimate bearing capacities of the composite girders. Sen *et al*. (2001) conducted another six steel-concrete composite girders strengthened by CFRP plates. It was concluded that strengthened girders could increase the ultimate bearing capacities ranging from 11% to 52%. Tavakkolizadeh and Saadatmanesh (2003) investigated steel-concrete composite girders strengthened by CFRP sheets, using the number of CFRP layers and the cut depth of tension flanges as the parameters. The tests results showed that the girders with different layers of CFRP sheets could increase the ultimate bearing capacities varying from 44% to 76% and epoxy-bonded CFRP sheets could restore the bearing capacities and stiffness of damaged steel-concrete composite girders. Schnerch *et al*. (2005) carried out two tests on steel-concrete composite girders strengthened using high modulus CFRP strips, which showed that the girders with high modulus CFRP strips could increase the bearing capacities varying from 16% to 45%. El-Hacha and Ragab (2006) investigated the failure modes of four steel-concrete composite girders strengthened by different advanced composite laminates. The experimental results showed that no bond failure was observed and the dominated failure mode was concrete being crushed. Shaat and Fam (2008) carried out ten tests on artificially damaged steel-concrete composite girders repaired using CFRP sheets. A total of eleven 2 m-span composite girders made of W150×22 steel section with 465×75 mm concrete slabs were tested in four-point bending. The results showed that the flexural strength and stiffness could be respectively reduced by 60% and 54% due to the damage. The strength of girders repaired with sheets, ranging in length from 8% to 97% of the span, varied from 46% to 116% of the original undamaged strength, whereas the stiffness range was 86% to 126% of the original stiffness. CFRP sheets failed with debonding when high modulus CFRP was ruptured. Sallam *et al*. (2010) carried out tests on steel-concrete composite girders strengthened using high modulus CFRP strips under four point bending. The test results showed that there was no growth of the intermediate debonding for all strengthened girders until the lower flange yielded and after yielding, the composite girders with pre-debonding area showed lower flexural capacity than those with fully bonding due to the rapid growth of the intermediate debonding. Deng *et al*. (2011) presented an analytical solution to calculate the flexural strength of strengthened composite beams. The finding showed that the non-linear finite element method could match well with the load-deformation curves in the test and when the CFRP plates ruptured, the flexural strength wouldn't be influenced by the permanent load and the prestressing force, but the flexural strength reduced with the permanent load and increased with the prestressing force when the failure was the crushing of concrete. Ellobady (2011) used the nonlinear 3-D finite element models to simulate the composite girders under static loading, which showed that the high concrete slab strength would increase the load capacity, ductility and initial stiffness of the girders. And the stiffness of the steel would influence the structural strength in the post-yielded stage. Yu *et al*. (2013) investigated the effectiveness of the CFRP plates in extending fatigue life of steel structure. The experimental results showed that the CFRP patches could effectively slow down the crack growth and prolong the fatigue life. Hmidan *et al*. (2014) presented the crack-tip behavior of wide-flange W4×13 steel beams strengthened with CFRP sheets, which showed that CFRP-strengthening was an effective means to reduce the stress intensity of the damaged beams, and was particularly beneficial when the level of initial damage increased and the crack-bridging effect induced by the externally bonded CFRP was consistently maintained.

Considering the limited research on the behavior of the steel-concrete composite girders strengthened by CFRP sheets and on that of the damaged steel girders strengthened with CFRP sheets. The mechanical properties of the damaged steel-concrete composite girders strengthened by CFRP sheets and prestressed CFRP sheets were studied, and the influence of different parameters was analyzed.

