Construction case and development for the upper surface strengthen method of bridge RC slab

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ABSTRACT: This study evaluated the fatigue durability and deflections of the strengthened RC slab with the fixed-point fatigue test. The overhanging part of a highway RC bridge slab was strengthened using Continuous carbon Fiber Strand Sheet (CFSS), Ultra-rapid Hardening Cement Mortar (UHCM) and epoxy. The mechanical properties such as interfacial fracture energy and bond strength of the carbon fiber strand sheet and concrete for this strengthening method were evaluated. Furthermore, upper surface overhanging part of the actual bridge was reinforced to evaluate the workability of the strengthening method. It was confirmed that the construction speed was about 4 times of the conventional external CFRP bonding method using the continuous fiber sheet and epoxy resin. Therefore, this strengthening method is highly effective to shorten the traffic control time.

1 INTRODUCTION

In recent years, there is a drastic increase in the road traffic. To cope with the traffic growth, congestion mitigation program has been implemented. For instances, increase in the number of entry and exit roads, widening of the RC slab bridge work, and central dividing work etc. However, in the case of such old design constructions, a change in the vehicle wheel running position which was not considered at the time of initial design may occur, and a negative bending moment may also act on the upper side of the main steel girder. Therefore, as a countermeasure against such negative bending moment, carbon fiber sheet adhesive reinforcement methods have been applied in many cases. Along with other reinforcing method, measures such as installing brackets for the reduction of the deflection. However, when applying reinforcement from the upper surface of the RC slab, longer traffic regulation time is necessary. Thus a new reinforcement method is necessary which can be performed quickly so that traffic regulation time is short. Also, it has been reported that many road bridge RC slabs in snowy cold region, suffer from the frost damage due to the spraying of the anti-freezing agents and traffic load fatigue. Therefore, development of a new method is necessary that can repair the damage and reinforce it at the same time.

In order to solve the above issues, a new strengthening method has been developed. The strengthening method include two new materials used together to form a new strengthening technique. The first material is a Continuous carbon Fiber Strand Sheet (CFSS) which is made by thin strands of carbon rods, impregnated and cured with resin then fabricated as sheet. The CFSS sheet uses rapid hardening epoxy adhesives to adhere to the structure. The second material is the Ultra-rapid Hardening Cement Mortar (UHCM) which is used for the rough surface repairing. This UHCM is a pre-mix of ultra-rapid hardening cement, fine sand, additive agent, and PVC fiber. In this paper, the above-mentioned materials were used to evaluate the bond characteristics between the concrete and the newly developed reinforcing method along with the fatigue durability of the actual RC bridge slab. The construction performance at the site was also confirmed which is reported in this paper.

2 SHEAR BOND TEST

2.1 Material Properties of CFSS, epoxy and UHCM

In this study, high tensile strength type CFSS was used. Table 1 shows the mechanical properties of the CFSS, UHCM and epoxy.

Table 1 Used material properties

CFSS (High tension type)		UHCM		Epoxy	
Tensile modulus	245GPa	Hardening time	47min	Compressive modulus(7days)	2495N/mm^2
FAW	600g/m^2	Compressive strength(3hrs.)	21.3N/mm^2	Handling time	84min
		Slump	120mm	Share tensile strength	16N/mm^2

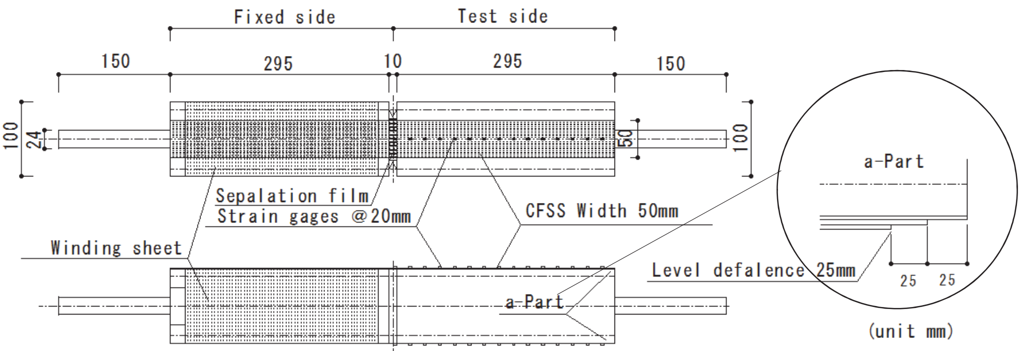


Figure 1. Schema of bond test specimens.

