Mechanical Anchorage of Prestressed CFRP Plate Used for Strengthening of Bridge Girders

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ABSTRACT

Structural damages and heavier live load require strengthening of existing bridges in railways. CFRP (Carbon Fiber Reinforced Polymer) is ideal for strengthening due to its lightweight, high tension strength and excellent durability. In particular, the prestressed CFRP plate attached to the bottom of concrete girders can provide an additional prestress effect to resist moment. A reliable anchorage of a prestressed CFRP plate is significantly important. In this paper, two mechanical anchors used for the prestressed CFRP plate were introduced and compared. One was the existing wave anchor. The other was the wedge anchor developed recently. Three types of tests were conducted for evaluation of the performance of these two anchors: tension test, fatigue test and relaxation test. By comparison, the wedge anchor outweighed the wave anchor.

Keyword: Strengthening, prestress CFRP plate, wave anchor, wedge anchor

INTRODUCTION

In China, existing railways are transformed into heavy haul railways. Figure 1 shows a current train in operation. The average axle load of the freight train is 23 tons while that for the pending heavy haul railway will be 27 to 30 tons. Heavier live load requires higher bearing capacity of the bridges on railways. For most bridges girders in service, the shear capacity is high enough while the margin of moment resistance is limited. Thus, how to strengthen these concrete girders with minimum cost is very attractive. Also, structural damages including crack, rusting and concrete spalling as shown in Figure 2, occur in existing reinforced concrete bridge girders or prestressed concrete girders, resulting in the decrease of their strength. Moreover, prestress losses develop in the long term, affecting serviceability of prestressed concrete bridge girders significantly (Jiang and Ma, 2013). It is of importance to introduce strengthening technique to ensure reliability and durability of the structure. Furthermore, the convenience of construction without traffic interruption shall be considered.

In recent years, FRP has been widely used in bridge engineering due to its lightweight, high tension strength and excellent durability (Jiang, Ma and Song, 2012). Prestressed CFRP bars were externally mounted to the bottom of the reinforced concrete beams to improve the flexural performance (El-Hacha and Gaafar, 2011). The research on the anchorage system for CFRP prestressing tendons was conducted, focusing on its reliability and durability (Al-Mayah, Soudki and Plumtree, 2001). Also, prestressed CFRP plate was applied to flexural strengthening. The CFRP plates were attached to the bottom of the concrete girder with adhesive. However, the adhesive may crack, following the girder failure (Garden and Hollaway, 1998). Is it possible to develop a mechanical anchor system to ensure the anchorage reliability? In this paper, two mechanical anchors used for the prestressed CFRP plate were introduced and compared. One is the existing wave anchor. The other is the wedge anchor developed recently by authors. Three types of tests were conducted for evaluation of the performance of these two anchors: tension test, fatigue test and relaxation test.

Figure 1 Current Freight Train with 21-ton Axle Load

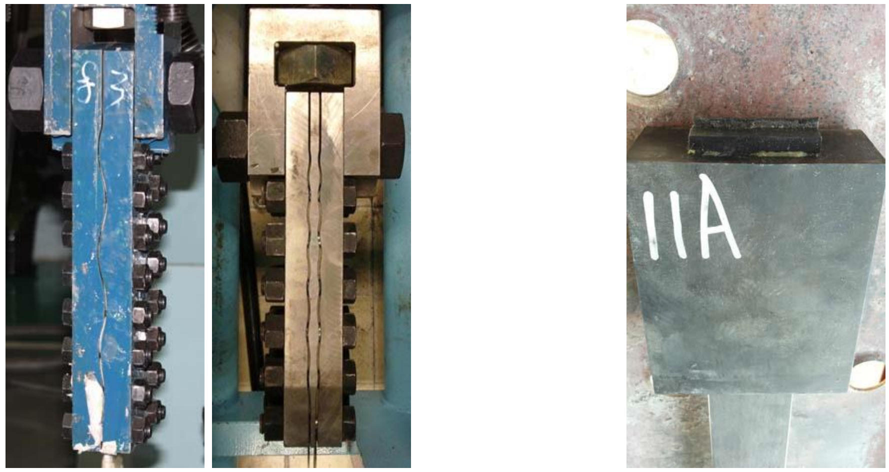
Figure 2 Damages at the Mid-span of a T Girder