3. Experimental program

A total of seven artificially damaged steel–concrete composite girders were fabricated. The girders were made of typical China Standard steel I20A of which the depth was 200 mm, the width of flange was 100 mm, the thickness of flange and web were 11.4 mm and 7 mm respectively and the area of section was 3,550 mm^2 attached to a reinforced concrete deck slab with a wide of 900 mm by 80 mm thick, as shown in Fig. 1. The steel sections were cut into 3.0 m-long beams and three different damage levels of 30%, 50% and 100% loss of tension flange were cut at mid-span of the steel beams, as shown in Fig. 2(a). Then the crossed shear studs with a diameter of 16 mm and a height of 60 mm were welded to the compression flange in two rows of 100mm spacing on center along two shear spans, as shown in Fig. 2(b). After constructing the concrete forms and securing the edges of the forms, the steel reinforcement cage with two layers of 12 mm HRB335 steel bars and stirrups provided with 6.5 mm plain bars at 150mm spacing was placed in the concrete forms of the slab, as shown in Fig. 2(c). The girders were kept moist under a plastic cover for one month, as shown in Fig. 2(d). The average concrete compressive strength was 24.6 MPa after 28 days. Tensile tests of the specimens for each type of steel were conducted. The results

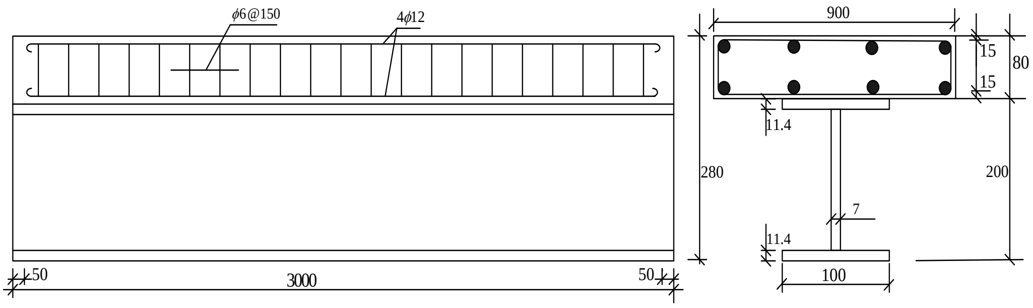
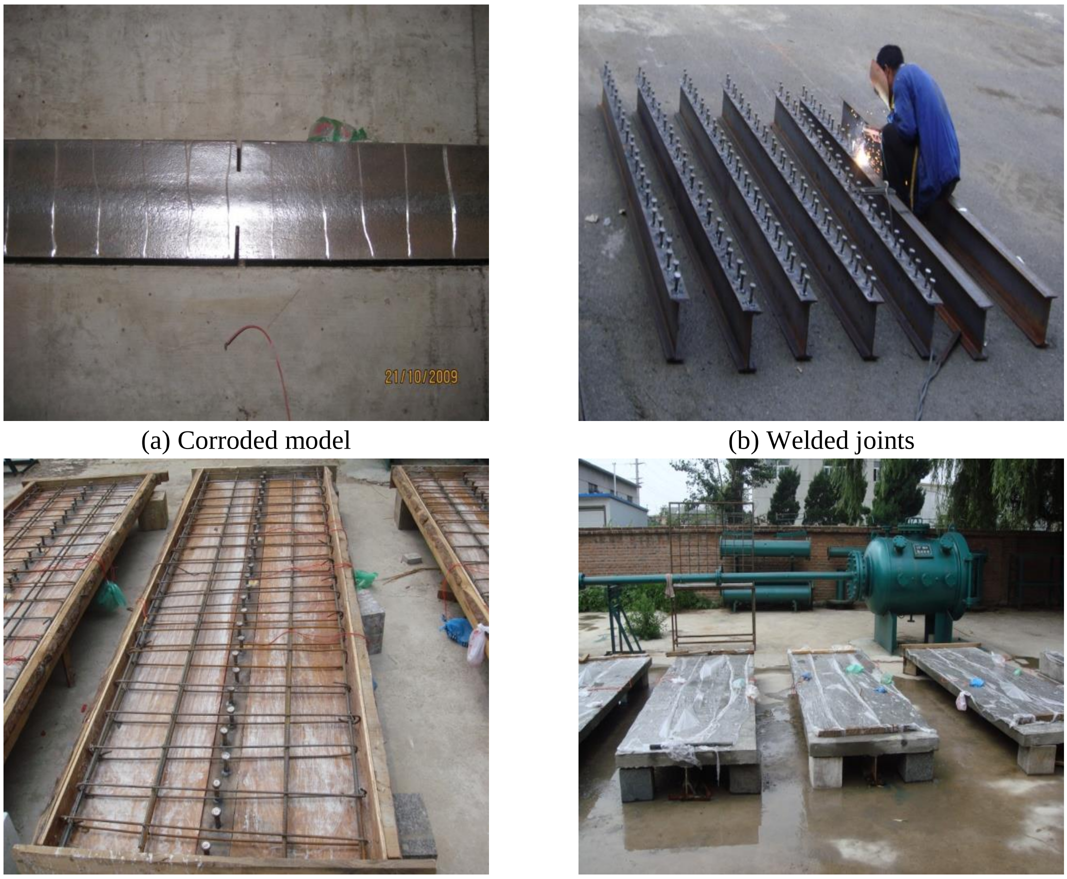


