Scientific paper

Basic Bond Characteristics of FRP Strand Sheet- Concrete Interface with Polyurea Resin

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Abstract

Aiming at improving bond strengths between FRP sheet and concrete, the FRP sheet bonding method using high elongation elastic resin as a buffer layer was developed. In this study, bonding tests were conducted to clarify the basic bond characteristics of FRP strand sheet-concrete interface with a polyurea resin. As a result of the bonding tests, it was found that the use of the polyurea resin as a buffer layer significantly improved the bond strength and the interfacial fracture energy between FRP sheets and concrete. In addition, bond stress-slip relationships with a polyurea resin were proposed. Finally, numerical analyses of bonding CFRP strand sheets and concrete were conducted so as to verify validity of the proposed bond stress-slip relationships. This paper is an extended version in English from the authors’ previous work [Kobayashi, A., Ozaki, M., Sato, Y., Arazoe, M., Tateishi, A. and Komori, A., (2020). “Study on bonding behavior of FRP sheets and concrete bonded with high elongation elastic resin.” Journal of Structural Engineering, JSCE, 66A, 855-867. (in Japanese)].

1. Introduction

Flexural capacities of RC members strengthened with FRP sheets are often governed by delamination of bonded FRP sheets. Therefore, we have to improve bond characteristics of the interface to bring out the greater strengthening effect. For instance, using anchoring devices (Ceroni and Pecce 2010; Chen et al. 2018), applying FRP rods (Khalifa et al. 1999), using carbon FRP ropes (Godat et al. 2017), the method of externally bonded reinforcement on groove (Moghaddas and

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attaching additional FRP sheets, using CF anchors and attaching steel fixing tools. The high elongation elastic resin has Young’s modulus of 60 N/mm² or more, which is higher than that of the flexible epoxy resin, and a breaking elongation of 400% or more. The developed buffer material does not lose the flexibility even at a low temperature range such as -10°C. In addition, FRP strand sheet has been developed in order to improve workability as FRP sheet. FRP strand sheet is that a continuous fiber bundle is pre-impregnated and cured with a resin as a binding material (Kobayashi et al. 2009).

This paper shows results of double-sided pullout test and single-sided pullout test at room temperature in order to evaluate the basic bond characteristics, such as delamination load, maximum bond stress, and bond stress-slip relationship, between FRP strand sheet and concrete with polyurea resin. In addition, numerical analysis based on force equilibrium considering bond stress-slip relationships identified from the bond test was conducted so as to understand the bond characteristics more deeply.

2. FRP sheet bonding method using high elongation elastic resin

In this study, polyurea resin was used as a high elongation elastic resin and CFRP strand sheet was used as a strengthening material. Figure 1 shows the cross section of the strengthened method developed by the authors. A urethane resin primer is applied after the surface of the concrete is treated with a disc sander. The polyurea resin, which is two-component mixed and curing type at normal temperature, is applied after the urethane resin primer is dried. The standard amount of application is 1.0 kg/m². After the curing of polyurea resin, both the FRP strand sheet and an epoxy resin were applied on the polyurea resin.

The high elongation elastic resin used in this method is a polyurea resin developed by the authors. Isocyanate prepolymer urethane resin component having NCO groups as reactive groups is used at the terminal of the main agent component, and an aromatic polyamine having amino groups as reactive groups is used at the terminal of the curing agent component. This polyurea resin is obtained by mixing two liquids that are the main component, and the curing agent components. The reaction equation between two agent components can be described as follows:

\[
(R - NCO) + (R' - NH_2) \rightarrow R - NH - CO - R'
\]

The newly developed polyurea resin has the following features.

1) The elastic modulus is about 60 to 100 N/mm², which is smaller than the typical epoxy resin whose value is about 2000 to 5000 N/mm². As shown in Fig. 2, a stress-strain relationship shows non-linearity similar to that of a typical resin. Its breaking elongation is over 400%, which is remarkably higher than that of typical epoxy resin, which breaks at a few percentage.

2) The glass transition temperature is around -20°C, and it can show rubber-like flexibility even in cold region.

3) It is a putty-like resin with high viscosity and can be applied to the wall or ceiling with a standard application amount of 1 kg/m² in application at one time.

4) The integration between the polyurea resin and the FRP sheets is ensured by applying the epoxy resin
for FRP sheet bonding onto the cured polyurea resin layer.

3. Bond characteristics based on double-lap shear bond test

3.1 Outline of experiment

Double-lap bond tests shown in Fig. 3(a) were conducted first for concrete specimens (hereinafter referred to as Type-A specimens) with CFRP strand sheet [Fig. 3(b)] using the polyurea resin in order to evaluate the bond characteristics between CFRP strand sheet and concrete using polyurea resin as high elongation elastic resin. The test followed the bond test method specified in draft standard JSCE-E 543-2013 (JSCE 2013) of the Japan Society of Civil Engineers. Tables 1 and 2 show the material properties of the CFRP strand sheet and the bond resin material used in the test, respectively. The properties of CFRP strand sheets in Table 1 and resins in Table 2 were obtained from the tests carried out according to the above JSCE draft standard (JSCE 2013), JIS K 7161(JSA 2014) and JIS K 7181 (JSA 2011). A notch on the two side was prepared at the center of a prismatic concrete block, and a spiral steel was inserted to prevent the bond failure of steel bars that transfer tensile forces from a loading machine to FRP strand sheets. The concrete was made from ordinary Portland cement and crushed aggregates of maximum size 25 mm. The compressive strength at the age of 75 days was 38.9 N/mm². Specimens, A-N-1 and A-N-2, without using polyurea resin and specimens, A-P1-1 and A-P1-2, with polyurea resin were prepared. Two specimens were tested with the same parameter in order to take scattering into consideration. The specimens are named -1, -2 in order in the same parameter. In each specimen, the width of the CFRP strand sheet was 50 mm and the bonded length of the CFRP strand sheet was 300 mm. Release films were inserted in between concrete and CFRP strand sheet at the notch on both sides.

