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Strengthening of steel and concrete structures using CFRP in Japan

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ABSTRACT: For over 30 years, FRP (Fiber Reinforced Polymer) has been tried to put in practice as a reinforcing material for infrastructures such as bridges. FRP sheets had been developed for repairing and strengthening of existing concrete structures. Nowadays, repairing and strengthening with FRP is widely used for concrete members of bridge such as piers, beams and slabs in Japan. Recently strengthening method for steel members of bridges using FRP have been developed and applied practically for steel bridges. This paper summarizes features of strengthening and repairing method for concrete and steel members of bridges using FRP in Japan.

1 INTRODUCTION

For over 30 years, FRP (Fiber Reinforced Polymer) has been tried to be applied to the materials for infrastructures such as bridges. This is because FRP is not only a lightweight and high strength material, but also a highly durable material. In 1980's, FRP reinforcements for construction such as FRP rod, cable and grid were developed. After that, researches to tray to apply FRP to concrete structures became active. FRP was applied to aero-spaces and sports field because of its characteristics of lightweight and high strength characteristics. However, in construction field, FRP reinforcement was not easily accepted because cost-effectiveness of FRP was inferior compared to conventional materials as steel.

In the early 1990's, researches to use FRP reinforcement such as FRP sheets and FRP strips for repairing and /or strengthening of existing structures became active. The lightweight property and workability of FRP sheets has captured attention because it didn't require heavy machineries and the only human power was required at work site of retrofitting of existing structures. Nowadays, the FRP sheets bonding method has become a very popular method for seismic retrofitting of reinforced concrete (RC) bridge piers and strengthening of super structures of bridges in the rehabilitation filed.

Recently strengthening method for steel members of bridges using FRP have been developed and applied practically for steel bridges. This paper summarizes features of strengthening and repairing method for concrete and steel members of bridges using FRP in Japan

2 FRP SHEETS

2.1 *Carbon Fiber Sheets*

As FRP materials for repairing and strengthening existing concrete structures, FRP sheets such as carbon fiber sheet (CFRP sheets) and aramid fiber sheet are widely used in Japan. In this method, the dry continuous fiber sheet is bonded to concrete surface using room temperature curing resin and impregnated with the same resin at the same time. After curing, FRP is formed on the concrete surface (Fig. 1). In recent years, this method has also been applied to repair and strengthen corroded steel structures.

There are three types of carbon fiber sheets; high strength, high modulus, and intermediate modulus type. Mechanical characteristics of carbon fiber sheets are shown in Table 1. The unidirectional FRP sheet which arranged carbon or aramid fiber in one direction is mainly used for strengthening concrete structures. Number of plies, the types of the sheet, and types of the fiber are determined according to the design calculations. As an adhesive between FRP and concrete, room temperature curing epoxy resin is widely used.

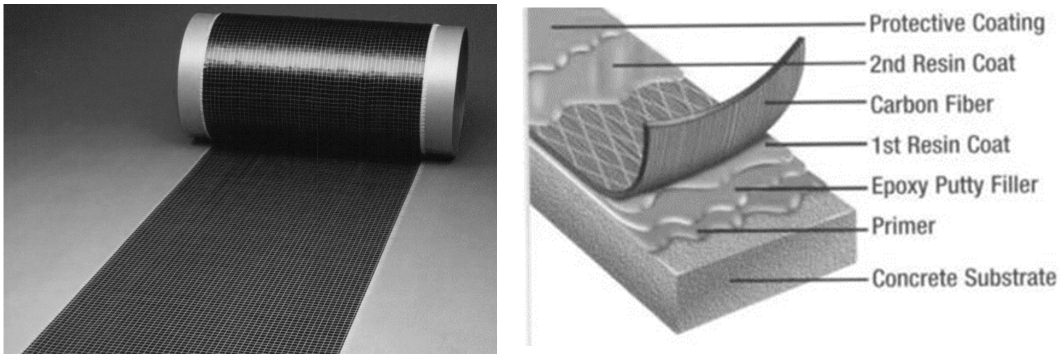


Figure 1. Carbon fiber sheet

Table 1. Mechanical characteristics of Carbon fiber.