Fig. 1 Geometry size and cross-section diagram of the specimen (unit: mm)

indicated that the yield strengths of steel bars with the diameter of 12 mm and 6.5 mm were 310 MPa and 335 MPa, respectively. The yield strength of I-shaped steel was 345 MPa.

The externally bonded strengthening systems selected for this study were high-strength CFRP

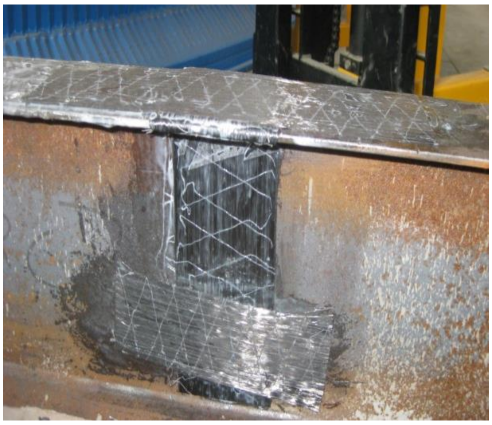


(a) Corroded model (b) Welded joints

(c) Formwork for concrete slab (d) Specimens maintaining

Fig. 2 The preparation of specimens

(e) Paste prestressed CFRP sheets



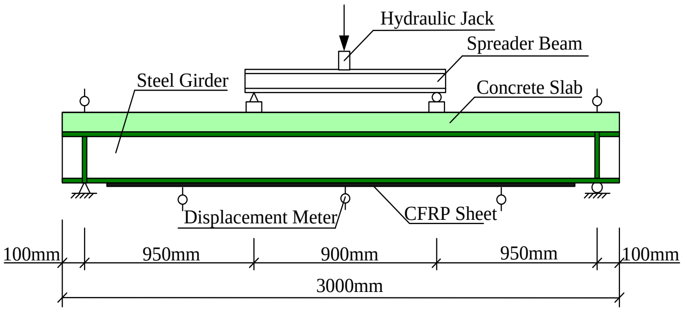
(f) Paste CFRP sheet and U-shaped hoop

Fig. 2 Continued

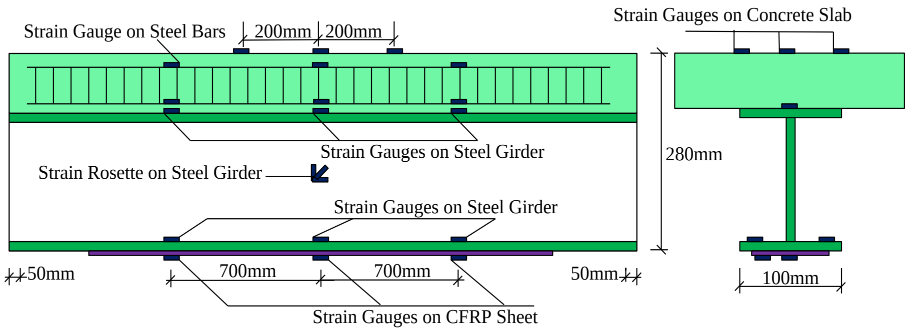
Table 1 Test matrix and results

Specimen Number	Prestressed Degree /(% P_u)	Damage level	Number of CFRP layers	Type of CFRP	Yield load P_y (kN)/ (% P_u)	Crack load of concrete P_c (kN)/ (% P_u)	Ultimate load P_u (kN)	Failure modes (CFRP sheet)
CSCB-1	0	30%	0	Not strengthened	170/ (64.1)	180/ (68.9)	265.2	——
CSCB-2	0	30%	one	CFRP sheet	175.2/ (60.7)	220/ (76.3)	288.5	rupture
CSCB-3	0	100%	one	CFRP sheet	106.7/ (50.8)	160/ (76.2)	210	debond with steel beam
CSCB-4	0	30%	two	CFRP sheet	175.6/ (58.1)	225/ (74.3)	302.2	rupture
CSCB-5	0	50%	one	CFRP sheet	158.9/ (56.4)	170/ (60.2)	281.5	rupture
CSCB-6	14	30%	one	Prestressed CFRP sheet	213.7/ (66.5)	210/ (65.3)	321.5	rupture
CSCB-7	14	30%	two	Prestressed CFRP sheet and CFRP sheet	215.3/ (63.7)	234/ (69.3)	337.9	rupture

sheets. The thickness of the CFRP sheets was 0.167 mm, the wide was 80mm and the length was 2,400 mm. Tensile test of CFRP sheets was conducted, and an average tensile strength was 3,456 MPa; elastic modulus was 258GPa. Two different attachment patterns were, namely, CFRP sheet and prestressed CFRP sheet. The prestress was applied to the CFRP sheets by using self-made stretching bed. Implementation method: fixed CFRP sheets by two steel slabs with four bolts at the end of stretching bed and four screws which could move up and down; applied prestress to the CFRP sheets by raising the supports horizontally and pasted prestressed CFRP sheets on the composite girders, as shown in Fig. 2(e); finally, pasted the U-shape hoops at the end of CFRP sheets to make sure the CFRP sheets could be anchored to the composite girders, as shown in Fig. 2(f). The detailed parameters of the composite girders were given in Table 1.