For the specimens without polyurea resin, concrete surface was polished with a disk sander and 3.0 kg/m² epoxy resin was applied and then CFRP strand sheets were bonded in the resin. For specimens using polyurea resin, the concrete surface was polished with a disk sander, 0.2 kg/m² urethane resin was applied, followed by application of 1.0 kg/m² polyurea resin, after which CFRP strand sheets were bonded in the resin. Finally 3.0 kg/m² epoxy resin was applied and then CFRP strand sheets were bonded. To ensure the side where delamination occurs, one layer of high-strength CFRP sheet with the properties shown in Table 1 was completely wrapped in the circumferential direction above the CFRP strand sheet over a half of specimen. After application of the resin and sheets, the specimens were cured at room temperature for at least one week.

Strain gauges were attached on the CFRP strand sheet at intervals of 20 mm from the end of the release film on the notch of the concrete block (hereafter, bonded end). A 100 kN universal testing machine was used. The steel bars at both ends of the specimens were gripped and the tensile force was applied monotonically by displacement control until the CFRP strand sheet would delaminate.

### Table 1 Material properties of the CFRP strand sheet.

| Fiber density (g/m²) | Thickness (mm) | Tensile strength (N/mm²) | Young's modulus (kN/mm²) |
|---------------------|----------------|-------------------------|--------------------------|
| 600                 | 0.333          | 4520                    | 259                      |

### Table 2 Material properties of resin material.

| Type | Material  | Tensile strength (N/mm²) | Compressive strength (N/mm²) | Compressive elastic modulus (N/mm²) |
|------|-----------|--------------------------|------------------------------|------------------------------------|
| HE   | PU        | 7                        | 44                           | 66                                 |
| AD   | EP        | 35                       | 74                           | 2805                               |

HE: High elongation elastic resin, AD: Adhesive agent, PU: Polyurea resin, EP: Epoxy resin.
3.2 Results and discussion

Table 3 shows the results of tests. Specimen A-N-1 without polyurea resin had a maximum load of 37.4 kN. The CFRP strand sheet was delaminated from the concrete surface as shown in Fig. 4(a). As shown in Fig. 4(b), in specimen A-P1-1 using polyurea resin, splitting failure of concrete was observed at the maximum load of 60.0 kN without delamination of CFRP strand sheet. The interfacial fracture energy, $G_f$ (N/mm) was calculated by Eq. (2) according to JSCE-E 543-2013 based on the previous study (Taljesten 1996).

$$G_f = \frac{P_{\text{max}}^2}{8b^2 \cdot E_f \cdot t_f}$$

where $b$, $E_f$, and $t_f$ : width (mm), Young’s modulus (N/mm²) and thickness (mm), respectively, of the CFRP strand sheets and $P_{\text{max}}$ : maximum load (N).

Figure 5 shows the strain distributions in the CFRP strand sheet at a given loading step. In specimens A-N-1 and A-N-2 without polyurea resin, bonded area can be divided into bond transmission area where the strain decreases towards the free end, and delamination area where strain keeps constant. The effective bond length was about 120 to 160 mm. Here, the effective bond length is the distance from the point where strain starts to decrease continuously to the point where the strain decreases to 5% or less of the strain at the starting point.

Various formulas for calculating the effective bond length have been proposed. Sato et al. (2001) proposed Eq. (3) assuming that the effective bond length depends on the tensile stiffness of the FRP sheet and that it is very slightly affected by concrete strength.

$$L_e = 1.89 \cdot (f_t \cdot E_t)^{0.4}$$

where $L_e$ : effective bond length (mm), $f_t$ : thickness (mm) of the CFRP strand sheets and $E_t$ : Young’s modulus (N/mm²).

Kanakubo et al. (2003) proposed Eq. (4) for calculating the bond strength between FRP sheet and concrete by an equivalent bond stress block.

$$L_e = \frac{2 \cdot \lambda_e \cdot s_e}{k_e}$$

where $\lambda_e$ : sheet bond parameter, given by $\lambda_e = \frac{f_t \cdot E_t}{\tau_{\text{max}}} \cdot \frac{s_e}{k_e}$ : local slip amount of effective bond area (mm), ($s_e = 0.354$ mm), $k_e$ : EBSD (Equivalent Bond Stress Block) stress coefficient (0.428) at effective bond length, $\tau_{\text{max}}$ : local maximum bond stress (N/mm²), given by $\tau_{\text{max}} = 3.5 \cdot \sigma_c^{0.19}$, and $\sigma_c$ : compressive strength of concrete (N/mm²).

