STUDY ON ANCHOR BEHAVIOR OF CFRP PLATE TO CONCRETE

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ABSTRACT :

In this study, direct shear type bond test is conducted to examine the anchor behavior of CFRP plate to concrete. CFRP plate is bonded to concrete and anchored by five types of anchor method. In case of anchorage method by carbon fiber sheet, the debonding of CFRP plate is restrained after maximum load. In case of anchorage method by multilayer CFRP plate, effectiveness of anchor strength is not confirmed. In case of anchorage method by steel plate, most effective anchor behavior is obtained and maximum load is more than 3.65 times of the calculated bond strength without anchorage. In case of anchorage method by mortar spacer and carbon fiber sheet, maximum load is 1.09-1.72 times of the calculated bond strength. Even if load decreases once, load increases again to about 0.6-0.9 times of the maximum load. In case of anchorage method by side CFRP plate and carbon fiber sheet, bond strength increases by sharing the tensile force through carbon fiber sheet.

KEYWORDS: CFRP plate, Bond, Anchor, Slippage, Carbon fiber sheet

1. INTRODUCTION

In recent years, continuous fiber sheet have been used as reinforcing material for concrete structure. Meanwhile, CFRP (Carbon Fiber Reinforced Plastic) plate with its greater stiffness than continuous fiber sheet has an advantage of workability. Therefore, CFRP plate has been used for flexural strengthening on beam or slab. It is the most important to transmit the force between CFRP plate and concrete. The bond strength between CFRP plate and concrete has been investigated in the previous research [1]. However, CFRP plate should be needed to anchor if design force of CFRP plate exceeds bond strength between CFRP plate and concrete. In this research, in order to increase bond strength by anchorage, five types of anchoring methods for CFRP plate are examined. Those are anchoring by overlap of fiber sheet, multilayer CFRP plate, steel plate and anchor bolts, mortar spacer and carbon fiber sheet and side CFRP plate and carbon fiber sheet. In this study, the specimens of concrete block on which CFRP plate is attached with epoxy resin, is loaded to confirm the effect of five types of the anchoring method and the local anchorage behavior of the CFRP plate is investigated.

2. OUTLINE OF LOADING TEST

2.1. Specimen

Figure 1 shows the shape of specimen. The specimen is the concrete block and reinforcing bar are set in it. CFRP plate with 50mm in width is attached on concrete block with putty type (high viscosity) epoxy resin. Then, each type of the anchoring method is applied.