(a) Displacement meters



(b) Strain gauges

Fig. 3 Schematic of strain gauges and locations of the displacement meters at girders

4. Experimental setup

A total of 7 specimens were tested as simple composite girders with a span of 2,800 mm. The girders were monotonically loaded in four-point bending with 900 mm spacing between the two concentrated point loads, and with two equal shear spans of 950 mm, as shown in Fig. 3. Rubber bearings were used at the supports. Loading was applied across the full width of the concrete slab by 150 mm deep steel hollow structural sections that were placed between the spreader beam and the rubber bearings on the top of the beam. Four-point bending tests were performed using 5,000 kN hydraulic jacks. In order to observe the behavior of the girders under investigation, the strains, loads and deflections were measured at the desired locations. The strains were measured by electrical resistance strain gauges which were placed on the steel bars, the mid-span and the two load points of the steel beam flange, the top of concrete slab and the underside face of CFRP sheets. Five displacement meters which were mounted at both the end of the girders and mid-span were used to measure the vertical deflection.

5. Test results and discussion

5.1 Failure modes

As indicated before, the steel-concrete composite girders repaired with adhesively bonded

(a) Longitudinal crack of concrete slab

(b) Cracks of the bottom slab of concrete

(c) Concrete being crushed

(d) Rupture of CFRP sheets

(e) Web crippling (CSCB-3)

(f) Typical deformation of specimens

Fig. 4 Failure modes of test specimens

CFRP sheets under four-point bending could display several distinct failure modes including: concrete being crushed, CFRP rupture, CFRP debonding, and the web of steel beam being crippled.

The bottom flange of the steel beams started to yield at about 50% to 60% of the ultimate load. When the load reached about 65% to 75% of the ultimate load, a few longitudinal cracks were observed at the top surface of the concrete slab along the web of steel beam, as shown in Fig. 4(a), but there was no any effect on the result due to the limited width.

