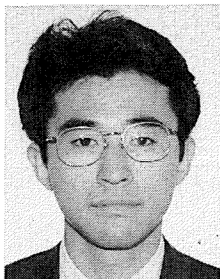
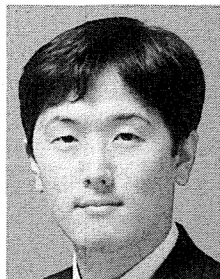


FUNDAMENTAL STUDY ON BOND MECHANISM OF CARBON FIBER SHEET

(Translation from Proceedings of JSCE, No.648/V-47, May 2000)



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The aim of this study is to clarify the bond mechanism at play when Carbon Fiber Sheet (CFS) is bonded to concrete using epoxy resin, and to propose numerical methods able to simulate CFS bond behavior and bond strength. A bond stress-slip-strain relation for CFS is developed on the basis of bond characteristics as clarified through experiments. A numerical method based on this bond stress-slip-strain relation accurately models actual bond behavior. Also reported is a bond strength equation developed from the numerical analysis, which is able to predict the experimental results with good accuracy.

Keywords: *Carbon fiber sheet, delamination, bond mechanism, bond stress-slip-strain, bond strength*

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1. INTRODUCTION

Continuous Fiber Sheet (CoFS) is widely used in the retrofitting of existing concrete structures, because it offers good mechanical characteristics and ease of construction.

The CoFS is usually attached to the concrete structures using an epoxy resin. As a result, the tensile force acting in the CoFS is transferred to the concrete through the bonding interface. Therefore, mechanical characteristics of concrete structures retrofitted with CoFS are greatly affected by the bonding behavior of CoFS [1].

Recently, on the basis of knowledge accumulated in past applications, design manuals for CoFS have been published [2]. These manuals rely on a conventional theory of reinforced concrete in which perfect bonding is assumed without a rational assessment of the delamination behavior of CoFS. At the same time, it has been pointed out that a new design concept is needed to take bond failure into account as a possible failure mode [3]. Indeed, rational verification method for all failure modes, including bond failure, is the only way to ensure that strengthened members exhibit the required performance. As yet, however, no rational method of predicting either the start of delamination or the point of complete delamination has been proposed.

The aim of this study is to clarify the mechanism by which carbon fiber sheet (CFS) bonded to concrete with epoxy resin. Bond tests in which the bond length, number of CFS layers, and bond width are chosen as experimental parameters were carried out to examine the bond mechanism (Section 3). Based on the bond mechanism thus clarified, a model for the bond stress-slip-strain relation was developed (Section 4). Furthermore, a bond strength equation is developed through numerical analysis based on the proposed bond stress-slip-strain model (Section 5). This results presented in the paper thus go part way toward developing a rational design method able to evaluate the bond failure of CFS-strengthened concrete members.

It is important to note that the surface treatment given to the concrete greatly affects the bonding of CFS. This study handles only the bond behavior of CFS bonded to concrete surface using disk sander which is widely used as a standard way. The bond strength equation proposed in this paper, therefore, is applicable only to the case where the CFS is bonded to concrete by the standard way with disk sander.

2. OUTLINE OF ANALYSIS

2.1 Materials Used

The CFS used in this study contains PAN carbon fibers of diameter $5\text{--}8\text{ }\mu\text{m}$ aligned in one direction. Two types of CFS were tested, one a high-strength type and the other high-stiffness type. The mechanical properties of these two types of CFS are given in Table 1.

The concrete was made of normal Portland cement. The maximum size of coarse aggregate was 20 mm.

2.2 Method of Attaching CFS

As noted above, the surface condition of concrete greatly affects bond strength. In this study, however, this influence was not examined. The surface of all specimens was polished using a disk sander until the aggregate was visible.

After casting the concrete, it was cured under a wet cloth for a week and then left in the air for a further three days. As this point in time, the concrete surface was polished and the CFS was attached. Thereafter, the CFS-reinforced specimen was cured in air for a week before testing.

Table 1 Mechanical properties of CFS

Type of CFS	t (mm)	ρ (g/m ²)	f_t (MPa)	E_{CFS} (GPa)	ϵ_u (%)
I	0.11	200	3479	230	1.5
II	0.165	300	2940	372	0.8

t : thickness of CFS

ρ : fiber density

f_t : tensile strength

ϵ_u : ultimate strain

E_{CFS} : Young's modulus

Table 2 Type of Specimens

Type of Specimen	Experimental parameters			Number of Specimens
	p_1	p_2	p_3	
A	○	○	○	13
B	—	○	—	3
C	—	○	○	3
D	—	—	○	1

p_1 : Influence on bond length of CFS

p_2 : Influence on amount of CFS

p_3 : Influence on bond width of CFS

2.3 Specimens and Test Method

Four types of specimen were prepared for this study. The experimental parameters were bond length, number of CFS layers, and CFS width. The relationships between specimens and these parameters are shown in Table 2, and an outline of each specimen is given below.

a) Type-A specimen (Fig. 1(a))

Bond stress was applied to the CFS by pulling on a D16 steel bar that had been embedded through the center of a pair concrete blocks with a cross section measuring 100×100 mm. The steel bar was separated between the two concrete blocks. To ensure that delamination took place in the zone to be tested (at one block), additional CFS was wrapped around the other concrete block.

The Type-A specimen was taken as the standard specimen. However, concrete failure is very likely to occur before bond failure when there are more CFS layers or the CFS is wider, because greater bond stress can be developed. Consequently, to extend the specimen range, Type-B, C, and D specimens were also prepared.

b) Type-B specimen (Fig. 1(b))

Tensile force was applied directly to the CFS bonded to one side of a concrete block measuring $250 \text{ mm} \times 500 \text{ mm} \times 200 \text{ mm}$ by directly pulling it from one of the sides clad in a steel plate.

c) Type-C specimen (Fig. 1(c))

Two concrete blocks were each sandwiched between a pair of steel plates with thickness of 20 mm. The steel plates were clamped together with four unbonded steel bars. Tensile force was applied to the CFS by pulling on additional steel bars connected to the center of the steel plates.

d) Type-D specimen (Fig. 1(d))

A pair of hydraulic jacks was set up between two concrete blocks with the cross section of 100×50 mm. Tensile force was applied to the CFS using two hydraulic jacks.

2.4 Measurements

CFS strain and the ultimate load were measured. A sample of strain gage arrangement is shown in Fig. 2. Since the maximum aggregate size was 20 mm, strain gages longer than 30 mm would have been ideal; however, with such long gages we would have been unable to detect localized bond behavior. Consequently, in most cases, strain gages measuring 5 mm in length were placed at a spacing of 10 mm. To overcome the limitations of shorter gages, the strain at a particular point was taken to be the average strain measured by three nearby gages. This means that the strain values used in the investigation represent average strains over a distance of 30 mm around the location in question.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Outline

The experimental results are shown in Table 3. The failure mode of each specimen is indicated by P, CF, or B, representing peeling failure (delamination), concrete failure, and CFS fracture, respectively. The majority of specimens failed as a result of delamination. As an example, failure condition in specimen B-1 is shown in Photo 1.

This section comprises a discussion of how the bond length, the number of CFS layers, and the width of CFS influence bond strength, strain, and bond stress distribution.

