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Pier Strengthening Technique Using Carbon Fiber Grid and under Water Curing Type Resin

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Abstract

From being reviewed quake-resistance standards on the experience of the Southern Hyogo Prefecture Earthquake, seismic strengthening work of the pier due to reinforced concrete jacketing method and carbon fiber sheet jacketing method is advanced in everywhere about the land-based pier is almost completed. However, seismic reinforcement of the underwater part (especially deep-water part) there is a problem with the existing method, there are still many piers that are not seismic strengthening works. We have developed a pier reinforcement technique using a carbon fiber grid and underwater curing type resin in this background. In this document, overview of the pier reinforcement technology, verification of reinforcing effect, the introduction of construction cases, we describe future prospects.

1. Introduction

Earthquake resistance is an important requirement for structures in an earthquake-prone country such as Japan. In the Southern Hyogo Prefecture Earthquake (maximum seismic intensity of 7 on the Japanese seven-level seismic scale and magnitude 7.3), many structures were damaged. In particular, reinforced concrete (hereinafter referred to as "RC") piers of road bridges such as highways collapsed, resulting in enormous damage. The collapse of piers was caused by the bending moment that was higher than predicted and that acted on the portions where the number of reinforcement bars in the axial direction of RC piers were reduced (hereinafter referred to as "reinforcement-reduction parts") due to the earthquake. Since the quake-resistance standards have been revised based on this earthquake experience, seismic strengthening work of RC piers has been advanced in each area in Japan.

As seismic strengthening methods, the RC jacketing method, carbon fiber sheet jacketing method, etc. are widely used. Using these methods, the seismic strengthening work for land-based RC piers is almost completed. However, when it comes to the reinforcement for the submerged parts of RC piers (especially in deep water) that require the coffering to create a dry environment and working space, and huge costs and time, many RC piers remain untouched. Against this background, pier reinforcement technology that allows for underwater work using carbon fiber grids and underwater curing type resins has been developed to reinforce the submerged parts of RC piers without requiring the coffering. This report introduces this pier reinforcement technology, verification of the reinforcement effect, and construction examples.

2. Outline of Pier Reinforcement Technology Using Carbon Fiber Grids and Underwater Curing Type Resins

2.1 Issues with conventional methods

In the conventional carbon fiber sheet jacketing method, for the work under water, (1) handling carbon fiber sheets is difficult, and (2) epoxy-based impregnated adhesive resin cannot be used. For these reasons, it is necessary to set a temporary steel sheet pile coffering structure to create a dry working space around the RC pier to be treated. However, the issues entailed when using a coffering structure include (1) requiring large-scale coffering work to reinforce a part in deep water; and (2) possibility of disturbing the water current due to the large occupying ratio in the cross-sectional area of a river during the entire work.

2.2 Features of the pier reinforcing technology using carbon fiber grids and underwater curing type resins

The carbon fiber grid used in this technology is shown in Photo

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1 and its specifications shown in **Table 1**. The properties of the underwater curing type resin are shown in **Table 2**. To address the issues that the carbon fiber sheet jacketing method has when used for a submerged part of an RC pier, a carbon fiber grid (hereinafter referred to as "CFG"), which is made from a carbon fiber sheet that is formed into the shape of a grid, is used. For the adhesion to the RC pier, a method in which an underwater curing type resin is injected by pump is adopted. A cross-sectional view of the reinforcing layer is shown in **Fig. 1**. To ensure strict adhesion of the injected resin to the RC pier surface, the surface treatment by scraping and underwater blasting is performed on the RC pier surface. In addition, the preliminarily manufactured CFG material, form, etc. are installed on the RC pier for reinforcement according to the measurement results



Photo 1 Carbon fiber grid (CFG)