The longitudinal cracks tended to increase with the increasing load and could have been prevented by transverse hoop reinforcement in the slab. A few transverse cracks were observed at the bottom surface of the concrete slab along the girder with the increasing load, as shown in Fig. 4(b).

The crushing of concrete, as shown in Fig. 4(c), was the dominating failure mode in all seven retrofitted girders. The tension rupture of CFRP sheets, as shown in Fig. 4(d), was the distinct mode of failure of the composite girders. The rupture of the CFRP sheet was sudden and there was no sign of bonding failure between the CFRP sheet and the steel flange in the specimens of CSCB-2, CSCB-4, CSCB-5, and CSCB-6.

The debonding failure which appeared between the CFRP sheets and the steel flange happened in specimen CSCB-7. When the load reached about 60% of the ultimate load, the tensile flange of steel beam yielded. The concrete failed in compression in the limit state and a part of CFRP sheets were tension ruptured.

Failure of steel beam being crippled and debonding between the CFRP sheet and steel flange happened in girder CSCB-3. The tensile flange of steel beam began to yield when the load reached about 50% of the ultimate load. As the load increased, the color of CFRP sheet began to darken. The debonding developed quickly from the first sign at the cut in the mid-span (when the load was 90% of the ultimate load). The web of the steel beam ruptured at the same time as the CFRP sheet debonded, as shown in Fig. 4(e).

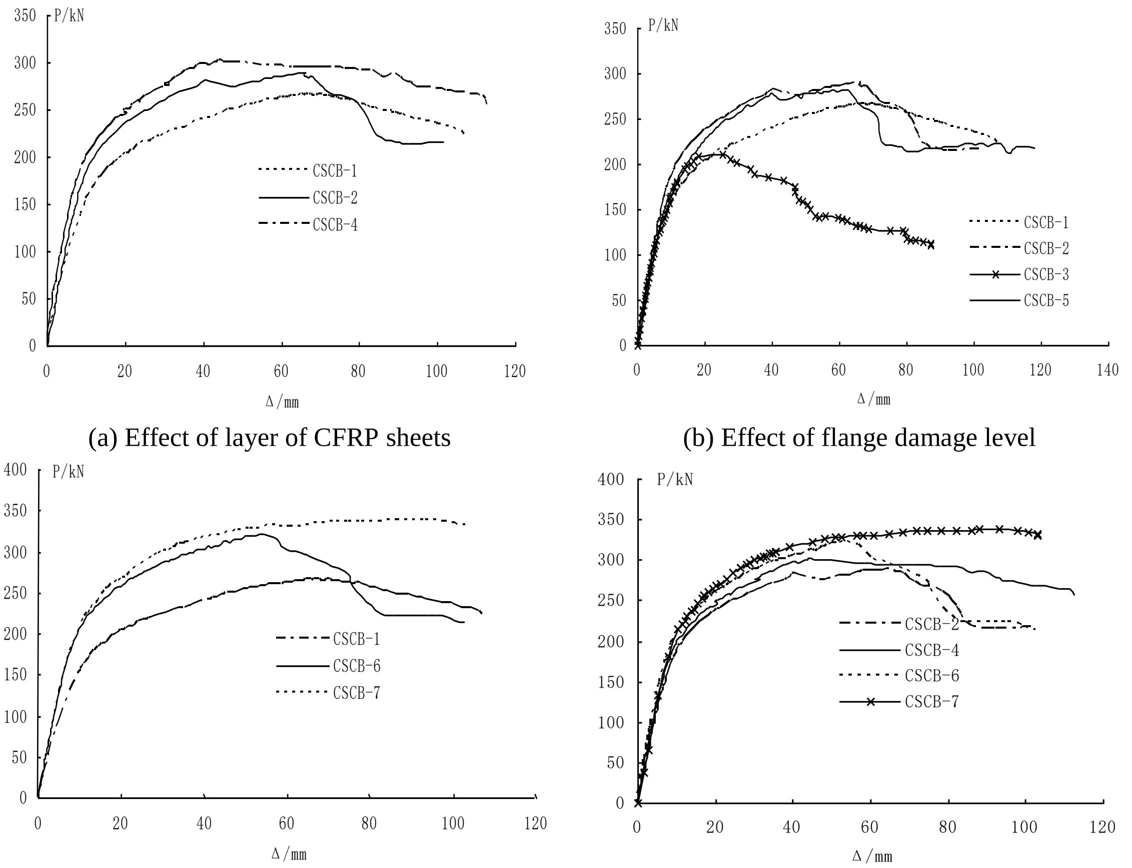
The experimental results revealed that ultimate failure was usually accompanied with large deflection and some transverse cracks of concrete slab at mid-span of girders. Both the webs and flanges of the steel beams were yielded, but there was no buckling and crippling, as shown in Fig.4 (f).