2.2 Outline of the bond Experiments

The concrete for the bond test used rapid-hardening cement, aggregate and sand. The dimensions of the bond test specimens are shown in Figure 1. The experiments were conducted based on the JSCE standard "the test methodology is a test method for bond properties of continuous fiber sheets to concrete" (JSCE-E 543-2007). The concrete surface was treated with alumina powder blasting. The carbon fiber sheet was wrapped at right angle to the CFSS in order to prevent peeling-off the testing area. As for the UHCM application, firstly, a liquid epoxy adhesive was applied at the rate of 1.4 kg/m^2 followed with 5 mm thickness of UHCM. Then, the same epoxy adhesive was again coated at the rate of 3.0 kg/m^2 and CFSS was buried in to the adhesive layer. After that about 5mm of UHCM was applied over it. All the procedures was completed before each one of materials was hardened. When more than 2 layers of CFSS application were needed, the edge of the upper layer was applied 25 mm shorter than the previous layer at the edge to avoid the stress concentration (see Figure 1.). Compressive strength of concrete specimen was 37.1 N/mm^2 and compressive modulus was 26 kN/mm^2, after 28 days of curing. After 14-16 days of cuing time, the bond tests of CFSS were carried out. In experiments, CFSS bonding layers were 1, 3 and 5layers.

2.2.1 Interfacial fracture energy, bond strength, and bond length

The specimens were fractured on either side of concrete where CFSS was applied at both sides. Interfacial fracture energy G_f, bond strength τ_u and other results were calculated by using equations (1), (2), (3), (4), based on JSCE-E543-2007.

$$G_f = \frac{P^2{}_{max}}{8b^2E_ft} \quad (1)$$

$$\tau_u = \frac{P_{max}}{2bl} \quad (2)$$

$$\tau_y = \frac{\Delta\epsilon_F \cdot E_F \cdot A_F}{S_g \cdot b} \quad (3)$$

$$le = \frac{P_{max}}{2\tau_y \cdot b} \quad (4)$$

Where, (G_f): Interfacial fracture energy(N/mm), P_{max}: Maximum-load (kN), b: CFSS bonding width (mm), E_f: CFSS tensile modulus(N/mm^2), t: CFSS design thickness (mm), τ_u: Bond strength (N/mm^2), l: CFSS bond length (mm), $\Delta\varepsilon_F$: Strain increase results (x10^{-6}), A_F: CFSS cross sectional area (mm^2), S_g: strain increase span (mm), L_e: Actual bond length (mm), τ_y: Maximum bond strength (N/mm^2)

2.2.2 Shear bond test results

The bond test was carried out with 1,3 and 5 layers of the CFSS and the results are shown in Table 2. The maximum load and the interfacial fracture energy increased with increase in the number of CFSS layers. In addition, interfacial fracture energy when CFSS was bonded using adhesive and UHCM was changed to 0.5N/mm which is the standard of the repair reinforcement needle of concrete structure using continuous fiber sheet, the number of installed layers changed The interfacial fracture energy is 1.44N/mm for the 1 layer, 1.09 N/mm for 3 layers and 1.42 N/mm for 5 layers which is 2.88, 2.18 and 2.84 times greater than the standard value. It is possible to design it on the safe side, setting the bond length using cfss to 300 mm for the CFSS five layer or less. if it is 300 mm for effective adhesion length up to CFSS 5 layers. In this study, inter facial fracture energy was saturated by the increase CFSS layers.

