INFLUENCE OF LOCAL BOND CHARACTERISTICS IN FRP-CONCRETE BOND BEHAVIOR

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ABSTRACT

Macro-level bond behavior between FRP laminates/sheet and concrete is influenced by local bond characteristics such as bond stress (τ) – slip (s) relationships. In this study, effect of local bond characteristics to macro-level bond behavior is investigated by numerical analysis based on the sequential integration method. Investigated influence factors are $\tau - s$ relation shapes, delamination fracture energy and FRP stiffness. Analytical results are concluded that influence of differences of $\tau - s$ relation shapes is relatively small, and macro-level bond strength is mainly influenced by fracture energy and FRP stiffness. To increase the macro bond strength, it is effective to increase fracture energy. However, when the fracture energy varies, the effective bond length can vary too. It is essential that the bond length should be greater than the effective bond length. When the ratio of local bond strength to ultimate slip is constant, the effective bond length remains the same, and macro bond strength and loaded-end slip are proportional to square root of fracture energy.

1 INTRODUCTION

As element-level macro bond characteristics between FRP laminates/sheet and concrete are influenced by micro bond characteristics (local bond characteristics) and various other factors (influencing factors). Macro characteristics as represented by the maximum load and the amount of slip (loaded-end slip) are subject to change. Micro bond characteristics and various influencing factors are closely related to each other, and the reinforcing material properties (e.g., stiffness) have especially strong influence on macro bond characteristics. On the other hand, there are cases in which macro bond characteristics do not change noticeably even when the bond stress (τ) – slip (s) relationship changes by various influencing factors which can have significant influence on micro bond characteristics. It is difficult to clearly distinguish between the influence of various influencing factors on micro bond characteristics and the influence of those factors on macro bond characteristics. Besides, even if those factors influence only micro bond characteristics, their influence is not always reflected directly in macro bond characteristics.

In this study, local bond stress – slip relationship and delamination fracture energy (one of the micro bond characteristics) and the reinforcing material stiffness (one of the influencing factor) as the factors that influence macro bond characteristics are adopted. The influences of those factors on macro bond characteristics are assumed that it changes independently of the other factors.

2 ANALYSIS METHOD

The bond characteristic analyzed is only shear bond characteristic (Mode II), and the analytical method used is the sequential integration method in which numerical calculations are performed based on force equilibrium and deformation compatibility conditions [1].

The specifications of the other calculating factors are as shown below. A concrete block having a 100 mm x 50 mm cross section (contains deformed bar D22 in the center) is bonded with FRP laminate (width: 50 mm) on one side. This gives the image of shear bond characteristic when the FRP laminate is subjected to an in-plane shear (Figure 1).

Concrete : Sectional area, A_c＝100 x 50mm Elastic modulus, E_c＝24GPa
Reinf. bar : Sectional area, A_s＝387mm^2 Elastic modulus, E_s＝206GPa
FRP laminate : Bonding width, b_f＝50mm

It is assumed that the behavior of the concrete, reinforcing bar, and FRP laminate within a finite bond length show only elastic behavior. This is different from the actual element-level behavior and the behavior within a member in terms of the occurrence of a crack in concrete and the presence or absence of an out-of-plane deformation.

