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Research Article

Flexural Strength of Carbon Fiber Reinforced Polymer Repaired Cracked Rectangular Hollow Section Steel Beams

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The flexural behavior of rectangular hollow section (RHS) steel beams with initial crack strengthened externally with carbon fiber reinforced polymer (CFRP) plates was studied. Eight specimens were tested under three-point loading to failure. The experimental program included three beams as control specimens and five beams strengthened with CFRP plates with or without prestressing. The load deflection curves were graphed and failure patterns were observed. The yield loads and ultimate loads with or without repairing were compared together with the strain distributions of the CFRP plate. It was concluded that yield loads of cracked beams could be enhanced with repairing. Meanwhile, the ultimate loads were increased to some extent. The effect of repair became significant with the increase of the initial crack depth. The failure patterns of the repaired specimens were similar to those of the control ones. Mechanical clamping at the CFRP plate ends was necessary to avoid premature peeling between the CFRP plate and the steel beam. The stress levels in CFRP plates were relatively low during the tests. The use of prestressing could improve the utilization efficiency of CFRP plates. It could be concluded that the patching repair could be used to restore the load bearing capacity of the deficient steel beams.

1. Introduction

Hollow section steel members have gained more widespread usage as load bearing in all directions and aesthetic appearance. They have been widely adopted as structural and nonstructural elements for onshore and offshore structures. Such existing steel structures are now facing the deficient loading bearing capacity due to corrosion, fatigue cracks, and increasing live loads. The conventional rehabilitation techniques are mainly externally bonding/welded steel plates. Steel plates showed their effectiveness in enhancing load bearing capacity. But they are cumbersome and prone to corrosion. More efficient retrofitting methods are required. Carbon fiber reinforced polymer (CFRP) patching method has become an attractive method due to its superior high strength, light weight, and lifetime properties. The technique was mainly used in the aviation industry and the effects were found to be effective [1, 2]. The method was extended to the repairing of damaged steel structures in civil engineering. Experimental tests and site applications [3–5] indicate that damaged steel structures patched by FRP can restore loading bearing capacity. Tickford bridge [6] was repaired with composite materials to increase its bearing capacity. This was also achieved with experimental tests of steel beams strengthened with carbon fiber reinforced polymer (CFRP) plates [7].

However, only a limited amount of research has been focused on the flexural behavior of hollow section steel beams. Haedir et al. [8, 9] wrapped steel circular hollow section (CHS) beams with CFRP sheets. Pure bending test results indicated that the reinforcement was favorable to the bending strength. The strengthening technique was also extended to offshore tubular steel members. Six 2.4 m long steel tubes wrapped with CFRP composites were subjected to four-point bending test [10]. It was concluded that the ultimate bending strength and flexural stiffness were increased. Photiou et al. [11] compared two retrofitting systems for degraded rectangular hollow section steel beams. It was observed that the U-shaped system could prevent peel failure and was regarded as an efficient rehabilitation method in comparison with flat plate repairing system. Elchalakani [12] also conducted series tests on rectangular hollow section steel

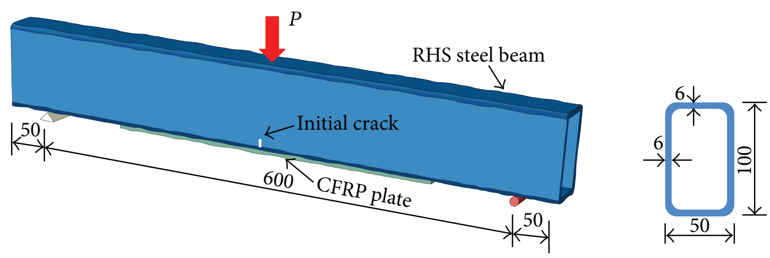


FIGURE 1: Geometry configurations.

beams wrapped with CFRP sheets or patched with CFRP plates. Both undegraded and artificially degraded beams were investigated. Considered parameters were reduction of thickness, section slenderness, and the amount of the CFRP materials. The strength increase ranges from 7% to 31% for degraded specimens. The previous research employed thinning areas to simulate the corrosion defects. However, cracks are usually found due to fatigue damage or other reasons. The defect of crack can also impair the bearing capacity and make the structures prone to brittle fracture. To restore the bearing capacity or retard crack propagation, CFRP plate was prestressed and patched to a steel pendulum with rectangular hollow section [13]. Scaled fatigue tests were conducted before the technique was applied to a site rehabilitation project. The long term field monitoring was carried out and results indicated that the patching repair was effective in mitigating stress around potential defects. Similar flat plate repairing system was also adopted by several researchers [14, 15].

In practice, hollow section members are suffering significant deterioration caused by the combination of external loading, corrosion, and cracking. Previous research has been focused on the strengthening of intact specimens or specimens with reduced thickness. Efforts have also been made to the strengthening of cracked RHS beams with a constant crack depth. Nevertheless, the specimens with different initial damage degrees have not been investigated. The knowledge gap should be fulfilled with regard to the strengthening effects on specimens with various crack depths. The purpose of this experimental study is to compare the performance of cracked rectangular hollow section (RHS) steel beams with various damage degrees repaired by CFRP plates or prestressed CFRP plates.