3.2 Influence of Bond Length and Stiffness

a) Bond strength

Figure 3 shows the relationship between bond strength and bond length as determined from our tests and also from previous studies [4]-[7]. These experimental results are grouped using different symbols for different CFS stiffnesses per unit width, where stiffness is Young's modulus multiplied by thickness. All these test results were

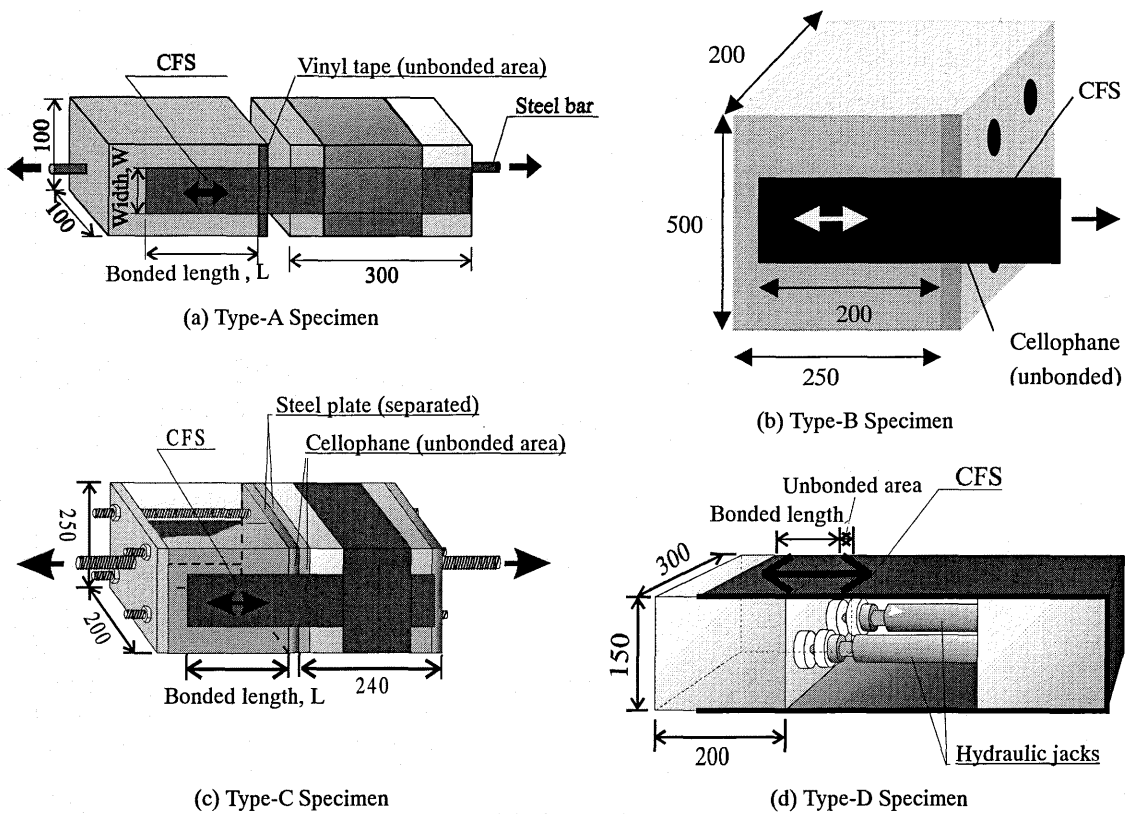


Fig.1 Specimens

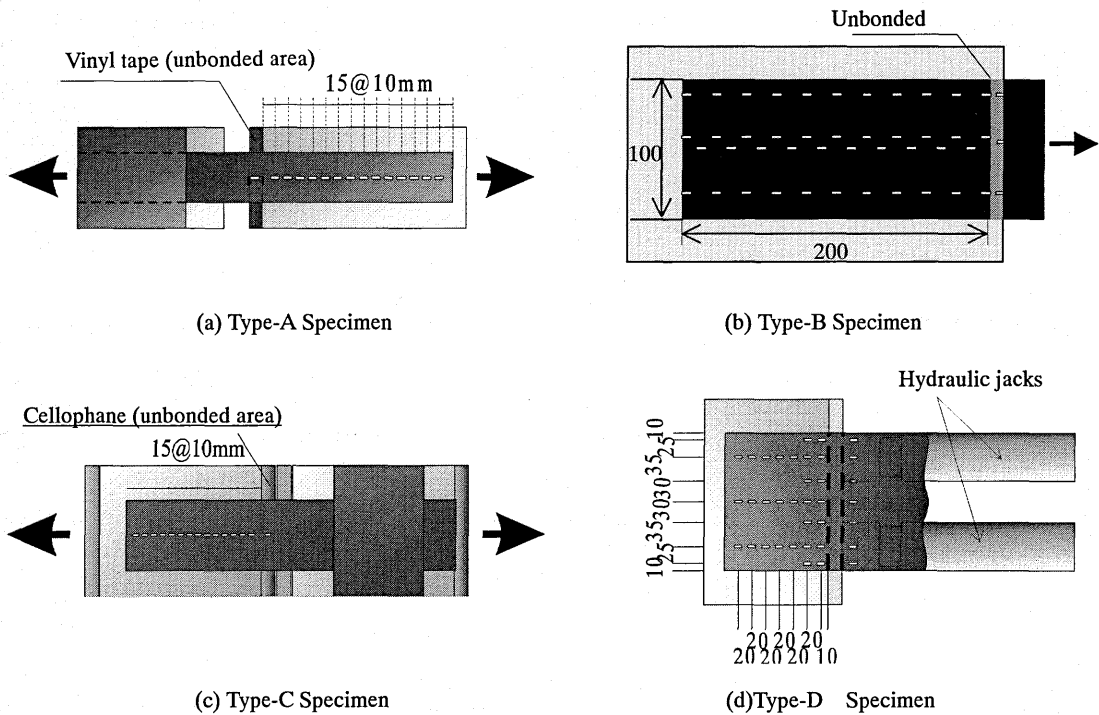
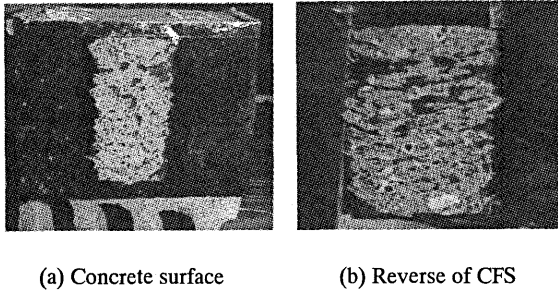
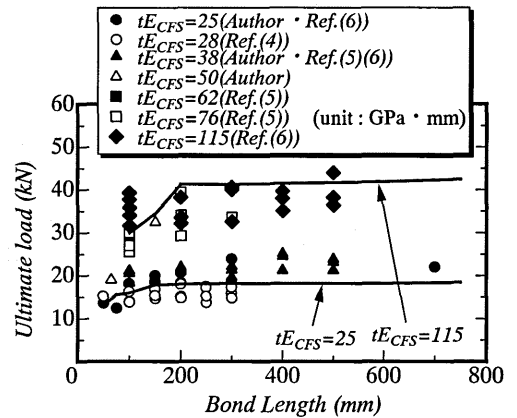


Fig.2 Arrangement of Strain Gages

Table 3 Experimental results

Specimen	Type of CFS	Bond length (mm)	Stiffness (GPa · mm)	Width of CFS (mm)	Compressive Strength (MPa)	Ultimate Load (kN)	Failure Mode ^{*1}
A	I	75	25	50	40.8	12.5	P
	I	150	25	50	40.8	18.4	P
	I	300	25	50	43.3	23.9	P
	I	75	50	50	42.4	20.0	CF
	I	150	25	50	42.4	14.6	B
	II	65	38	50	42.7	19.1	CF
	I	150	50	50	42.7	32.5	P
	I	700	25	50	39.8	22.0	P
	I	150	25	50	23.8	20.0	P
	I	150	25	10	23.8	4.8	B
	I	150	25	20	23.8	10.7	B
	I	150	76	20	24.7	18.5	P
	I	150	127	20	24.7	23.5	P
B	I	200	25	100	40.9	20.6	P
	I	200	76	100	45.9	38.0	P
	I	200	76	100	45.9	34.1	P
C	I	150	25	50	39.2	18.8	P
	I	150	25	100	39.2	37.2	P
	I	150	25	100	39.2	36.0	P
D	I	150	25	200	33.5	68.6	P

*1 P: Peeling of CFS B: Breakage of CFS CF: Concrete Failure

**Photo 1** Failure condition**Fig. 3** Relationships between bond strength and bond length

obtained from specimens strengthened with uni-directional CFS, and in all cases the test method was the same as for the Type-A specimen in this study.

Since the width of the CFS has a great effect on bond strength, as revealed later, results for bond widths ranging from 40 to 100 mm are plotted in Fig. 3. The vertical axis indicates the observed ultimate load normalized to a width of 100 mm (namely, the observed load divided by the actual width in mm and multiplied by 100). The bond strength does not increase with bond length once the bond length exceeds 100 to 200 mm. Greater CFS stiffness results in higher bond strength.