5.2 Effect of layer of CFRP sheets

Fig. 5(a) shows the load versus mid span deflection of the composite girders with 30% flange damage of the steel beams. The thickness of the CFRP sheets was constant and the number of layers was 0, 1, and 2 which were respectively used in the CSCB-1, CSCB-2 and CSCB-4. The yield load of CSCB-2 was 175.2 kN, which was 3.1% greater than that of CSCB-1, and the elastic stiffness was 15.38% greater than that of CSCB-1. The yield load of CSCB-4 was 175.6 kN, that was 3.3% greater than that of CSCB-1, and the elastic stiffness was 26.73% greater than that of CSCB-1. The ultimate load of CSCB-2 was 288.5 kN, which was 8.8% greater than that of CSCB-1, and the ultimate load of CSCB-4 was 302.2 kN, that was 14% greater than that of CSCB-1. The results showed that epoxy-bonded CFRP sheets had significantly increased the ultimate bearing capacity and the elastic stiffness of the steel-concrete composite girders. The effect of CFRP sheets on the yield load was not significant.

5.3 Effect of flange damage level

Fig. 5(b) shows the load versus mid span deflection of the composite girders with different



(a) Effect of layer of CFRP sheets (b) Effect of flange damage level

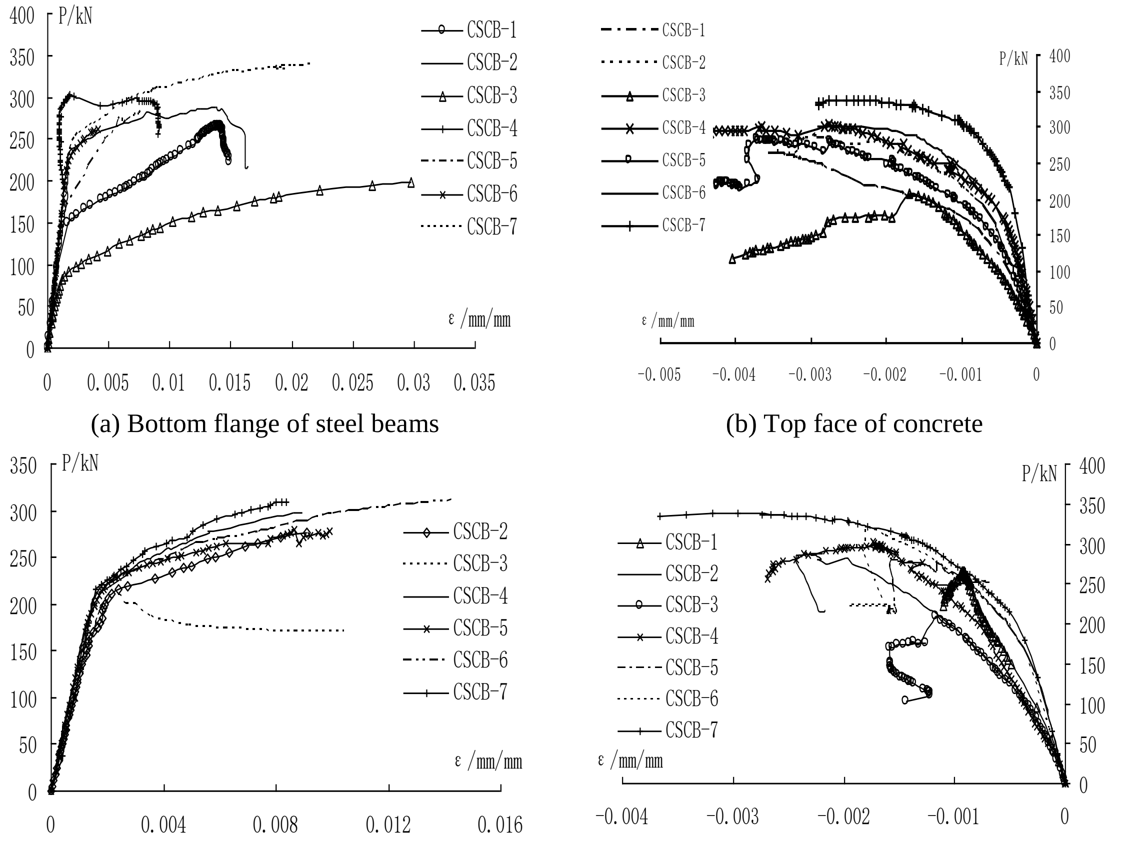
(c) Effect of prestressed CFRP sheets (d) Effect of prestressed degree (one or two layers)

