Bonding performance of CFRP plate and concrete with soft layer system

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Abstract. The use of CFRP (Carbon Fiber Reinforced Polymer) plate to strengthen RC (Reinforced Concrete) structure has become popular, nowadays. Meanwhile, bonding behavior between CFRP plate and concrete is an important issue in application. Many research works had been done to improve the bonding performance of this method. In prior study, it was reported that the bond strength could be increased by increasing the stiffness of CFRP or using a soft adhesive layer with a small shear stiffness. With this assumption, the bond strength will be enhanced by putting a soft layer (polyurea) between CFRP plate and usual adhesive (epoxy). To obtain the complete view of bonding behavior of CFRP plate-concrete, a double face tensile test setup was conducted in this research. Both high modulus type and high tension type of CFRP plate with soft layer and without soft layer were tested. CFRP plate used in this study had a thick of 1mm, 2mm and 4mm, respectively, and had a width of 50mm for all specimens. The results showed that soft layer system has a big influence for high tension type.

1. Introduction

External bonding of carbon fiber reinforced polymer (CFRP) plate is commonly used for strengthening and retrofitting of both concrete and steel structure. Despite having a fairly expensive price, CFRP plate has many advantages such as corrosion resistance, high tensile strength, durability, good fatigue resistance, lighter specific gravity, easy and fast work in application. Bonding behavior of plate-concrete interface in producing an effective stress transfer is an important issue in application of this method. Therefore, a good understanding of the bonding behavior of the CFRP plate and concrete interface has to be developed for the efficient application of this method. It can be noted that the term interface that used in this paper is used to refer to interfacial part of bonded joint that experienced relative slip between CFRP plate and concrete, during loading, including the adhesive and the concrete surface [1].

Important task facing the CFRP/FRP strengthening technology is to improve the bonding behavior. Recently, many researchers have been undertaken to understand the bonding behavior of interface between concrete and FRP. Nakaba et al [2] have researched about bond behavior of interface between FRP and concrete and used the Popovic’s equation fitting and apply it to their experiments. Pelegrino and Modena [3] have reported their study about bonding behavior between FRP sheets and concrete and produced simple relationship for their research by attempting to find a relationship between the
maximum bond stress, the slip at maximum bond stress and ultimate slip using the bending test and double shear test.

Dai et al [4] and Zhou et al [5] developed a simple method to derive the local bond-slip relationship at the FRP-concrete interface based on the relationship between load and slips at the loaded end from a pull-off test. A research from Ko and Sato [6] proposed a bond stress-slip relationship between FRP sheet and concrete interface under cyclic load with three types of FRP sheets (aramid, carbon, and polyacetal). Pham and Al-Mahaidi [7] reported about modelling of CFRP bonded on concrete using a wet lay-up method and compared with bond slip curve from experimental and theoretical result.

A set of three bond-slip model for FRP sheet/plate bonded to concrete was developed by Lu et al [1]. It should be noted that the scope of this research has been limited to adhesive layer that has shear stiffness, $K_a$ (= $G_a/ta$, where $G_a$ = elastic shear modulus of the adhesive and $ta$ = the adhesive layer thickness), is no less than 2.5 GPa/mm. Dai and Ueda [8] reported that the use of very soft adhesive layer could increase the bond strength of FRP-concrete. This research was limited with shear stiffness between 0.14 and 1.00 GPa/mm.

However, the research regarding bonding behavior of the CFRP plate and concrete with a soft layer system has never been done. This paper aims to clarify the effect of putting a polyurea soft layer between usual adhesive (epoxy) and concrete. It can be noted that by adding a soft layer between plate and concrete, the active bond zone will be longer. It means that the effective bonding length will be increased so it is expected that the use of soft layer can enhance bond strength and bonding behaviour. Arazoe et al [9] has conducted a similar study using CFRP strand sheet and polyurea soft layer system to see the bonding and flexural behavior. It was reported that specimen with polyurea soft layer system can increase the maximum load more than three times than specimens without polyurea soft layer system.

| Table 1. CFRP plate material properties. |
|------------------------------------------|
| Properties                  | High Modulus Type | High Tension Type |
| Tensile modulus (MPa)        | 410,000           | 167,000           |
| Tensile strength (MPa)       | 1,625             | 2,400             |
| Unit Weight (kg/mm$^2$)      | 1,700             | 1,600             |

2. Experimental program
This study used epoxy putty (FE-Z) as adhesive and polyurea putty as soft layer. Meanwhile, two CFRP plate types used in this experiment that is high tension type and high modulus type. Table 1 show the mechanical properties of the plate. Furthermore, mean compressive strength was 49.8MPa and mean tensile strength of concrete was 4.3MPa from splitting test. Because of the main objective of this research is to find out the effect of polyurea soft layer, twenty four specimens comprising 1mm and 2mm in thickness for high tension type and 2mm and 4mm in thickness for high modulus type of CFRP plate with soft layer and without soft layer for three specimens each case have been tested in this study. For more detail, Figure 1 shows the application methods of with and without polyurea soft layer. The identity of each specimen can be seen at the Table 2.