It has been reported in a previous study [8] that bond strength is proportional to the 2/3 power of concrete compressive strength. Figure 4 shows relationships between bond strength and compressive strength obtained

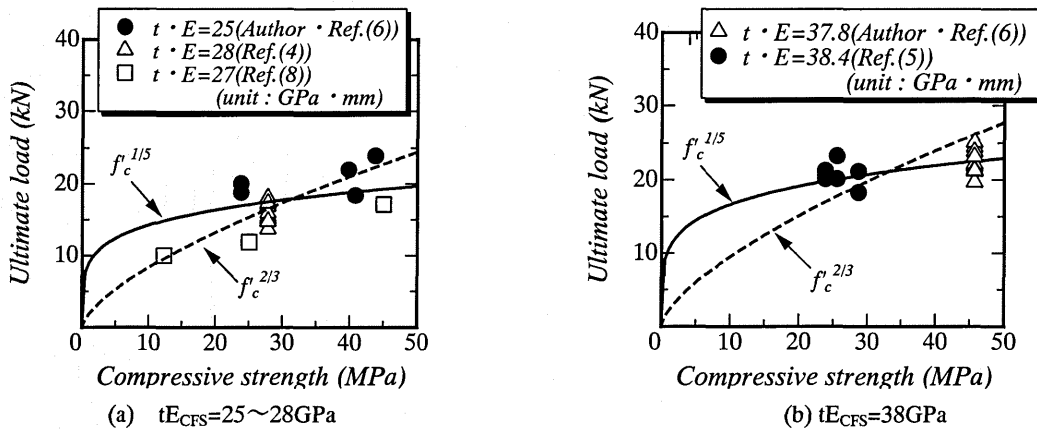


Fig.4 Influence of Compressive Strength on Bond Strength

from experimental results reported in previous studies by the authors and others [4]–[8]. Figures 4(a) and 4(b) are for specimens with CFS stiffness ranging from 25 to 28 GPa·mm and of about 38 GPa·mm, respectively. Experimental results for bond lengths greater than 200 mm and for CFS widths from 40 to 100 mm are plotted. The vertical axis indicates the observed ultimate load normalized to that for a width of 100 mm. The experimental results for bi-directional CFS obtained by Izumo et al.[8] are also shown ($\square$ in Fig. 4). The broken line indicates the results of regression analysis on the assumption that bond strength is proportional to the $2/3$ power of compressive strength. Clearly, the agreement is not good. The ultimate load increases more gradually than the broken line as compressive strength increases. Instead, the experimental results agree better with the solid regression line calculated on the assumption that bond strength is proportional to the $1/5$ power of compressive strength. Since the concrete strength of all specimens in this study is around 40 MPa, except in the case of a few specimens of smaller CFS width (see Table 3), the discussion hereafter proceeds on the understanding that the influence of concrete strength is negligible.

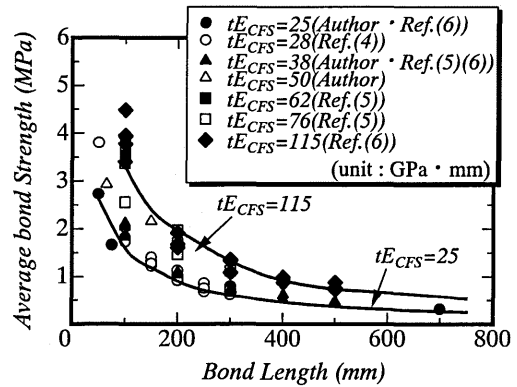


Fig.5 Relationships between Average Bond Strength and Bond Length

Figure 5 shows the relationship between bond length and average bond strength, which is the ultimate load divided by the bonded area. The average bond strength increases as bond length is reduced. The reason for this will be explained later.

b) Strain distribution

Figure 6 shows examples of strain distributions as observed in the experiment. Figures 6 (a) and 6 (b) are strain distributions for specimen A-1 with a bond length of 75 mm and for specimen A-3 with a bond length of 300 mm, respectively. Up to an applied load of 11 kN in specimen A-1, the strain distribution follows a quadratic curve except in the region close to the loaded end. At a load of 11.5 kN, the strain is reasonably uniform within a distance of 20 mm of the loaded end and followed by linear strain reduction. There is a possibility of slip occurring at the free end because some strain can be observed even 5 mm from the free end.

Specimen A-7 exhibits the same behavior as specimen A-1 (see Fig. 6 (b)). The strain distribution at 18.1 kN indicates that strain is constant within 50 mm of the loaded end, with a linear fall in strain between 50 mm and 100 mm from the end. The area of constant strain then extends toward the free end, shifting the region of linear strain reduction in the direction of the free end without increasing the pullout load. This indicates that actual bond-resisting area is a part of the area bonded to concrete but the whole bonded area. Delamination begins to

propagate when the resisting area is unable to sustain the load. The ultimate load does not increase because delamination starts at a certain load and propagates through the entire bonded area without an increase in pullout load, even for longer bond lengths. Therefore, the average bond strength, which is the ultimate load divided by the bonded area, decreases as bond length increases (See Fig. 5).

Figure 7 shows the strain distributions for specimens B-1 and B-2, which have different CFS stiffness but identical bond length and CFS width. Smaller strains and strain gradients are observed in specimen B-2, with higher CFS stiffness, at the same pullout load (14 kN). At the ultimate stage, a lower maximum strain and greater region with strain, i.e., effective bonded length, are observed.

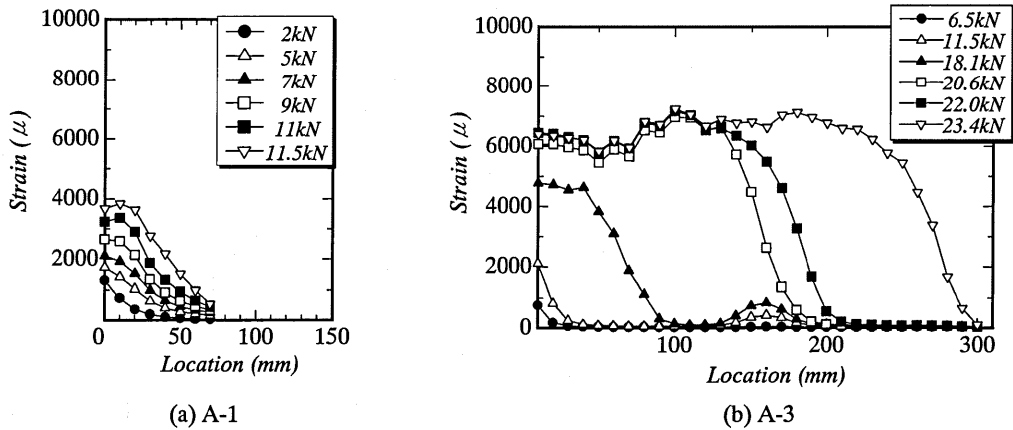


Fig.6 Strain Distribution

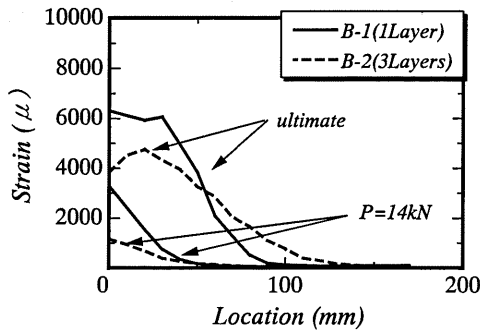
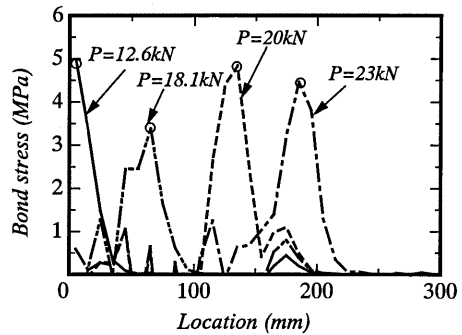


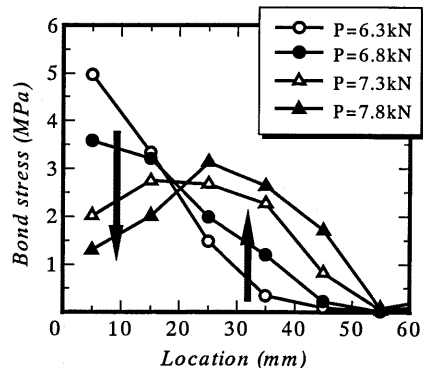
Fig.7 Strain Distribution

c) Bond stress

Figure 8 shows the changes in bond stress distribution in specimen A-3, which has a bond length of 300 mm. Figure 8 (a) illustrates the shift in bond stress towards the free end. The maximum bond stress is similar for all loads. Figure 8 (b) shows the bond stress distribution within a distance of 60 mm from the loaded end at applied loads between 6.3 kN and 7.8 kN. A decrease in bond stress in the area within 20 mm of the loaded end and an increase in the area between 30 and 60 mm from the loaded end are observed. Figure