Type		High Tensile Strength			Int.Mid Modulus	High Modulus
No.		FTS-C1-20	FTS-C1-30	FTS-C1-60	FTS-C5-30	FTS-C8-30
Fiber mass per unit area	g/m^2	200	300	600	300	300
Design thickness	mm	0.111	0.167	0.333	0.165	0.143
Tensile strength	N/mm^2	3400	3400	3400	2900	1900
Tensile modulus	kN/mm^2	245	245	245	390	640

2.2 *CFRP Strand Sheets*

As a common reinforcing method, the dry carbon fiber sheets and FRP strips are being used. However, there are some demerits using these materials. When dry carbon fiber sheets are used, adhesion defects may occur caused by poor impregnation of resin. Also when also using FRP strips, the de-lamination may occur at lower load because of interfacial shearing stress concentration between CFRP and concrete or steel at its tips.

In order to solve these problems, the FRP strand sheets were developed. The strand sheet (Fig. 2) is made out of fine CFRP strands which are individually impregnated with resin and hardened. Hundreds of these strands are arranged horizontally in 1m width and woven with thread to make it into a sheet form.

The strand sheet bonding method is a reinforcing method for concrete or steel members by bonding the strand sheets on the surface with epoxy resin in a form of paste. The strand sheet bonding method has following features;

i. Thick sheets with high fiber mass per unit area can be produced.
ii. Since there is enough space in between strands, it easily lets the bubbles between concrete surface and the strand sheets to go out, application failures will be decreased dramatically.
iii. Unlikely the CFRP strip bonding method, because the thin layer of reinforcing sheet is bonded on the reinforcing area of the concrete element, the same reinforcing effect as the continuous fiber bonding method can be obtained.
iv. Overlap splice can be applied just as continuous fiber sheet bonding method, so that it is able to translate the stress between the separate strand sheets through the joint.

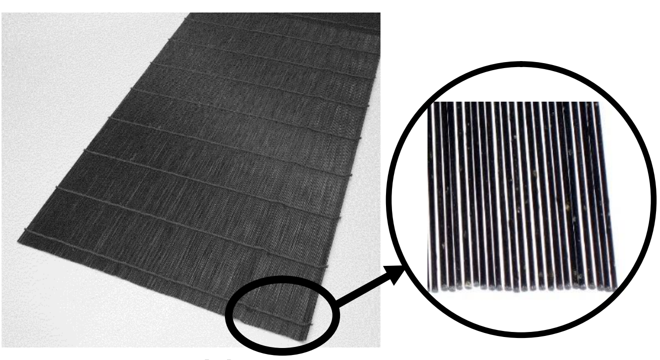


Figure 2. FRP strand sheets

3 STRENGTHENING OF CONCRETE STRUCTURES

3.1 *Seismic Retrofitting of Reinforced Concrete (RC) Bridge Piers*

In the case of RC bridge piers which had been designed according to old specifications, anchoring length at termination of main reinforcements are often inadequate and, also, amount of shear reinforcement are often short. The FRP sheet jacketing method is applied in order to prevent fracture at the termination of main reinforcements and to improve the shear capacity and ductility. For the flexural strengthening of column at the termination of main reinforcements, the FRP sheets which have appropriate length at upside and down side from the termination section are attached on concrete surface in vertical direction. For the shear and ductility reinforcing, the circumferential FRP sheets are attached to the concrete column. In these cases, the high strength type CFRP sheet is usually used.

Figure 3 shows seismic retrofitting of RC high piers of an express highway with using CFRP sheets (Osada, N. et al. 2000). This 60m high RC pier had hollow circular cross section to minimize self-weight. The longitudinal reinforcements were curtailed at several levels according to the old design specification.

In the planning phase, the CFRP sheet jacketing method was compared to concrete jacketing method and steel plates jacketing method. The concrete jacketing method was impossible to apply because the cross sectional diameter of pier after concrete jacketing was too large and the flow of river might be obstructed. It was also difficult to set up concrete form on the riverbed. In the case of steel plate jacketing method, the construction cost was calculated to be expensive because it was necessary to build temporary structure in the river to carry heavy steel panels.

Whereas, carbon fiber sheets were very light weight and easy to handle, construction works could be conducted using a gondola without any temporary structures in the river. Therefore the carbon fiber sheet jacketing method was adopted.

Figure 3. Seismic retrofitting of high piers

3.2 *Strengthening of Road Bridge RC Slabs*

The fatigue deterioration of road bridge RC slabs has become a serious problem. The deterioration of RC slabs are caused by several reasons such as wheel loads greater than their designed load, ever increasing traffic, in-adequate slab thickness, insufficient distribution bar amount, low concrete quality, improper concrete pavement, etc.