Chen and Teng (2001) reported that the effective bond length is calculated by following equation.

$$L_e = \frac{E_t \cdot f_t}{\sqrt{f_t}}$$

Table 3 Results of Type-A specimen.

| Specimen | $P_{\text{max}}$ (kN) | Average $P_{\text{max}}$ (kN) | $G_f$ Average (N/mm) |
|----------|-----------------------|-------------------------------|----------------------|
| A-N-1    | 37.4                  | 35.3                          | 0.81                 |
| A-N-2    | 33.1                  |                               | 0.64                 |
| A-P1-1   | 60.0                  | 51.8                          | 2.09*                |
| A-P1-2   | 43.6                  |                               | 1.10*                |

*Not the real interfacial fracture energy but a reference value because failure was non-delamination failure.

Fig. 4 Failure condition of Type-A specimen.

Fig. 5 Strain distributions in Type-A specimen.
where $f'_c$: concrete compressive strength (N/mm$^2$).

In addition, Neuba uer and Rostásy (1997) proposed also the equation, given as,

$$L_e = \frac{E f'_c}{2 f_t}$$

(6)

where $f_t$: concrete tensile strength (N/mm$^2$). In this study, it is calculated from following equation according to the Japanese code (JSCE 2007).

$$f_t = 0.23 f'_c^{2/3}$$

(7)

The effective bond length $L_e$ calculated from Eqs. (3) to (6) was 178, 143, 118, and 128 mm, respectively. The calculated results were close to the values (120 to 160 mm) that were observed in the experiment.

In contrast, in the case of specimens A-P1-1 and A-P2-2 in which CFRP strand sheets are bonded using polyurea resin, the strain decreases over the whole bond length from the loaded end to the free end. The effective bond length was estimated to be over 300 mm, which is significantly greater than the value calculated by the existing equations.

Figure 6 shows the bond stress distributions calculated from the strain of the CFRP strand sheets at a given load step in Type-A specimen. The bond stress was calculated from Eq. (8) using adjacent strain gauges.

$$\tau_i = \frac{P_{i-1} - P_i}{x_{i-1} - x_i} \quad i = (1, 2, 3 \cdots)$$

(8)

where $\tau_i$: local bond stress between point $i$ and $i-1$, $x_i$: the location of strain gauge from loaded end, $\varepsilon_i$: strain of the $i^{th}$ strain gauge from the loaded end and $n_f$: the number of FRP sheets ($n_f = 1$ in this test) and $P_i$ is the tensile force of FRP sheet at point $i$, which is given by $P_i = E f'_t \varepsilon f_{nt}$.

In specimen A-N-1 without polyurea resin, after delamination occurs, a peak-shaped bond stress distribution with length of about 100 mm is observed and the area moved to the free end as the tensile force increases. On the other hand, in the case of specimen A-P1-1 with polyurea resin, the bond stress gradually decreases towards the free end and develops along the whole bonded area from the initial loading stage. In specimen A-P1-1, the bond stress at the distance of 100 mm from the loaded end is extremely small. The measured value of the strain at 100 mm and 120 mm are almost same as shown in Fig. 5(b). This might be caused by initial adhesive defect because of float between adhesion layers or the influence of minute irregularities on the concrete surface. The maximum bond stress in specimens A-N-1 and A-N-2 are 4.2 N/mm$^2$ and 7.5 N/mm$^2$, respectively, and those of specimens A-P1-1 and A-P1-2 are 3.3 N/mm$^2$ in both cases. The maximum bond stress of the specimen with polyurea resin was smaller than that without polyurea resin despite the maximum load is much greater as shown in Table 3.

As described above, it was confirmed that the polyurea resin makes the effective bond length, interfacial fracture energy, and maximum load increase, while the maximum bond stress decrease. However actual bond characteristics could not be obtained in the double-lap shear bond test because the effective bond length might be longer than specimen length, 300 mm and splitting failure of concrete would happen earlier than the delamination of the sheet. Therefore, bond test method itself should be improved.

4. Bond characteristics based on single-lap shear bond test and analysis

4.1 Outline of experiment

When the FRP sheet was bonded to concrete using polyurea resin, splitting failure of concrete occurred around the steel bar in the double-lap shear bond test as described in Section 3. Therefore, the single-rap shear bond test which does not require any steel bars for applying tension force. In the test, a rather massive concrete block is fixed to the base frame so that the longer bond length can be introduced.

In this study, the effect of the presence or absence of polyurea resin and the amount of polyurea resin on the bond characteristics was evaluated using single-lap shear bond test specimens shown in Fig. 7(a) (hereinafter referred to as Type-B specimen). Fig. 7(b) shows the method to fix the concrete block. Two specimens, B-N-1 and B-N-2, without polyurea resin and 6 specimens with polyurea resin were prepared. Specimens B-P1-1 and
B-P1-2, specimens B-P2-1 and B-P2-2, and specimens B-P3-1 and B-P3-2 contain the amount of 1.0, 2.0, and 3.0 kg/m² polyurea resin, respectively. Two specimens were tested with the same parameter in order to take scattering into consideration. The specimens are named -1, -2 in order in the same parameter. The concrete used was normal Portland cement concrete with crushed aggregates. The compressive strength at the age of 35 days when the tests started was 35.1 N/mm².