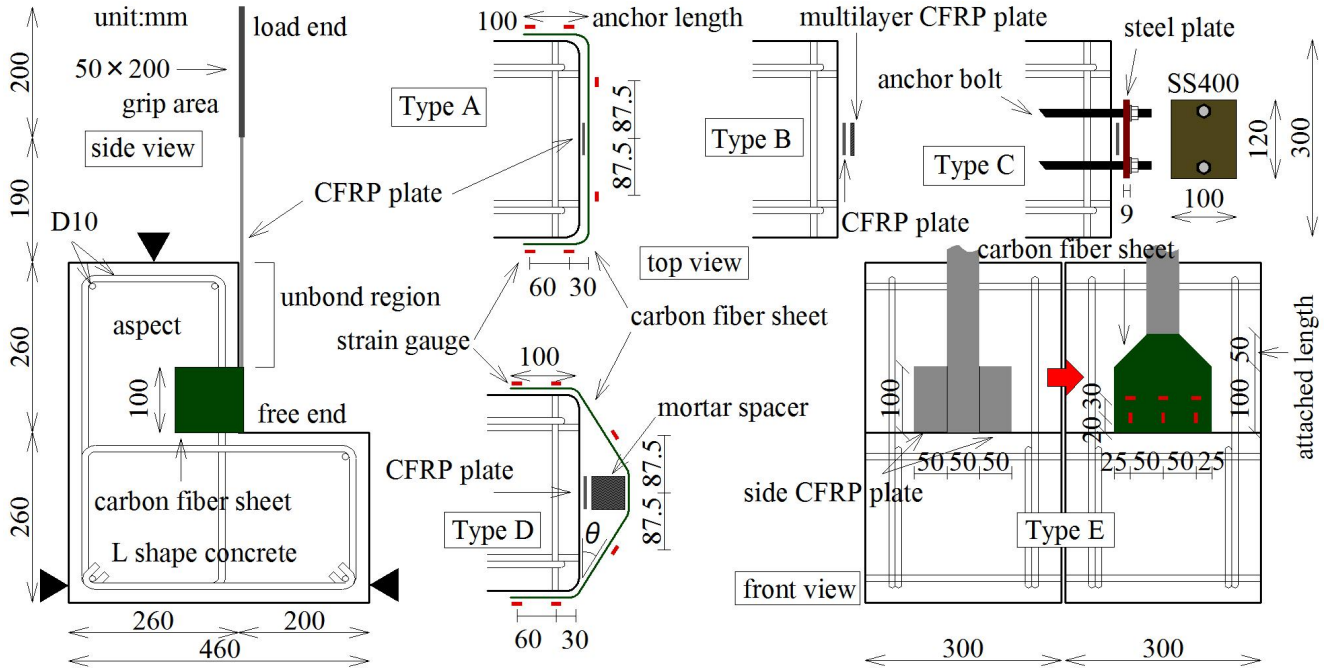

Figure 1 The shape of specimen

Type A anchorage method is that carbon fiber sheet with 100mm in width is attached on free end of CFRP plate. Their fiber direction is perpendicular to CFRP plate. The sheet is attached on lateral side of concrete block by 100mm or 0mm, called anchorage length. In case that anchorage length is 0mm, the sheet is three layered. In case that anchorage length is 100mm, the sheet layer is 1. In Type B anchorage method, multilayer CFRP plate, which length is 100mm and same type and thickness of base CFRP plate, is attached over the base plate at the free end. Their fiber direction is same. Type C anchorage method is using steel plate and anchor bolts. The thickness of steel plate is 9mm. The anchor bolt is inserted to concrete by 10 times of its diameter. Type D anchorage method is that carbon fiber sheet with 100mm in width is attached on free end of CFRP plate after mortar spacer which shape is rectangular is fixed on same position by epoxy resin. Anchorage length of fiber sheet is 100mm. The one-way type fiber sheet or two-way type fiber sheet is applied. Type E anchorage method is that additional CFRP plates, which lengths are 100mm, are attached at the both sides of base CFRP plate. Moreover, two-way type carbon fiber sheet which shape is symmetric hexagon is attached on them. The layer numbers of carbon fiber sheet is 1, 2 or 3 and the length from the up-end position of side plate is 50mm or 100mm. The type and thickness of side plate is same as base plate. The total specimen number is 51.

2.2. Used Material

Normal concrete of three levels of compressive strength, 13.5, 21 and 36MPa are used. Table 1 shows the results of compression test of test piece. Elastic modulus is a 1/3 secant modulus. Table 2 shows mechanical properties of CFRP plate. The two types CFRP plate, high strength type and high stiffness type, are tested. The width of CFRP plate is 50mm. The stiffness of CFRP plate is defined as thickness times elastic modulus of CFRP plate. Table 3 shows mechanical properties of carbon fiber sheet. The unit weight of fiber sheet is 300g/m^2. The width of carbon fiber sheet is 100mm. For type A anchorage method, three layered carbon fiber sheet is attached in case of 0mm anchorage length, and one layered sheet is attached in case of 100mm anchorage length. Steel plate has the rectangular shape with 120mm in width, 100mm in length and 9mm in thickness. Steel plate has 2 or 4 holes for anchor bolt which diameter is 12mm or 16mm. The number of anchor bolt is 2 or 4. Mortar spacer is the shape of rectangular solid with 50mm in width, 100mm in length and 40 or 80 or 120mm in thickness. The result of compression test of test piece of mortar shows that compressive strength is 50.9MPa and elastic modulus is 25.4GPa.