CFRP PLATE AND ANCHOR

Instead of attaching CFRP plates to the bottom of girders with epoxy resins, anchoring a prestressed CFRP plate is more attractive, providing an axial compression and an extra resisting moment. However, how to reliably and conveniently anchor CFRP plates to existing structure is a challenge. Two types of mechanical anchors were investigated: wave anchor and wedge anchor. The cross section of CFRP plates were designed to match the anchors, and the tensile strength of CFRP plates were 2500 MPa.

The wave anchor is shown in Figure 3(a). A CFRP plate was sandwiched between two wave-shaped plates, clamped together with bolt and nut. The anchorage was mainly ascribed to the mechanical interlock. Adhesive was filled to provide an extra adhesion between the CFRP plate and the anchor. Stress concentration can be improved through the adjustment of the wave and the bolted connection.

The wedge anchor is shown in Figure 3(b). The anchorage is generated from the wedge effect. A CFRP plate, sandwiched between two wedge-shaped plates, filled into the trapezoid cavity of the anchor with adhesive. The anchorage performance is determined by the shape of the wedge, the hardness and the contact state.



(a) Wave Anchor (b) Wedge Anchor

Figure 3 Two Types of Mechanical Anchors

TEST PLAN

The objective of this research was to develop a reliable assembly of anchor and CFRP plate. The size of the anchorage and the corresponding CFRP plate shall be matched. After the locking of CFRP plate in the anchor, the local stress concentration at the anchor may affect the performance of the assembly to some extent. An inappropriate anchorage may result in unexpected failure. The failure mode of the assembly could be the break or tear at the anchor before the CFRP plate reached its designed tensile strength due to the over-tight or uneven anchorage. Worse, the failure mode could be the sudden anchorage failure if the anchor or the bolted connection was not adjusted appropriately. Therefore, the performance of the assembly of anchor and prestressed CFRP plate shall be investigated and evaluate.

A series of experimental tests were performed including static loading test, fatigue test and relaxation test. Both wave anchor and wedge anchor were investigated. Also, the wave anchors were designed to lock both single plate and double plates, so that the strengthening force caused by the prestressed CFRP can be adjusted within a larger range. Two types of wedge anchors were developed for CFRP plate with different cross section area.

The test matrix is shown in Table 1 and Table 2. In the item of ID, the first character designates the anchor type. B represents wave anchor while X represents wedge anchor. The first number designates the specific type of the wave anchor or the wedge anchor. B1 represents an assembly of wave anchor and a single plate, and B2 is an assembly of wave anchor and double plates. The two types of wedge anchor were designed for the CFRP plates of different size of the cross section. The character next to the dash designates the test type. J represents static loading test, P represents fatigue test and S represents relaxation test. The last number indicates the ID number of the identical tests. An example is B1-J1, which is the first specimen for the static loading test of the assembly of wave anchor and a single plate. The cross section of the CFRP plate is shown in the item Size. In the item Loading Type and

History, four types are listed, LH-I (static loading test), LH-II fatigue test and following static loading test), LH-III (relaxation test and following static loading test) and LH-IV (relaxation test).