Table 1 Specification of carbon fiber grid

Grade		Cross-sectional	Tensile	Degree of	Pitch of bar
		area of bar	strength	elasticity	$(mm)\times(mm)$
		(mm ² /bar)	(N/mm^2)	(N/mm^2)	(11111)^(11111)
	CD4	6.6			100×100
	CK4	0.0	1 400	100 000	50×50
ų	CD5	12.2			100×100
arbo	CKS	13.2			50×50
h ci	CD (17.5			100×100
engt	СКО	17.5			50×50
stre	CR8	26.4			100×100
igh-					50×50
Hi	CR10	39.2			100×100
	CR13	65.0			100×100
	CR16	100.0			100×100
	CMR5	13.2			50×50
city	CMR6	17.5		165 000	50×50
asti	CMR8	26.4	1 200		50×50
n elá carb	CMR10	39.2	1200		100×100
Hig	CMR13	65.0			100×100
H	CMR16	100.0			100×100

Table 2 Property of underwater curing type resin

Item	Property values	Remarks
Adhesion strength	$\geq 2.0N/mm^2$	$23^{\circ}C \times 7 \text{ days}$
Compressive strength	55 N/mm ²	23°C × 7 days
Bend strength	49 N/mm ²	23°C × 7 days
Tensile strength	32 N/mm ²	23°C × 7 days
Density	2.05 g/cm ³	23°C



Fig. 1 Cross-sectional view of reinforcement layer

obtained in advance. Paying attention to avoid the inclusion of bubbles, the resin is injected from the lower end of the form using a pump. After filling the form with the resin is completed, the upper end of the form is sealed with underwater curing type epoxy resin putty. Then, the reinforcement work is completed.

The use of the carbon fiber grid and underwater curing type resin facilitates the work in water and eliminates the need for coffering, which is required in conventional methods. Only underwater operations by divers are required for the reinforcement. As all one needs is simple single tube scaffolding during the reinforcement work, the occupying ratio in the cross-sectional area of a river is small, causing little water current disturbance. There are other advantages over the RC jacketing method, such as the small occupying ratio in the cross-sectional area of a river also after completion, light-weight materials used in this method, and no heavy equipment required.

As described above, this method has excellent features as a reinforcement method for underwater parts of RC structures. In the next chapter, the reinforcement effects of this method are explained showing the test data obtained during the verification of reinforcement effects in bending and shear tests.

3. Verification of the Reinforcement Effects

3.1 Verification of the reinforcement effect against the bending load¹⁾

3.1.1 Outline of the test

To verify the bending load resistance effect of a structure member reinforced by laminating a CFG layer, a three-point bending test for concrete beam members that were reinforced using one CFG layer and two CFG layers laminated on the surfaces of the beams was performed.

3.1.2 Method of three-point bending test

Reinforced concrete beams $(2100 \times 200 \times 150 \text{ mmt}; \text{ t: thickness})$ were scraped using a belt sander. Next, they were immersed in seawater for 24 hours. As shown in **Fig. 2**, CFG layers were then laminated on the beam surfaces for reinforcement. Two types of reinforcement standard were tested: reinforcement using one CFG layer and that using two CFG layers.

The three-point bending test method used is shown in **Fig. 3**. The fulcrum interval was determined to be 1 800 mm and the loading speed 1 kN/min. The initial crack load, initial peel-off load, reinforcing bar yield load, and fracture load were measured. In addition, for measuring the strain associated with the load, strain gauges were mounted at 13 locations on the lateral faces of the test piece and at five locations on the surface of the CFG reinforcement layer. 3.1.3 Test result

The relationship between the displacement and the load during the bending test is shown in **Fig. 4**, along with the test results of a carbon fiber sheet (hereinafter referred to as "CFS"). When a CFG reinforcement layer was formed, compared to the unreinforced test piece, the bending resistance was improved by 23% with one CFG