Table 1 Mechanical properties of concrete

Concrete type (MPa)	The type A or B or C of anchorage method		The type D or E of anchorage method	
	Compressive strength (MPa)	Elastic modulus (GPa)	Compressive strength (MPa)	Elastic modulus (GPa)
13.5	15.6	21.2	18.6	26.6
21	24.6	26.4	27.4	28.0
36	37.6	31.2	42.2	31.0

Table 2 Mechanical properties of CFRP plate

Type	Name	Tensile strength (MPa)	Elastic modulus (GPa)	Thickness (mm)	Stiffness (kN/mm)
High strength	G1	2970	175	1.0	175
	G2	3520	165	2.0	330
High stiffness	H2	1620	480	2.0	960

Table 3 Mechanical properties of carbon fiber sheet

Fiber direction	Type	Thickness (mm)	Tensile strength (MPa)	Standard elastic modulus (GPa)	Elastic modulus (GPa)	Anchorage method
1	High strength	0.167	4510	230	233	A
			4810			D
	Middle elastic		3964	390	384	A
2	High strength	0.0833	4040	230	229	A, D, E

2.3. Methods of Loading and Measurement

Direct shear type bond test is conducted by pullout the upper area of CFRP plate. Load, horizontal and vertical displacements and strains of carbon fiber sheet are examined. The horizontal displacement is measured at the position of 150mm from the free end of CFRP plate and vertical one is measured at 100mm from it. Uni-axial strain gauges are used in the case of the one-way type fiber sheet and tri-axial strain gauges are used in the case of two-way type fiber sheet.

3. BOND STRENGTH CALCULATION

In order to compare maximum load obtained by loading test with bond strength in case that CFRP plate is attached to concrete only by epoxy resin, bond strength is calculated as bond length in 100mm by previously reported method [1]. The bond strength calculation formulas are shown below.

$$\tau_{b,\max} = 2.5 \cdot \sigma_B^{0.23} \tag{3.1}$$

$$l_e = \sqrt{\frac{2 \cdot t_{fp} \cdot E_{fp} \cdot s_e}{k_e \cdot \tau_{b,\max}}} \tag{3.2}$$

$$P_b = \begin{cases} k_e \cdot \tau_{b,\max} \cdot b_{fp} \cdot l_e & (l_b > l_e) \\ k \cdot \tau_{b,\max} \cdot b_{fp} \cdot l_b & (l_b < l_e) \end{cases} \tag{3.3}$$

$$k = \frac{1-k_e}{2} \cdot \cos\left(\frac{l_b}{l_e}\pi\right) + \frac{1+k_e}{2} \tag{3.4}$$

Where, maximum local bond stress $\tau_{b,\max}$, concrete compressive strength σ_B, effective bond length l_e, width b_{fp} and thickness t_{fp} and elastic modulus E_{fp} of CFRP plate, local slippage of the effective bond area s_e (0.234mm), stress coefficient of EBSB (Equivalent Bond Stress Block) in case of effective bond length k_e (0.428), bond length l_b, bond strength P_b, stress coefficient of EBSB k. Effective bond length is defined as the region that bond stress becomes more than 10% of the maximum bond stress. Table 4 shows calculated bond strength.

Table 4 Calculated bond strength

Concrete type (MPa)	CFRP plate	The type A or B or C anchorage method		The type D or E anchorage method	
		Effective bond length (mm)	Bond strength (kN)	Effective bond length (mm)	Bond strength (kN)
13.5	G1	201.7	16.88	197.7	17.35
	G2	277.0	19.63	271.5	20.30
	H2	472.5	22.08	463.0	22.93
21	G1	191.4	18.12	189.1	18.42
	G2	262.9	21.38	259.6	21.81
	H2	448.3	24.35	442.8	24.92
36	G1	182.3	19.30	179.9	19.63
	G2	250.3	23.11	247.0	23.60
	H2	427.0	26.66	421.4	27.32

4. RESULTS OF EXPERIMENT

4.1. Type A Anchorage Method

Table 5 shows results of experiment. The maximum load tends to increase with increase of concrete strength or the stiffness of CFRP plate. It is considered that the elastic modulus of carbon fiber sheet does not affect the maximum load. When the high strength type CFRP plate is anchored by the type A anchorage method, the maximum load of two-way type fiber sheet is larger than that of one-way type. In other hand, in case of the high stiffness type CFRP plate, same trend is not observed. Almost same maximum load for anchorage length 0mm is obtained with anchorage length 100mm. The ratio of maximum load to calculated bond strength ranges from 0.93 to 1.50. In almost all specimens, the maximum load exceeds calculated bond strength and bond strength can be improved by anchorage.

