Application of Tensioned CFRP Strip Method to an Existing Bridge

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Synopsis: Tensioned carbon fiber reinforced polymer (CFRP) strip method or Outplate-method™ was applied to the 28 years old reinforced concrete (RC) box girder bridge in order to rehabilitate and increase the load capacity of the bridge. The Chofu Bridge had been deteriorated by 28 years of heavy traffic and had many cracks on the underside of the main girders. Before and after the CFRP application, on-site load tests of the bridge were conducted using a 45 ton-weight vehicle. Results of the tensioned CFRP strip application to the bridge girders proved effective to reduce the stress in the reinforcing bars and to reduce crack widths.

Keywords: anchor; prestress; stiffness; strengthening method; tensioned CFRP strip

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INTRODUCTION

Recently in Japan, many bridges have experienced damage and deterioration resulting from heavy traffic and many years of natural exposure. Many rehabilitation methods, such as steel plate bonding, concrete overlays, externally bonded carbon fiber sheets, and external cable method such as post-tensioning, have been tried. At the Chofu bridge, which is reinforced concrete (RC) box girder bridge, many cracks had formed and water leakage from the cracks was observed at several locations (shown in Photograph 1). Also, the deflection of the main girders caused by the heavy traffic increased and the decreased stiffness of the bridge became obvious.

In order to rehabilitate this bridge, passive applications such as steel plate or carbon fiber sheet bonding methods without prestressing is not enough. In order to both increase the load capacity and decrease the crack width, an external cable post-tensioning would have been used. But in this case, restriction of the application spaces, flat surface terrain, and weak concrete not suitable for attaching the brackets, made it impossible to apply external cables. Also, in-situ application was needed because the bridge has interchange ramps and it was very difficult to stop the traffic. So, the new prestressing method was needed.

Tensioned CFRP strip method (Outplate Method™)

The tensioned CFRP strip method consists of a tension plate, base plates, and intermediate anchoring devices. The tension plate is a carbon fiber reinforced polymer (CFRP) strip that has anchoring devices at both ends. Base plates are steel frame which are attached to the concrete surface for anchoring the tension plate and for holding the specially modified hydraulic jack. And intermediate anchoring devices are simple stainless steel plates and anchor bolt (Shown in Figure 1).

First, the concrete at both ends of the main girders is chipped away and the base plates are attached with anchor bolts. Then, the hydraulic jack, which is specially modified for this application, is set onto one of the base plates. One of the anchoring devices of the tension plate is bolted to the other base plate, and the other anchoring device is attached to the hydraulic jack. Before tensioning the tension plate, adhesive paste is put on the upper surface of CFRP strip. By tensioning the tension plate, compressive stress is introduced to the concrete girder. The CFRP strip is then adhered to the concrete surface. After tensioning, intermediate anchoring devices are attached with anchor bolts. Using this procedure, tensioned CFRP strips are applied in-situ to the underside of the main girders inside the bridge span as shown in Photograph 2.

Advantages

One of the most advantageous points of this method is that by applying prestress to the concrete member, this method is effective in increasing not only the live load but also the dead load capacity of the member. Therefore, crack widths caused by dead load can be decreased by applying this method, which is very difficult by applying carbon fiber sheets passively. Another advantage is that by introducing a prestress, a redundant force is introduced to the upper surface of the continuous bridge girder, so the tensile stress on the intermediate fulcrum is decreased. In other words, the upper surface of the intermediate fulcrum is also reinforced by this underside application. The distribution of bending moment is schematically shown in Figure 2.

A tension plate is a thin material, so it can be applied to very narrow spaces. Also, since the introduced prestress is not too large (around 140 kN), the concrete damage at the anchoring area is minimal. In the case of external cable post-tensioning, concrete damage at the anchoring area is sometimes so large that additional reinforcement at the anchoring area is required.

Specification of tension plate

The CFRP strip is 2mm thick and 50mm wide. Each end of the strip is inserted into an anchoring device which is made of steel. Both ends are embedded and anchored by an expansive paste. The CFRP strip is made up of high strength carbon fibers and thermo-setting resin, fabricated using a Pultrusion method. Characteristics of the CFRP strip are shown in Table 1. The expansion pressure and the embedment length were determined from the results of the tensile test [2].

Tensioning system

A hydraulic jack is specially designed for this application. It is divided into two parts (a reaction block and a cylinder) and each part is very light weight, so each one can be handled by one person. Also the weight of a base plate is saved in order to handle it by two persons. This tensioning system does not need reaction frame. The hydraulic jack is attached directly to the base plate so the girder itself becomes the reaction frame [3].