Table 1 Tests of Assembly of Wave Anchor and CFRP Plate

ID	Size （mm）	Ultimate Strength （MPa）	Fatigue Test			Loading Type and History	Layers of CFRP Plates in an Assembly
			Lower Limit （MPa）	Upper Limit （MPa）	Cycles (10^6)		
B1-J1	50×3	2371	/	/	/	LH-I	Single
B1-J2	50×3	2607	/	/	/	LH-I	Single
B1-J3	50×3	2443	/	/	/	LH-I	Single
B1-J4	50×3	2693	/	/	/	LH-I	Single
B1-J5	50×3	2727	/	/	/	LH-I	Single
B1-J6	50×3	2800	/	/	/	LH-I	Single
B1-P1	50×3	2610	1400	1600	400	LH-II	Single
B1-P2	50×3	2685	1500	1660	400	LH-II	Single
B1-P3	50×3	2625	1500	1700	400	LH-II	Single
B2-J1	50×2	3101	/	/	/	LH-I	Double
B2-J2	50×2	3078	/	/	/	LH-I	Double
B2-J3	50×2	3065	/	/	/	LH-I	Double
B2-P1	50×2	3015	1400	1600	400	LH-II	Double
B2-P2	50×2	2885	1500	1660	400	LH-II	Double
B2-P3	50×2	2925	1500	1700	400	LH-II	Double
B2-S1	50×2	3025	/	/	/	LH-III	Double

Table 2 Tests of Assembly of Wedge Anchor and CFRP Plate

ID	Size (mm)	Ultimate Strength (MPa)	Fatigue Test			Loading Type and History	Layers of CFRP Plates in an Assembly
			Lower Limit (MPa)	Upper Limit (MPa)	Cycles (10^6)		
X1-J1	80×3	2792	/	/	/	LH-I	Single
X1-J2	80×3	2917	/	/	/	LH-I	Single
X1-P1	80×3	2708	1200	1320	800	LH-II	Single
X1-P2	80×3	2500	1200	1280	600	LH-II	Single
			1200	1360	600		
X1-P3	80×3	2708	1200	1400	600	LH-II	Single
X1-S1	80×3	2592	/	/	/	LH-III	Single
X1-S2	80×3	/	/	/	/	LH-IV	Single
X2-J1	50×3	2607	/	/	/	LH-I	Single
X2-J2	50×3	2520	/	/	/	LH-I	Single
X2-J3	50×3	2600	/	/	/	LH-I	Single
X2-J4	50×3	2600	/	/	/	LH-I	Single
X2-J5	50×3	2593	/	/	/	LH-I	Single
X2-J6	50×3	2360	/	/	/	LH-I	Single
X2-J7	50×3	2703	/	/	/	LH-I	Single
X2-P1	50×3	2566	1500	1700	400	LH-II	Single
X2-S1	50×3	2627	/	/	/	LH-III	Single

STATIC PERFORMANCE

The modulus of elasticity of the CFRP plate was tested on the test machine as shown in Figure 4. A 500-mm-long triangle-shaped strain gauge was attached to the plate. The average strain within this length was evaluated. Typically, the clear length of the tested plates between anchors was 1000 mm. The loading rate was 3 to 5 mm/min. The maximum test tension was controlled at 85% ultimate tension of CFRP plate, avoiding the damage to the strain gauge at the break of plate. The stress was calculated based on the tensile force and the cross section area of the plate. A typical stress-strain curve is shown in Figure 5. The relationship between the stress and the strain was regarded as linearly elastic. Through three tests, the average modulus of elasticity was 151.0 MPa. Accordingly, the ultimate elongation rate may reach 1.65% when the tensile stress went up to the nominal tensile strength 2500 MPa.