Table 5 Test results (Type A anchorage method)

Specimen No.	Name of specimen*	At maximum load		At maximum bond stress		Maximum load / Calculated bond strength
		Load (kN)	Horizontal displacement (mm)	Bond stress (MPa)	Slippage (mm)	
1	A13-G2-230-100-1	24.10	0.260	4.82	0.138	1.23
2	A13-H2-230-100-1	20.57	0.214	4.11	0.008	0.93
3	A21-G1-230-100-1	20.96	0.004	4.19	0.187	1.16
4	A21-G1-390-100-1	22.40	-0.328	4.48	0.302	1.24
5	A21-G2-230- 0-1	26.20	0.474	5.24	0.097	1.23
6	A21-G2-230- 0-2	31.96	0.084	6.39	0.195	1.50
7	A21-G2-230-100-1	24.00	-0.276	4.80	0.199	1.12
8	A21-G2-230-100-2	25.18	0.408	5.04	0.108	1.18
9	A21-G2-390-100-1	23.51	0.228	4.70	0.105	1.10
10	A21-H2-230- 0-1	27.50	0.164	5.50	0.399	1.13
11	A21-H2-230- 0-2	24.59	-0.162	4.92	0.106	1.01
12	A21-H2-230-100-1	27.58	-0.120	5.52	0.077	1.13
13	A21-H2-230-100-2	27.23	0.236	5.45	0.065	1.12
14	A21-H2-390-100-1	26.77	0.236	5.35	0.005	1.10
15	A36-G2-230-100-1	31.75	0.306	6.35	0.162	1.37
16	A36-H2-230-100-1	28.64	0.206	5.73	0.037	1.07

* Anchorage method, concrete strength-CFRP plate-elastic modulus of carbon fiber sheet-anchorage length-fiber sheet type

Figure 2 shows the bond stress versus slippage relationship. Bond stress decrement after the maximum bond stress finishes at slippage around 2mm and then bond stress increases slightly with increase of the slippage.

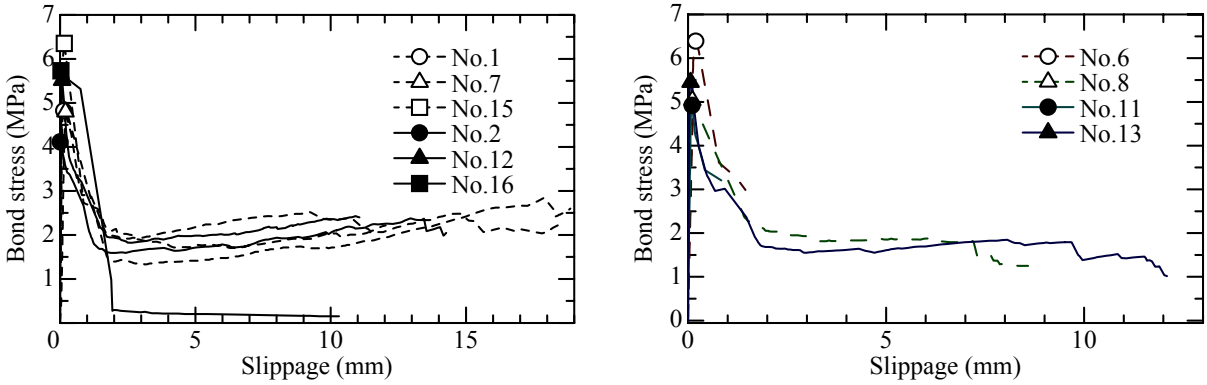

Figure 2 Bond stress versus slippage relationship

4.2. Type B Anchorage Method

Table 6 shows the results of experiment. The maximum load increases with increase of the thickness of CFRP plate and the number of multilayer CFRP plate. However, it decreases with increase of the elastic modulus of CFRP plate. The ratio of maximum load to calculated bond strength ranges from 0.73 to 0.94. There is no improvement by this type of anchorage method for local bond strength.

Table 6 Test results (Type B anchorage method)

Specimen No.	Name of specimen*	At maximum load		At maximum bond stress		Maximum load / Calculated bond strength
		Load (kN)	Horizontal displacement (mm)	Bond stress (MPa)	Slippage (mm)	
17	B21-G1-G1-1	14.71	0.806	2.94	0.100	0.81
18	B21-G2-G2-1	19.20	0.516	3.84	0.101	0.90
19	B21-G2-G2-2	20.18	0.274	4.04	0.074	0.94
20	B21-H2-H2-1	17.78	0.688	3.56	0.037	0.73

* Anchorage method, concrete strength-CFRP plate-multilayer CFRP plate-number of multilayer CFRP plate

Figure 3 shows the bond stress versus slippage relationship. The slippage at maximum bond stress tends to decrease with increase of the stiffness of CFRP plate. The slippage around maximum bond stress suddenly increases.