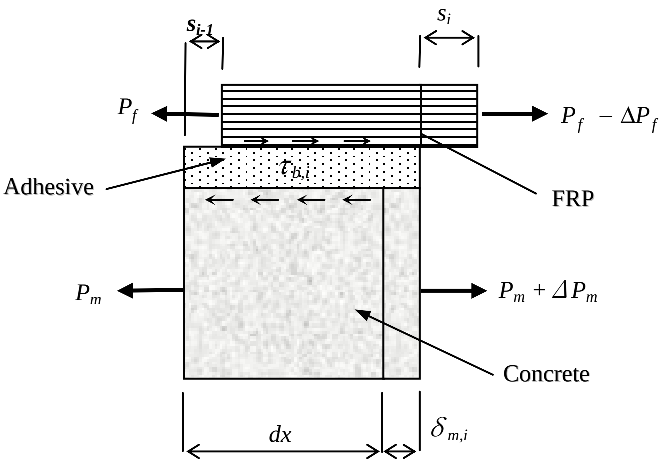


Figure 1 Image of analysis target

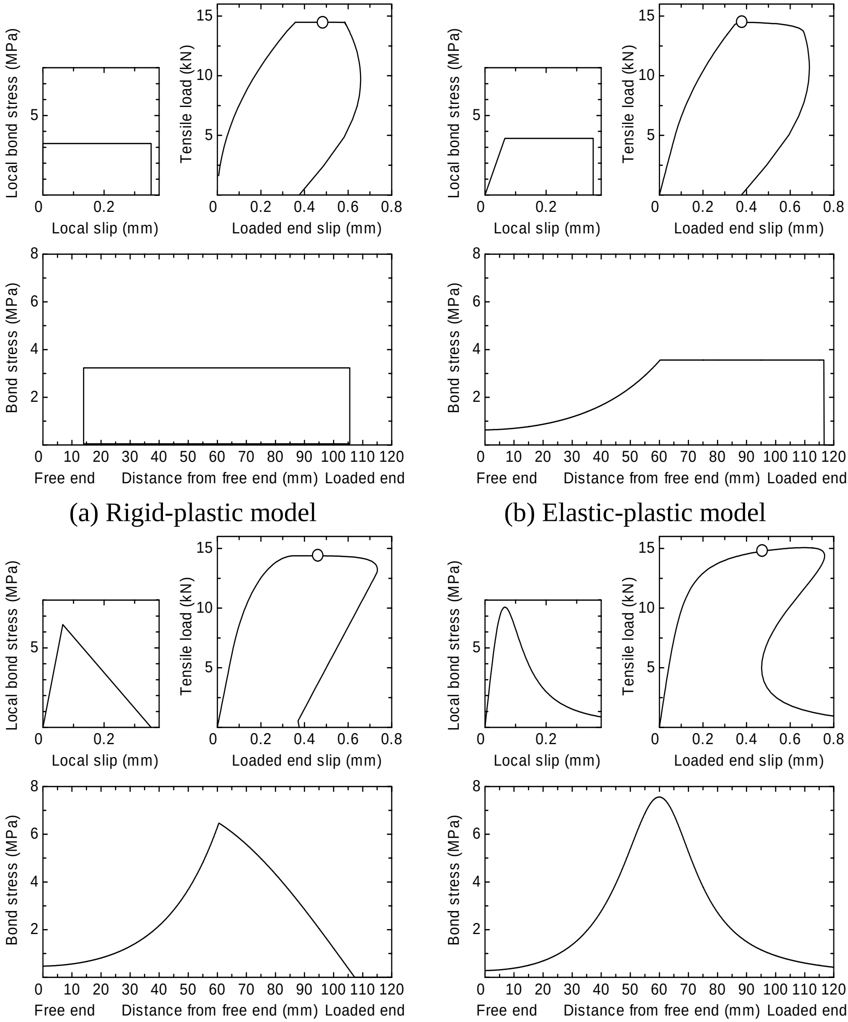
3 ANALYTICAL RESULTS AND DISCUSSION

3.1 Influence of shape of local bond stress – slip relationships

To investigate the influence of the shape of local bond stress (τ) – slip (s) relationship, the four models shown in Figure 2 are used. They are: (a) perfectly rigid-plastic model, (b) perfectly elastic-plastic model, (c) bi-linear model (softening type), and (d) Popovics model [1]. Since the influence of only the shape of $\tau - s$ relationship is to be investigated, the delamination fracture energy (area enclosed by $\tau - s$ relationship) and the FRP stiffness are assumed to be the same for all the models. The values of analysis factors are as shown below. It should be noted that for the Popovics model, the range of calculation of fracture energy is 0 to 0.354 mm in terms of the amount of local slip.

Fracture energy G_f＝1.145N/mm
FRP stiffness $t \cdot E$＝ (0.167mm) x (230GPa) ＝38.4kN/mm
Bond length l_b＝120mm

The relationship between loaded-end tensile load and loaded-end slip and the bond stress distributions in the bonded region are shown in Figure 2. The bond stress distribution is obtained one at the point marked with the circle on the tensile load – loaded-end slip relationship.



(a) Rigid-plastic model (b) Elastic-plastic model

(c) Bi-linear model (d) Popovics model

Figure 2 Local $\tau - s$ relations and macro bond behavior

From the analysis results obtained by the each model, the bond stress distribution differs among the models. However, there is no remarkable difference in maximum tensile strength among the models: they are in the range from 14.4kN to 15.1kN. With the exception of the Popovics model, the loaded-end slip under maximum tensile load is less than 0.4 mm. Thus, as long as the fracture energy and FRP stiffness are the same, the shape of the local bond stress – slip relationship, which is one of the micro bond characteristics, does not have significant influence on the macro bond characteristics.

3.2 Influence of delamination fracture energy

To investigate the influence of delamination fracture energy (G_f), an analysis is performed by using the bi-linear model for local bond stress – slip relationship and the same FRP stiffness. The fracture energy is assumed to be in the range from 0.045N/mm to 2.045N/mm, and a similar bi-linear model shown in Figure 3 is used. The values of the other analysis factors are as shown below:

FRP stiffness $t \cdot E =$ (0.167mm) x (230GPa) $=$38.4kN/mm

Bond length $l_b =$120mm

The relationship between fracture energy and maximum tensile load obtained by analysis and the relationship between fracture energy and loaded-end slip at maximum load are shown in Figure 4. For the maximum tensile load, which is proportional to square root of G_f, the approximate expression shown in the figure is obtained in this analysis. The loaded-end slip at the maximum load is also proportional to square root of G_f.