Application

At the Chofu bridge, the Outplate Method^{TM} was adopted because of its effectiveness to reduce dead load stress and dead load deflection, because the prestress level of this method is suitable to the present condition, it is reasonably economical, and it's application period is dramatically short.

The number of tension plates (CFRP strips) was determined by matching the allowable tensile stress in the longitudinal reinforcing bars considering the dead and live load bending moments, compressive stress, eccentric bending moment, and redundant force introduced by prestressing. As a result, six pieces of CFRP strip were installed at the bottom of each of the RC box girders at each of the bridge spans. Only under the center span of the bridge was the carbon fiber sheet method also applied because tensioned CFRP strip method alone was not adequate to increase the load bearing capacity of the span sufficiently. Allocation of CFRP strips and application procedure are shown in Figure 3 and Figure 4, respectively.

OUT LINE OF TESTS

A load test of the existing bridge was carried out to verify the strengthening effect. A prestress introducing test was also conducted to examine the soundness of the concrete at the anchoring devices. Finite Element (FE) analysis was done and results were compared with measured values.

Load test

A 45 ton-weight vehicle (shown in Photograph 3) was placed statically at three different positions, shown in Figure 5.The stress in the longitudinal reinforcing bars, concrete crack width and depth, and deflection of the main girder were measured during the load test, which were performed both before reinforcing and after the tensioned CFRP strip application. The 450kN (45 ton-weight) load corresponds to 26.3% of the design live load at the center of the side span. Measurement points are shown in Figure 6.

In addition to static load tests, dynamic load tests were also conducted by driving 45 ton-weight vehicle at a speed of 50km/h in the traffic lane, while all other traffic was stopped. The test was performed at night. During the dynamic load test, the natural frequency of the main girder was measured.

Prestress introducing test

A prestress introducing test was carried out at the two CFRP strips applied to the center web. Each CFRP strip was tensioned to a 160kN force. The stress in the longitudinal reinforcing bars and concrete, and crack widths in the concrete were measured at the center of the span and at the vicinity of the anchoring devices. Measurement points are shown in Figure 7.

RESULTS AND DISCUSSION

Load test

Tensile stress in the longitudinal reinforcing bars -- Observed tensile stresses in the longitudinal reinforcing bars under loading are shown in Table 2. Stresses in the longitudinal reinforcing bars were calculated by multiplying the measured strain with its Young's Modulus of Elasticity 200,000N/mm^2.

At point S1 (center of the span, center in the direction of span-width), the tensile stress before reinforcing was 9.8N/mm^2 and after the tensioned CFRP plate application was 7.8N/mm^2. The latter was 20% smaller than the former. It was confirmed that the stress in the longitudinal reinforcing bar was decreased with the introduction of prestress by the tensioned CFRP strip method.

Concrete crack width and depth -- Observed concrete crack width and depth under loading are shown in Table 3 and Table 4, respectively. At point C2 (center of the span, center in the direction of span-width) the crack width decreased from 0.226mm to 0.188mm after reinforcing (16.8% smaller) and, also the crack depth decreased from 153mm to 138mm after reinforcing (9.8% smaller). It was confirmed that crack opening and extension were restricted with the introduction of prestress by the tensioned CFRP strip method.

Deflection -- Observed deflections under loading are shown in Table 5. At point D1 (center of the span, center in the direction of span-width) deflection after reinforcing was decreased by 30% from 1.53mm to 1.07mm. Deflection was decreased by 40% from 1.88mm to 1.12mm at point D2 (center of the span, edge side in the direction of span-width). Thus, it is clear that the stiffness of main girder improved dramatically.

Natural frequency -- Observed natural frequency of the primary mode was improved from 4.4Hz before reinforcing to 5.2Hz after reinforcing. This increase of natural frequency corresponds to a mean decrease of amplitude, in other words, decrease of deflection. Therefore, this dynamic load test result corresponds to the observed reduction in deflection during the static loading test.

An eigenvalue analysis was conducted with a Finite Element Method (FEM) model calculated assuming that there is no cracking of the concrete, shown in Figure 8. The natural frequency of the primary mode was determined to be 5.393Hz and this value was found to be very close to the measured value after reinforcing application. This result implies that the rigidity of the main girder was improved by this reinforcing method.