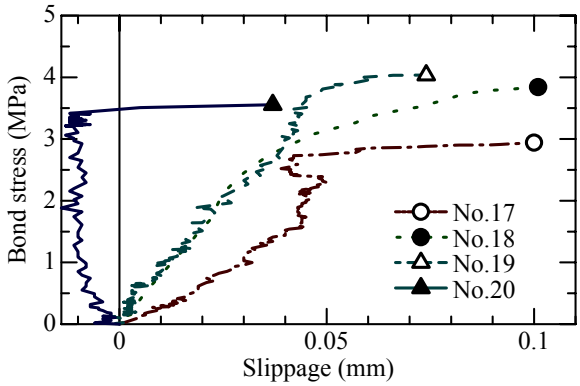

Figure 3 Bond stress versus slippage relationship

4.3. Type C Anchorage Method

Table 7 shows the results of experiment. The maximum load tends to increase with increase of concrete compressive strength, the stiffness of CFRP plate and increase of the total sectional area of the anchor bolts in generally. The ratio of maximum load to calculated bond strength ranges from 3.65 to 5.66. Bond strength can be largely improved up by steel plate and anchor bolt anchorage method.

Table 7 Test results (Type C anchorage method)

Specimen No.	Name of specimen*	At maximum load		At maximum bond stress		Maximum load / Calculated bond strength
		Load (kN)	Horizontal displacement (mm)	Bond stress (MPa)	Slippage (mm)	
21	C13-H2-M12-2	80.51	0.684	16.10	1.578	3.65
22	C13-H2-M16-2	93.67	0.802	18.73	1.916	4.24
23	C21-G1-M12-2	91.20	0.508	18.24	1.494	5.03
24	C21-G1-M16-2	70.92	0.850	14.18	0.776	3.91
25	C21-G2-M12-2	94.25	1.208	18.85	0.965	4.41
26	C21-G2-M12-4	120.91	0.696	24.18	0.951	5.66
27	C21-G2-M16-2	102.10	0.832	20.42	1.160	4.78
28	C21-H2-M12-4	94.99	0.730	19.00	0.188	3.90
29	C21-H2-M16-2	113.97	0.778	22.79	0.956	4.68
30	C36-H2-M12-2	100.55	0.916	20.11	0.863	3.77
31	C36-H2-M16-2	102.78	0.856	20.56	2.659	3.86

* Anchorage method, concrete strength-CFRP plate-the diameter of anchor bolt-the number of anchor bolt

4.4. Type D Anchorage Method

Table 8 shows the results of experiment. The maximum load increases in almost linear to concrete strength in the case of G2. However, the same tendency is not observed in the case of H2. The maximum load increases with increase of the stiffness of CFRP plate in the case of D13 and D21 specimens. The maximum loads are almost same between 40 and 80mm of the thickness of mortar spacer, while it increases in the case of 120mm. The maximum load with two-way type fiber sheet is larger than that of one-way fiber. The ratio of maximum load to calculated bond strength ranges from 1.09 to 1.72. In all specimens, the maximum load exceeds the calculated bond strength and bond strength increases by mortar spacer and carbon fiber sheet anchorage.

Table 8 Test results (Type D anchorage method)

Specimen No.	Name of specimen*	At maximum load			At maximum bond stress		Maximum load / Calculated bond strength
		Load (kN)	Horizontal displacement (mm)	Confinement force (kN)	Bond stress (MPa)	Slippage (mm)	
32	D13-G2- 80-1	25.28	0.550	4.37	5.06	0.365	1.25
33	D13-H2- 80-1	29.59	0.144	2.07	5.92	0.156	1.29
34	D21-G2- 40-1	30.17	0.402	0.80	6.03	0.101	1.38
35	D21-G2- 80-1	29.12	0.272	2.02	5.82	0.143	1.34
36	D21-G2- 80-2	37.59	0.154	1.06	7.52	0.242	1.72
37	D21-H2- 40-1	35.68	0.334	0.60	7.14	0.053	1.43
38	D21-H2- 80-1	34.76	0.006	1.13	6.95	0.098	1.39
39	D21-H2-120-1	42.73	0.430	2.21	8.55	0.129	1.71
40	D36-G2- 80-1	35.57	0.580	3.31	7.11	0.225	1.51
41	D36-H2- 80-1	29.81	0.290	1.33	5.96	0.045	1.09