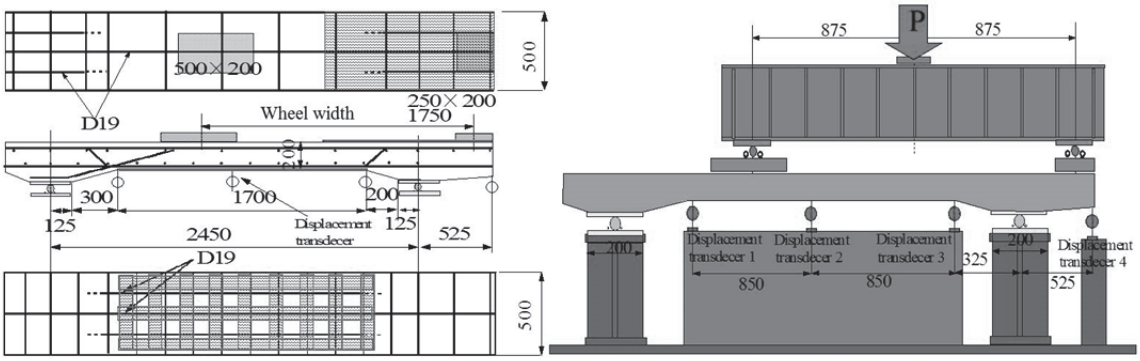
Table 2 Shear bond test results

CFSS Layers	Maximum-load P_{max} (kN)	Interfacial fracture energy (Gf) (N/mm)	Bond strength(τu) (N/mm^2)	Bond length (L_e) (mm)	Maximum bond strength (τ_y) (N/mm^2)
1	48.2	1.44	1.72	127	3.8
3	72.8	1.09	1.46	267	2.73
5	107.1	1.42	2.14	232	4.62

3. FIXED POINT FATIGUE TEST

3.1 Outline of fixed point fatigue test

The actual RC bridge slab which was used in snowy cold region for 33 years, damaged by the salt and frost specimen was used as the test specimen using the new reinforcing method with CFSS, UHCM and epoxy. The specimen without reinforcement and with reinforcement was evaluated under the fixed-point fatigue test. The average compressive strength of the concrete slab during the experiment was 31.1N/mm^2, and D 19 type re-bar was used. The cross-sectional area of the re-bars on the upper side had reduced due to corrosion by about 20%. One layer of medium modulus CFSS of FAW 600 g/m^2 was used as the reinforcement to supplement the reduced diameter of the re-bar. The CFSS with UHCM and epoxy resin was installed on the upper surface in the direction perpendicular to the bridge axis. In order to prevent the positive bending failure of the deck, CFSS was bonded on the bottom surface of the RC slab in a lattice pattern using epoxy putty paste. The cross section of the specimens is shown in Figure 2 (1), (2). Figure 2. (1) shows the dimensions of the reinforced specimen and the reinforcing material installation range. Figure 2. (2) shows the test condition of the beam specimen. The upper surface side of the displacement transducer 3 is positioned where the negative bending moment has occurred.



(1) Dimension of the reinforced specimen (2) Test condition

Figure 2. Specimens cross section.

3.2 Evaluation of fatigue resistance of reinforced RC slab

The RC slab support width is 2450mm, the slab thickness is 190mm, and the over-hanged part length is 525mm. For the fixed-point fatigue test, two slabs with only section repair and two slabs reinforced by proposed reinforcing method were prepared. The name of the repaired slabs specimens are RC.O-1 and RC.O-2 and reinforced slabs are RC.O-C1 and RC.O-C2. The thickness of the deck after repair/reinforcement was 200 mm and the beam structure was 500 mm width. Reinforcement thickness was about 13 mm, including UHCM, CFSS and epoxy. The specimens RC.O-1 and RC.O-2 were initially loaded to 150 kN (=75kN+75 kN) and increased by 50 kN in every 2 million cycles. After 200 kN the load was increased by 20kN. Initial load for the specimen RC.O-C1, and 2 was 150 kN, and it was increased by 50 kN every 2 million cycles. Here, since the load is applied in step, the number of equivalent repetitions is calculated by the equation (5).

$$Neq = \sum_{i=1}^{n} ({}^{P}i/_{P})^{m} \times n_i \qquad (5)$$

Where, *Neq*: Equivalent number of cycles (times), P_i: Actual load (kN), P: Standard load:60kN, n_i: Experimental running cycles (times), $_m$: Absolute value of reciprocal slant on S-N curve (=12.7)

3.3 *Fixed point fatigue test results*

3.3.1 Results of Equivalent number of cycles

The average equivalent number of cycles of the repaired specimens RC.O-1 and RC.O-2 was 107.99x10^6. Similarly, the average equivalent number of cycles for the reinforced specimens RC.O-C1 and RC.O-C2 was 445.97x10^6 times. When comparing the average number of cycles for the specimens subjected only to repair, reinforced specimens showed a reinforcing effect of 4.1 times. The results showing equivalent number of cycle is shown in Table 3.