Prestress introducing test

Compressive Stress in the longitudinal reinforcing bar -- Observed results are shown in Table 7. The stress in the longitudinal reinforcing bar was calculated by multiplying measured strain by its Young's Modulus of Elasticity 200,000N/mm^2. The compressive stress in the longitudinal reinforcing bar at the center of the span (S1) was 2.4N/mm^2

after tensioning two CFRP strips. This value agreed well with the 2.56N/mm^2 stress calculated in the FEM analysis. Therefore, it was confirmed that required prestress was introduced by tensioning two CFRP strips.

Concrete Crack width -- Observed results are shown in Table 8. Concrete crack width at the center of the span (C2) was decreased 0.015mm after tensioning two CFRP strips. In order to verify this result, the crack width was calculated by using the crack width equation reported in reference [4]. Taking into account the effect of introducing prestress into the CFRP strip, the crack width was calculated to be 0.02mm. There was an excellent agreement between measured value and calculated value.

Tensile stress in concrete -- The tensile stress in the concrete at the vicinity of the anchoring devices is shown in Table 9. Concrete stress was calculated by multiplying measured strain by its Young's Modulus of Elasticity 25,000N/mm^2. After the CFRP strips are tensioned, tensile stress occurs in the concrete behind the anchoring devices. This stress was a maximum of 0.55N/mm^2. Compared with a stress of 1.4N/mm^2 calculated with the FEM analysis and cracking limit of 1.9N/mm^2 reported in reference [4], the measured value was small enough and very far from the stress which induces concrete cracking. Therefore, it was confirmed that the tensioned CFRP strip method is a safe method for the concrete even when the concrete strength is relatively small.

CONCLUSION

Load tests of an existing bridge reinforced with the tensioned CFRP strip method were carried out and the strengthening effect was evaluated. The most distinguished effects of this repair were the decrease of deflection at the center of the span and an increase in the natural frequency of the primary mode. These effects imply that the stiffness of the main girder was improved.

Load-carrying capacity and durability of the main girder is expected to improve due to the reduction in stress in the reinforcing bars and reduction in concrete cracking.

Moreover, it was confirmed that the concrete in the vicinity of the anchoring area was sound enough even after the CFRP strip was tensioned, because the induced tensile stress into the concrete is quite small compared with the cracking limit. Therefore, the tensioned CFRP strip method is considered to be a very effective strengthening method for reinforced concrete bridges.

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Table 1 — Characteristics of CFRP strip

Width	(mm)	50
Thickness	(mm)	2
Tensile strength	(N/mm^2)	2400
Modulus of elasticity	(N/mm^2)	165,000
Tensile capacity	(kN)	240

Table 2—Observed tensile stresses in longitudinal reinforcing bars

Point	Before reinforcing	After reinforcing
S1	9.8 N/mm^2	7.8 N/mm^2
S2	4.8 N/mm^2	5.2 N/mm^2
S3	6.6 N/mm^2	5.0 N/mm^2

Table 3—Observed crack width

Point	Before reinforcing	After reinforcing
C1	0.227mm	0.218mm
C2	0.226mm	0.188mm
C3	0.222mm	0.193mm
C4	0.107mm	0.090mm
C5	0.105mm	0.086mm

Table 4—Observed crack depth

Point	Before reinforcing	After reinforcing
C1	130mm	102mm
C2	153mm	138mm
C3	112mm	99mm
C4	102mm	102mm
C5	162mm	146mm

Table 5—Observed deflection

Point	before reinforcing	after reinforcing	strengthening effect ratio
D1	1.53mm	1.07mm	30.1% decrease
D2	1.88mm	1.12mm	40.4% decrease

Table 6—Natural frequency

Point	Before reinforcing	After reinforcing	Strengthening effect ratio	Analysis result
A2	4.4Hz	5.2Hz	18.2% increase	5.393 Hz

Table 7—Compressive stress in longitudinal rebars

Point	Observed result
S1	2.4 N/mm^2
S2	1.2 N/mm^2
S3	1.8 N/mm^2

Table 8—Observed Concrete Crack width

Point	Observed result
C1	0.007mm decrease
C2	0.015mm decrease
C3	0.012mm decrease
C4	0.006mm decrease

Table 9—Tensile stress in Concrete

Point	Observed result
CS1	0.48 N/mm^2
CS2	0.13 N/mm^2
CS3	0.55 N/mm^2
CS4	0.53 N/mm^2
CS5	0.13 N/mm^2
CS6	0.48 N/mm^2