2. Experimental Program

2.1. Material Properties. The materials were steel tubes, CFRP, and adhesive. The steel tubes had nominal yield strength of 298 MPa and an ultimate strength of 368 MPa and the modulus of elasticity was 1.87×10^5 MPa by coupon test. It should be noted that the elastic modulus is relatively low for conventional steel. This might be due to manufacture process. The chemical compositions were listed in Table 1. The tensile strength of the CFRP plates with 1.4 mm thickness was 3089 MPa and elastic modulus was 1.91×10^5 MPa provided by the manufacturer. The two-component epoxy adhesives were mixed with a proportion of 2.5 : 1. The two-component epoxy adhesive was mixed with a proportion of 2.5 : 1. It was supplied by Shanghai Yichang Carbon Fiber Material Co., Ltd. The tensile strength and elastic modulus were 40 MPa and 2500 MPa, respectively.

TABLE 1: Chemical compositions of steel (%).

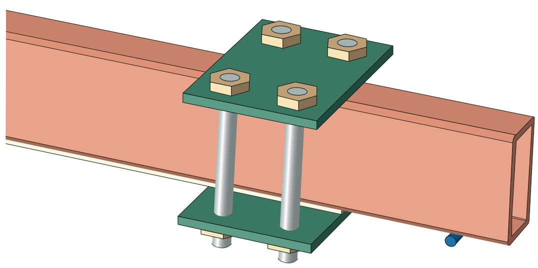
C	Mn	Si	P	S
0.13–0.18	0.42–0.46	0.16–0.24	0.014–0.026	0.027–0.040

2.2. Test Specimens. A total of eight steel beams with rectangular hollow section (RHS) were designed with various depths of initial crack. Considering workability and test facility at laboratory, the length of the specimen was chosen as 700 mm and the effective span was 600 mm for a three-point bending test. The cross section of RHS is 100 mm × 50 mm × 6 mm. The basic geometry of the cracked RHS steel beams and test setup is shown in Figure 1. Initial crack was cut on the bottom of the beam for simulating different damage degrees. The depths, which were cut with saw, were 3 mm, 6 mm, and 30 mm, respectively. The specimens were classified as three groups. Three beams were not repaired and were used as control beams. Another three beams were repaired with CFRP plates without prestressing. Two beams were patched with prestressed CFRP plates. With regard to nonprestressed CFRP plate repaired specimens, one CFRP plate with length of 400 mm and width of 50 mm was positioned and applied on the bottom of a specimen without prestressing. With regard to prestressed CFRP plate repaired specimens, one CFRP plate with length of 400 mm and width of 40 mm was patched to the specimen subjected to a prestresss of 10% of the ultimate tensile strength of CFRP material. Full details of all the specimens are given in Table 2.

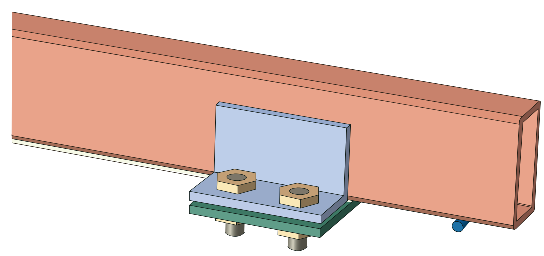
2.3. Specimen Preparation. The specimen preparation involved surface preparation, applying adhesives and patching CFRP plates. Proper surface preparation of the steel substrate is crucial to the bonding between the steel and the CFRP plate. In this study, bottom surfaces were ground with an abrasive disk to remove rust and get chemically active steel surface [16, 17]. Then surfaces were cleaned with acetone to remove dust and grease. The two-part epoxy adhesive was then mixed and uniformly spread over both the steel surface and the CFRP plate. The CFRP plate was patched to the steel

Table 2: Details of specimens.

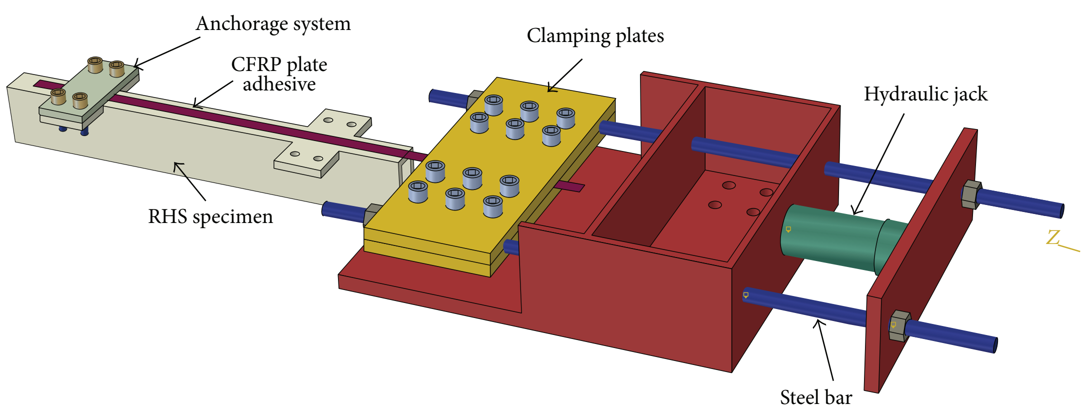
Test groups	Specimen number	CFRP plate (layers)	Initial crack depth (mm)	Prestressed level (%)	Anchorage
I	RHS-I-03	0	3	—	—
	RHS-I-06	0	6	—	—
	RHS-I-30	0	30	—	—
II	RHS-II-03-P0	1	3	0	—
	RHS-II-06-P0	1	6	0	Type A
	RHS-II-30-P0	1	30	0	Type A
III	RHS-III-06-P10	1	6	10	Type B
	RHS-III-30-P10	1	30	10	Type B