Fig. 2 Overview figure of test piece



Fig. 3 Method of three-point bending test



layer, and was improved by 47% with two CFG layers. Toughness was improved by 45% with one CFG layer and two CFG layers alike. Furthermore, when compared to the case using a CFS layer, although the amount of carbon fiber in one CFG layer was no more than 2/3 of that in one CFS layer, the bending resistance of the test piece showed a value almost equivalent to that of one CFS layer. To investigate the factor of the reinforcement effect against the bending load, the number of cracks (**Fig. 5**) and the crack width (**Fig. 6**) on the test piece were measured. As shown in Fig. 5, the number of cracks on each test piece reinforced using one CFG layer and two CFG layers was larger than that on the unreinforced test piece and CFS-reinforced test piece. Figure 6 also shows that even though the amount of carbon fiber in one CFG layer was no more than 2/3 of that in one CFS layer, the width of cracks on the test piece using one CFG layer was significantly smaller than that of the unreinforced



Fig. 5 Relation between the number of cracks and load



Fig. 6 Relation between the width of the cracks and load

test piece. These results indicate that the CFG-reinforcement had a distribution effect of the bending stress due to reduction of the crack width, as well as a constraining effect of crack occurrence.

3.2 Verification of the reinforcement effect against shear load²⁾ 3.2.1 Outline of the test

To verify the shear load resistance effect of a structure member reinforced by laminating a CFG layer, a flexural shear test was performed using concrete beams that were reinforced by laminating CFG layers on the lateral faces and bottom face.

3.2.2 Flexural shear test method

Concrete beams $(1350 \times 150 \times 200 \text{ mmt})$ were used as test pieces. As with 3.1.2, after the surface treatment and immersion in seawater for 24 hours, the underwater curing type resin layer and CFG layers were laminated on the test pieces in water. The CFG-reinforcement was applied to two lateral faces and the bottom face of each test piece in a horseshoe shape (**Fig. 7**).

3.2.3 Test results

The results of the flexural shear test are shown in **Fig. 8**. The line plot of No. 5 is formed by the data obtained in an additional test for the results of a reference paper.²⁾ Compared to the test piece without reinforcement as shown by the line plot of No. 1, the CR3-50 layer (with 1/2 the fiber amount for reinforcement against the shear load) of No. 4 was improved in terms of shear capacity by 53%, and one layer using CR3-50 of No. 5 was improved by 80% in shear capacity. The reinforcement effect that was equivalent to or greater than that of the CFS-reinforced test piece of No. 3 was confirmed.



Fig. 7 Dimension of test piece and reinforcement layer



Fig. 8 Results of flexural shear test

3.3 Verification of the effect against compression³⁾

3.3.1 Outline of the test

To verify the reinforcement effect obtained using a CFG layer against the compression load, a uniaxial compression test was performed using test pieces of concrete cylinders to which one CFG layer or two CFG layers was fixed to the side of each cylinder for reinforcement.

3.3.2 Compression test method

The surfaces of concrete cylinder test pieces (150 mm in diameter \times 300 mm in length) were scraped by sandblasting. Next, the test pieces were immersed in seawater for 24 hours, and then laminated with an underwater curing type resin layer and one CFG layer or two CFG layers (**Fig. 9**) in water. In the same manner, a test piece reinforced using a CFS layer was also manufactured in air. As described in 3.1 and 3.2, if the amount of carbon fiber in a CFG layer is equivalent to or greater than the CFS layer, the reinforcement effects against the bending/shear loads are also equivalent or greater. Given this, in order to make comparisons, the circumferential direction fiber weight of a CFG layer was determined to be 57 g/m²



Fig. 9 Configuration of the reinforcement layer

Fable 3	Standards	of reinforcement	t
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No.	Specs of reinforcement	Number of layers	Circumferential direction fiber weight (g/m ²)
1	Unreinforced		
2	CR3-60	1	57
3	CR3-50	1	68
4	CR3-30	1	114
5	CR3-30	2	228
6	C0-10	1	50

(CR3-60), which was similar to the circumferential direction fiber weight of a CFS layer at 50 g/m² (C0-10). Furthermore, in order to compare the relationship between the CFG grid spacing and fracture morphology, three types of CFG grid spacing: 30 mm, 50 mm, and 60 mm were used (**Table 3**). The loading speed was determined to be 10 kN/min and the axial direction displacement, axial strain and circumferential strain were measured during the test.