Fracture mode of RC slabs in actual bridges is punching shear failure without the fatigue failure of reinforcing bars. Damage in RC slabs of road bridges starts with the generation of single-direction cracking, and leads to the development of the two-direction cracking, followed by the propagation of fine cracks. Penetration and the formation of concrete blocks in the slab is the next step. Finally, the concrete slab separates into pieces and reaches punching shear failure (Okada, M. et al. 2003, Fig. 4).

In Japan, there are several strengthening methods for slabs; such as an additional stiffening girder method, a steel plate bonding method, a CFRP sheet bonding method, a concrete overlay method, etc. To strengthen RC slabs using CFRP sheets, the first layer of CFRP sheets is attached in the main reinforcing bar direction, and the second layer of CFRP sheets is attached in the distribution reinforcing bar direction on bottom surface of RC slab with epoxy resin. As shown in Figure 5, there are two bonding pattern. One is the full surface bonding, and the other is the grid bonding. The advantages of the CFRP sheet bonding method are no need to stop vehicles traffic on the bridge, free from rust, good resistance to chemicals, and minimum maintenance. Therefore this method is widely used to strengthen road bridge RC slabs in Japan.

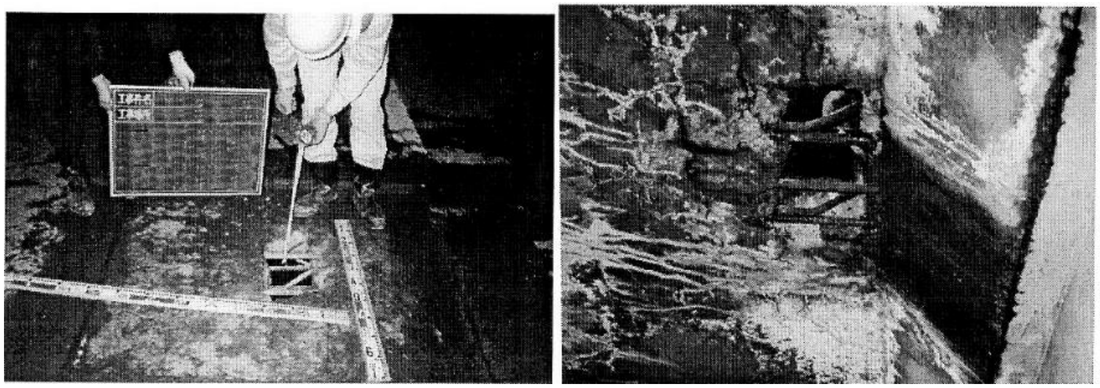
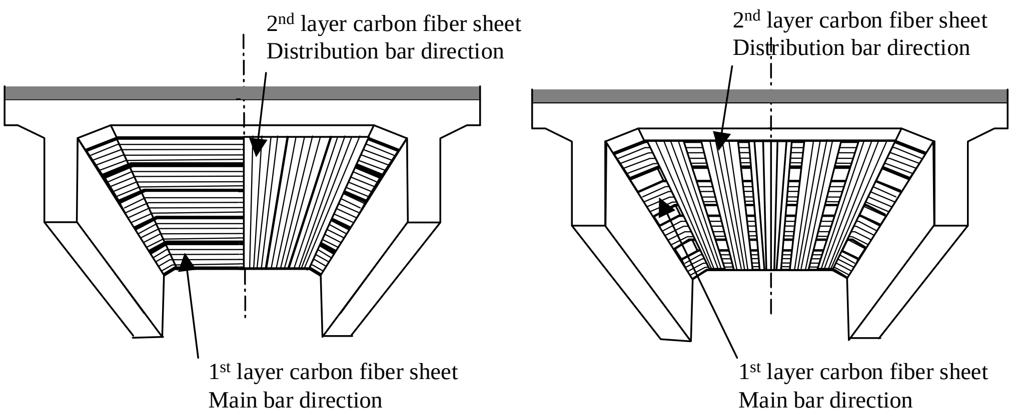


Figure 4. Punching failure of the slab after 32 years



(a) Full surface bonding (b) Grid bonding

Figure 5. Strengthening of RC bridge slabs with carbon fiber sheets

By bonding a CFRP sheet to the bottom surface of the RC slabs, it is possible to reduce the slab deflection and also reduce the stress in the tensile reinforcing bars. The CFRP sheet is also effective to constrain the development of cracks in the concrete at the bottom surface of the RC slabs. Therefore, by bonding a CFRP sheet to the bottom surface of the RC slabs that have been damaged, it is possible to prolong the slab fatigue life remarkably.