(a) Type A



(b) Type B



(c) Prestressing instrumentation

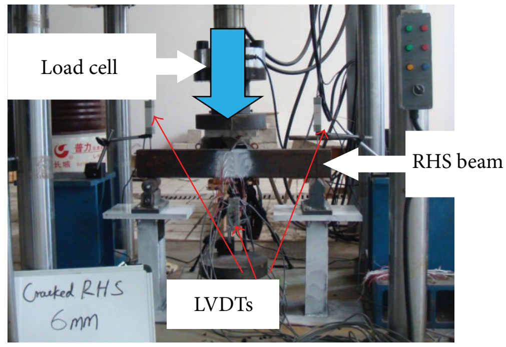
Figure 2: Anchorage systems and prestressing instrumentation.

surface with a controlled adhesive thickness. All of the test specimens were cured for more than one week under ambient temperature. To delay or prevent debonding of bonded CFRP plates, two anchorage systems were used for strengthened specimens, as shown in Figures 2(a) and 2(b). For type A, the CFRP plate end was clamped by two identical steel plates connected with four bolts. For type B, L shape angles were welded to the tube, and, thereafter, a steel cover plate was screwed to clamp the CFRP plate.

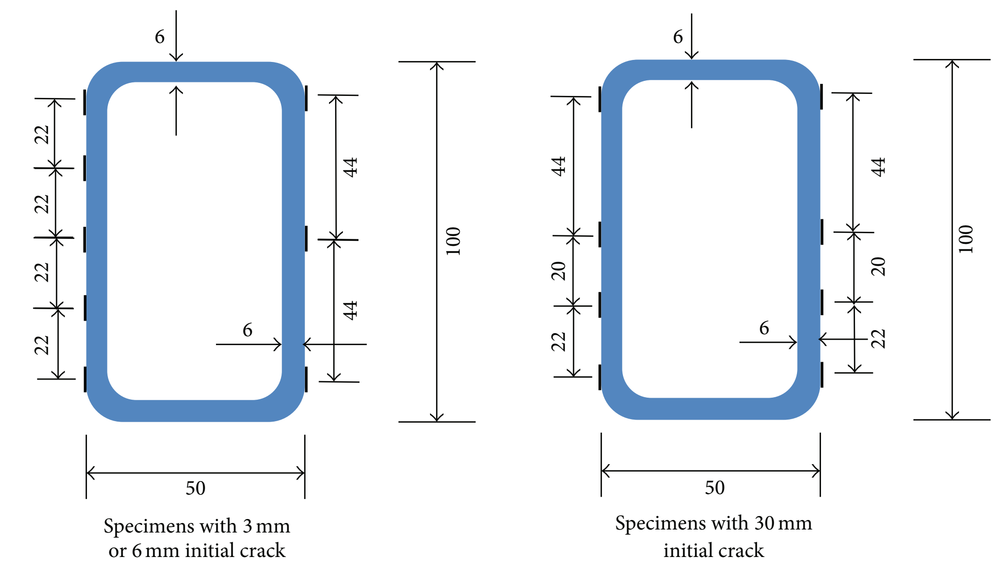
Figure 2(c) illustrates the prestressing instrumentation for the prestressed CFRP repaired specimens. Firstly, the CFRP plate was cleaned and fixed at one end by the anchorage system. The other end was clamped by two steel plates that connected to the far end steel plate through two steel bars. A hydraulic jack was used to fulfill the prestressing force. Meanwhile, a load cell and strain gauges were adopted to monitor the stress level to the controlled values. After that, the bolts were screwed at the other end of the specimen. The specimens were cured for more than one week under ambient temperature.

2.4. Instrumentation and Test Setup. The beams were tested with a three-point loading system as shown in Figure 3. The flexural loading was applied by imposing statically loading with a 500 kN hydraulic ram in the middle of the specimen. Load interval was determined with nominal yield bending moment. When the load-displacement curve exhibited nonlinear characteristic, the displacement controlled loading method was adopted until failure.

The deflections at middle point were monitored using three linear variable displacement transducers (LVDTs). Strain gauges were mounted along the height direction in



(a) Test setup



(b) Strain gauge arrangement

FIGURE 3: Test setup and instrumentation.

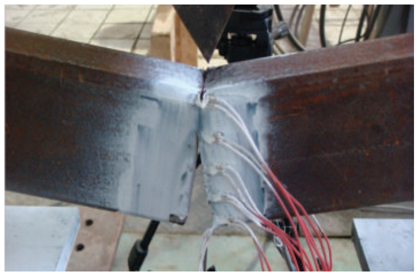
the middle span to examine the strain distribution of the cross section, as shown in Figure 3(b). Five strain gauges were mounted on the surface of the CFRP plate at a spacing of 100 mm. Meanwhile, the loads and actuator displacements were recorded with data acquisition systems.