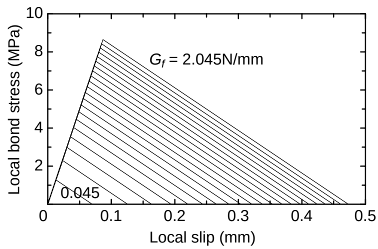


Figure 3 Bi-linear model varied by G_f

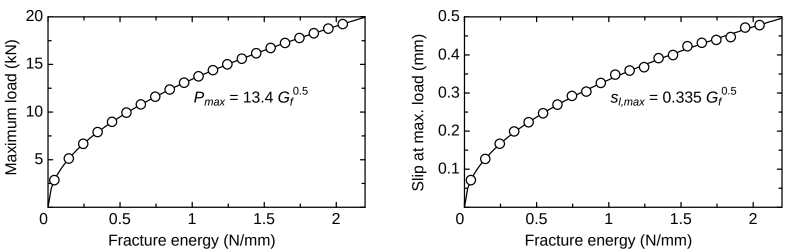


Figure 4 Fracture energy and macro bond behavior

3.3 Influence of FRP stiffness

To investigate the influence of FRP stiffness, an analysis is performed by using a bi-linear model (τ_{max} = 6.47MPa, s_{max} = 0.065 mm, s_u = 0.354 mm) for the bond stress – slip relationship. The stiffness of the FRP is assumed to be 2.51kN/mm to 1030kN/mm. The values of the other analysis factors are as shown below.

Fracture energy $G_f =$1.145N/mm

Bond length $l_b =$600mm

The relationship between FRP stiffness and maximum tensile load and the relationship between FRP stiffness and loaded-end slip at maximum load are shown in Figure 5. For the maximum tensile load, which is nearly proportional to $\sqrt{t \cdot E}$, the approximate expression shown in the figure is obtained in this analysis. The loaded-end slip at maximum load is almost constant.

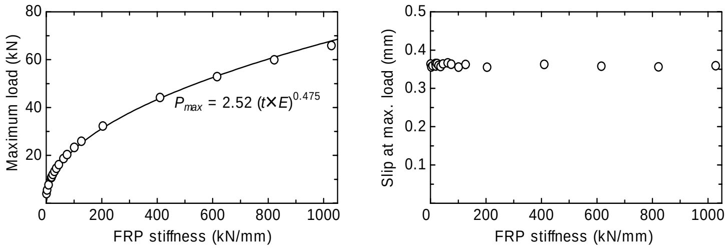


Figure 5 FRP stiffness and macro bond behavior

4 INFLUENCE FACTORS FOR MACRO BOND BEHAVIOR

When the bond length is sufficiently large and the concrete deformation is negligibly small, there is the following correlation among bond strength, fracture energy, and reinforcing material stiffness [2, 3].

$$P_{max} = b_f \cdot \sqrt{2 \cdot G_f \cdot t \cdot E} \tag{1}$$

where,

P_{max} : bond strength
b_f : FRP width
G_f : delamination fracture energy
$t \cdot E$: FRP stiffness

Substituting the values used in the analysis in Equation (1), P_{max} with the analysis factors shown in 3.2 becomes as follows:

$$P_{max} = 13.9 \cdot \sqrt{G_f} \tag{2}$$

Similarly, with the analysis factors shown in 3.3, P_{max} becomes as follows:

$$P_{max} = 2.39 \cdot \sqrt{t \cdot E} \tag{3}$$

The approximate expressions obtained in the analysis are close to the above expressions. The slight difference between the approximate expression shown in 3.3 and the above expression (3) is considered due to the fact that the difference in stiffness between the FRP and concrete is not negligible. In practical use, however, Equation (1) is considered sufficient.

To calculate effective bond length roughly, the following expression is considered effective.

$$l_e = s_u \cdot \sqrt{\frac{2 \cdot t \cdot E}{G_f}} \tag{4}$$

where,

l_e : effective bond length

s_u : ultimate slip in local τ-s relationship (at point where bond stress = 0)

$t \cdot E$: FRP stiffness

G_f : delamination fracture energy

Equation (4) is derived from Equation (5) which represents the anchoring conditions of FRP when the local bond stress – slip relationship is assumed as a perfectly rigid-plastic model with bond stress τ_y and ultimate slip s_u.

$$s_u = \frac{\tau_y}{2 \cdot t \cdot E} \cdot l_e^2 \tag{5}$$

$$G_f = \tau_y \cdot s_u \tag{6}$$

5 SUMMARIES

Analytical results show that the influence of differences of local bond stress – slip relation shapes is relatively small, and macro-level bond strength is mainly influenced by fracture energy and FRP stiffness. To increase the macro bond strength, it is effective to increase the fracture energy. However, when the fracture energy varies, the effective bond length can vary too. It is, therefore, essential that the bond length should be greater than the effective bond length. Generally speaking, when the ratio of local bond strength to ultimate slip is constant, i.e., the local bond stress – slip relationship is similar, the effective bond length remains the same, and the bond strength and loaded-end slip are proportional to $\sqrt{G_f}$. Since the macro bond strength is proportional to $\sqrt{t \cdot E}$, the macro bond strength can be increased by using a stiffer FRP. In this case, the effective bond length also increases in proportion to $\sqrt{t \cdot E}$, whereas the loaded-end slip remains the same.

Acknowledgement

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References

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