Fig. 5 Relationship between load and deflection of retrofitted composite girders

flange damage levels, which were repaired with one layer of CFRP sheet. The damage levels of 30%, 50% and 100% loss of tension flange were cut at mid span of steel beams in CSCB-2, CSCB-5 and CSCB-3 respectively, and CSCB-1 was a control specimen. The yield load and ultimate load of CSCB-2 were 175.2 kN and 288.5 kN, which were respectively 10.2% and 3.2% greater than that of CSCB-5, and were 64.2%, 37.4% greater than that of CSCB-3. The ultimate load of CSCB-5 was 281.5 kN, which was 6.1% greater than that of CSCB-1; the ultimate load of CSCB-3 was 210 kN, which was 20.8% smaller than that of CSCB-1. It showed that the yield load and ultimate load had been obviously changed as a result of flange damage level; one layer of CFRP sheet could not cover the girders' shortage of bearing capacity with 100% flange damage, but it could cover the girders' shortage of bearing capacity with 30% and 50% flange damage.

5.4 Effect of prestressed CFRP sheets

Fig. 5(c) shows the load versus mid span deflection of the composite girders with 30% flange damage, which were repaired with prestressed CFRP sheets. CSCB-1 was a control specimen. CSCB-6 was repaired with one layer of prestressed CFRP sheet, and CSCB-7 was repaired with



(a) Bottom flange of steel beams (b) Top face of concrete

(c) CFRP sheets (d) Longitudinal steel bars

Fig. 6 Relationship between load and strain of retrofitted composite girders

one layer of CFRP sheet and one layer of prestressed CFRP sheet. The yield load of CSCB-6 was 213.7 kN, which was 25.7% greater than that of CSCB-1, and the elastic stiffness was 35.33% greater than that of CSCB-1. The yield load of CSCB-7 was 215.3 kN, that was 0.8% greater than that of CSCB-6, and the elastic stiffness was 1.6% greater than that of CSCB-6. The ultimate load of CSCB-6 was 321.5 kN, which was 21.2% greater than that of CSCB-1. The ultimate load of CSCB-7 was 337.9 kN, which was 5.1% greater than that of CSCB-6. Fig. 5(d) shows the load versus mid span deflection of the composite girders with 30% flange damage, which were repaired with CFRP sheets or prestressed CFRP sheets. CSCB-2 was repaired with one layer of CFRP sheet, CSCB-6 was repaired with one layer of prestressed CFRP sheet, CSCB-4 was repaired with two layers of CFRP sheets and CSCB-7 was repaired with one layer of CFRP sheet and one layer of prestressed CFRP sheet. The yield load and elastic stiffness of CSCB-6 were 22% and 17.3% greater than that of CSCB-2, respectively. The yield load and elastic stiffness of CSCB-7 were 22.6% and 5.1% greater than that of CSCB-4, respectively. The ultimate load of CSCB-6 was 11.4% greater than that of CSCB-2. The ultimate load of CSCB-7 was 11.8% greater than that of CSCB-4. The test results showed that the yield load, elastic stiffness, and ultimate bearing capacity of strengthened steel-concrete composite girders had been changed as a result of prestressed CFRP sheets.