The length of the concrete block was fixed to 600 mm, which is approximately twice the length of the double-lap bond test specimens. The bonded length was 520 mm and the CFRP strand sheet was bonded considering the arrangement of the fixture and clip gauge. Aramid fiber FRP (AFRP) tabs were bonded to both sides of the CFRP strand sheet at the loading side to grip the end tightly by the chuck of the testing machine. The width of the CFRP strand sheet was set to 25 mm because the maxim width of the chuck of the testing machine was 25 mm. The procedure for bonding the CFRP strand sheet is the same as for Type-A specimens except for the amount of polyurea resin. An unbonded area was provided using a release film within a range of 20 mm from the upper edge of the concrete block. Therefore, bond stress starts to develop a position from 20 mm below the upper edge and the 13 strain gauges were attached at 40 mm intervals from the loaded end, which is the position from 20 mm below the upper edge. A clip gauge was installed at the free end of the CFRP strand sheet to measure slips at bottom of the CFRP strand sheet. The concrete block was fixed to the bottom frame of a 100 kN universal testing machine using a steel fixture. The AFRP tab at the end of the CFRP strand sheet was gripped, and monotonically loaded by displacement control until delamination occurred. At this time, the specimen was carefully installed so as not to generate eccentric load.

4.2 Results and discussion

4.2.1 Delamination condition and load-displacement relationship

In the bond test of Type-B specimens, all specimens failed in delamination of the CFRP strand sheet as shown in Fig. 8 without splitting failure of concrete block observed in the single-lap shear bond test using Type-A specimen.

In the specimen without polyurea resin, some pieces of cement paste and fine aggregates were left behind thinly to the back surface of the sheet delaminated [see Fig. 8(a)]. In some specimens using polyurea resin, small area of polyurea resin layer was partially left on the concrete surface as shown in Fig. 8(b). The damaged depth of the concrete surface layer was slightly deeper than that of the specimen without polyurea resin, and coarse aggregate was partially exposed on the surface as shown in Fig. 8(c).

![Fig. 7 Arrangement of Type B specimens.](image)

![Fig. 8 Delamination condition of Type-B specimen.](image)
Figure 9 shows the relationships between the applied load and the loading point displacement of specimens with different amounts of the polyurea resin. The load-point displacement was calculated from Eq. (9).

\[
s_0 = \sum_{i=1}^{13} \varepsilon_i - \varepsilon_0 - \Delta x + s_{end}
\]

where \(s_0\): load-point displacement (mm), \(\varepsilon_0\): strain measured by strain gauges (\(\varepsilon_0\) is regarded 0 at free end), \(\Delta x\): length between strain gauges (40 mm) and \(s_{end}\): slip at free end measured by the clip gauge (mm).

The initial slope in the load-displacement relationship of specimens B-P1, B-P2 and B-P3 with polyurea resin is slightly smaller than that of specimen B-N-1 without polyurea resin in Fig. 9. In the case of specimen B-N without polyurea resin, the load suddenly decreases at the time of initial delamination and keeps on increasing and decreasing several times as the displacement increases. Finally, the CFRP strand sheet was delaminated completely without exceeding the initial delamination load. The occurrence of the initial delamination was confirmed by the strain distribution change around the loaded end of the CFRP strand sheet. In the case of specimens B-P1 and B-P2 with polyurea resin of 1.0 kg/m² and 2.0 kg/m², after the load decreased at the initial delamination, the load increased again overt the first delamination load as the displacement increased, and the CFRP strand sheet was delaminated completely when the maximum load was observed. In the case of specimen B-P3 with polyurea resin of 3.0 kg/m², the load increased monotonously without showing a clear drop in load and overall delamination occurred.

4.2.2 The maximum load and the interfacial fracture energy

Table 4 shows the test results. The interfacial fracture energy in the single-lap shear bond test was calculated from the maximum load by Eq. (10).

\[
G_f = \frac{P_{\text{max}}^2}{2h^2 \cdot E_f \cdot t_f}
\]

The average interfacial fracture energy of specimen B-N without polyurea resin is 0.8 N/mm, which is about 9% higher than the average value of Type-A specimen, A-N of 0.73 N/mm in the double-lap shear bond test with a sheet width of 50 mm. This fracture energy of specimen B-N is about 10% lower than 0.94 N/mm in the double-lap shear bond test of the CFRP strand sheet reported in the previous literature (Kobayashi et al. 2009). There is no significant difference between the results of this test.
Table 4 Results of Type-B bond test.

| Specimen | $P_{\text{max}}$ | $G_f$ |
|----------|-----------------|-------|
|          | Experimental    | Average| Experimental | Average |
|          | value (kN)      | (kN)  | value (N/mm) | (N/mm)  |
| B-N-1    | 9.5             | 9.3   | 0.84         | 0.80    |
| B-N-2    | 9.0             |       | 0.75         |         |
| B-P1-1   | 21.0            | 24.0  | 4.09         | 5.43    |
| B-P1-2   | 27.0            |       | 6.76         |         |
| B-P2-1   | 22.8            | 24.7  | 4.82         | 5.67    |
| B-P2-2   | 26.5            |       | 6.51         |         |
| B-P3-1   | 27.3            | 27.8  | 6.91*        | 7.38*   |
| B-P3-2   | 28.2            |       | 7.85*        |         |

$P_{\text{max}}$: Maximum load, $G_f$: Interfacial fracture energy.

*Not the real interfacial fracture energy but a reference value because failure was non-delamination failure.

and the previous one. According to previous studies (Sato et al. 2001; Izumo et al. 2000), the smaller width of the FRP sheet gives the greater bond strength. However, there was no significant influence of the sheet width within the range of this experiment.

The average maximum loads in specimens B-P1, B-P2, and B-P3 using polyurea resin are 24.0, 24.7, and 27.8 kN, respectively. These maximum loads are more than twice as high as 9.3 kN of specimen B-N without polyurea resin. The interfacial fracture energies of the above three specimens were 5.43, 5.67, and 7.38 N/mm, respectively, which were significantly higher than 0.8 N/mm of specimen B-N. Wu et al. (2001) conducted bond tests on double-lap shear bond test in which various types of FRP sheets were used with typical epoxy resin. The interfacial fracture energy observed in the experiment was range between 0.7 and 1.82 N/mm.