(a) Distribution between 0 and 300 mm



(b) Distribution between 0 and 60 mm

Fig.8 Bond Stress Distribution

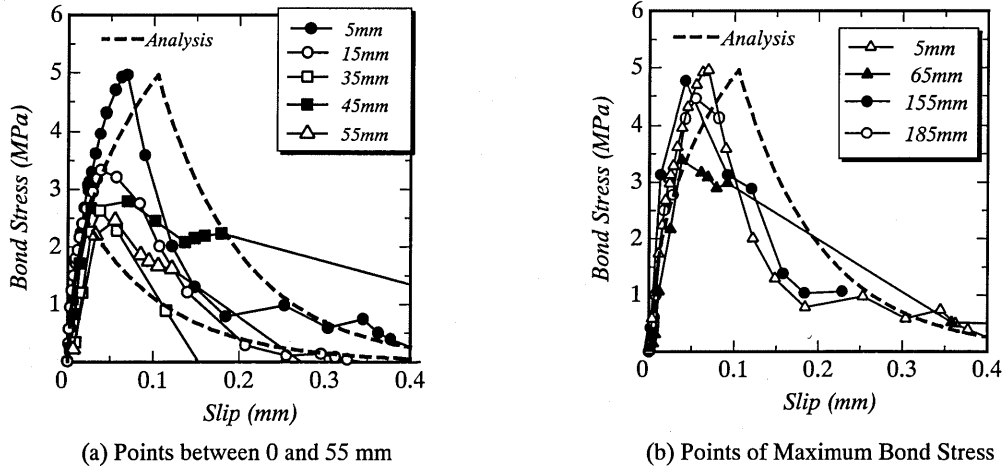


Fig.9 Bond-Slip Curves (Specimen A-3)

9 shows the relationship between bond stress and slip for the location marked in Fig. 8 (b). Slip is obtained by integrating the CFS strain, since concrete strain is negligible [13]. The bond stress is given by the following equation:

$$\tau = tE_{CFS} \frac{d\epsilon_{CFS}}{dx} \quad (1)$$

where t is CFS thickness, E_{CFS} is Young's modulus of the CFS, and $d\epsilon_{CFS}/dx$ is the gradient of the strain distribution.

The initial stiffness in the bond stress versus slip curve is the same for each location. However, the maximum bond stress differs between locations. The maximum bond stress at a point 5 mm from the loaded end is around 5 MPa, while elsewhere it is around half this value. Softening behavior, rather than a sudden reduction in bond stress to zero, is observed at all locations beyond the maximum stress.

If it is assumed that the decrease in bond stress is caused by the start of delamination (in other words, the maximum bond stress corresponds to the point at which delamination begins), then the reason for the variation in maximum bond stress with location can be explained as follows. The bonding layer of the surface concrete fractures at the 5 mm point when the maximum bond stress is reached (that is, delamination starts). This fracture induces mechanical damage in the bonding layer surrounding the fracture, because the fracture zone has a finite volume. The bonding layer originally has the same strength as at the 5-mm point when there is no damage; however, once damage occurs, delamination can take place with less bond stress, so delamination propagates toward the free end. However, as delamination and damage move further away from 5-mm point, the degree of damage is reduced until it finally reaches a negligible level at a certain distance. In this study, the distance within which the maximum bond stress reduction was observed was 80 mm. This corresponded to the distance within which the bond stress had been already developed when the softening in bond stress versus slip relationship started at the point of 5 mm from the loaded end.

The changes in strain and bond stress distributions, which represent the delamination behavior described above, are shown schematically in Fig. 10. Initially, the strain distribution follows a quadratic curve, while the bond stress is linear within region L_b (see Fig. 10 (a)). Once the bond stress in the vicinity of the loaded end reaches the maximum value, the bond stress begins to decrease, and an area of constant bond stress, L_{b1} , appears. The strain distribution in area L_{b1} can be represented by a linear curve [9] (see Fig.10 (b)). The bond stress in area L_{b1} falls to zero at the same time bond stress rises in area L_{b2} . However, the bond stress in area L_{b2} is unable to reach τ_{max} because of the damage already caused by fracturing of the bonding layer in the adjoining area. The next location at which the bond stress is able to reach τ_{max} is a certain distance further away from the loaded end (around 80 mm in the experiment). Comparing Step 1 with Step 3 (Figs. 10 (a) and (b)), the pullout force may be greater in Step 3 than that in Step 1 because the force balanced with bond stress exiting in area L'_b is added. The

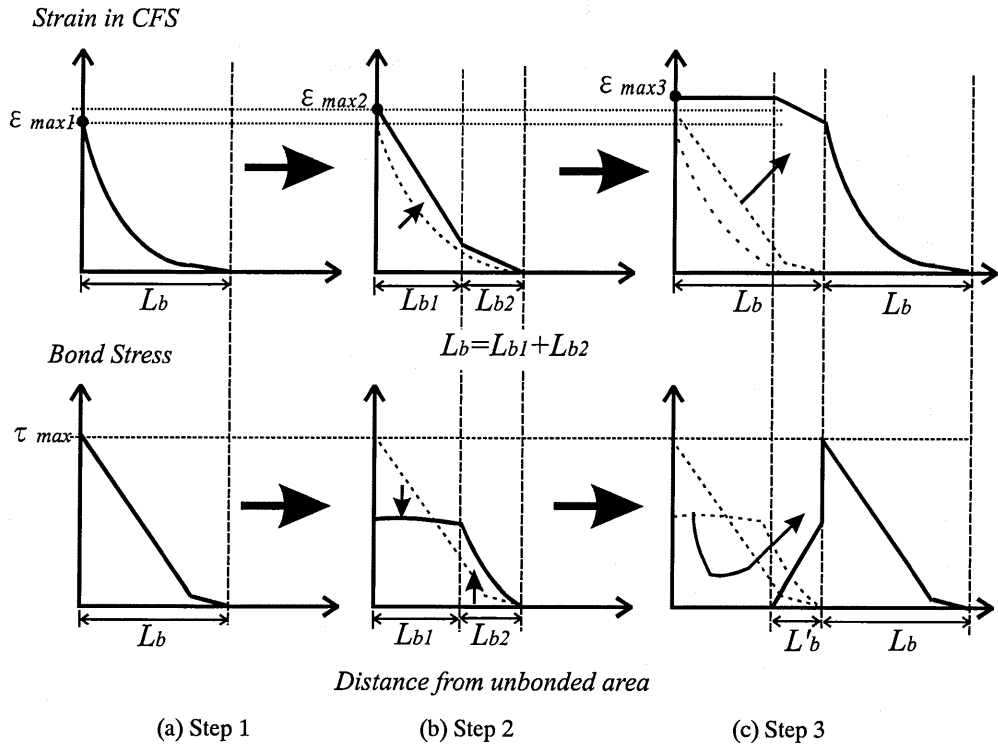


Fig.10 Schematic Relationships between Bond Stress and CFS Strain

demonstrates that, when considering the ultimate load, not only must maximum bond stress be taken into account, but also the bond stress in the softening region.

Figure 9 (b) shows τ - s curves at the point where the largest bond stress was observed. The maximum bond stress varies little with location and is between approximately 4 and 5 MPa.

The reason for the appearance of softening behavior is now discussed. The bonding layer at the concrete surface consists of aggregate and mortar in a random distribution or orientations relative to the fibers. The CFS bonds to both mortar and aggregate, with bond strength probably depending on the material. Where CFS bonds to the aggregate, it is likely that bond strength is greater, while on mortar is probably lower. When the peak stress is reached, bond stress does not fall vertically because delamination from mortar and from aggregate does not take place at the same time. This suggests that if very small strain gages were used, large variations in strain would be observed among adjoining gages. As already noted, the τ - s curves presented in this study represent an average response over an area of a certain size. In order to clarify bond failure more precisely, it will be necessary to consider the distribution of aggregate in the concrete and the variations in bond strength at different locations.

