# EXPERIMENTAL STUDY ON BOND BEHAVIOR BETWEEN CFRP PLATE AND CONCRETE UNDER COMBINATION OF FRACTURE MODE

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## 1. INTRODUCTION

In case of flexurally strengthened concrete beams, the bond properties of FRP material and concrete interface have been affected by a combination of fracture mode (Mode I and Mode II). The objective of this study is to understand bond behavior and strength in CFRP plate and concrete systems in peeling and shear interface fracture simultaneously using special double-face shear bond test specimen.

## 2. EXPERIMENTAL PROGRAM

### 2.1 Specimen

Basic concept of this study is to obtain bond behavior directly using double shear bond specimen. A total of 12 specimens, which have curved surface to connect two different cross sections for each specimen to allow an initial angle, were prepared to test by uniaxial static loading. The detail of specimen is shown Fig.1. The M24 steel bars have no connection at the center of the specimen, and the pre-crack is introduced before loading. The specimen list is shown in Table 1. They were divided into 2 groups according to whether "fully bond", or "pre-unbond" region was set at the center to cause the combination of fracture mode clearly at the bonding region. The variables factors are initial angles, which ranged 5°,10° and 20° and concrete strength (target strength is 13.5MPa and 21MPa). High strength type CFRP plate which thickness is 1mm is utilized.

### 2.2 Loading and measurement

All specimens were subjected to tensile force by a 1MN actuator. Each specimen was instrumented with 8 strain gauges at intervals 50mm on CFRP plate in one side. The total displacement and crack width at the pre-cracked notch were measured by using linear variable displacement transducers.

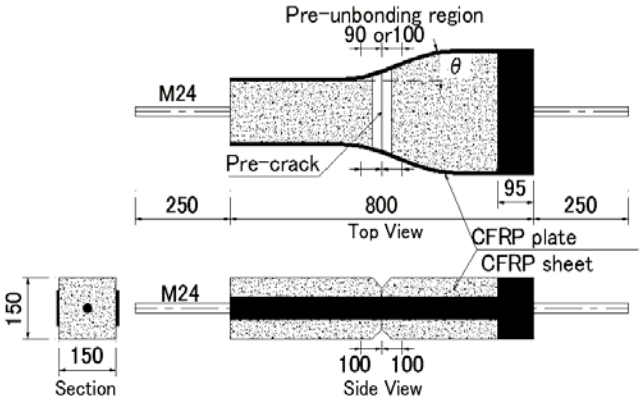


Fig.1 Specimen detail

Table 1 Specimen list

| Group | Specimen | Concrete Strength (MPa) | Bond condition | Initial angle (degree) |
|---|---|---|---|---|
| 1 | S13.5-5-1 | 16.8 | Fully bond | 5 |
| | S13.5-10-1 | | | 10 |
| | S13.5-20-1 | | | 20 |
| | S21-5-1 | 28.8 | | 5 |
| | S21-10-1 | | | 10 |
| 2 | S21-20-1 | | Pre-unbond (90mm) | 20 |
| | S13.5-5-2 | 16.9 | Pre-unbond (100mm) | 5 |
| | S13.5-10-2 | | | 10 |
| | S13.5-20-2 | | | 20 |
| | S21-5-2 | 30.8 | | 5 |
| | S21-10-2 | | | 10 |
| | S21-20-2 | | | 20 |

## 3. TEST RESULTS AND DISCUSSIONS

### 3.1 Failure progress

All the specimens were subjected to tensile force until debonding failure on either side. Typical failure surfaces from experimental result are shown in Fig.2. Two groups specimens' failure progress are difference. In the Group 1 specimens, at first, central position of CFRP plate debonded with sudden decrease of tensile load. The failure interface is inside of concrete surface. After that, CFRP plate peeled off toward the loaded end of the specimen with gradual increase of tensile load. The failure face of this debonding is between CFRP plate and adhesive. It is considered that this debonding mechanism is due to the combination of fracture mode (peeling and shear).

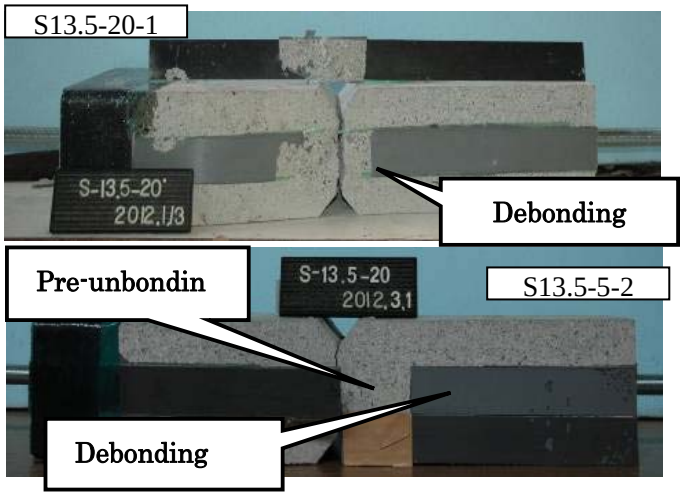


Fig.2 Typical failure surface

Keywords: CFRP plate, Peeling, Shear bond, Bond strength, Peeling angle
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Fig.3 illustrates the debonding progress in Group 1 specimens. The peeling angle is defined as the angle between the axial direction and tangential line taken from the surface of specimen to the position of peeling as shown in Fig.3. The peeling angle decreases as the peeling position moves toward the loaded end of specimen. In the Group 2 specimens, CFRP plate peeled off toward the loaded end of the specimen with gradual increase of tensile load. The failure face is between CFRP plate and adhesive. This debonding is just the same as that of Group 1 specimens after decrement of tensile load.