Several prediction equations for interfacial fracture energy have been proposed. Toutanji et al. (2007) and Dai et al. (2005) have proposed the Eqs. (11) and (12), respectively.

$$G_f = \begin{cases} 0.014 f_e' & 0 \leq f_e' \leq 46.2 \text{ MPa} \\ 0.65 & f_e' \geq 46.2 \text{ MPa} \end{cases}$$  \hspace{1cm} (11)

$$G_f = 0.514 f_e'^{0.236}$$  \hspace{1cm} (12)

The interfacial fracture energies calculated by Eqs. (11) and (12) were 0.49 N/mm and 1.19 N/mm, respectively, which were almost same as the previous experiment. However, in this test, when the polyurea resin was used, the interfacial fracture energy exceeding 5 N/mm was obtained, and the effect of increase of bond strength was remarkably recognized. The maximum load and the interfacial fracture energy were the highest when the applied amount of polyurea resin was 3.0 kg/m². In this experiment, the scattering between B-P1 and B-P2 was large, and there was no significant difference in the maximum load between B-P1 and B-P2 compared to B-P2 and B-P3 as shown in Table 4. Therefore, there was no significant difference between the applied amounts of polyurea resin of 1.0 kg/m² and 2.0 kg/m². The bond strength can be remarkably improved even when amount of 1.0 kg/m² polyurea resin is applied.

4.2.3 The strain distribution of CFRP strand sheet and bond stress distribution

Figure 10 shows examples of the strain distributions of the CFRP strand sheet at each given load step in specimens with different applied amounts of polyurea resin. In the case of specimen B-N-1 without polyurea resin [Fig. 10(a)], the CFRP strand sheet delaminated when the strain at the loaded end was about 4000 μ, and the delaminated area, which is judged from the constant strain zone, and the active bonding area where strain decreases can be seen. The delaminated area and the active bonding area move toward the free end as the load step increases. The effective bond length was about 120 mm. Wu et al. (2001) reported that the effective bond length of a high-strength CFRP sheet with a fiber density of 400 g/m² was 50 to 75 mm, and the higher the tensile stiffness of the FRP sheet, the longer the effective bond length of the FRP sheet. Izumo et al. (2000) reported that the effective bond length of high-strength CFRP sheets and AFRP sheets with a fiber density of up to 300 g/m² was 100 mm. The effective bond length of 120 mm in this experiment is slightly larger than these values. This is due to the large fiber density of 600 g/m². When the effective bond length $L_e$ was calculated from Eqs. (3) to (6) in consideration of the stiffness of the FRP sheet, they were 178, 143, 121 and 132 mm, respectively. The experimental value of 120 mm was slightly smaller than that of calculated value.

As shown in Figs. 10(b), (c) and (d), the maximum strain in specimens B-P1-2, B-P2-2 and B-P3-2 with polyurea resin is about 12000 μ and almost the same regardless of amount the polyurea resin. The maximum strain is much larger than that of specimen B-N-2 without polyurea resin. In addition, the active bonding area where the strain decreases linearly is longer than that without the polyurea resin, and the effective bond length is about 400 mm in specimens B-P1-2 and B-P2-2. It can be considered that in the case of specimen B-P3-2 with a applied amount of 3.0 kg/m², the effective bond length might be longer than the bond length of the sheet, 520 mm because the strain also arises even at the position of 480 mm from the beginning. The prediction Eqs. (3) to (6) are not applicable to the case with polyurea resin.

Figure 11 shows the bond stress distributions calculated from Eq. (8) using the strains of the CFRP strand sheet at each given loading step. In the calculation, the strain at the free end of the sheet at 520 mm is assumed to be 0. Figure 11(a) shows a high bond stress of 9.7 N/mm² at a load of 9.5 kN just before the initial delamination at a position of 30 mm from the loaded end. A sharp mountain-shaped bond stress distribution is observed in the active bonding area and moves towards the free end. Figures 11(b), (c) and (d) show the bond stress...
distributions in the specimens with the applied amounts of polyurea resin of 1.0, 2.0 and 3.0 kg/m², respectively. As in the case of specimen B-N-1 without polyurea resin, there is no mountain-shaped stress distribution in a narrow range of about 100 mm with sharp peaks. In the initial stage of the loading step, the distribution has the peak at 60 mm near the loaded end. The bond stress is gradually reduced to the free end and distributed over a wide range. As the loading step increases, the position of the peak of the bond stress moves to the free end.

The maximum bond stress in specimens B-P1-2, B-P2-2, and B-P3-2 are 4.3, 3.9, and 3.1 N/mm², respectively, excluding the 500 mm position at the free end. As the applied amount of polyurea resin increases, the maximum bond stress decreases. The maximum bond stress at the position of 500 mm in a specimen B-N-1 is about 0.4 N/mm² as shown in Fig. 11(a). However, the maximum values of the bond stress in specimens B-P1-2, B-P2-2, and B-P3-2 at this point are 2.0, 2.6, and 3.3 N/mm², respectively. The greater bond stress can be developed at free end.

In the case of specimen B-P3-2 with 3.0 kg/m² of polyurea resin, the bond stress is further reduced, and the maximum bond stress at the position of 500 mm is about 0.3 N/mm².