3. Test Results

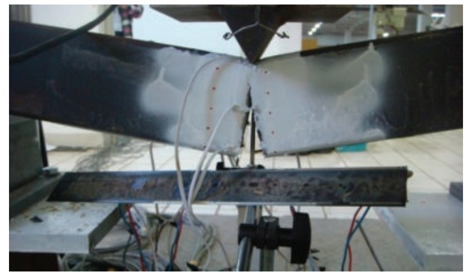
3.1. Failure Patterns. Typical failure patterns of the tested specimens are shown in Figure 4. Crack propagated along the initial vertical cut with the increase of the loading. The governing mode of failure is yielding of the cracked cross section. In the case of RHS-II-03-P0 without anchorage system, CFRP plates suddenly dropped off when load attained to peak value. This is due to the fact that interface debonding occurred and developed quickly. Meanwhile, debonding can be deferred with anchorage systems. With regard to other specimens in Group II and III, CFRP plate can be deformed with RHS steel beams until failure. Hence it suggests that the anchorage systems can effectively improve the loading and deformation capacity of repaired specimens. At failure, it was observed that CFRP cracked in the longitudinal direction.

3.2. Load-Deflection Relationships. The load-deflection responses for the control and repaired beams are plotted in Figure 5. Measured deflections were located at the bottom of the middle span. These curves provided valuable evaluation of the parameters reflecting the stiffness, strength, and flexure capacity of the specimen. All repaired specimens display lesser deflection than that of control ones. It means that the repaired specimens were stiffer than the bare steel specimens. The additional stiffness was attributed by the external bonded CFRP plate on the steel surface. The quantity of bonded CFRP plate has effect on the stiffness improvement. The stiffness of prestressed specimens should be less than the stiffness of nonprestressed ones since 40 mm width plate was used for prestressed ones instead of 50 mm width plate for nonprestressed ones. This can be justified by the fact that the curve of specimen RHS-III-30-P10 locates between the curves of RHS-I-30 and RHS-II-30-P0.

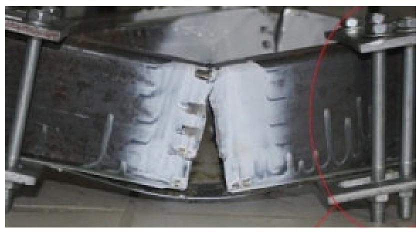
It can be observed that there is a load drop for all repaired specimens. This is due to the sudden debonding between steel and CFRP plate. With regard to the specimen RHS-II-03-P0, which was not anchored, the load decreased continuously with an increase in the deflection due to