3.3.3 Test results

Table 4 shows the compression test results, and Fig. 10 shows the load/displacement curve. Compared to the test piece without reinforcement, the maximum loads of No. 2 to No. 4 were increased by 23 to 54 kN along with the increase of the circumferential direction fiber weight. Each circumferential strain at the maximum load of No. 2 to No. 4 was also increased as the maximum load increased. The maximum load of No. 5, which was reinforced using two CFG layers, was increased by 207 kN with 3.8 mm displacement at the maximum load, showing an improvement of the deformation property 3.5 times that of the unreinforced test piece. The fracture morphology was not affected by the CFG grid spacing. The maximum load of No. 6 reinforced with a CFS layer was increased by 7 kN compared to the unreinforced test piece. These results confirm that CFG-reinforced No. 2 and No. 3 and CFS-reinforced No. 6 with similar circumferential direction fiber weight (50 to 68) showed a comparable reinforcement effect against the compression load.

3.4 Verification of the CFG adhesion property⁴⁾

3.4.1 Outline of the test

To verify the effect of the adhesion property on the CFG reinforcement level, a double shear pulling test was performed and the interfacial peeling/fracture energy and effective adhesion length were compared. In addition, a simple formula for calculation of the effective adhesion length when using CFGs is proposed, the significance of which is verified by comparing with the experimental values.

No.	Specs of reinforcement	Number of layers	Circumferential direction fiber weight (g/m ²)	Maximum load (kN)	Displacement at the maximum load (mm)	Circumferential strain at the maximum load (μ)	Final fracture morphology
1	Unreinforced	_	_	440	1.1	867	Concrete fracture
2	CR3-60	1	57	463	1.7	2679	After CFG fracture, concrete fracture
3	CR3-50	1	68	480	1.7	2714	After CFG fracture, concrete fracture
4	CR3-30	1	114	494	1.7	3 2 9 4	After CFG fracture, concrete fracture
5	CR3-30	2	228	647	3.8	3810	After CFG fracture, concrete fracture
6	C0-10	1	50	447	1.2	1 157	After CFG fracture, concrete fracture

Table 4 Results of compression test

Table 5 Results of compression test

Standards		Configuration of the reinforcing fiber	Fiber level (mm ²)	Number of row	Fiber level	Sharing width	Converted
	CFG				per a row	per a row	norminal tickness
					(mm ²)	(mm)	(mm)
А	CR10-100	$39.2 \mathrm{mm^2 \times 43\% \times 2 row \times 1 layer}$	33.712	2	16.856	100	0.169
В	CR3-50	$4.4 \mathrm{mm^2} \times 43\% \times 3 \mathrm{row} \times 4 \mathrm{layer}$	22.704	3	7.568	50	0.151
С	CR3-30	$4.4 \mathrm{mm^2 \times 43\% \times 2 row \times 2 layer}$	7.568	2	3.784	30	0.126



Fig. 10 Load-deformation curve

3.4.2 Double shear pulling test standards

Table 5 shows the reinforcement standards tested and the number of CFG layers applied. The following three standards were set for verification of the effect of the reinforcement amount: Standard A at a reinforcement level that is typical in reinforcement work; standard B with multiple CFG layers at a low reinforcement level; and standard C using a test piece smaller than those of A and B and at a reinforcement level equivalent to B.

3.4.3 Test results

Table 6 shows the double shear pulling test results. As an index of adhesion strength, the interfacial peeling/ fracture energy G_f (N/mm) was obtained from the following formula.

$$G_{f} = P_{max}^{2} / (8b^{2} \times E_{frp} \times t_{frp})$$
(1)
Maximum load: P_{max} (N)
CFG grid spacing: b (mm)
CFG tensile elasticity: E_{frp} (N/mm²)