* Anchorage method, concrete strength-CFRP plate-thickness of mortar spacer-fiber sheet type

Figure 4 shows the bond stress versus slippage relationship. After the bond stress reached the maximum, the bond stress decreases about half of the maximum one at slippage of 1.5mm and then the bond stress increases again to about 60-90% of the maximum. The specimen of two-way fiber sheet shows rupture of fiber sheet before large slippage.

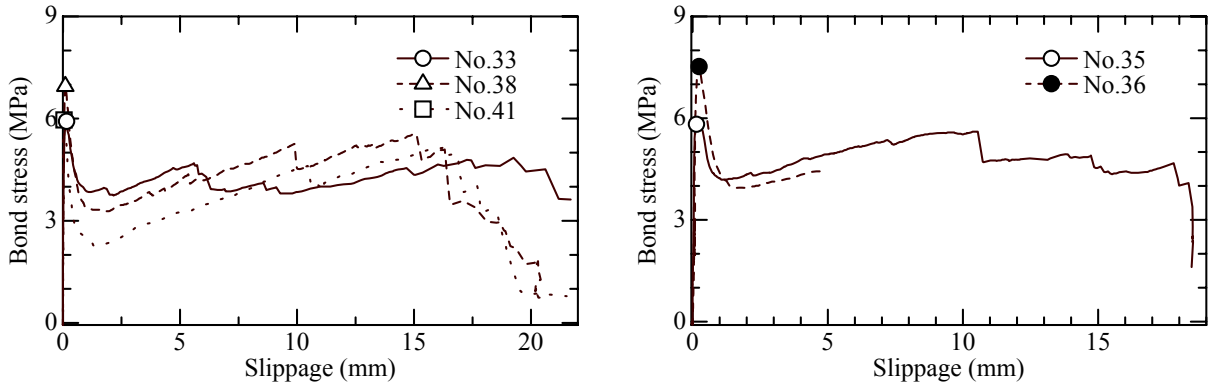

Figure 4 Bond stress versus slippage relationship

The tensile force of fiber sheet T_f is calculated by the strain ε_f obtained by strain gauges using Eq. (4.1).

$$T_f = E_f \cdot \varepsilon_f \cdot t_f \cdot b_f \tag{4.1}$$

E_f is the elastic modulus of the carbon fiber sheet, t_f is the thickness and b_f is the width. The perpendicular component $T_f \sin\theta$ is the confinement force for CFRP plate. Figure 5 shows confinement force versus slippage relationship. Table 8 also shows the confinement force at maximum load. The confinement force at maximum load is about 2kN, which would contribute to the increase of the bond strength. However, the maximum load does not tend to increase with the increment of confinement force at the maximum.

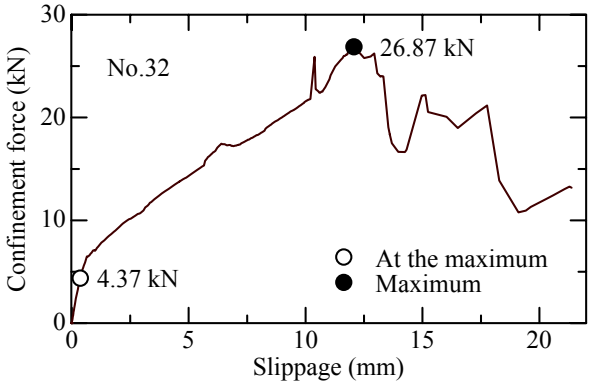

Figure 5 Confinement force versus slippage relationship

4.5. Type E Anchorage Method

Table 9 shows the results of experiment. The maximum load increases with increase of the thickness of CFRP plate and the number and attached length of the carbon fiber sheet. The ratio of maximum load to calculated bond strength ranges from 1.52 to 2.38. In all specimens, the maximum load exceeds the calculated bond strength. The bond strength can increase by the increment of bonded are of CFRP plate and force transmission through fiber sheet.