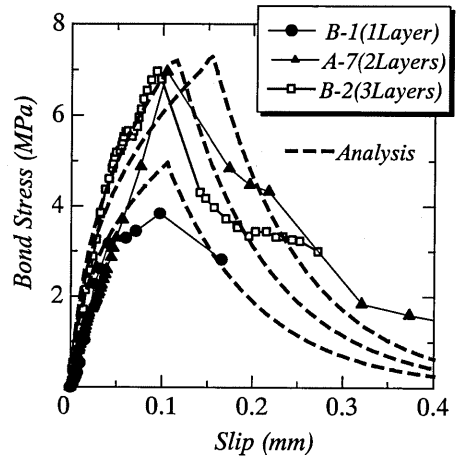


Fig.11 Comparison of Bond Stress-Slip Curves for Different Number of CFS Layers

The influence of the number of CFS layers is now discussed. Figure 11 shows the relationships between bond stress and slip for specimens B-1, A-7, and B-2, which have one, two, and three layers of CFS, respectively. In

specimens B-1 and B-2, the maximum bond stress within 30 mm of the loaded end was extremely small, but this characteristics was not observed in Type-A specimens. In Type-A tests, the tensile load was applied from both ends, while the load acts at one end only in the case of Type-B. The poorer bonding observed near the loaded end in Type-B specimens, is considered attributable to damage resulting from unexpected out-plane forces while setting up the specimen and tensile forces arising from incorrect specimen placement. It is understood in this study that the bond strength became small because of the reasons mentioned above. So as to avoid errors arising from this reduced bond strength, different points are compared in the figure: the 5-mm point in specimen A-7 and the 35-mm point in specimens B-1 and B-2. It can be said from Fig. 11 that the gradient of the τ - s curve becomes steeper as the number of CFS layers is increased. With two CFS layers, the maximum bond stress is 1.7 times that with one layer and the same as that with three CFS layers. Slip at the maximum stress in the case of one layer is 0.08 mm, while with two and three layers it is 0.1 mm.

Figure 12 shows the relationships between slip and strain for specimens B-1 and B-2. Strain falls as the number of CFS layers is increased, and stiffness becomes greater for a given value of slip.

Shima et al., have carried out bond tests with reinforcing bars of different Young's modulus, namely bars made of steel and aluminum [10]. This work clarified that the bond stress of an aluminum bar, whose Young's modulus is less than that of a steel bar, is less than that of steel reinforcement because the strain in the aluminum bar is greater than that in steel for a given value of slip. It is possible to explain the results obtained with CFS by considering stiffness instead of Young's modulus. That is, the bond stress becomes smaller as the stiffness of the CFS increases, because strain becomes smaller for a given value of slip.

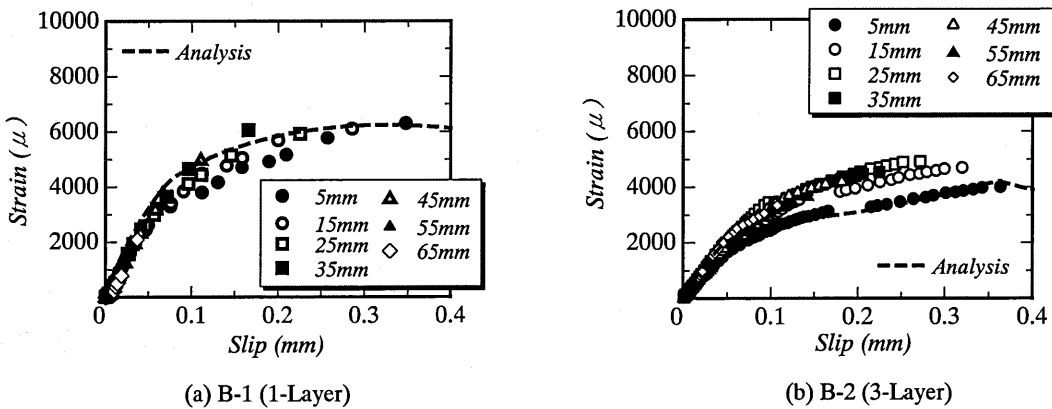


Fig.12 Strain-Slip Curves (3-Layer)

3.3 Influence of Bond Width

Figure 13 shows the relationship between bond strength and width of CFS for one and three layers of CFS. The vertical axis indicates the ultimate load normalized to a width of 100 mm. The concrete compressive strength of specimens with CFS widths up to 20 mm was around 24 MPa, while that of specimens with CFS widths 50 mm and over was 40 MPa on average. In this figure, the ultimate loads have been converted to equivalents at 40 MPa by assuming that the bond strength is proportional to the 1/5 power of compressive strength (see Fig. 4).

In the experiment, the CFS fractured in specimens A-10 and A-11, where the CFS width was 10 and 20 mm, respectively. The ultimate load at which bond failure occurs was, therefore, not reached. For the case of one layer of CFS, bond strengths for widths from 50 to 200 mm are similar, but the strengths for widths up to 20 mm are greater. For the case of three layers of CFS, the bond strength at a width of 20 mm is 30% greater than that at a width of 100 mm.

Figure 14 shows the relationship between bond strength and slip at the loaded end in specimens A-11, A-12, and A-13; these specimens had a CFS with width of 20 mm and various numbers of layers. The maximum bond

stresses are approximately 1.5 times those with CFS widths of 50 and 100 mm. However, the maximum bond stresses at locations far from the loaded end were little different among cases with different CFS widths.

The width of the fractured bonding layer was not the same as the CFS width, as shown in Photo 1. The fracturing layer includes part of the surface mortar surrounding the CFS. Small cracks, invisible in Photo 1, were observed in the concrete surrounding the CFS. This evidence indicates that the load-supporting area is wider than the CFS itself. The effect of this increased area may be more significant near the loaded end.

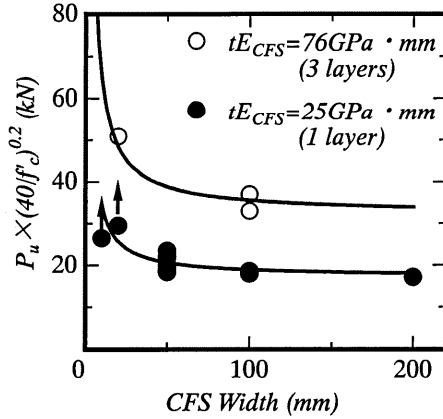


Fig.13 Influence of CFS Width on Bond Strength

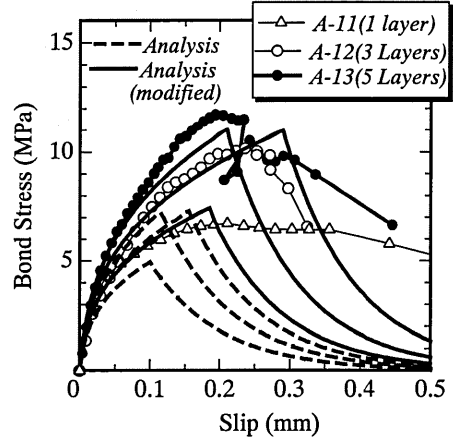


Fig.14 Influence of CFS Width on Bond-Slip Relation

4. THE BOND STRESS-SLIP-STRAIN RELATION

4.1 Formulation of Relation

The bond stress-slip-strain relation (τ - s - ϵ) will be formulated using the data obtained in tests on CFS with widths ranging from 50 to 200 mm, since no variation in bond strength was observed in this range.

As noted above, the bond stress increases as slip becomes greater and as strain becomes smaller. The gradient of the bond stress versus slip relation appears to become more linear as the stiffness of the CFS rises; that is, as the strain becomes smaller for a given value of slip (see Fig. 11). Moreover, concrete compression strength affects the bond strength. Taking these factors into account, the following bond stress-slip-strain relation for maximum bond stress can be written:

$$\frac{\tau}{f_c'^a} = \frac{f(s)}{g(\epsilon)} = \frac{\alpha s}{1 + \beta \epsilon} \quad (2)$$

where, f_c' is concrete compressive strength, $f(s)$ is a factor for the influence of slip, and $g(\epsilon)$ is a factor for the influence of strain. The power term a for f_c' , α , and β are coefficients. Little influence of concrete compressive strength on the bond stress-slip-strain relation was observed in the experimental results for compressive strengths between 33.5 and 45.9 MPa (the average was 40MPa), so it is difficult to determine the value of coefficient a . In this study, therefore, it is taken to be 0.2 based on the result (in Fig. 4) that the bond strength is proportional to $f_c'^{0.2}$. When this coefficient is set to 0.2, coefficient α and β are 148 and 1000, respectively, at the points where delamination begins.

Figure 15 shows the relationships between maximum bond stress and CFS stiffness at the point where delamination begins. The maximum bond stress can be calculated as follows:

$$\tau_{\max} = 9.1 \cdot f'_c{}^{0.2} \cdot E_{\text{CFS}} \cdot 10^{-5} \quad (3)$$

$$(\tau_{\max} \leq 3.49 f'_c{}^{0.2} \text{ MPa})$$

The solid line in Fig. 15 shows the curve predicted by Eq. (3), which a compressive strength of 40 MPa.