Table 6 Results of both pull shearing test

No.	CFG	Sharing width (mm)	P _{max} (N)	G _f (N/mm)	Tensile strength (N/mm ²)
A-1	CR10-100	100	187980	2.85	2788
A-2			193150	3.01	2865
A-3			222810	4.00	3 3 0 5
Ave.				3.29	2986
B-1	CR3-50	50	167770	4.49	3 6 9 5
B-2			171120	4.67	3 768
B-3			161150	4.14	3 5 4 9
Ave.				4.44	3671
C-1	CR3-30	30	56935	3.88	3 7 6 1
C-2			53 0 50	3.37	3 504
C-3			54275	3.53	3 5 8 5
Ave.				3.59	3617

CFG nominal thickness: t_{frp} (mm)

In view of G_f of standard B equivalent to that of standard A, laminating CFG layers at a low reinforcement level would not affect the adhesion strength.

Next, the effective adhesion length was calculated using the following formulas:

$$\begin{aligned} \tau_{y} &= \Delta \varepsilon_{F} \times E_{frp} \times AF/S_{g}/b \end{aligned} \tag{2} \\ L_{e} &= P_{max}/(2 \times \tau_{y} \times b) \end{aligned} \tag{3}$$

 $L_e = P_{max} / (2 \times \tau_y \times b)$ Maximum adhesion stress: τ_v (N/mm²)

Difference from the strain gauge value in the strain increasing section: $\Delta \varepsilon_c$

Cross-sectional area of the reinforcement fiber: AF (mm²)

Gauge distance in the strain increasing section: S_g (mm²)

Effective adhesion length: L_e (mm)

Table 7 shows the calculation result of the effective adhesion length. The effective adhesion lengths obtained for all standards were in the range between 195 mm and 221 mm, showing that they were similar values. Moreover, the effective adhesion length for each standard was calculated in order to make comparisons with the experimental values, using our simple calculation formula represented by Eq. (4) as follows.

$$L_{e}' \geq \frac{1.479 \sqrt{E_{frp}} t_{frp}}{f_{c}'^{0.095}}$$
CFG fixing length: L_{e}' (mm)
$$(4)$$

CFG tensile elasticity: E_{fip} (N/mm²) CFG nominal thickness: t_{fip} (mm)

Compression strength of concrete: f_c' (N/mm²)

The comparison results between the experimental values and calculated values of the effective adhesion length are shown in **Fig. 11**. The calculated values were comparable to the experimental values, indicating the significance of the simple calculation formula. Next, the CFS fixing length at a certain reinforcement level can be obtained by calculation using the following Eq. (5) used in many cases as a calculation formula of the fixing length of a CFS.

$$h = \frac{\sigma_{CF} \times t_{CF}}{\tau_{CF}} = 862 \text{ mm}$$
(5)
CFS fixing length: *h* (mm)

Table 7 Results of calculation enable attachment length

No	CEG	$P_{\rm max}$	$ au_{v}$	L _e
INO.	Cru	(N)	(N/mm^2)	(mm)
A-1	CR10-100	187980	2.29	220
A-2		193 150	2.09	221
A-3		222810	2.37	217
Max				221
B-1	CR3-50	167770	2.14	190
B-2		171120	1.96	182
B-3		161150	1.61	208
Max				208
C-1	CR3-30	56935	3.45	165
C-2		53 0 50	3.19	166
C-3		54275	2.79	195
Max				195



Fig. 11 Comparison of experimental value and calculated value

Design tensile strength: $\sigma_{CF} = 2300 \text{ (N/mm^2)}$

Sheet thickness: $t_{CF} = 0.169 \text{ (mm)}$

Design adhesion strength: $\tau_{CF} = 0.45$ (N/mm)

Meanwhile, when the fixing length of this reinforcement technology using a CFG layer assuming the same reinforcement level as a CFS layer and the underwater curing type resin is calculated using the simple calculation formula of Eq. (4), the results are as follows.

$$L_{e}' \ge \frac{1.479 \sqrt{E_{frp} t_{frp}}}{f_{e}'^{10.095}} = 209 \text{ mm}$$

CFG fixing length: $L_{e'}$ (mm) Design tensile strength: $E_{frp} = 230\,000$ (N/mm²) Converted nominal thickness: $t_{frp} = 0.169$ (mm) Concrete compression strength: $f_{e'} = 33.3$ (N/mm²)

As described above, the fixing length of a CFG could be shortened to about 1/4 of the fixing length of a CFS.