Table 3 Fatigue test results

Specimen		Equivalent number of cycles (times)	Averaged Equivalent number of cycles (times)	Enhancing ratio
RC.O-1	Repaired	81,330,803	107,995,266	1
RC.O-2		134,659,728		
RC.O-C1	Reinforced	595,566,383	445,976,550	4.1
RC.O-C2		296,386,718		

3.3.2 Results of slab deflection and equivalent number of cycles

Measurements of deflection by the displacement transducer were performed at 4 points as shown in Figure 2. (2), and the equivalent number of cycles up to failure and the deflection at each equivalent number cycles of repair and reinforced slab specimens, and fatigue durability were evaluated. The deflection of the measurement point 3 is shown in Figure 3. The initial deflection of the repaired slab specimen RC.O-1 and 2 were 0.7mm and 0.6mm respectively. The initial deflection of the reinforced slab specimens RC.O-C1 and 2, were 0.49 mm and 0.50 mm respectively. In the repaired slab specimen RC.O-1, the deflection began to decrease from around the equivalent number cycles of 12.0x10^6 times, and it became negative deflection (lifting direction) from around 42.1x10^6 times. The deflection at failure were -2.6mm and -3.2mm. The reinforced slab specimen RC.O-C1 started to deflect from the vicinity at the equivalent number of cycles 2.0x10^6, and became negative deflection from around the equivalent number of cycles 296.3x10^6, and the deflection at failure was -1.52 mm. The specimen RC.O-C2 had negative deflection from around 47.1x10^6 times, and the deflection at fracture was -0.75mm. In specimens reinforced with CFSS on the upper and lower surfaces of the slab compared with the repaired slabs, the decrease in flexural rigidity on the overhanging part near support and in the center of the span was reduced, and the increase in negative deflection was suppressed.

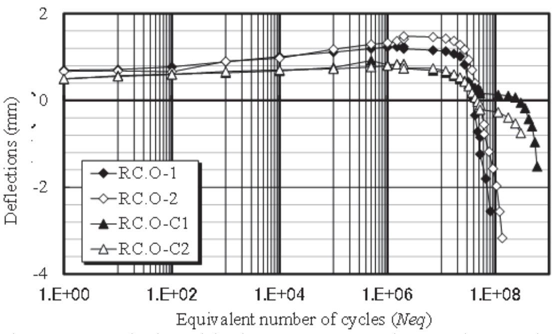
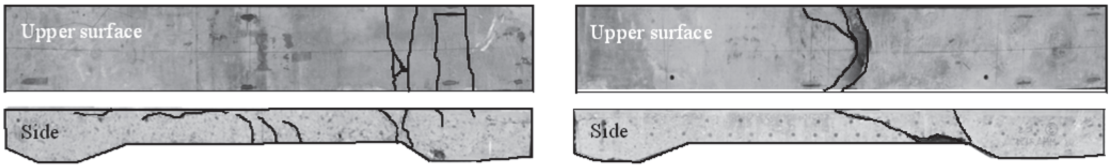


Figure 3. Relationship between over-hanged part slab deflection and running times

3.3.3 Results of slabs failure mode

The failure modes of the specimens are shown in Figure 4. The failure of the repaired slab specimen is shown in Figure 4. (1) which was due to negative bending failure. The cracking occurred directly at the slab support point.
The failure of the reinforced slab specimen is shown in Figure 4. (2). Shear cracks from the hunch part progressed toward the center of upper slab.



(1) Repaired specimen (2) Reinforced specimen
Figure 4. Specimens failure mode

4 CONSTRUCTION CASE OF ACTUAL BRIDGE

Based on these research results, the construction work was carried out in the actual bridge RC slab.

4.1 Overview of the actual bridge RC slab

The RC slab of this bridge is constructed according to the road bridge specification of 1964. The thickness of the slab and the allowable stress level of the main re-bar etc. was not enough. As a result of checking the stress level of the RC slab according to the current road bridge specification, the stress of the axial re-bar above the support was the same as that of the main re-bars of the 1964 Road Bridge specification. It was 130.9N/mm^2 which was less than the allowable stress degree, but since it exceeded the main allowable stress degree (120N/mm^2) of the current road specification book, it was decided to reinforce the upper surface direction of the main direction above the support. The reinforcement was performed only in the direction perpendicular to the axis of the support upper bridge axis, where the rebar stress level exceeded. The arrangement of the reinforcement is shown in Figure 8. For the CFSS which is a high-tension type reinforcing material, was used on the intermediate girder and high modulus type was used for the end overhanging part. The target bridge is a three-span steel truss bridge with one lane on one side as shown in Figure 9. Although the traffic volume of this bridge is estimated to be 13,100 to 16,100 vehicles/day according to the survey on 2013, it was a bridge which is difficult to reinforce with full road closure because there are no detours in the vicinity.