As described before, bond stress differs for different locations (see Fig. 9 (a)). Figure 16 shows variation of maximum bond stress among different locations. The maximum bond stress decreases linearly until a point at 30 mm from the starting point of delamination and becomes constant beyond this point. In this study, therefore, the maximum bond stress can be represented as follows:

$$\tau_{\max-i} = \tau_{\max} \left(1 - \frac{x}{60} \right) \quad (4)$$

$$(\tau_{\max-i} \geq 0.5 \tau_{\max})$$

where, $\tau_{\max-i}$ is the maximum bond stress at the point concerned (MPa), $\tau_{\max}$ is the maximum bond stress at each delamination initiation point, and x is the distance from each delamination initiation point. Equation (4) gives the maximum value of bond stress that can be reached at a point x mm from each delamination point once the bond stress at that point reaches the maximum value given by Eq. (3). Equation (4) is applicable to every 80 mm increment representing the distance between adjacent delamination points. In the case of a 200 mm bond length, the maximum value of bond stress will occur at points 0 mm, 80 mm, and 160 mm from the loaded end, and the bond strength linearly decreases between 0 and 30 mm, 80 and 110 mm, 160 and 190 mm. The bond strength in areas between 30 and 80 mm, 110 and 160 mm, 190 and 200 mm is 50% of the maximum bond strength given by Eq. (3). These assumptions are based on experimental results with specimens having one layer of CFS, as shown in Figs. 6(b) and 8(a). In this study, however, experimental evidence is not presented for cases where specimens have a CFS stiffness other than that given by one layer. Thus, the applicability of the assumption needs to be examined through bond tests on specimens with longer bond lengths and greater stiffness in the future. The suitability of the assumption in numerical analysis using the proposed bond stress-slip-strain relation was examined by changing the length of the constant maximum bond stress zone from 40 to 120 mm. The calculated ultimate load was found to be unchanged.

The softening branch of the bond stress-slip-strain relation was formulated in the following way. First, considerable scatter was observed in the softening curve. However, since the influence of CFS stiffness and

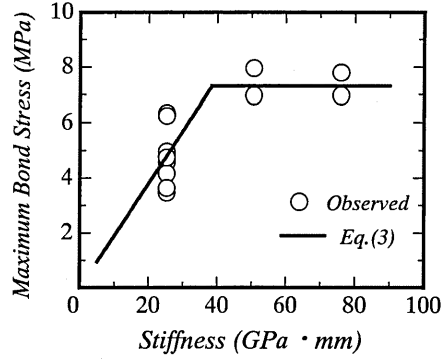


Fig.15 Relationships between Max. Bond Stress and CFS Stiffness

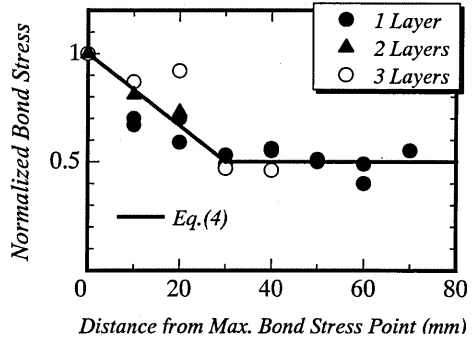


Fig.16 Reduction of Max. Bond Stress

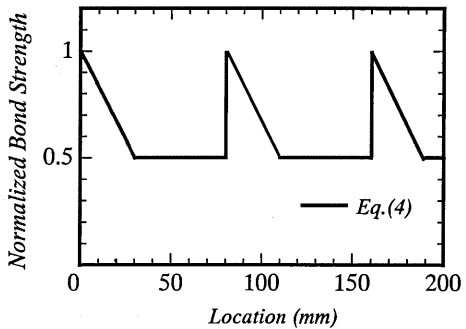


Fig.17 Bond Strength Distribution

strain is not observed, the bond stress in the softening branch can be represented as follows:

$$\tau = \tau_{\max-i} \cdot e^{-10(s-s_0)} \quad (5)$$

where, s is slip and s_0 is the slip at maximum bond stress.

The broken lines in Figs. 9 and 10 indicating bond stress versus slip relation and in Fig. 12 indicating the slip-strain relation were obtained using Eqs. (1) to (5). The prediction agrees appropriately with the experimental results.

4.2 Consideration of Influence of Bond Width

The influence of CFS width is now discussed. The broken line in Fig. 14 represents τ - s relation for a CFS width of 20 mm as predicted by Eqs.(1) to (5). The gradient obtained in the experiment is greater than that predicted, and the maximum experimental value of bond stress is 1.5 times greater than predicted. When α is 210, the bond stress, which is 1.5 times greater than that predicted by Eq. (3), agrees well with the experimental result. However, the shape of the predicted softening curve is entirely different from the experimental results. To properly formulate the softening curve, further experimental results need to be accumulated.

As described in Section 3 (3), the actual surface width of the concrete that resists the tensile force in the CFS appears to be greater than the CFS width. It is possible, as a simple means of taking the influence of bond width into account, to adopt a virtual width (or equivalent width), thus requiring no modification to the proposed bond stress-slip-strain relation. In this case, bonding force in a small element can be represented as follows:

$$\Delta P = \tau(b + 2\Delta b)\Delta x \quad (6)$$

where, ΔP is the bonding force in the small element, τ is the bond stress, b is the width of the CFS, Δb is the additional concrete width resisting the tensile force, and Δx is the length of the small element.

When Δb is taken to be 3.4 mm, in numerical analysis using the bond stress-slip-strain relation, the predicted ultimate load agrees well with the experimental results (solid line in Fig. 13). In this paper, therefore, the analysis is carried out with a Δb value of 3.4 mm.

4.3 Comparison with Experimental Results

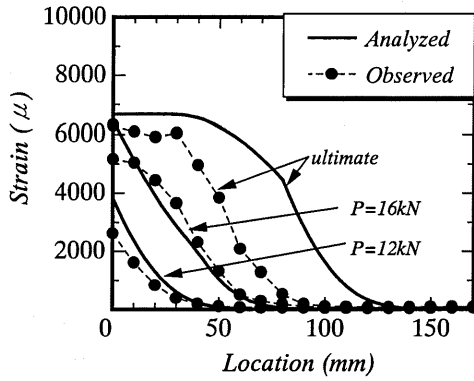
A comparison of the numerical results calculated using Eqs. (1) to (5) with the experimental results for bond strength and strain distribution was carried out. The calculation flow chart is shown in the Appendix.

a) Comparison of bond strength

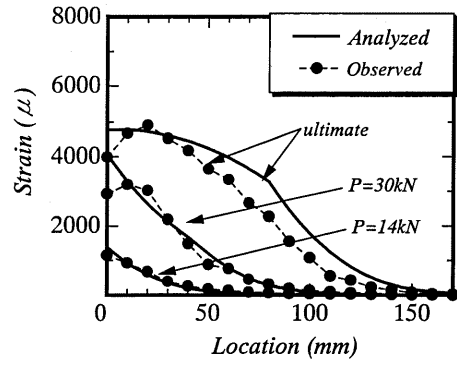
The solid line in Fig. 3 represents the bond strength as predicted by the analysis. Analytical results for stiffnesses of 25 GPa-mm and 115 GPa-mm are shown. The analysis closely matches the experimental results, except for short bond lengths where slip occurs at the free end. The numerical analysis is unable to accurately simulate this region because it does not take into account bond failure caused by slip at the free end. Bond strength increases with bond length, except for bond lengths greater than approximately 150 and 200 mm in the case of CFS stiffness of 25 GPa-mm and 115 GPa-mm, respectively.

b) Comparison of strain distribution

Figure 18 compares the strain distributions obtained by the analysis and observed in the experiment. For specimen B-1, the strain distributions around 12 kN, 16 kN, and at the ultimate stage are shown. For specimen B-2, on the other hand, strain distributions around 14 kN, 30 kN, and at the ultimate stage are shown. Although there is a small discrepancy at the ultimate stage for specimen B-1, it can be said that the analysis generally predicts the experimental results with good accuracy. Certainly, the analysis reflects the phenomena by which CFS strain at the ultimate stage falls and the length with bond stress increases as CFS stiffness increases. The ultimate loads of specimens B-1 and B-2 in the experiment were 20.6 and 39.4 kN, respectively, while the analysis gave figures of 17.4 and 40.0 kN.