Fatigue tests of bridge slabs strengthened with CFRP sheets were conducted by Matsui, S. et al. using a wheel running machine that is capable to reproduce slab fatigue damage (Matsui, S. et al. 1996). The schematic diagram of the wheel running machine is shown in Figure 6. The slab specimens were obtained from an existing bridge that had been in service for 26 years. Two plies of intermediate modulus CFRP sheet were applied to under the surface of the slab. The first ply was applied in the main reinforcing bar direction and the second ply was applied in the distribution reinforcing bar direction. The deflection of the slab at center point is a function of the number of cycles, as is shown in Figure 7. It can be seen that the deflection of the reinforcing slab increased very slowly in comparison with the deflection of the control slab without CFRP sheets. No breakage of CFRP sheet and no peeling off of the sheet were observed during the fatigue test. It was confirmed that the CFRP sheet con-strained the deflection of the slab and the opening of the cracks, thereby improving the slab fatigue life noticeably.

The S-N diagram of RC slabs strengthened with CFRP sheets are shown in Figure 8 (Okada, M. et al. 2003). The thicknesses of RC slabs were 150mm and 180mm. The slabs strengthened with several types of CFRP sheet which had various Young's modulus and fiber weight per unit area. A normalized S-N curve was developed to facilitate the fatigue life prediction of RC slabs designed in accordance with different specifications by Matsui (Matsui, S. et al. 1991). This S-N equation of the RC slab without CFRP sheet was shown in Figure 8 as a solid line. The test results of slabs strengthened with CFRP sheets were plotted in upper-right side area of this S-N equation. Therefore it is considered that strengthening using CFRP sheets remarkably prolong the life of RC slabs. It is assumed that the life of RC slabs strengthened with CFRP sheet depends on magnitude of load and several properties of the CFRP sheet and RC slab, such as stiffness of CFRP sheet, thickness of slab, amount of existing reinforcing steel bars, concrete strength, deterioration condition of RC slab before strengthening, etc. Therefore, in order to evaluate the effect of strengthening, it is important to develop S-N equation of RC slab strengthened with CFRP sheets.