The bonding test was done by adopting the JSCE-E543–2007 [10], about the test method for bonding properties of continuous fiber sheet to concrete. A common double-face tensile test setup was applied in this study. CFRP plate used in this research had a width of 50mm. The specimen consists of a concrete block with size of 150x150x1200mm. In the block center was installed PVC plate has the width of 4mm. The two steel bars imbedded in a concrete and also had no connection. It means that the concrete block was divided by two sections and connected only through by CFRP plate. The one side of the concrete block was clamped by steel plate to ensure the occurrence the failure only at the other side where strain gauge were set. On the two surfaces of prism, the strain gauge interval was set at 40mm and distributed in range from 10mm to 570mm from center of prism. To avoid stress concentration, a release film was placed on the concrete surface at the block center. The loading rate for load application was 5kN/min. The detail of the test set up can be seen at Figure 2, Figure 3 and Figure 4.
3. Results and discussion

3.1. Failure modes

The experimental results are shown in Table 2. The failure mode of each specimen is shown by CF, IF, and AF representing concrete, interfacial, adhesive and/or polyurea failure, respectively. Generally, polyurea soft layer specimens show concrete failure mode. As an example, the failure condition in specimen 4HMS1, 2HTN1 and 1HTN3 is presented in Figure 5(a), 5(b) and 5(c) for CF, IF and AF, respectively. Concrete failure was identified by destruction of the concrete prisms as deep as 5mm to 10mm. The surface of concrete prism failure zone was uneven, with the aggregate being clearly seen. Interfacial failure was mostly along the adhesive-concrete interface. The failure surface of interfacial failure was a few millimeter on the concrete-adhesive interface. Much less or little concrete was attached to the CFRP plate elsewhere. Then, the adhesive failure was identified as a separation on the epoxy or on the polyurea or between epoxy and polyurea.

![Figure 1. Detail of specimen bonding method.](image1)

![Figure 2. Test set up.](image2)

![Figure 3. Specimen detail.](image3)
3.2. Strain distribution at the maximum load

Figure 6 (a), Figure 6 (b), Figure 6 (c) and Figure 6 (d) show the strain distribution for each of specimens when the maximum load was achieved. It can be found that high tension type (1HT and 2HT) specimen with polyurea soft layer indicate an increase in ultimate strain around three times for 1mm in thickness and twice for 2mm in thickness compared with no soft layer ones. Furthermore, polyurea soft layer application produce almost linear strain distribution and there is a possibility of slip is happening at the free end because some strain can be seen near at free end. These profiles show a more uniform distribution of stresses. This application give indicate that all the surface of concrete is actual bond-resisting area from plate to concrete and, obviously, crack or delamination can start from anywhere on the bonding area. This phenomenon gives fact that the effective bond length of polyurea soft layer specimen is longer than bonding length.

This behavior is different for high modulus type (2HM and 4HM) specimen. It can be seen that the strain distribution exhibit more evenly for both soft layer and no soft layer specimen with a similar ultimate strain value. This phenomenon, obviously, produce the same maximum load. Polyurea soft layer does not give effect to the high modulus type. Moreover, maximum load of the 4HMS specimen is smaller than the no soft polyurea layer specimen (4HMN specimen) (see Table 2). This is probably due to the bonding length of high modulus type specimen is shorter than effective bond length. To give a clear explanation can be done by conducting research with a longer specimen, although in the fact that it is difficult to be conducted because the limitation of existing equipment.
Table 2. Specimen identity and experimental results.

| Specimen code | Soft layer | $E_p$ $t_p$ (kN/mm) | $P_{max}$ (kN) | $\tau$ (MPa) | Failure Mode |
|---------------|------------|---------------------|----------------|--------------|--------------|
| 1HTS1         | Yes        | 167                 | 167            | 2.83         | AF+CF        |
| 1HTS2         | Yes        | 163                 | 167            | 2.76         | AF+CF        |
| 1HTS3         | Yes        | 149                 | 149            | 2.53         | AF           |
| 1HTN1         | No         | 59                  | 59             | 1.00         | AF           |
| 1HTN2         | No         | 76                  | 76             | 1.30         | AF           |
| 1HTN3         | No         | 57                  | 57             | 0.97         | AF           |
| 2HTS1         | Yes        | 177                 | 177            | 3.00         | CF           |
| 2HTS2         | Yes        | 166                 | 166            | 2.81         | CF           |
| 2HTS3         | Yes        | 334                 | 334            | 2.83         | CF           |
| 2HTN1         | No         | 87                  | 87             | 1.47         | IF           |
| 2HTN2         | No         | 98                  | 98             | 1.66         | IF           |
| 2HTN3         | No         | 88                  | 88             | 1.49         | IF           |
| 2HMS1         | Yes        | 161                 | 161            | 2.73         | IF           |
| 2HMS2         | Yes        | 183                 | 183            | 3.10         | CF           |
| 2HMS3         | Yes        | 164                 | 164            | 2.79         | CF           |
| 2HMN1         | No         | 170                 | 170            | 2.88         | AF           |
| 2HMN2         | No         | 154                 | 154            | 2.60         | AF+IF        |
| 2HMN3         | No         | 155                 | 155            | 2.63         | AF+IF        |
| 4HMS1         | Yes        | 180                 | 180            | 3.05         | CF           |
| 4HMS2         | Yes        | 206                 | 206            | 3.49         | CF           |
| 4HMS3         | Yes        | 1640                | 1640           | 3.19         | CF           |
| 4HMN1         | No         | 215                 | 215            | 3.64         | IF           |
| 4HMN2         | No         | 215                 | 215            | 3.64         | IF           |
| 4HMN3         | No         | 229                 | 229            | 3.88         | IF           |