Also, the specimens were tested to the failure to investigate their ultimate tensile strength after the strain gauge was detached. The static test results are shown in Table 1, Table 2 and

Figure 6. The ultimate tensile strength of most specimens was higher than the nominal tensile strength 2500 MPa. For specimens B1-P1 through B1-P3, B2-P1 through B2-P3, X1-P1 through X1-P3 and X2-P1, the static loading test was performed to the failure after the fatigue test. For specimens B2-S1, X1-S1 and X2-S1, the static loading test was performed to the failure after the relaxation test. In this way, the effect of testing history on the ultimate strength was investigated. It revealed that the testing history had no significant effect on the ultimate strength. The failure mode of two types of assemblies was shown in Figure 7. The failure occurred all of a sudden, with break of fibers and tearing of matrix. The failure of the CFRP plate occurred when the tensile strength reached its ultimate strength. The fracture did not result from the local concentration. The fracture existed within an area close to the middle part. The length of each fractured fiber was not the same. This length varied between 1/3 to 2/3 of the total length of the fiber.

Figure 4 Static Loading Test Setup

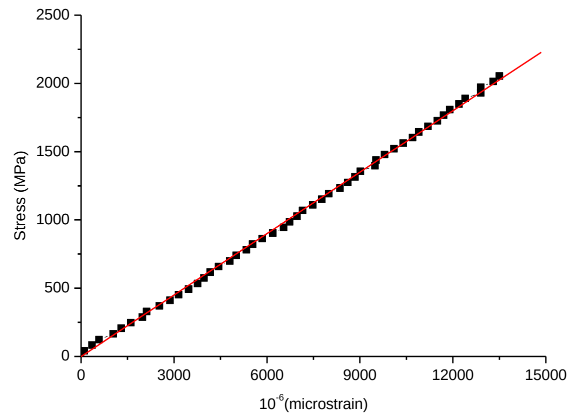


Figure 5 Typical Stress-Stain Curve of Assembly in Static Loading Test

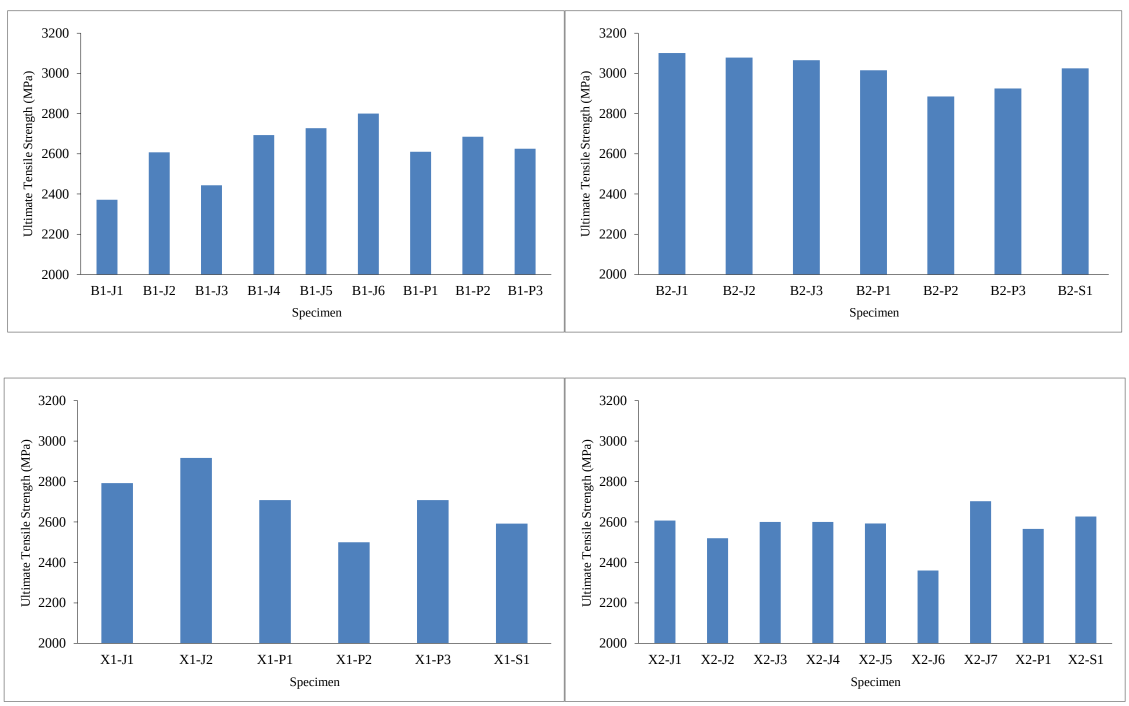


Figure 6 Test Results of Static Loading Test

(a) Wave Anchor (b) Wedge Anchor

Figure 7 Failure Mode

FATIGUE

The fatigue performance of the assembly was investigated. According to the previous research, for the prestressed CFRP used for the simply supported bridge girders (span length was less than 32m), the stress amplitude was within the range of 40 MPa through 80 MPa, under the designed live loads. In this research, the effect of stress amplitude and cyclic times in the fatigue test was analyzed. The cyclic frequency was 5 through 6 Hz. As shown in Table 1 and Table 2, for the assemblies of wave anchor and CFRP plate, the stress level was at 1400 