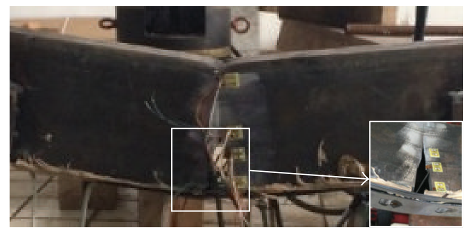
(a) RHS-I-03



(b) RHS-II-03-P0

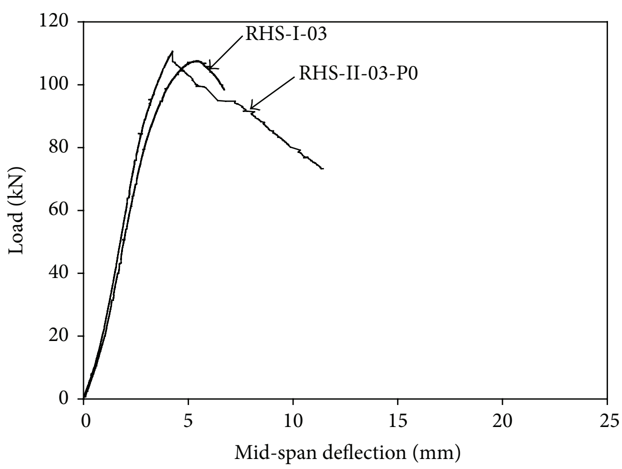


(c) RHS-II-30-P0

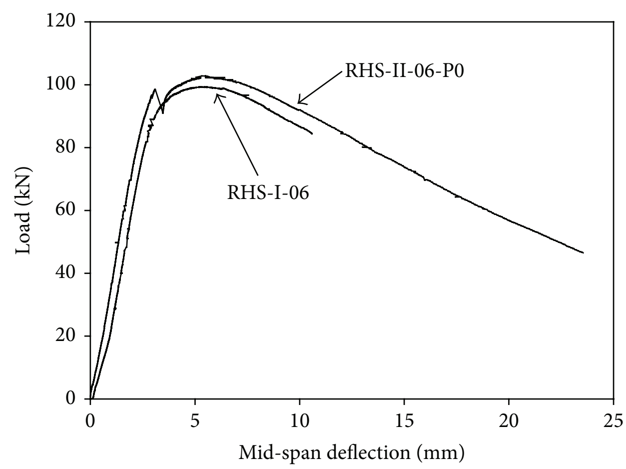


(d) RHS-III-30- P10

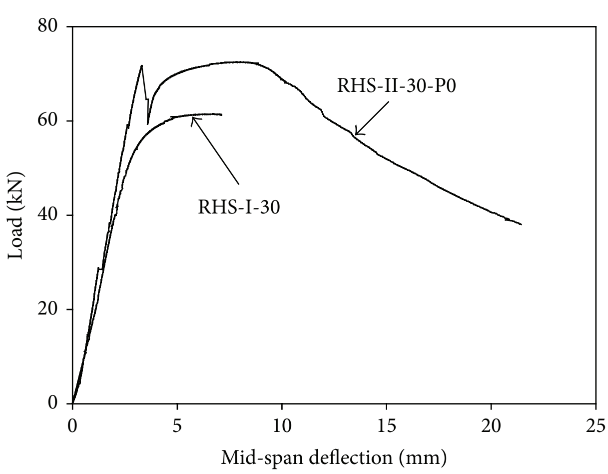
FIGURE 4: Failure patterns of the tested specimens.



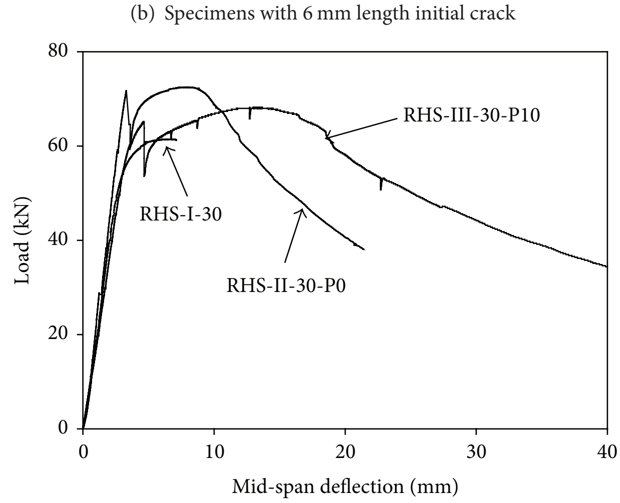
(a) Specimens with 3 mm length initial crack



(b) Specimens with 6 mm length initial crack



(c) Specimens with 30 mm length initial crack



(d) Prestressed specimens with 30 mm length initial crack

FIGURE 5: Load versus mid-span deflection curves.

Table 3: Yield load and ultimate load.

Specimen number	Theoretical yield load (kN)	Experimental yield load (kN)	Experimental ultimate load (kN)
RHS-I-03	64.36	63.20	107.50
RHS-I-06	45.51	50.90	99.40
RHS-I-30	25.98	25.22	61.50
RHS-II-03-P0	75.07	73.35	110.60
RHS-II-06-P0	58.39	59.85	102.80
RHS-II-30-P0	43.29	48.55	72.50
RHS-III-06-P10	67.00	70.02	104.35
RHS-III-30-P10	52.18	55.20	68.20

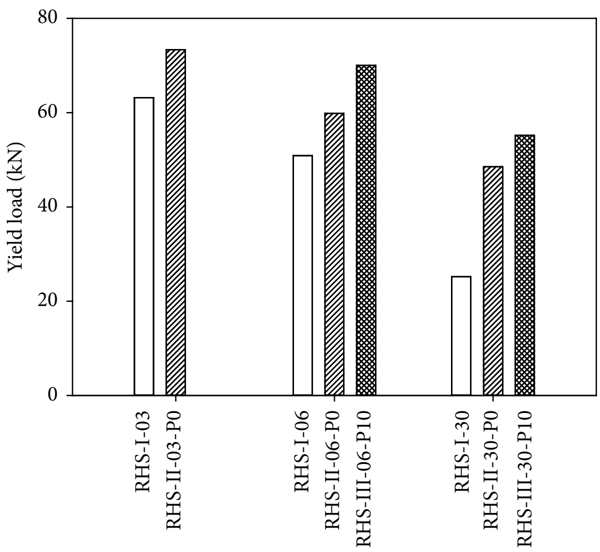


Figure 6: Experimental yield load.