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**Fig. 10** Strain distributions of the CFRP strand sheet.

**Fig. 11** Bond stress distributions.
polyurea resin, at the time of maximum load, the greater bond stress was observed at the free end. This result indicates that the effective bond length could be longer than the bond length of 520 mm.

4.2.4 The bond stress-slip relationship and interfacial fracture energy

Figure 12 shows the relationship between load and slip at the free end. In specimen B-P1-1, the slips could not be measured because of due to the measuring instrument defect. The slip increased linearly at the initial stage of specimen B-P1 with 1.0 kg/m² and specimen B-P2 with 2.0 kg/m² of polyurea resin. After the initial delamination, the increment of the slip became larger gradually as the load increased. The slip in specimen B-P3 with 3.0 kg/m² of polyurea resin is larger than in specimens B-P1 and B-P2. The amount of polyurea resin greatly affects the slip at the free end.

Figure 13 shows the relationships between bond stress and slip at different locations. The relationship in specimen B-P1-1 is not reliable because the slip at the free end could not be measured accurately as mentioned earlier. Two test specimens with the same amount of resin were tested to reduce the scatter even slightly. The bond stress in each section was calculated from the measured strain using Eq. (8), and slip was calculated from the strain and the slip at free end measured by the clip gauge as in Eq. (13).

\[
s_{k+\Delta x/2} = \varepsilon_{k+\Delta x/2} - \varepsilon_k \Delta x/2 + \sum_{x_{k+1}}^{x_{k+1}} \varepsilon_{x_{k+1}} - \varepsilon_k \Delta x + s_{end} \quad (13)
\]

where \( s_{k+\Delta x/2} \): slip at the center of the section between \( x_{k+1} \) and \( x_k \) (mm).

Because bond stress-slip relationships were calculated using adjacent strain gauges, the bond stress can be defined as an average value in each section between the strain gauges. It is well known, the bond stress-slip relationships are strongly affected by boundary conditions (Sato et al. 2001). In this study, therefore the bond stress-slip relationships at three different locations, around loaded end part, middle part and free end part, were examined. As a representative value in loaded end part, bond stress at 60 mm position was selected. In the middle part, the bond stress-slip relationships were successfully observed at very few locations. Therefore the representative location in the middle part could not be fixed at only relative position. For B-N, incidentally, a strain gauge was also attached at the 20 and 60 mm positions, because the effective bond length was predicted to be as short as 100 mm. Therefore, Figs. 13(a) and (b) also show the bond stress-slip relationships at the 10, 30, 50, and 70 mm positions, which mean the center of the adjacent strain gauges.

Figures 13(a) and (b) show the bond stress-slip relationship in specimens B-N-1 and B-N-2 without polyurea resin. The bond stress quickly increases and then suddenly drops. The shape of bond stress-slip curve is like a triangular having a clear peak. The relationship can be represented by bi-linear curve as shown Fig. 14(a). The peak value of the bond stress at the location of 30 mm, which was recorded at the time of first delamination, was about 10 N/mm² for both specimens and was the greatest among all locations. However, the peak value at other locations, which was observed at progress delamination stage after the first delamination was about 6 N/mm². The slip at the peak stress was about 0.1 mm regardless of locations. After the peak of the bond stress, there was a softening region where the bond stress decreased. When the softening region was approximated by a straight line, the slip \( \delta_n \), where the bond stress became 0 (hereinafter referred to as the ultimate slip) was about 0.25 to 0.4 mm.

Figures 13(c) to (h) show the bond stress-slip relationships in specimens with the polyurea resin. The shape of the curve is totally different from the triangular with a clear peak observed in the specimens without the polyurea resin. The maximum value of the bond stress was lower than that of specimen without polyurea resin. Bond stresses are developed over the entire bonded length. The bond stress-slip relationship can be approximated to a tri-linear curve shown in Fig. 14(b). In the ascending branch, bond stress linearly increases until the slip becomes \( \delta_s \) and then keeps increasing with smaller stiffness than initial one up to the maximum bond stress. In the softening branch, bond stress linearly decreases and becomes 0 at the slip of \( \delta_s \). There is no significant difference between specimen B-P1 with 1.0 kg/m² and specimen B-P2 with 2.0 kg/m² of the polyurea resin. However, specimen B-P3 with 3.0 kg/m² of polyurea resin has smaller maximum bond stress \( \tau_r \) and the greater ultimate slip \( \delta_s \).

It seems that the bond stress-slip relationships differ from different locations. The maximum stress and the

![Fig. 12 Relationship between load and slip at free end.](image1)

![Fig. 14 Conceptual diagram of bond stress-slip relationship.](image2)
slip at the maximum stress become greater with increasing distance from the loaded end. Besides softening branch cannot be seen at the free end. It can be considered that the strain in the CFRP strand sheet and the free end slip affect the bond stress-slip relationships (Sato et al. 2002; Dai et al. 2006). Therefore, a bond stress-slip model that can consider those effects directly should be prepared so as to simulate bonding behavior precisely. Model 1, Model 2 and Model 3 in Fig. 13 are the bond stress-slip models at the part of the loaded end, middle and free end corresponding to the positions shown in Table 5. For B-N, the model was determined from all positions because there were few differences in the positions.