Photograph 1—State of damages

Photograph 2—Applied tensioned CFRP strip

Photograph 3—45 ton-weight vehicle

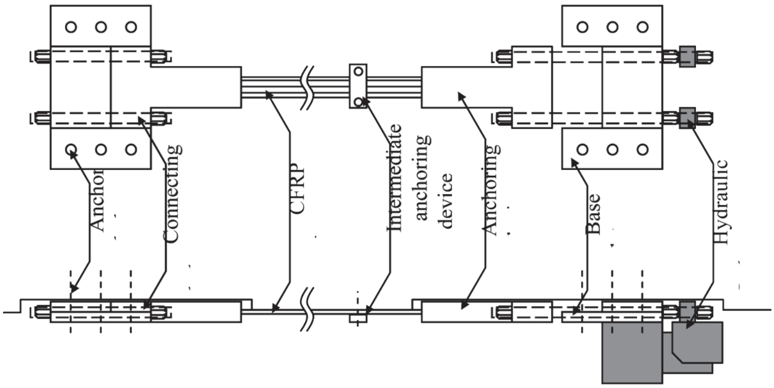

Figure 1—Tensioning system

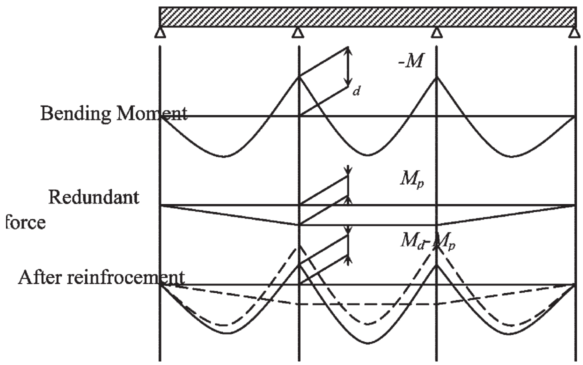

Figure 2—Distribution of bending moment

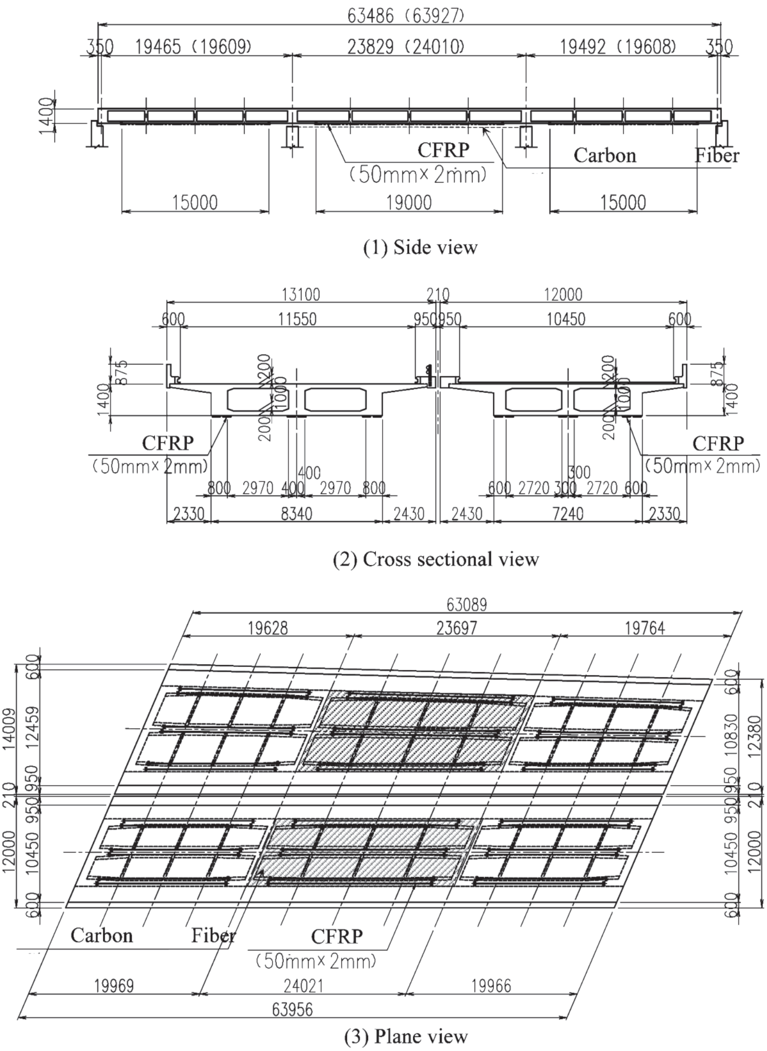

Figure 3—Allocation of CFRP strips