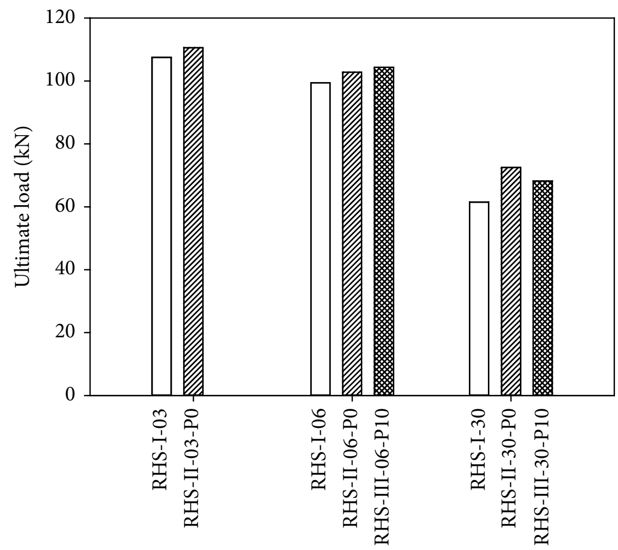


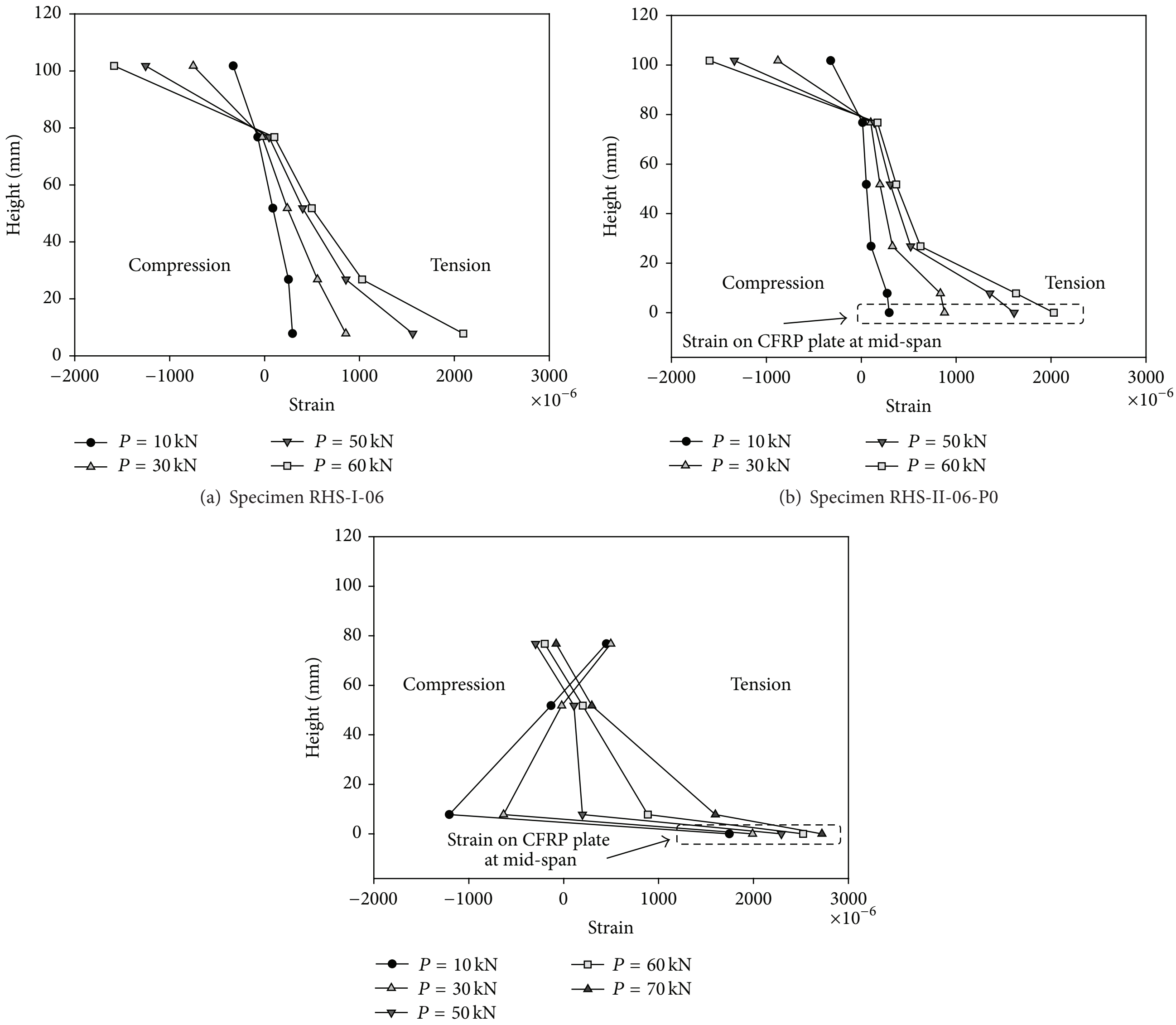
Figure 7: Experimental ultimate load.

the loss of CFRP plate. Meanwhile, the specimens that have mechanical anchorage regained load bearing capacity and deformed with large deflection. This indicates that CFRP plate can work together with steel beam even after debonding for the restraints provided by the anchorage. Comparing the ultimate load bearing capacities, it can be observed that repaired specimens have larger values. The increment of the load bearing capacity is more significant for deeper crack length.

3.3. Yield Load and Ultimate Load. The yield load and the ultimate load capacity obtained from the test for both the control specimens (bare steel beam) and CFRP patched specimens are shown in Table 3. Good agreement between theoretical and experimental yield loads was observed.

The effectiveness of CFRP patching was examined by comparing with the control specimens to quantify the percentage increase in yield and ultimate load carrying capacity (Figures 6 and 7). With regard to the specimens with an initial cut length of 3 mm, the yield load of a patched specimen is 75.07 kN which is slightly under the value of 79.81 kN which is the theoretical yield load of an unpatched intact specimen. This means that the CFRP repairing can restore the yield load for slightly damaged specimens. For the specimens with the same damage degree, namely, 3 mm crack depth, the yield load of patched specimen increased by 16.06% compared to the control specimen. The ultimate load of a patched specimen with 3 mm initial crack is 110.60 kN which is less than 154.63 kN of the theoretical ultimate load of an unpatched intact specimen. This indicates that even a small crack can imperil the ultimate load of the specimen. The ultimate load of a patched specimen increased a little by 2.88% compared to the control specimen for specimens with 3 mm crack depth.