The above confirms that the reinforcing method using a CFG and the underwater curing type resin was able to obtain the reinforcement effects against the bending, shear and compression loads equivalent to or greater than those of the conventional reinforcement method. From the verification of the adhesion property, the fixing length of a CFG could be reduced to about 1/4 of the CFS fixing length.

4. Construction Examples

4.1 Repair work of the Yumesakigawa River crossing conduit bridge piers, Hirohata Works

4.1.1 Outline of the work

The RC piers of the conduit bridge (**Photo 2**) over the Yumesakigawa River on the premises of Hirohata Works, Nippon Steel & Sumitomo Metal Corporation were in a state of severe deterioration with the concrete peeling off and the reinforcing bars inside exposed and corroding (**Photo 3**). As a result of a concrete core sampling



Photo 2 Yumesakigawa River crossing conduit bridge



Photo 3 Situation of deterioration



Fig. 12 Flow of installation about major construction

test, this deterioration was considered to be corrosion by salt because chloride ions had entered the pier structure and reached the reinforcing bars, and also because the conduit bridge concerned was located about 1 km upstream from the estuary of the Yumesakigawa River, meaning that the bridge was located in a seaside type environment. The deterioration had spread to portions in air and in water alike. For the portions in air, the carbon fiber sheet jacketing method was applied in order to recover the cross-sectional condition, prevent concrete from peeling off, and protect the surfaces of the piers. For the submerged portions, the reinforcement method using the carbon fiber grids and underwater curing type resin was used. The next subsection describes the underwater repair work for the RD piers of this bridge as an example of actual construction.

4.1.2 Construction status

The construction flow is shown in **Fig. 12**. For the portions where concrete was lost and reinforcing bars were exposed, recovery work for the cross-sectional condition was performed after rust-proof treatment. The surface was sandblasted to allow a CFG to be securely fixed to existing concrete. For the specification of the carbon fiber grid used, CR5-50P (bar cross-sectional area: 13.2 mm²; distance between bars: 50 mm; P represents the number of pitches) was selected to compensate for the loss of corroded reinforcing bars. To reduce the number of processes for installation of the CFG and SUS form, metal members for retaining the CFG and SUS form were installed at the lower end of the repairing range; and the CFG and SUS forms were integrated in advance by reducing the CFG on the inner faces of the SUS form (**Photo 4**).

After the CFG-SUS form integrated member and falsework, the underwater curing type resin was injected by pump into the form. During the process of filling the form with the underwater curing type resin, the resin temperature was raised using temperature rising equipment to mobilize the resin and the resin temperature was controlled. Furthermore, in order to prevent inclusion of air in the resin that was pumped into the form, and to neatly inject the resin into the form, the resin was injected from the lower part of the SUS form. After this process was completed, the upper end of the SUS form was sealed with the underwater curing type epoxy resin putty to complete the reinforcement work (**Photo 5**).

From this experience, we learnt (1) the usefulness of the integra-



Photo 4 CFG-SUS form



Photo 5 Completion of construction



Photo 6 RC pier in the rivers

tion of a CFG with the SUS form in terms of the process reduction and (2) the conditions for working in an actual river environment. Since the RC piers in this case were linear, manufacturing and installation of the CFG and SUS form were relatively easy. While CFSs, which are in the shape of sheets, are not easily affected by any shapes of the members that are to be reinforced, it is necessary for CFGs to be processed in advance to enable them to fit the shape of the target member.