(a) B-1 (1-Layer)



(b) B-2 (3-Layer)

Fig.18 Comparison on Strain Distribution

c) Comparison of bond stress distribution

Figure 19 shows the bond stress distribution as predicted by the analysis. The analytical distribution agrees well with the experimental results given in Figs. 8 and 10. That is, the analysis simulates the gradual shift of the active bond area towards the free end.

5. DEVELOPMENT OF BOND STRENGTH EQUATION

5.1 Formulation

A bond strength equation was formulated on the basis of numerical results obtained with the proposed bond stress-slip-strain relation. This bond strength equation is applicable to cases where the bond length is sufficient to prevent slip at free end and where the concrete compressive strength is less than 45 MPa.

The bond strength can be written in terms of effective bond length L_e and bond stress developed over the effective bond length as follows:

$$P_u = (b + 2\Delta b)L_e \int_0^{L_e} \tau dx \quad (7)$$

where, P_u is the ultimate capacity, b is the CFS width, and Δb is the additional concrete width resisting the tensile force (3.7 mm).

Equation (7) can be rewritten using average bond stress in effective bond length for simplicity.

$$P_u = (b + 2\Delta b)L_e \bar{\tau} \quad (8)$$

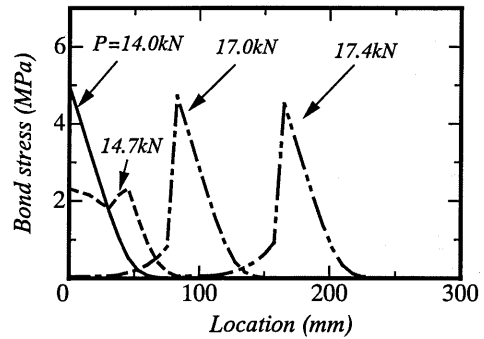


Fig.19 Bond Stress Distributions in Analysis

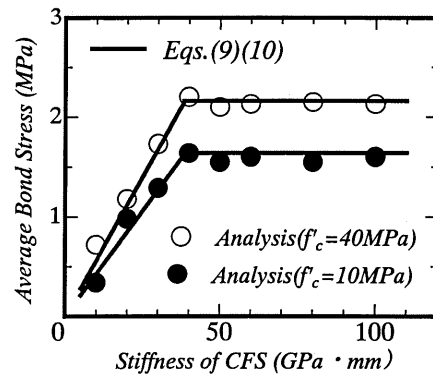


Fig.20 Relationships between Average Bond Stress and CFS Stiffness

Figure 20 shows relationships between average bond stress derived from the numerical analysis and CFS stiffness. The average bond stress increases proportionally with stiffness up to around 40 GPa-mm, and is constant for greater stiffnesses. The average bond stress is proportional to the 0.2 power of concrete compressive strength. The average bond stress is given by the following equations:

$$\text{For } tE_{CFS} \leq 38.4 \text{ GPa} \cdot \text{mm} \\ \bar{\tau} = 2.68 \cdot f'_c{}^{0.2} \cdot tE_{CFS} \times 10^{-5} \quad (9)$$

$$\text{For } 38.4 \text{ GPa} \cdot \text{mm} \leq tE_{CFS} \\ \bar{\tau} = 1.03 f'_c{}^{0.2} \quad (10)$$

Figure 21 shows the relationships between effective bond length and stiffness. The effective bond length is not influenced by concrete compressive strength and is proportional to the 0.4 power of stiffness. The effective bond length can be represented as follows:

$$L_e = 1.89 (tE_{CFS})^{0.4} \quad (11)$$

Finally, the bond strength can be written as follows:

$$\text{For } tE_{CFS} \leq 38.4 \text{ GPa} \cdot \text{mm} \\ P_u = \bar{\tau} L_e (b + 2\Delta b) \\ = 5.06 f'_c{}^{0.2} (tE_{CFS})^{1.4} (b + 2\Delta b) \times 10^{-5} \quad (12)$$

$$\text{For } 38.4 \text{ GPa} \cdot \text{mm} \leq tE_{CFS} \\ P_u = \bar{\tau} L_e (b + 2\Delta b) \\ = 1.95 f'_c{}^{0.2} (tE_{CFS})^{0.4} (b + 2\Delta b) \quad (13)$$

Figure 22 shows relationships between bond strength as calculated by numerical analysis and the values given by Eqs. (12) and (13). It is clear that the simplified method agrees well with the numerical results.

5.2 Comparison with Experimental Results

The applicability of the proposed bond strength equation was confirmed by comparing it with the experimental results given in references [4] through [7], as referred to in Section 3, and reference [11], which includes data for bi-directional carbon fiber sheet. Figure 22 shows relationships between ratio of bond strengths observed in experiments to those calculated using the proposed equations (bond strength ratio) and CFS stiffness. The proposed equation assumes that the actual bond length is greater than the effective bond length. For cases where the bond length is shorter than the effective bond length, bond strength is approximated for simplicity by multiplying the average bond stress obtained from Eq.(8) by the area derived from the actual bond length and effective width.

Firstly, we discuss the applicability of the model in cases where the bond length is greater than the effective bond length. It can be said from Fig. 23 (a) that agreement is achieved between experiment and prediction for uni-directional carbon fiber sheet (all symbols except for symbol X in Fig. 24). The average of the bond strength

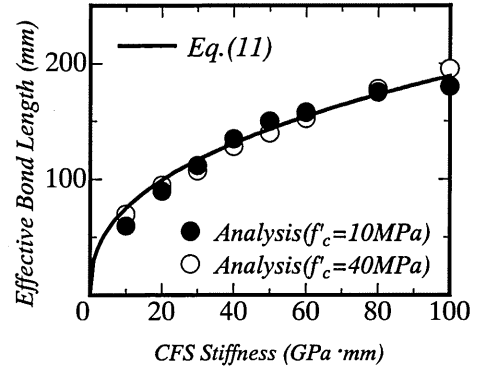


Fig.21 Relationships between Effective Bond Length and Stiffness of CFS

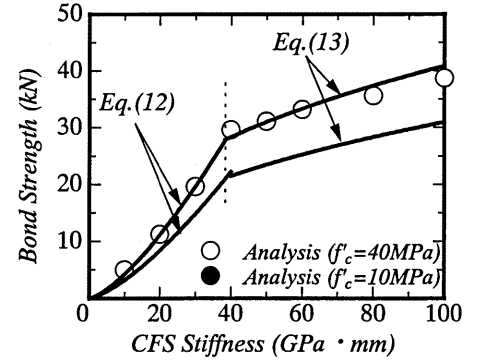


Fig.22 Relationships between Bond Strength and Stiffness of CFS

ratio is 0.85 for uni-directional carbon fiber sheet and 0.51 for bi-directional fiber sheet (symbol X in Fig. 24). The average bond strength ratio for the authors' experimental results is different from that in the references, being 1.0 for the authors' results. On the other hand, the proposed equation slightly overestimates the experimental results of other researchers and the average strength ratio is 0.8. Differences in failure mode may be considered the reason for this discrepancy.

Takeo et al. reported that two failure modes occurred: concrete surface failure and resin failure. In this study, only concrete failure was observed, as shown in Photo 1. There is thus a possibility that the authors' experiment yielded different failure modes than those of other researchers; a study on the influence of concrete surface treatment on failure mode will be a task for future study. It is difficult to explain why the bond strength of bi-directional fiber sheet is less than that of uni-directional fiber sheet, and clarifying this is another future task.