Figure 6 shows the bond stress versus slippage relationship. The slippage around maximum bond stress suddenly increases. For the specimen No.48, after maximum bond stress, bond stress decreases slowly while slippage increases to more than 2mm.

Table 9 Test results (Type E anchorage method)

Specimen No.	Name of specimen*	At maximum load		At maximum bond stress		Share rate of the force			Maximum load / Calculated bond strength
		Load (kN)	Horizontal displacement (mm)	Bond stress (MPa)	Slippage (mm)	Left (%)	Center (%)	Right (%)	
42	E21-G1-3- 50	35.36	0.274	7.07	0.265	6.2	70.0	23.8	1.92
43	E21-G1-3-100	37.85	0.018	7.57	0.145	9.3	77.1	13.6	2.05
44	E21-G2-1-100	38.73	0.002	7.75	0.232	2.4	85.2	12.4	1.78
45	E21-G2-2-100	43.17	-0.004	8.63	0.182	5.9	86.0	8.1	1.98
46	E21-G2-3- 50	41.62	0.138	8.32	0.179	5.7	78.5	15.8	1.91
47	E21-G2-3-100	51.92	0.052	10.38	0.229	-	-	-	2.38
48	E21-H2-1-100	37.80	-0.016	7.56	0.144	2.3	73.6	24.1	1.52
49	E21-H2-2-100	40.21	0.038	8.04	0.223	0	90.9	9.1	1.61
50	E21-H2-3- 50	38.62	0.100	7.72	0.122	0	84.7	15.3	1.55
51	E21-H2-3-100	50.21	-0.020	10.04	0.202	6.2	91.1	2.7	2.01

* Anchorage method, concrete strength-CFRP plate-number of sheet layer-attached length

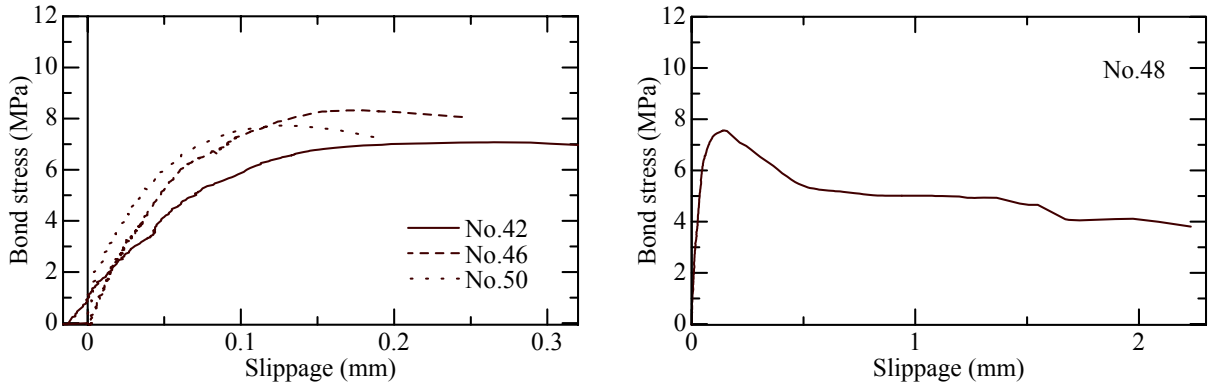

Figure 6 Bond stress versus slippage relationship

The load, which is carried by side CFRP plates through carbon fiber sheet from base CFRP plate at maximum load, is obtained by the vertical strain of carbon fiber sheet. The share rate is defined as the ratio of carried force by side plate to whole tensile load. The result of calculation is shown in Table 9. The force from 70 to 90% is carried on the base CFRP plate.

5. CONCLUSIONS

1. In case of anchorage method by carbon fiber sheet, the debonding of CFRP plate is restrained after maximum load.
2. In case of anchorage method by steel plate, most effective anchor behavior is obtained and maximum load is more than 3.65 times of the calculated bond strength.
3. In case of anchorage method by mortar spacer and carbon fiber sheet, maximum load is 1.09-1.72 times of the calculated bond strength. Even if load decreases once, load increases again to about 0.6-0.9 times of the maximum load.
4. In case of anchorage method by side CFRP plate and carbon fiber sheet, bond strength increases by sharing the tensile force through carbon fiber sheet.

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