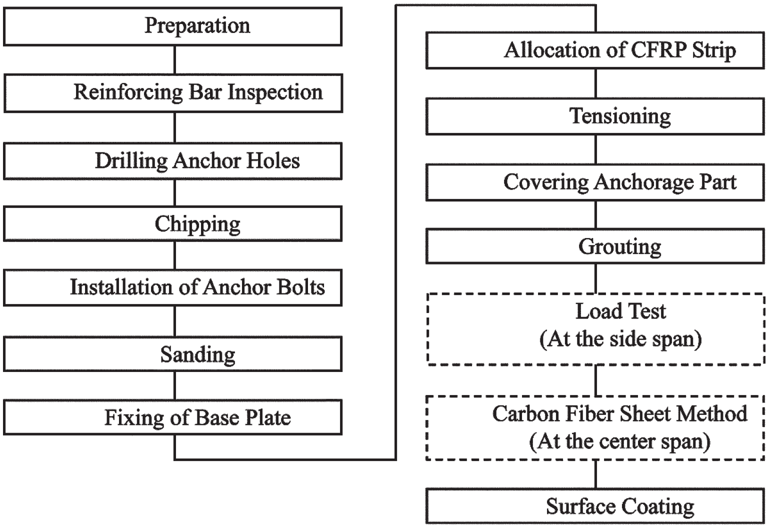

Figure 4—Application Procedure

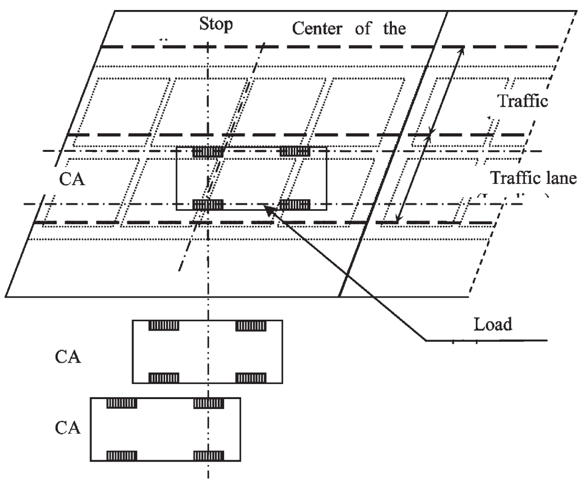

Figure 5—Loading points

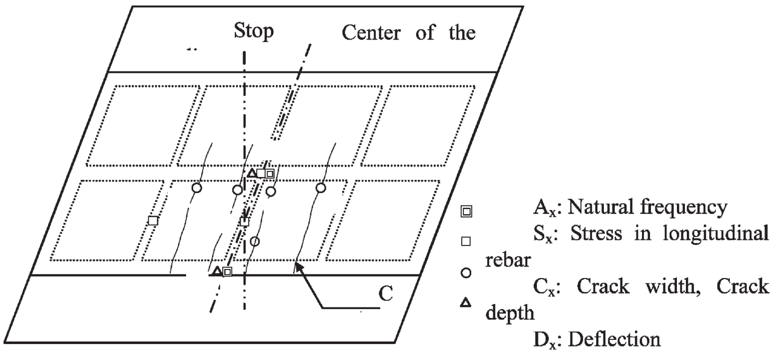

Figure 6—Measurement points of load test

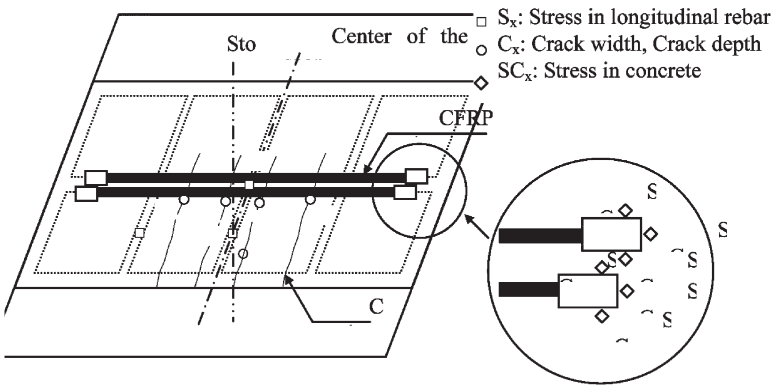

Figure 7—Measurement points of prestress introducing test

Figure 8—Primary mode (FEM)