![Fig. 13 Relationships between bond stress and slip.](image-url)
### 4.2.5 Bond models for test specimens

Many bond stress-slip models have been proposed based on experiments for FRP sheet bonded with typical epoxy resin \( \text{Savoia et al.} \, 2005; \, \text{Yuan et al.} \, 2004, \, 2012; \, \text{Dai et al.} \, 2005; \, \text{Lu et al.} \, 2005; \, \text{Gravina et al.} \, 2017). \) Those models cannot be directly applied to the case with the polyurea resin.

As described in Section 4.2.4, bond stress-slip relationships differ from different locations. The maximum stress and the slip at the maximum stress become greater with increasing distance from the loaded end. Because of simplicity, in this study, three kinds of simple bond stress and slip curves shown in Fig. 15 are used for interface with the polyurea resin. M1, M2 and M3 in Fig. 15 are the bond stress-slip models given by taking the average of the results of two specimen shown in Table 5. How ever, for B-N, M2 and M3 are equal to Model 2 and Model 3, respectively, because the B-P1-1 values are reference values since slip at the free end could not be measured.

The mathematical expressions of the models are given as follows;

\[
\begin{align*}
\tau &= \alpha_1 \cdot s \quad (0 \leq s \leq \delta_1) \\
\tau &= \tau_r + \alpha_2 \cdot (s - \delta_1) \quad (\delta_1 < s \leq \delta_2) \\
\tau &= \tau_r + \alpha_3 \cdot (s - \delta_2) \quad (\delta_2 < s \leq \delta_3) \\
\tau &= 0 \quad (\delta_3 < s)
\end{align*}
\]

(14)

where

\[
\alpha_1 = \frac{\tau_r}{\delta_1}, \quad \alpha_2 = \frac{(\tau_r - \tau_r)}{(\delta_2 - \delta_1)}, \quad \alpha_3 = \frac{-\tau_r}{(\delta_3 - \delta_2)}
\]

Table 5 shows the values of the bond stress-slip models and the calculated values of interfacial fracture energy in B-P1-1 are reference values because slip at the free end could not be measured.

*Not the real interfacial fracture energy but a reference value because the effective bond length exceeded the bond length.

**The model for B-N was determined from all positions because there were few differences in the positions between the load end and the middle part.

#### Table 5 Parameters of bond stress-slip models and calculated value of the interfacial fracture energy.

| Specimen | Location (mm) | $\delta_r$ (mm) | $\tau_r$ (N/mm$^2$) | $\delta_1$ (mm) | $\tau_1$ (N/mm$^2$) | $\delta_2$ (mm) | $\tau_2$ (N/mm$^2$) | $\tau_f$ (N/mm) | $G_f$ (N/mm) | Model |
|----------|---------------|-----------------|--------------------|-----------------|--------------------|----------------|--------------------|----------------|-------------|-------|
| B-N-1    | 460           | -               | -                  | 0.01            | -                  | -              | -                  | -              | -           |       |
| B-N-2    | 460           | -               | -                  | 0.018           | -                  | -              | -                  | -              | -           |       |
| B-P1-1   | 220           | 0.30            | 1.10               | 2.30            | 3.30               | 3.70           | 6.88               | 6.76           | 1           |
| B-P1-2   | 220           | 0.25            | 1.60               | 1.85            | 3.40               | 2.70           | 5.65               | 6.51           | 2           |
| B-P2-1   | 100           | 0.20            | 1.20               | 2.40            | 2.40               | 4.50           | 6.60               | 6.91*          | 3           |
| B-P2-2   | 100           | 0.50            | 1.65               | 3.25            | 3.00               | 4.00           | 7.93               | 7.85*          |            |
| B-P3-1   | 460           | -               | -                  | 0.94            | -                  | -              | -                  | -              |            |
| B-P3-2   | 460           | -               | -                  | 0.98            | -                  | -              | -                  | -              |            |

$G_f$: Interfacial fracture energy, $\delta_r$, $\tau_r$, $\delta_1$, $\tau_1$, $\delta_2$, $\tau_2$: Parameters of bond stress-slip models shown in Fig. 14.

The values of the parameters of the bond stress-slip models and the calculated values of interfacial fracture energy in B-P1-1 are reference values because slip at the free end could not be measured.

*Not the real interfacial fracture energy but a reference value because the effective bond length exceeded the bond length.

**The model for B-N was determined from all positions because there were few differences in the positions between the load end and the middle part.
The slip in the calculation is defined as total slip given by summing up slip calculated by strains from the loaded end to the free end on FRP strand sheet and slips at the free end. M1, M2 and M3 are used for the area from the loaded end to 60 mm, 60 to 460 mm, and 460 mm to the free end, respectively. The thickness of the FRP sheet, $t_f$, is 0.333 mm, and the Young’s modulus of the FRP sheet, $E_f$, is 259 kN/mm².

\[ \tau = t_f \cdot E_f \frac{d\varepsilon_f}{dx} \]  

Equation (15)

The calculation procedure is shown in the Appendix. Figure 16 shows the relationships between the applied load and the slip at the loaded end observed in the experiment and the analysis. In the case of specimen B-N without polyurea resin, the load-slip relationship calculated agrees well with the experimental results until the load reaches the maximum one. However, the load becomes a constant at the maximum load because the same maximum bond stress was set to for different locations in the analysis. In the case of specimens with the polyurea resin, the initial stiffness in the load-slip curve in the analysis is slightly smaller than that in the experiments. It can be concluded, however, that the analysis could predict overall behavior reasonably.