Note: $\tau$ = average shear stress, $\tau = \frac{P_{max}}{b y h}$, CF= Concrete failure, IF= Interfacial failure, AF= Adhesive failure

Figure 6. Strain distribution at maximum load.
3.3. Maximum load and CFRP plate stiffness relationship

Stiffness of the CFRP plate is defined as the multiplication of the elasticity modulus of the plate and thickness of the plate ($E_{pt}$). Figure 7 shows the relationship between maximum load and stiffness of CFRP plate, this figure is divided into two lines that is solid line and broken line for soft layer soft layer specimen and no specimen, respectively. Clearly, it can be seen from the results of the regression line that soft layer specimens produce almost similar the maximum load for each of CFRP plate stiffness. The mean maximum load of the soft layer specimen is 172.58kN. The broken line, for the no soft layer specimen, shows different behavior. The broken line shows that the maximum load increases as the CFRP plate stiffness is increase and the results of regression analysis on maximum load is proportional almost equal to $(E_{pt})^{0.5}$. This result is consistent with the previous study [4, 8].

4. Summary

This article presented the result of polyurea soft layer effect from a testing program of 24 CFRP plate bonding test with a variety of parameter including type of CFRP plate, thickness of CFRP plate with soft layer and no soft layer condition. A FEM of the bonding tests has been described followed by verification study of a prediction method. The conclusion can be drawn up as follows.

- Soft layer specimen is generally experienced fracture on the concrete, concrete failure was identified by destruction of the concrete prisms as deep as 5mm to 10mm or more.
- On the high-tension type of CFRP, the polyurea soft layer can enhance the performance of bonding behavior. However, polyurea soft layer does not give effect on the high modulus type.
- It clearly be seen that on the soft layer specimens show an increase of interfacial fracture energy with decreasing the plate stiffness. The smaller the CFRP plate stiffness the more effective soft layer can increase the interfacial fracture energy.
- The results of CFRP stiffness and maximum load relationship show that maximum load is proportional to $(E_{pt})^{0.5}$.

References

[1] Lu X Z, Ye L P, Teng J G, and Jiang J J 2004 Meso-Scale Finite Element Model for FRP Sheets/Plates Bonded to Concrete Engineering Structures 27 pp 564-575
[2] Nakaba K, Kanakubo T, Furuta T and Yoshizawa H 2001 Bond Behavior between Fiber-Reinforced Polymer Laminates and Concrete ACI Structural Journal 98 (3) pp 359-367
[3] Pelegrino C and Modena C 2008 Bond-Slip Relationship between FRP Sheets and Concrete 4th
International Conference on FRP Composite in Civil Engineering (CICE)

[4] Dai J G, Ueda T, and Sato Y 2005 Development of the Nonlinear Bond Stress-Slip Model of Fiber Reinforced Plastics Sheet-Concrete Interface with a Simple Method Journal of Composite for Construction ASCE 9 (1) pp 52-62

[5] Zhou Y W, Wu Y F and Yun Y C 2010 Analytical Modelling of the Bond-Slip Relationship at FRP-Concrete Interfaces for Adhesively-Bonded Joint Composite: Part B 41 pp 423-433

[6] Ko H, and Sato Y 2007 Bond Stress-Slip Relationship between FRP Sheet and Concrete under Cyclic Load Journal of Composite for Construction ASCE 11 (4) pp 419-426

[7] Pham B H and Al-Mahaidi R 2007 Modelling of CFRP-Concrete Shear lap Test Construction and Building Materials (21) pp 727 – 735

[8] Dai J G and Ueda T 2003 Local Bond Stress Slip Relations for FRP Sheets–Concrete Interface in Proc. of 6th International Symposium on FRP Reinforcement for Concrete Structure Singapore World Scientific Publication pp 143-52

[9] Arazoe M, Kobayashi A, Takahashi Y and Sato Y 2014 Bonding and Flexural Behaviors of RC Members with CFRP Strand Sheets–Polyurea Soft Layer System The 7th International Conference on FRP Composite in Civil Engineering (CICE) Vancouver Canada

[10] Japan Society of Civil Engineering (JSCE) 2007 Standard Specification for Concrete and Structure, Test Method and Specification