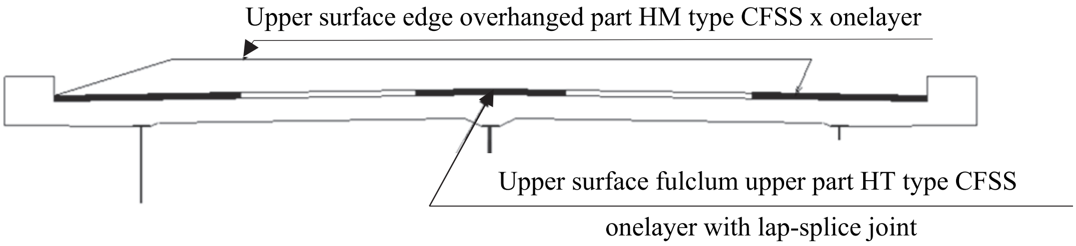


Figure 8. Schema of actual bridge showing CFSS install area

Figure 9. Overview of the actual bridge.

(1) Surface treatment (2) Application of epoxy (3) Surface leveling (UHCM)

(2)

(4) Installation of CFSS (5) Covering with UHCM (6) Covering with a sheet

Figure 10. Work procedure showing the strengthening procedure

4.2 Work procedure and results

Work procedure of the strengthening method of the actual RC slab is shown in Figure 10

Asphalt pavement over the upper surface of the slab, was removed using a pavement cutting machine. The remaining material was completely removed with an electric sander and cleaned with the air. Then the epoxy was applied at the rate of 0.7kg/m^2 by the paint-roller. Before hardening of the epoxy, UHCM was mixed and placed over the epoxy to make a smooth surface with a trowel. Then, before the UHCM cures, another layer of epoxy was applied over the UHCM at the rate of 3.0kg/m ^{2}. CFSS was laid and press down until the epoxy floats on the surface. Thereafter, UHCM was applied again to a thickness of 5mm before the epoxy cured to form a protective layer of CFSS. UHCM and epoxy were sealed and cured for 3 hours or more with plastic film until cured. Finally, after 3 hours elapsed, the film was removed and asphalt waterproof material was applied. Finally, the asphalt pavement was laid and reinforcement work was completed. This construction was used one-side alternate traffic section. It used lap-splice joint for the CFSS install.

This new reinforcement method allowed construction in a short time because no waiting time is needed for the curing of epoxy or UHCM during the construction. The overall curing time of only 3 hours is necessary after completion of the construction.

It is possible to reinforce approximately 4 times the area per day compared to the conventional reinforcement method using onsite impregnation carbon fiber sheets and epoxy. This new reinforcement technique would be useful for shortening the traffic regulation time.

5 CONCLUSIONS

In this study, from the evaluation of the results of the adhesion performance and fatigue resistance, the new reinforcement method was applied to the overhanging part of the actual road bridge RC slab, and the following findings were obtained.

The proposed strengthen method has shear bond strength of 0.5N/mm^2 or more, which is the reference value for design, when reinforced design from the results of the shear bond test by the allowable stress level method, it can be designed on the safe side. Moreover, in the design using interfacial fracture energy, it has high interfacial fracture energy and it is possible to effectively utilize the high tensile strength of CFSS, and if it is 300 mm for effective adhesion length up to CFSS 5 layers, it becomes safe to design.

As a result of reinforcement of the actual bridge RC slab which was removed 33 years after the service, showed 4.1 times greater equivalent number of cycle compared to the deck which is only repaired. Since the negative bending failure did not occur and the deflection of the negative bending part was greatly reduced, the effect of this reinforcing method is promising.

Compared with the traditional on-site impregnation carbon fiber sheet and epoxy RC slab upper surface reinforcement method, the construction speed was faster which made it possible to execute about 4 times of the amount of work per day. Finally, in future, we would like to conduct research and development so that short-term construction which can be performed even in the winter environment.

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