5.5 Load- strain relationship curves

At the beginning of the experiment，the load-strain relationship of the retrofitted composite girders was linear, as shown in Fig. 6. The lines represented the strains in the bottom flanges of steel beams, the top surface of the concrete slabs, the CFRP sheets and the longitudinal steel bars. The bottom flanges of the steel beams started to yield at about 60% of the ultimate loads. After yielding, the effectiveness of the CFRP laminates was much more outstanding. The strains in the tension flanges of the retrofitted composite girders decreased significantly. As the same load level, the strains of the girder with big flange damage were greater than other girders. After tension flange yielding, the compressive strains on the top surface of the concrete slabs became nonlinear and then the compressive concrete reached the limit strain value in the limit state. Because of the steel beam ruptured, the loads of CSCB-3 were smaller than other girders. The CFRP strains of the composite girders strengthened by prestressed CFRP sheets reached over 15,000 $\mu\varepsilon$, the CFRP strains of the composite girders strengthened by CFRP sheets were about 9,000 $\mu\varepsilon$ and the strains of longitudinal steel bars in the concrete slabs reached over 1,500 $\mu\varepsilon$. All of them yielded in limit state. It showed that utilization ratio of CFRP sheets could be effectively improved by applying prestress to the CFRP sheets. The flange damage level of the girders could affect the strains of the retrofitted composite girders.

6. Conclusions

The findings of this study have shown that adhesively bonded CFRP sheets can be effectively used to repair damaged steel-concrete composite girders. The following conclusions are drawn:

• The yield load and ultimate load of the girder with 30% flange damage repaired with one layer of CFRP sheet were respectively 2.9% and 8.8% greater than that of the girder without repaired. The yield load and ultimate load of the girder with 30% flange damage repaired two layers of CFRP sheets were respectively 3.3% and 14% greater than that of the girder without repaired. In addition, the elastic stiffness of the girders repaired with one or two layers of CFRP sheets were respectively 15.38% and 26.7% greater than that of the girder without repaired.

• The yield load and ultimate load of the girder repaired with one-layer prestressed CFRP sheet were respectively 22% and 11.4% greater than that of the girder repaired with one-layer CFRP sheet. In addition, the elastic stiffness of the girder repaired with one-layer prestressed CFRP sheet was 17.3% greater than that of the girder repaired with one-layer CFRP sheet. The results showed that the yield load, elastic stiffness, and ultimate load of the strengthened composite girder had been obviously changed as a result of prestressed CFRP sheets.

• The yield load and ultimate load of the girder with 30% flange damage were respectively 9.3% and 2.4% greater than that of the girder with 50% flange damage, and were respectively 39.1% and 27.2% greater than that of the girder with 100% flange damage. Elastic stiffness of the girder with 30% flange damage was 3.7% greater than that of the girder with 50% flange damage, and was 1.9% greater than that of the girder with 100% flange damage. It showed that elastic stiffness of strengthened composite girders had not been obviously changed as a result of flange damage levels. But both the yield load and ultimate load had been changed as a result of flange damage levels. And CFRP sheets could cover the girders' shortage of bearing capacity of 30% and 50% flange damage.

• The CFRP strains of composite girders strengthened by one-layer prestressed CFRP sheet and one-layer CFRP sheet reached over 15,000 $\mu\varepsilon$ and 9,000 $\mu\varepsilon$, respectively. It showed that utilization ratio of CFRP sheets could be effectively improved by applying prestress to the CFRP sheets.

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