MPa through 1700 MPa, the stress amplitude was taken as 160 MPa or 200 Mpa, and the cyclic times were 4 million. For the assemblies of wedge anchor and CFRP plate, the stress level was at 1200 MPa through 1700 MPa, the stress amplitude was taken as 80, 120,160 and 200 MPa, and the cyclic times were taken as 4 million, 6 million and 8 million. In particular, for specimen X1-P2, fatigue tests of 6 million cycles (stress amplitude 160 Mpa) ensued the previous fatigue tests of 6 million cycles (stress amplitude 80 MPa).

During the fatigue test, no damage or defect of the assembly was detected. Both the anchor and the CFRP plate remained intact. After the fatigue test, static loading test was conducted to investigate the ultimate tensile strength. As mentioned above, there is no significant difference of the tensile strength after the fatigue test.

RELAXATION

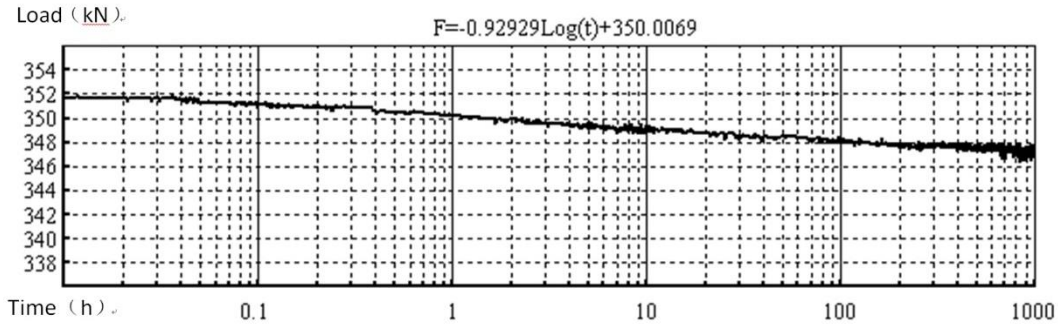
Relaxation occurs for most construction materials. As time increases, the stress decreases gradually. For concrete girders reinforced with prestressing CFRP plate, relaxation results in the loss of prestress, weakening the strengthening effect. As shown in Figure 8, the relaxation test was performed in the lab. The ambient environment temperature maintained at 18 ^{0}C to 22 ^{0}C. The stress measurement was the same as in the static loading test. The test result is shown in Table 3. The initial stress was controlled at 0.54 to 0.71 ultimate stress of CFRP plate. The duration for specimen X2-S1 was 100 h, and the duration for the others was 1000h.

It indicated that the relaxation rate was less than 1.5% at 100 h, and the rate was less than 2% at 1000 h. After 100 h, the relaxation rate was 75% to 80% of the rate at 1000 h. The relaxation rate increased approximately linearly with $\log_{10}(t)$ as shown in Figure 9. Moreover, the static loading tests of these three specimens were conducted after the relaxation test. As shown in Table 1, the ultimate strength was not significantly affected after the relaxation test, and the failure mode was the same as that of other specimens.