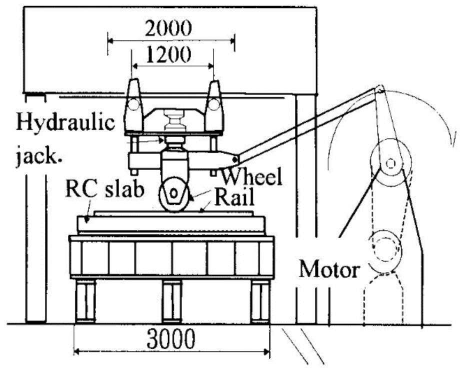


Figure 6. Wheel Running Machine

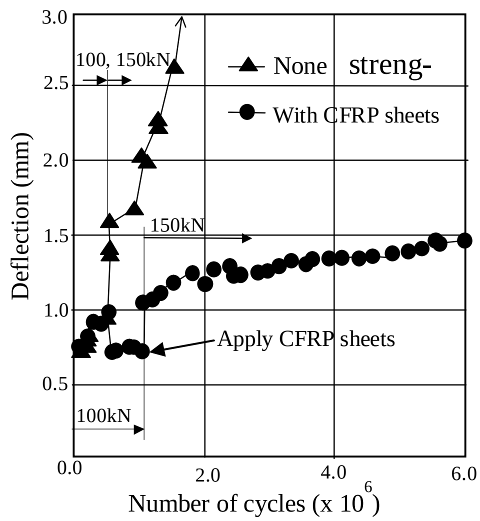


Figure 7. Result of wheel running test

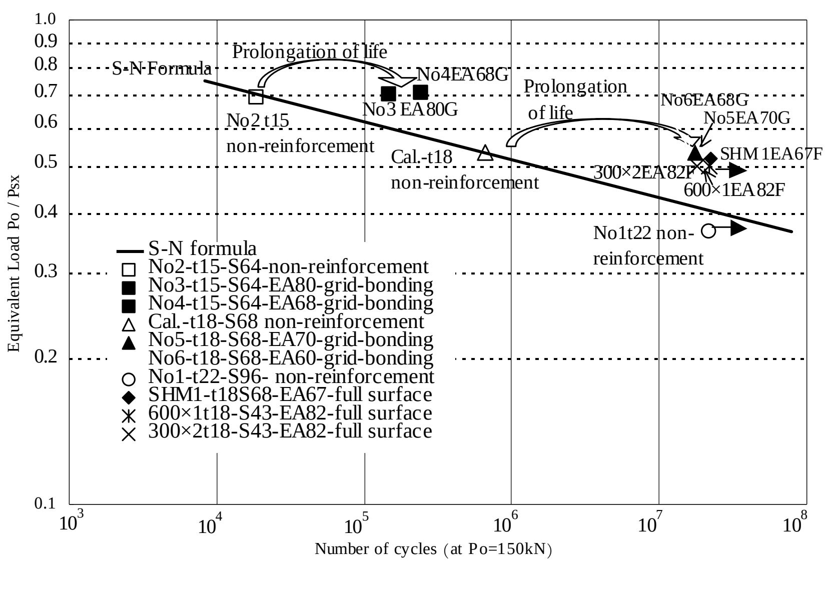


Figure 8. The relationship between number of cycles until failure and load P_o/P_{sx}

4 STRENGTHENING OF STEEL STRUCTURES

4.1 *Feature of CFRP Bonding Method for Steel Structures*

Steel structures are corroded by various mechanisms. When the reduction of steel cross section by corrosion can't be negligible, some repairing method that can recover steel cross section should be applied. Conventionally, a new steel plate is attached on to the corroded steel by welding or bolting. These conventional repairing methods have some disadvantages. In case of welding heat management on site is difficult. In case of bolting, bolt holes induce additional defect on existing steel plate and cost of bolting is expensive.

In order to overcome these problem, new repairing method using CFRP have been developed. In this method, high modulus CFRP is simply bonded on steel surface by epoxy adhesion as shown in Figure 9. At first, corroded steel surface is grinded, then primer resin is coated on the steel surface, then epoxy adhesion is coated and some layers of strand sheets are bonded on the surface. At last finishing paint is coated on the strand sheet. This method does not require heavy equipment. There is no need of welding or bolting. It leads to efficient and economical repairing works.

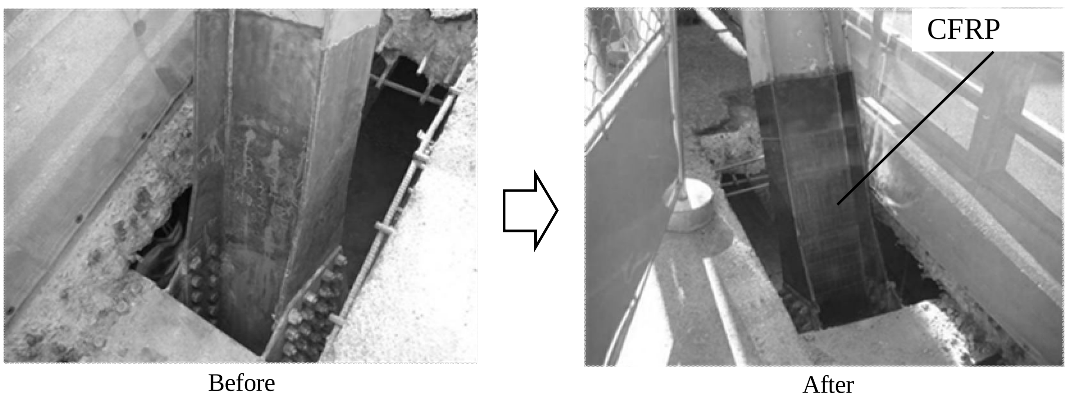


Figure 9. Example of repairing of steel member with CFRP

4.2 *Strengthening of Axial Members*

4.2.1 *Outline of design*

Generally in CFRP bonding method, the CFRP with a larger rigidity than the rigidity of the missing cross-sectional area of the steel member is bonded to avoid the yielding of the steel at defected parts. Therefore, the amount of CFRP is determined by the following Equation 1:

$$E_{cf}A_{cf} \geq E_s A_{sd} \tag{1}$$

where E_{cf} = Elastic modulus of the CFRP; A_{cf} = Cross-sectional area of the CFRP; E_s = Elastic modulus of the steel; A_{sd} = Cross-sectional area of the missing cross-sectional area of the steel.