Table 6 shows a comparison between the experimental and the analytical results on the initial delamination load and the maximum load. In the experiment, the initial delamination load in the specimen with 2.0 kg/m² of the polyurea resin is higher than that in B-P1 of 1.0 kg/m². In the analysis, however, the initial delamination load is the almost same in both specimens B-P1 and B-P2. Because, in the bond stress-slip relationship used in the analysis, the interfacial fracture energy of Model 1 and Model 2 was the same.

In the maximum load, both the experimental and the analytical values increased in the order of specimen B-N, B-P1, B-P2, and B-P3 except for the analytical value in B-P3. However, the maximum value of B-N without polyurea resin was noticeably smaller in both the experiment and the analysis. The experimental maximum load in specimen B-P3 with 3.0 kg/m² of the polyurea resin was about 13% higher than that of specimen B-P2, but no significant difference was observed in the analytical results. This may be due to the effect of modeling the bond stress-slip relationship, such as the maximum bond stress $\tau_y$ of B-P3 being smaller than B-P2 in the bond stress-slip relationship, or the actual effective bond length for B-P3 may be longer than the bonded length. The ratios of the initial delamination load and the maximum load obtained by the experiment were between 1.07 and 1.32, and ratios obtained by the analysis were between 0.94 and 1.15. The analysis method considering simply bond models could predict experimental results well.

5. Conclusions

The findings obtained from the bond tests and analysis of
concrete and FRP strand sheet bonded with polyurea resin as high elongation elastic resin are shown below.

1. In the double-lap shear bond test specified by the Japan Society of Civil Engineers, the bond strength was greatly improved when polyurea resin was used. It was found, however, that the bond length of the standard type specimen was insufficient because the effective bond length was much longer than ordinary FRP sheet bonding using epoxy resin.

2. The single-lap shear bond test was conducted as so to obtain actual bond characteristic of CFRP strand sheet with polyurea resin. If the applied amount of polyurea resin is 1.0 kg/m² or more, the maximum delamination load is improved by more than twice as compared with the case of no application. However, no significant difference was observed by increasing the amount of polyurea resin applied to 2.0 kg/m². The highest load was obtained when the applied amount of polyurea resin was 3.0 kg/m².

3. The polyurea resin can increase significantly effective bond length and interfacial fracture energy of CFRP strand sheet. This is the reason why the maximum delamination load of CFRP strand sheet bonded on concrete can be increased using polyurea resin.

4. When the polyurea resin is not applied, the bond stress-slip relationship can be approximated by a mountain-shaped bi-linear curve with a sharp peak and a softening region. When a polyurea resin is applied, the bond stress-slip relationship can be approximated by tri-linear curve with a ductile softening branch and the relationships differ from different locations.

5. The interfacial fracture energy of the interface with polyurea resin calculated from the area of the bond stress-slip curve becomes remarkably larger than that without polyurea resin. It was found that the application of polyurea resin increased the interfacial fracture energy at the bonding interface and improved the bond strength.

6. The analysis method considering three kinds of simple bond models for the area around the loaded end, for the area between the loaded end and the free end, and for the area around the free end could predict experimental results well.

In addition, when a high elongation elastic resin with a low elastic modulus is used for the flexural strengthening of the concrete member with the FRP sheet, the shearing stiffness of the bonding interface is reduced, and the opening and deformation of the crack may increase. However, the effect of reducing the delamination range of the FRP sheet near the crack is also considered. The load capacity, deformation and cracking behavior of concrete members reinforced with high elongation elastic resin are considered for further study. Besides, a bond model that can consider the influence of boundary condition precisely and the optimum amount of polyurea resin will be also examined in the future.

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Appendix

Using the set bond stress-slip relationship, the relationship between load and slip was calculated by the following procedure. The elongation of resin and FRP is taken into account in the slip of bond stress-slip relationship, while the deformation of concrete is ignored in this calculation. The explanation below refers to Fig. 17.

1) Giving the slip $s_0$ at the point $x_0$.
2) Assuming the strain $\varepsilon_0$ at the point $x_0$.
3) The bond stress $\tau_1$ in the section $0 - 1$ in Fig. 17 is obtained from Eq. (14).
4) The strain $\varepsilon_1$ at the point $x_1$ is calculated by Eq. (16).

$$
\varepsilon_1 = \varepsilon_0 - \frac{\tau_1 dx}{E_f}
$$

5) The slip $s_1$ at the point $x_1$ is obtained by subtracting the strain integrated in section $0 - 1$ from the slip $s_0$.
6) From $s_1$ obtained in steps 4) and 5), the bond stress $\tau_2$ in section $0 - 1$ is calculated by Eq. (14).
7) For the section up to $x = 1$, calculate the slip, strain, and bond stress at each position according to the calculation procedure described in steps 4) to 6) above.
8) The tension force of the CFRP strand sheet is calculated by Eq. (17).

$$
P = b \sum_{i=1}^{n} \tau_i dx
$$

9) Compare the tension obtained from the strain $\varepsilon_0$ at the point $x_0$ with the tension force obtained in step 8), re-assume the strain $\varepsilon_0$ at the point $x_0$ until the difference becomes less than 0.1% of the load, repeatedly.
10) If the two forces are balanced in step 9) and the slip obtained by integrating the strain at each point is smaller than the given $x_0$, the difference is regarded as the slip at the end (position $n$).
11) Add a minute slip (0.001 mm) to the slip assumed in step 1) above, proceed to the next step, and repeat the calculation until the maximum value of the load is obtained.

Fig. 17 The analysis model.