4.2 Example of reinforcement of a RC pier with curves supporting a river bridge

4.2.1 Outline

Photo 6 shows the curved RC pier installed in a river to which this method was applied. The aseismic design of the pier, which had reinforcement-reduction parts described previously, was not strong enough in some portions and required aseismic reinforcement of the reinforcement-reduction parts. As the portion with insufficient strength for which reinforcement was needed was in water, and also the occupying ratio of the pier in the cross-sectional area of the river was restricted during the reinforcement work and after the reinforce-

ment work was completed as well, the reinforcement method using a CFG and the underwater curing type resin was proposed, and adopted. Furthermore, the RC pier, the horizontal cross-section of which was elliptical in shape had curves, which made it difficult for a standard-type CFG (flat sheet, $2 \text{ m} \times 3 \text{ m}$) to be used as-is, the shape of the CFG suitable for the curves was also examined.

4.2.2 Reinforcement design of the reinforcement-reduction parts with insufficient strength

The CFG-reinforcement design for the reinforcement-reduction parts is described. A schematic of the RC pier moment curve is shown in **Fig. 13**. The design method involves obtaining the insufficient strength moment ΔM at the reinforcement-reduction parts as with the case of reinforcement design using CFSs, and determining the CFG cross-sectional area such that the insufficient moment can be compensated. The following describes the reinforcement design in the bridge axial direction as an example.

$$M_{yt} = \frac{h_1 - h_2}{h_1} \cdot M_y B \tag{6}$$

 $\Delta M = 1.2 M_{yt} - M_{y}$ (7) Moment acting in the reinforcement-reduction position for verification: M_{yt} (kNm)

Insufficient moment for reinforcement-reduction parts: ΔM (kNm)

Inertia force acting position: $h_1 = 8.170$ m Reinforcement-reduction position for verification:

$$h_2 = 2.625 \text{ m}$$

Base yield moment: $M_y B = 6658.9$ kNm

Yield moment at the reinforcement-reduction parts: $M_{\rm c} = 4247.7 \text{ kNm}$

When the values above are substituted, M_{yt} and ΔM are obtained as follows.

$$M_{yt} = \frac{h_1 - h_2}{h_1} \cdot M_y B = 4519.4 \text{ kNm}$$

$$\Delta M = 1.2M - M = 1.175.6 \text{ kNm}$$

From insufficient moment at reinforcement-reduction position ΔM as calculated, the necessary cross-sectional area of the CFG is obtained.

$$A_{cf} = \frac{\Delta M}{\sigma_f \times \frac{7}{8} \times d}$$

$$\approx 800 \,\mathrm{mm^2}$$
(8)

Necessary CFG cross-sectional area: A_{cf} (mm²) CFG design tensile strength: $\sigma_f = 933$ N/mm² ($\approx 1400 \times 2/3$)



Fig. 13 Overview figure of moment curve

Effective height in the bridge axis direction: $d = 1\,800$ mm From the necessary CFG cross-sectional area, the specification of the CFG is determined. As a prerequisite, assuming the pier linear portion width: $b=1\,700$ mm and bar pitch: a=50 mm, when the CFG cross-section per unit: A_g is calculated, the result is as follows: $A_g = A_{cf}/(b/a) = 23.5$ mm²

From Table 1, the CFG specification that satisfies A_{a} is CR8-50P (bar cross-section: 26.4 mm²>23.5 mm²). Since the reinforcement range is the intersection $L_{a} = 1.202$ m between the resistance moment of reinforcement-reduction parts for verification and working moment, it is +2.625 m to +3.827 m assuming that the origin is the pier base. In addition, the range from +2.115 m to +4.337 m extending the fixing length $L_{cf} = 0.510$ m⁵) from each upper and lower end of the reinforcement range is the actual CFG installation range. As described above, reinforcement using CFGs can be designed in the same manner as the carbon fiber sheet jacketing method.