4.2.2 *Experimental study*

In order to clarify the reinforcing effect and delamination property of CFRP bonded to steel members, tensile tests of steel strengthened with high modulus CFRP strand sheets, conventional sheets and strips were performed. As shown in Figure 10, CFRP strand sheets, conventional CFRP sheets, and CFRP strips were bonded to both sides of a steel plate (yield strength: 385 N/mm^2). The simple tensile tests of the reinforced steels were performed until the applied load reaches the yield load of the steel (200 kN). The mechanical properties of CFRP materials are shown in Table 2. The strains in CFRP and steel were measured and delamination be-tween CFRP and steel was observed. In order to reduce the stress concentration, each layer was staggered 25 mm and laminated with steps.

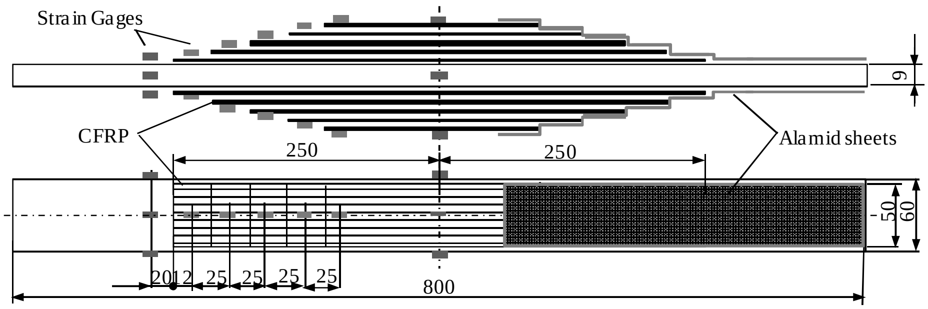


Figure 10. Specimen for tensile tests

Table 2. Mechanical properties of CFRP materials

Type	Carbon fiber sheet	CFRP strand sheet	CFRP strip
Mass per unit area (g/m^2)	314	910	-
Thickness (mm)	0.143	0.429	2.0
Elastic modulus (GPa)	682	710	450
Tensile stiffness (kN/mm)	97.5	305	900

Table 3. Results of tensile tests.

No.	CFRP type	Number of ply	Tensile stiffness of CFRP (kN)	Strengthening effect (%) Experimental value / Theoretical value	Debonding
CF 10	Carbon fiber sheet	10	97520	86.4	>100%
SS 3	CFRP strand sheet	3	91380	97.2	>100%
PL 1	CFRP strip	1	90000	100.6	33%