Similarly, the yield and ultimate load of patched specimen RHS-II-06-P0 increased by 17.58% and 3.42% compared to the control specimen RHS-I-06, respectively. With regard to the specimens with large initial cut length, namely, 30 mm, the yield load of patched specimen significantly increased by 92.51% compared to the control specimen. The ultimate load of patched specimen increased by 17.89% compared to the control specimen. It is apparent that repair effect is more significant for specimens with deeper initial cut. It is also observed that the increase of the ultimate load is relatively less than the increase of the yield load. The reason may be due to the fact that the CFRP debonded with the steel beam in the latter range of loading.



(a) Specimen RHS-I-06

(b) Specimen RHS-II-06-P0

(c) Specimen RHS-II-06-P10

Figure 8: Comparison of strain distribution on cross section.

It can be observed that prestressed CFRP patching technique is beneficial to the increase of yield and ultimate load. In terms of yield strength enhancement, prestressed specimens RHS-III-06-P10 and RHS-III-30-P10 show 37.56% and 118.87% more load increment than the control beams. Likewise, the two specimens increased 4.98% and 10.89% of the ultimate load compared to the control beams.

3.4. Strain Distribution at Mid-Span. The measured strain distribution on the cross section can provide valuable information on the assessment of the steel beams under external loading. Figure 8 shows comparisons of strain distributions on cross section at mid-span when the initial crack is 6 mm. The abscissa is strain measured at the mid-span, while the ordinate is the distance from the bottom of the CFRP plate with repaired specimens. It can be observed from Figure 8(a) that the strain distribution is almost linear along height direction except that the top strain and bottom strain are a little large. The same phenomenon is observed from Figure 8(b) which also plotted the strain on CFRP plate. This may be due to the strain concentration at the crack tip and the local influence of the load cell on the top of beam. At the same load level, strain values of repaired specimen are slightly smaller than the values of the control one by comparison of Figures 8(a) and 8(b). This indicates that CFRP plate works together with the steel beam. Meanwhile, strain of CFRP is around 2000×10^{-6} under yield load.

With regard to the specimen repaired with prestressed CFRP plate, strains on the CFRP plate are relatively large, as shown in Figure 8(c). It ranges almost from 1400×10^{-6} to 5000×10^{-6} with the increase of the loading level. The lower part of the specimen changed from compression to

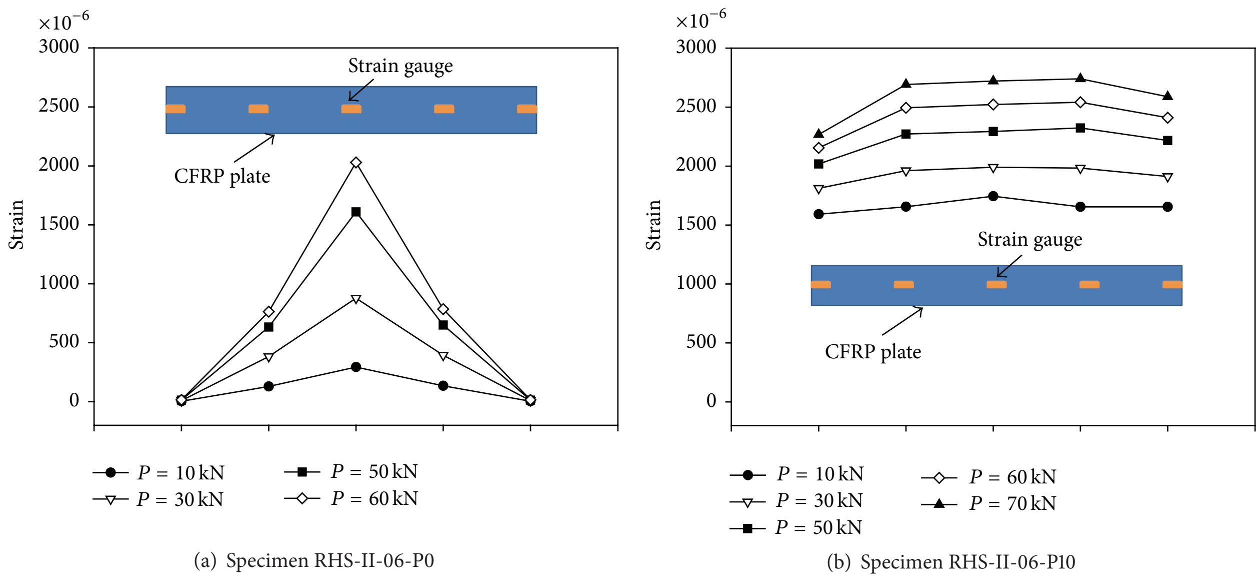


Figure 9: Comparison of strain distribution on CFRP plate.

tension state. This is due to the fact that prestressed CFRP plate introduced compression stage at lower part of the beam and it is predominant with relatively low loading level. This is beneficial to the serviceability since compression state can prevent crack propagation. When the loading level surpassed certain value, the lower part changed to tension state. And crack began to propagate when the effective stress intensity factor is larger than the threshold value.