4.2.3 Conforming to the pier shape

The horizontal cross-sectional shape of the RC pier concerned was elliptical in shape and consisted of linear and curved parts. Since standard-type CFGs cannot be used for the curved parts, the existing pier was measured in advance by divers to prepare a custom-made curved CFG. The curved CFG was manufactured in a factory according to the data of pier width, squareness, etc., obtained by the preliminary measurement and the CFG installation range as calculated in 4.2.2. Photo 7 shows the state of the pier with the curved CFG and SUS form installed. Since the linear CFG materials and curved CFG materials were required to be connected to each other at joints, the CFG materials and SUS form were not integrated this time. After the installation of the CFG materials, the SUS form was set to the pier. In the subsequent processes, supports were installed as with the work described in 4.1. The reinforcement work was completed by filling the SUS form with the underwater curing type resin using a pump and sealing the inlet at the end of the form with putty (Photo 8).

As described above, when preliminary measurement of the existing pier is conducted and the required CFG materials are manufactured according to the data obtained by the measurement, CFGs can conform to various shapes such as a rectangular cylinder, ellipse, tapered ellipse (trapezoidal elliptic cone), etc. However, if



Photo 7 State of installation curved CFG and SUS form



Photo 8 Completion of construction

there is a large projection or unevenness due to loss of concrete on the surface in the reinforcement range, it is difficult to apply CFGs. In such case, preliminary processing such as removal of the projection, smoothing the unevenness, repair of the cross-section, etc. may be required.

5. Future Prospect

Table 8 shows a list of reinforcements to which the method using CFGs in this report is applied. This method was started with RC foundation repair and reinforcement on the premises of Nippon Steel & Sumitomo Metal, and the application of this method is now beginning to be expanded to public office projects that mainly involve river RC pier reinforcements. Along with this expansion of application, the CFG-reinforcement is accumulating experience in dealing with various shapes of reinforcement objects, such as an elliptic horizontal cross-section and tapered horizontal cross-section. In particular, this method is suitable for piers located in small rivers in urban areas, given the thickness of the finished reinforcement layer that is no more than 20 to 30 mm requiring a small occupying ratio in the river's cross-sectional area during and after the work, and also the use of light-weight materials eliminating the need for heavy machinery. As described in the introduction, we will strive to expand the demand for this pier reinforcement method using carbon fiber grids and the underwater curing type resin, which has advantages described above.

6. Conclusion

This report described a pier reinforcement technology using carbon fiber grids and underwater curing type resins in four parts: an outline of the technology, verification of the reinforcement effects, introduction of case examples, and future prospects. The following provides a summation of the results.

(1) This reinforcement method, which uses carbon fiber grids and underwater curing type resins, eliminating the need for coffering or unwatering work and allowing underwater work by divers, is a reinforcement technology advantageous for working on structures in deep water where it is difficult to provide a

Timing of implementation	Place	Facility name	Area of CFG
•••••	•		6.0.2
2000.9	Iwate	Pier pile	6.0 m^2
2006.5	Hyougo	Water tank	3.0 m ²
2009.3	Hyougo	Pier	32.0 m ²
2013.1	Aichi	Bank protection	25.0 m ²
2014.1	Tottori	Beams of pier	187.0 m ²
2014.11	Toyama	Pier	30.0 m ²
2014.11	Toyama	Pier	25.0 m ²
2015.1	Tottori	Beams of pier	75.0 m ²
2015.2	Miyagi	Pier	50.0 m ²
2016.3	Tokyo	Pier	63.0 m ²
2016.4	Aichi	Bank protection	4 390.0 m ²
	4886.0 m ²		

Table 8 Construction results list

coffering structure or in locations where the occupying ratio of the cross-sectional area of a river is problematic.

- (2) Using the test data in the past, it was verified that this reinforcement method has reinforcement effects against the bending, shear, and compression loads equivalent to or greater than the reinforcement effects of the carbon fiber sheet jacketing method. Also it was confirmed from the verification of the adhesion property that the reduction of fixing length is allowed.
- (3) Using examples of reinforcement work, it was confirmed that the same design method as that used for the carbon fiber jacketing method can be used for designing when this reinforcement method is used.
- (4) The use of this method started from RC foundation repair and reinforcement on the premises of Nippon Steel & Sumitomo Metal has been expanded to projects of public offices recently. Going forward, we will strive to further expand the demand for this pier reinforcement method using CFGs and underwater curing type resins.

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