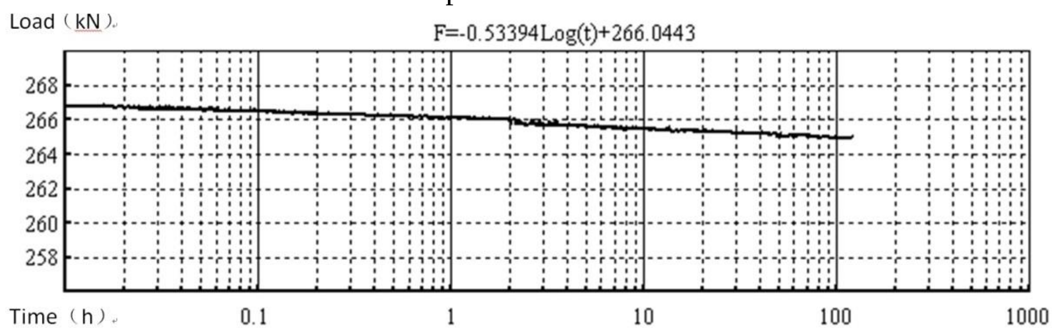
Figure 8 Relaxation Test

Table 3 Test Results of Relaxation Test

ID	X1-S1	X1-S2	B2-S1	X2-S1
Initial Stress σ_0（MPa）	1356	1411	1760	1779
Duration t（h）	1000	1000	1000	100
100h Relaxation Rate ρ_1	1.494%	1.156%	1.080%	0.675%
1000h Relaxation Rate ρ_2	1.930%	1.600%	1.307%	/
ρ_1/ρ_2	77.4%	72.3%	82.6%	/



Specimen B2-S1



Specimen X2-S1

Figure 9 Relationship between Load and Time in Relaxation Test

CONCLUSIONS AND DISCUSSION

Through the static loading test, the fatigue test and the relaxation test of two types of assemblies of mechanical anchor and prestressed CFRP plate, the following conclusions were drawn. The relationship between the stress in the CFRP plate of the assembly and its strain was linearly elastic. The failure was the sudden break and tearing of the CFRP plate, not the failure of the anchors. Even after the fatigue test and the relaxation test, the static performance was not affected. During the fatigue test, the assembly remained intact and no damage was detected. The relaxation rate at 100 h was less than 1.5%, and the rate at 1000 h less than 2%. Thus, both two types of anchors ensured a reliable anchorage of the prestressed CFRP plate.

Although the performance of two types of assemblies is the same, the wedge anchor outweighs the wave anchor. In general, the size of the former is much smaller than the latter. The wedge anchor occupies less space when it is attached to the bottom of the concrete girders with anchor bolts. The fabrication and construction is more convenient for the wedge anchor. No bolt or nut was used in the assembly of the wedge anchor and the CFRP plate. On the contrary, the adjustment of bolted connection affects the contact between the wave anchor and the CFRP plate significantly, i.e., it affects the anchorage performance. At this point, the anchorage performance of the assembly of the wedge anchor and CFRP plate is more stable and reliable.

As shown in Figure 10, a prestressed CFRP plate was installed at the bottom of a reinforced concrete girder. The CFRP plate was tensioned using jack cylinder and temporary anchor system. When the prestress force reached the designed level, bolts and nuts were used to anchor the assembly to the steel plate at the bottom of the girder. An additional prestress was provided to increase the moment resistance. In engineering practice, the actual tensile strength of the CFRP plate was controlled between 50% to 70% of the ultimate tensile strength, ensuring no occurrence of unexpected fracture of fibers. For a concrete girder requiring strengthening, the required total prestress was calculated and assessed based on its capacity and the load. Then, the number of CFRP plates and the prestress level were determined.

Figure 10 Assembly Installed at the Bottom of a Girder

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