3.5. Strain Distribution on CFRP Plate. To better understand the repair efficiency of CFRP plate, strains on the CFRP plates were plotted along length direction as shown in Figure 9. It clearly shows that strains distribute uniformly on CFRP plate for prestressed specimen. With regard to specimen without prestressing, a symmetrical distribution shape was observed and strain at mid-span achieved maximum value. The strain value significantly decreased away from middle span to two ends. This is a clear indication that prestressed CFRP plate utilization efficiency is better than nonprestressed one.

4. Concluding Remarks

This research has experimentally investigated CFRP repairing RHS steel beams. It is observed that external patching CFRP plate can significantly increase the yield load with the increase of the damage degree, while the repairs can only slightly increase the ultimate load. Debonding of interface between CFRP and steel is vital to the specimens under large load. Therefore two anchorage systems were proposed and they can fasten CFRP plate at both ends to specimen. The experimental results clearly indicate the techniques can significantly reduce the deformation of repaired cracked specimens. The prestressing CFRP plate can further increase the yield load and increase the utilization efficiency of the CFRP plate. This paper only presents test results of failure patterns and strain distributions. Numerical analysis and parametric studies are necessary in the future. Besides this, fatigue test is essential since the CFRP repair can alleviate stress level of steel beam.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

Acknowledgments

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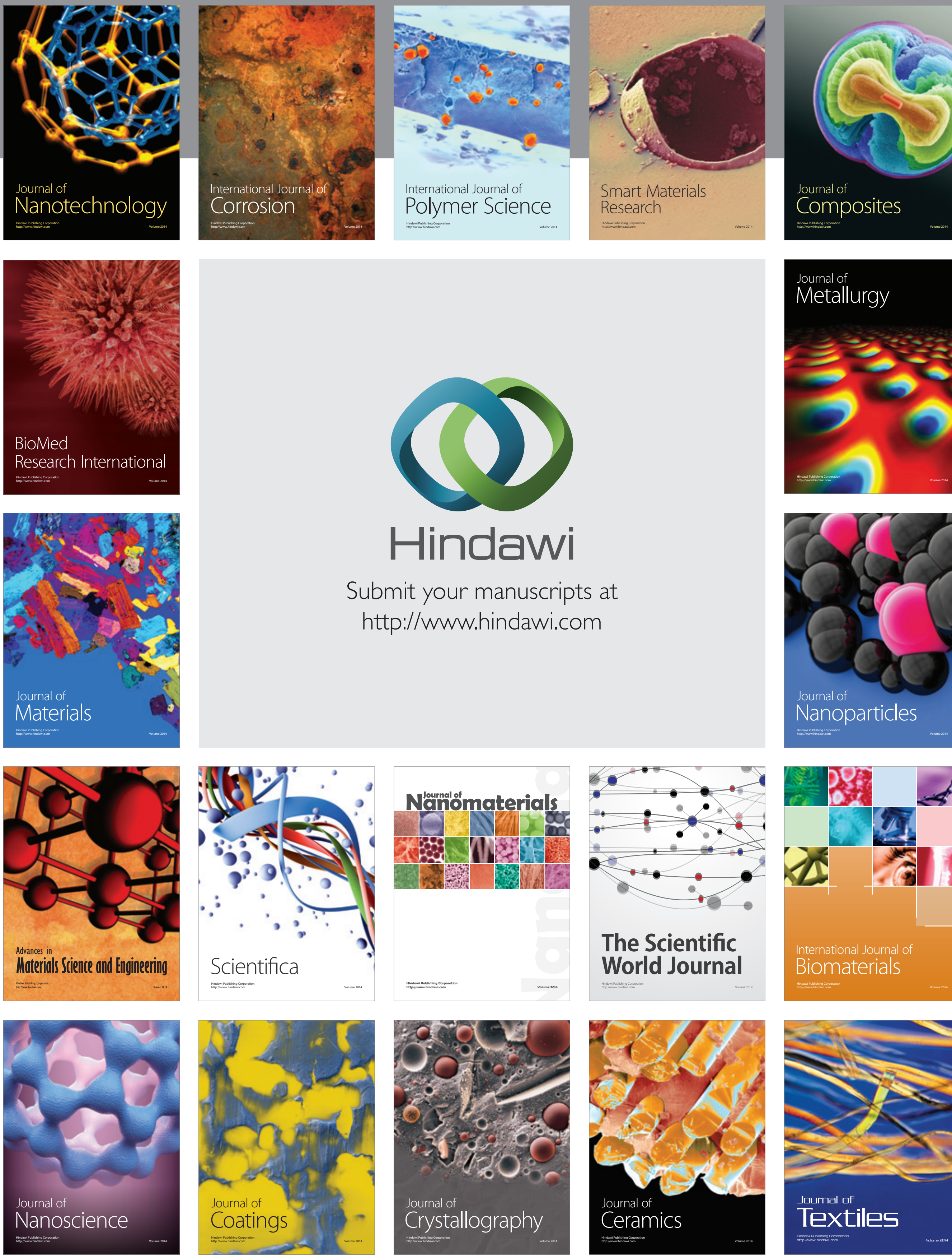

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