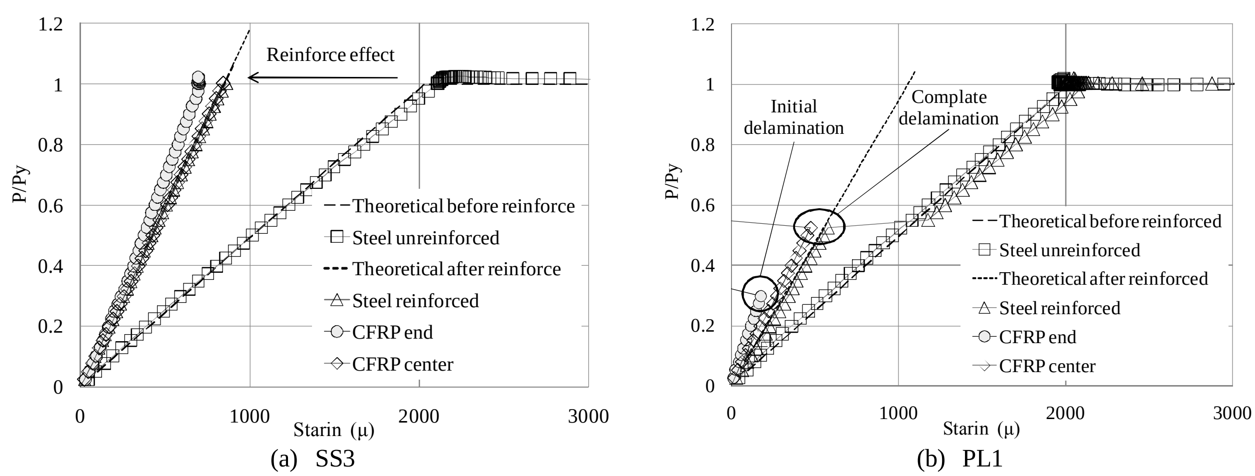


Figure 11. Load – strain curves of SS3 and PL1

Table 3 shows the comparison between experimental and theoretical value of tensile stiffness. In this table, tensile stiffness of CFRP was calculated using the elastic modulus, cross-sectional area and number of layered CFRP. Figure 11 shows the relationship between load and strain of No. SS3 without debonding and No. PL1 with debonding of CFRP.

In each specimen, the experimental tensile stiffness agrees well with calculated stiffness. It is shown that the CFRP reinforced steel can be dealt with as composite cross section both steel and CFRP.

In case of specimen reinforced with CFRP strips, it was observed that the debonding occurred before yield of the steel from tip of the CFRP and then debonding grows to the center. On the other hand, no debonding occurred until yield load of the steel in case which uses conventional carbon fiber sheets and CFRP strand sheets.

4.2.3 *Application examples*

Figure 12 (a) shows an application example for corroded steel hungers. This bridge is located on the seaside. Severe corrosion damage was observed at some spots on steel hungers. Epoxy putty was used to fill the reduced section of steel hungers. 3 layers of high modulus CFRP strand sheets were wrapped around steel hungers using epoxy adhesive.

Figure 12 (b) shows the application example for corroded steel truss. There were some spot corrosion due to the water leak at the top face of bottom chord member. These defects were filled by epoxy putty, and then, each of the 3 layers of carbon fiber sheets were applied to top flange and both webs.

In addition, in Japan there are many CFRP reinforcing case of corroded steel member.

Before After Before After

(a) Steel hunger (b) Steel truss

Figure 12. Photograph of construction example

4.3 *Strengthening of Flexural Members*

4.3.1 *Outline of designing*

Here it will be explain about how to design reinforced with CFRP of members subjected to bending moment, such as steel girders. The geometrical moment of inertia of the strengthened steel by CFRP can be calculated by following Equation 2:

$$I_i = I_s + \frac{E_{cf}}{E_s}\left(I_{cf} + A_{cf} \cdot e_{cf}^{\ 2}\right) \qquad (2)$$

Where E_s, E_{cf} = elastic modulus of steel and CFRP; I_i = geometrical moment of inertia of composite cross-section at *i*_th layer; I_s, I_{cf} = geometrical moment of inertia of steel and CFRP; A_{cf} = cross-sectional area of CFRP; e_{cf} = distance from neutral axis to centroid of CFRP

4.3.2 *Experimental study*

H-shaped steel girders were used to conduct flexural tests as shown in Figure 13. High modulus CFRP strand sheets were bonded to lower flanges. The three-point loading tests were performed until yield load of steel (1,020 kN) or until debonding of CFRPs occurs. Measured values were deflection and strain in CFRP/steel. The experimental parameters were the bonding length of each layer as shown in Table 4. The numbers of ply of CFRP strand sheets was 10 layers.

The load-strain curves of F10C and F10D are shown in Figure S-6. From this figure, it is found that the strains of the steel and the CFRP agree well with the theoretical values in both specimens. In F10C the debonding occurred at 800kN from tip of CFRP strand sheet. On the other hand, in F10D no debonding occurred until yield load of steel girder.

From these results it is found that the steel beam strengthened with CFRP strand sheets can be designed as composite cross section and no debonding occur if the bonding length is enough long.