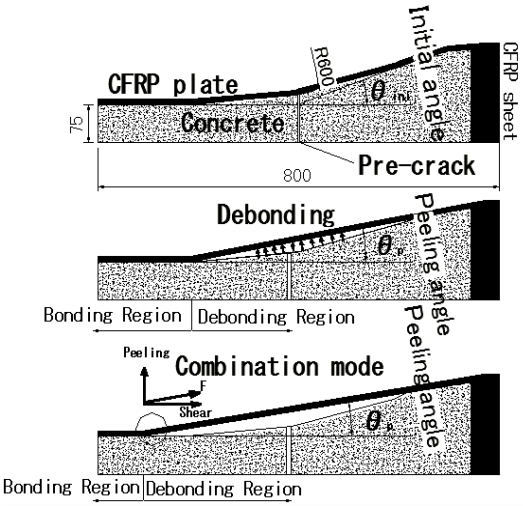


Fig.3 Debonding in Group 1 specimens

**3.2 Tensile load vs displacement relation and strain distribution**

Load versus displacement relation of two groups specimens are shown in Fig.4. In Group 1 specimens, it can be seen that the first peak of the load appears at the debonding of the central position of the specimen. After sudden drop, the load increases again. In Group 2 specimens, the load is smaller that that of Group 1 specimens. The maximum load of Group 2 specimens corresponded to the fully debonding of the CFRP plate from the specimen. The initial angle decreases, as the maximum load increases. The observed strain distribution, with the tensile force versus crack width diagram for specimen S21-10-2 is shown in Fig.5. The strain distributions correspond to mark plots on the tensile force versus crack widths diagram. Some negative strains are observed due to bending of CFRP plate during debonding progress. As the debonding progresses, the position of negative strain also moves to the loaded end.

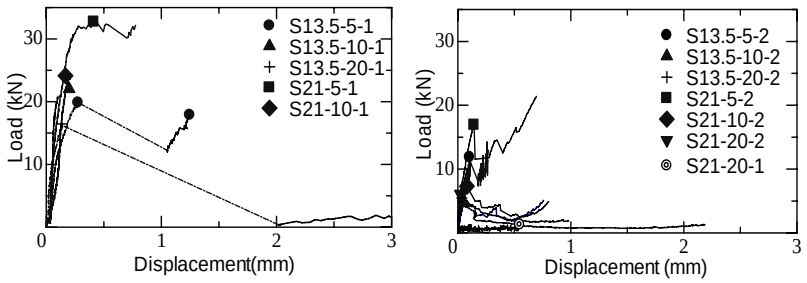


Fig.4 Load-Displacement relationship

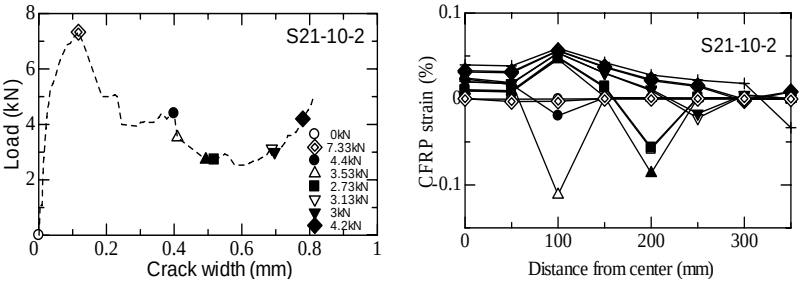


Fig.5 Strain distribution

**3.3 Bond strength evaluation**

Bond strength affected by combination of fracture mode is evaluated as same method for the case of FRP sheet bonding system.[1] The peeling angle is obtained as the angle between the axial direction and tangential line taken from the specimen surface to the position of negative strain of CFRP plate. The ratio of tensile load $P$ to the calculated bond strength $P_{cal}$ [2] is plotted against the peeling angle (tan $\theta_p$) in Fig.6 for some specimens. It can be seen that the tensile load decreases with the increase of the peeling angle. The fitting line of the behavior of tensile load for the Group 2 specimens can be represented by Eq.(1).

$$P / P_{cal} = 0.0073 (\tan \theta_p)^{-0.99} \quad (1)$$

Fig.7 plots the Eq.(1) and calculated bond strength which varies by bond length confirmed by the peeling angle. The intersection points give the bond strength under combination of fracture mode.

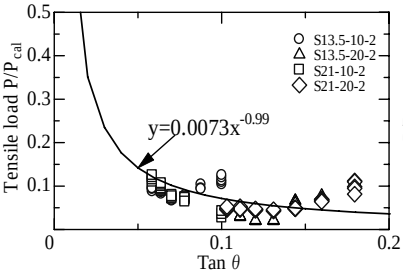


Fig.6 Tensile load-peeling angle relationship

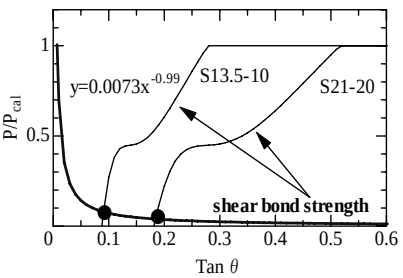


Fig.7 Bond strength diagram

## 4. CONCLUSIONS

The bond behavior under the combination of fracture mode is observed using special specimens which have curved surface. The bond strength decreases as the peeling angle increases. The relationship between peeling angle and tensile load is determined to evaluate the bond strength under the combination of fracture mode. The authors acknowledge the support of Mr. Tsutomu Yano, Constec Engi. Co.

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