Secondly, we look at applicability to cases where the bond length is less than the effective bond length. It seems from Fig. 23 (b) that the bond strength ratio becomes greater than 1.0 when the CFS is very stiff. It is thus impossible to apply the proposed method to cases where the bond length is short. The average bond strength ratio is 1.22 for uni-directional fiber sheet and 0.69 for bi-directional fiber sheet. Further study is required to develop a

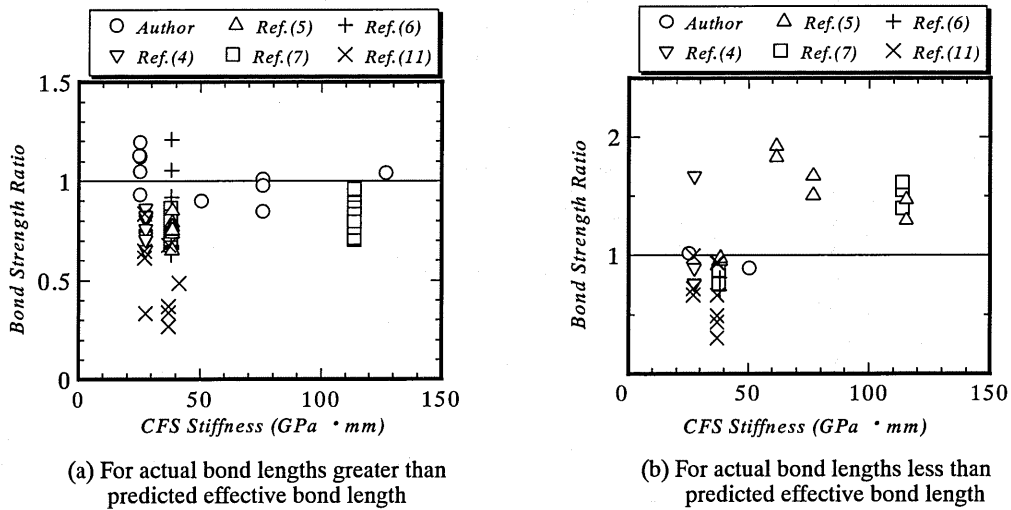


Fig.23 Relationships between Bond Strength Ratio and CFS Stiffness

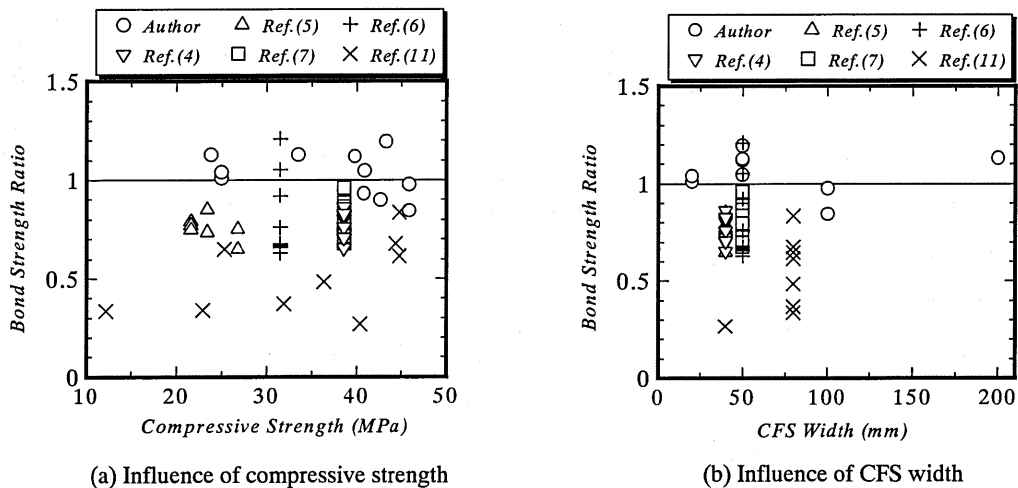


Fig.24 Influences of Concrete Compressive Strength and CFS Width on Bond Strength Ratio

the stress state differs from that observed in the specimens shown in Fig. 1. Because a moment-induced CFS stress gradient arises in CFS bonded to the tension face of a flexural member, this equation is limited to cases where CFS is bonded to the side face of a concrete member. Even in this case, the influence of different boundary conditions needs to be considered: such as whether the free end is mechanically anchored or over-wrapping with CFS. Another application of the proposed bond strength equation is in using the predicted bond strength as an index of bonding properties. The equation yields a reference value that may be used in the selection of resin type and reinforcing material, and in examinations of the influence of concrete surface treatments and site environmental conditions.

A method [12] by which the proposed equation can be used to predict the bond strength of CFS bonded to the side face of a concrete beam will be presented in the near future.

6. CONCLUSIONS

The experimental and numerical analysis carried out in this study have resulted in the following conclusions:

- (1) The bond strength of CFS increases as the stiffness of the CFS is increased. The bond strength also increases with increasing bond length up to a certain value. The reason for this limit is that the effective area of the bonding action does not increase once the bond length reaches a certain value. The effective bond length is around 100 mm for CFS with a stiffness of 25 GPa-mm and 200 mm for 115 GPa-mm.
- (2) Bond strength is affected by CFS width, with strength increasing at smaller widths. The influence of width is more notable at lower CFS widths.
- (3) Bond strength gradually increases as the compressive strength of the concrete increases, and is proportional to the 0.2 power of concrete compressive strength.
- (4) The bond stress versus slip relation differs according to the stiffness of the CFS. As the CFS stiffness increases, the bond stress increases and the strain decreases for a given value of slip. The maximum bond stress increases as the CFS stiffness increases, but here too there is an upper limit. The upper limit is approximately 7.4 MPa for a concrete strength of 40 MPa.
- (5) A bond stress-slip-strain relation that takes into account the effect of concrete compressive strength and CFS width was developed. Numerical analysis using this relation yields results that match the bond behavior of CFS.
- (6) Bond strength equations developed on the basis of the numerical analysis correctly account for the influences of concrete compressive strength, CFS width, and CFS stiffness, and can predict experimental results with good accuracy within their applicable range and assuming that the failure mode is concrete surface failure.

Acknowledgements

This study was made possible by the valuable input of Prof. KAKUTA Yoshio of Hokkaido University and Mr. KOBAYASHI Akira of Nippon Steel Composite Co., Ltd. The authors would also like to express their gratitude to Mr. MORIWAKI Wataru (Toda Construction Co., Ltd.) and Ms. SAKAI Atsuko (Asahikasei Homes Co., Ltd.), former students of Hokkaido University, for their great help in the experimental study. This research was supported by the Grant-in Aid for Scientific Research, Ministry of Education, Science and Culture of Japan (Grant No.10750350).

Appendix

The process of calculation using the bond stress-slip-strain relation is as follows (refer to Fig. A):

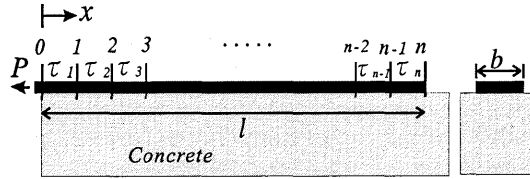


Fig. A Definition of variables

- (1) Give slip S_0 at point x_0 .
- (2) Assume strain ϵ_0 at point x_0 .
- (3) Calculate bond stress τ_1 for section 0-1 using Eq. (2).
- (4) Recalculate bond stress τ_1 using Eq. (5) when bond stress τ_1 is greater than the maximum stress derived from Eq. (3).
- (5) Calculate strain ϵ_1 at location x_1 using Eq. (1).
- (6) Calculate slip S_1 at point x_1 by subtracting slip integrated over section 0-1 from slip S_0 .
- (7) Calculate bond stress τ_2 for section 1-2 using Eq. (2) with S_1 and ϵ_1 as calculated at (5) and (6). If the bond stress τ_1 for section 0-1 as calculated at (4) is in the softening zone, compare bond stress τ_2 with the maximum stress ($\tau_{\max-1}$) as given by Eq. (4). If bond stress τ_2 is greater than $\tau_{\max-1}$, recalculate bond stress τ_2 using Eq. (5).
- (8) For the section between the loaded end and point $x = 80$ mm, calculate slip, strain, and bond stress at each point on the basis of the method given in (5) through (7). If the bond length is greater than 80 mm, calculate the maximum stress using Eq. (3) for points x that are multiples of 80 (160, 270...) and Eq. (4) for others. While comparing the calculated bond stresses with the maximum bond stresses given by Eq. (3) or (4), calculate bond stress, slip, and strain at each point, using the above process.
- (9) Calculate slip S^* by integrating the strain at each point.
- (10) Compare S_0 assumed at (1) with S^* . If S_0 agrees with S^* , go to the next step using a slip value obtained by adding a small increment to the slip assumed at (1). If S_0 does not agree with S^* , go back to (2), assume a new strain ϵ_0 , and redo steps (3) to (9) until $S^* = S_0$ is achieved.
- (11) Stop the calculation if any strain appears at point $x=l$ because it has not been confirmed whether the proposed bond stress-slip-strain relation is applicable to cases where there is strain at the free end. The pull-out force is calculated using the bond stress $\tau_{i-1,n}$ at each point as follows:

$$P = (b + 2\Delta b) \int_0^l \tau_i dx$$

where, Δb is 3.7 mm.

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