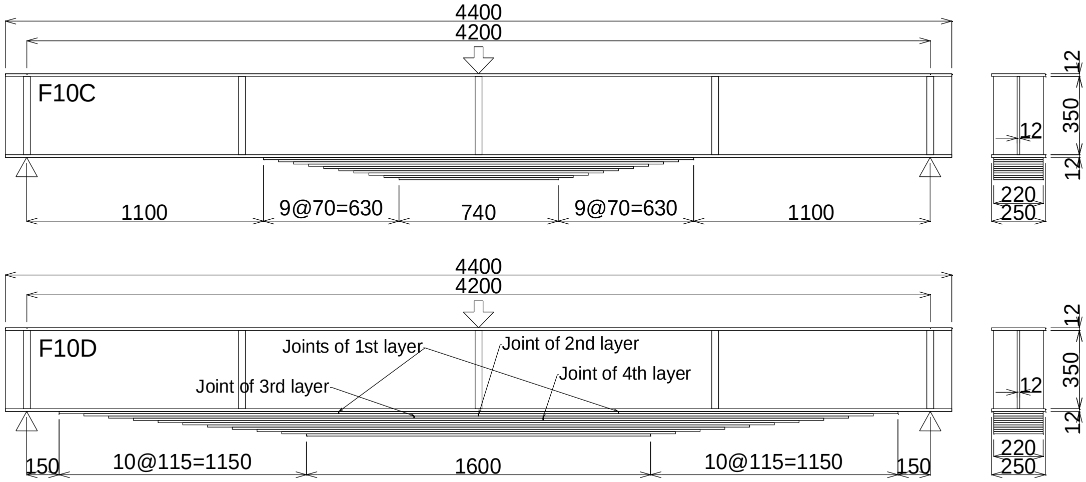
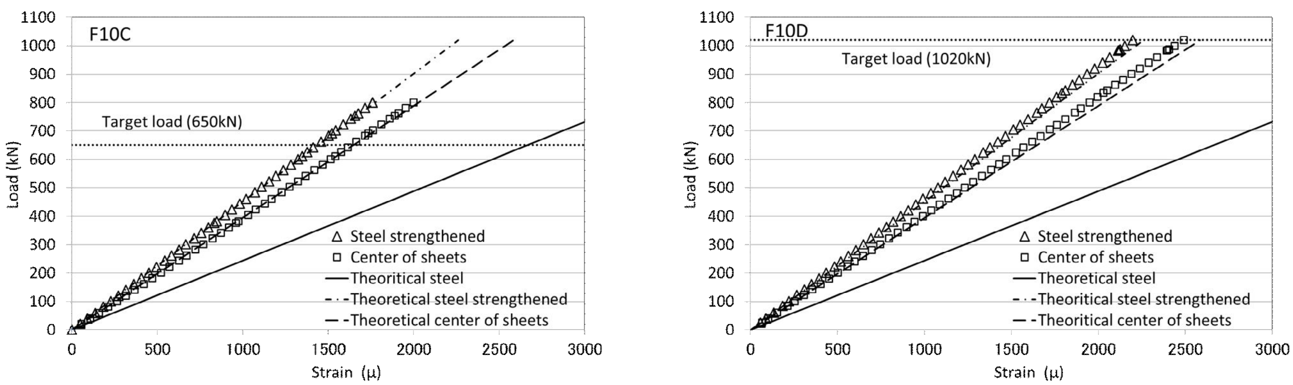


Figure 13. Flexural tests specimens

Table 4. Experimental parameter of Flexural tests

Specimen	Number of ply	Length of 1st layer mm	Length of outer layer mm	Length of step mm
F10C	10	2,000	740	70
F10D	10	3,900	1600	115



(a) F10C (b) F10D

Figure 14. Load-strain curves of F10C and F10D

Figure 15. Photograph of construction example for steel girder

4.3.3 *Application examples*

Figure 15 shows an application example for steel girders. In this case, 10 layers of high modulus CFRP strand sheets were applied in the undersurface of bottom flange due to the increase of the dead load. Because the CFRP strengthening only bears only the post load, it is necessary to apply it before increasing of dead load.

In addition, there are some examples such as overhead crane runway girder for fatigue countermeasures in Japan.

5 CONCLUSIONS

This paper summarized the characteristics of FRP sheets and CFRP strand sheets which are widely used as FRP reinforcement for concrete and steel in Japan. Experimental studies and application examples are also presented and the following conclusions were obtained.

i. The retrofitting methods using CFRP sheets have become popular for the rehabilitation of RC bridge piers, super structures of bridges and other concrete structures because of its advantages such as light weight, good workability and good environmental resistance.
ii. Newly developed CFRP Strand Sheets have good workability and excellent strengthening effects
iii. The CFRP sheet bonding method is effective to improve seismic resistance of RC pier and to life prolongation of road bridge RC slabs.
iv. It is confirmed that high modulus CFRP sheets are effective for corroded steel members, because high modulus CFRP sheets can reduce strain of steel members which are subjected tensile and/or bending forces.
v. Recently high modulus CFRP sheets have widely used to repair and strengthen steel members of bridges.

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