ABSTRACT
This paper presents an experimental study on bond behavior of longitudinal bars in hanging region of RC beam failed in bond. In order to realize the bond splitting failure, CFRP rods were used as longitudinal reinforcement instead of steel bars. Totally sixteen simply supported RC beams were tested in order to know the magnitude of bond stress in hanging region. The main test variables are (a) transverse reinforcement ratio and additional embedment length in the hanging region, and (b) transverse reinforcement ratio in the shear span. Based on the test results a model for predicting tension force at the support was presented.

Keywords: reinforced concrete beam, CFRP rods, bond strength, hanging region, shear span.

1. INTRODUCTION
A certain quantity of the tensile force (tension shift) exists at the support when the diagonal shear crack develops in the shear span of reinforced concrete beam. The existence of the tension force at the support of simple supported reinforced concrete beam also has been clarified by using the strut and tie model. Therefore, longitudinal reinforcement of simply supported beam must be embedded past through the support to avoid bond-splitting failure known as the additional embedment length.

The codes provide different suggestion for this requirement. For example, in AIJ Code [3], the additional embedment length at the support of simple supported beam must be equal or greater than the effective depth of the beam, while ACI Code Sec. 12.11.1 [1] requires that the reinforcement should be extend from the support at least 150 mm.

Some theoretical equations evaluating the tension shift due to the diagonal shear crack have been proposed e.g. [4, 9]. Most of them are derived based on the truss mechanism, but there have been few experimental studies evaluating quantitatively the relationship of the tension shift and additional embedment length. The aim of this paper is to fill up this blank by focusing the study on the hanging region of simply supported RC beams subjected to two point symmetric load.

Experimental study conducted by Komiya et al. [6] related to the bond characteristic of Carbon Fiber Reinforced Polymer (CFRP) rod showed that it has lower bond strength comparing to the conventional steel bar, but this value is still higher than the required bond strength for steel bar by Fujii-Morita [7]. Due to this fact and higher tensile strength, CFRP rods are favourable materials to investigate the additional embedment length or anchorage length of reinforced concrete members and to realize the bond splitting failure of the beam consciously. Hence, the CFRP deformed rods were used in this experiment as the longitudinal tension bars instead of the conventional steel bars.

Totally sixteen reinforced concrete beams were monotonically loaded to failure. Four of them were not comprised of any additional embedment length in the hanging region to observe the failure mode and the improper behavior due to lack of additional embedment length. The main test variables were (a) transverse reinforcement ratio and additional embedment length in the hanging region, and (b) transverse reinforcement ratio in the shear span.

2. EXPERIMENTAL STUDY
In this study, sixteen reinforced concrete beams have been tested. Specimens were divided into two groups G1 and G2. Details of specimen,
material properties, and test variables are shown in Table 1. All of the specimens were 130 mm wide and 230 mm deep. The specimen was simply supported and subjected to two-point loads with 450 mm shear span.

The longitudinal reinforcements (compression) for all specimens were ordinary deformed steel bars with yield strength, \( f_y = 403 \text{ MPa} \). To observe bond stress in the shear span, strain gages were attached on the tension longitudinal reinforcement at the support and the loading point. Specimen detail and loading position are shown in Fig. 1.

In the case of beam group 1 (G1), the effect of additional embedment, \( L_b \), length in hanging region to the bond characteristic on the specimens were investigated by using three different hanging lengths: 160, 220, 280 mm (see Table 1). The influences of transverse reinforcement in hanging region were also examined by using three different reinforcement ratios, \( \rho_{wh} \) (0.27, 0.54, and 0.72%).

Furthermore, in the case of G2, the influence of transverse reinforcement in shear span was observed by using four different reinforcement ratios, \( \rho_{ws} \) in shear span (0.68, 0.77, 0.87, and 0.97 %). The effect of additional embedment length, \( L_b \) (0 and 100 mm) was also investigated and steel sleeves were used to eliminate bond between CFRP rods and concrete as illustrated in Fig. 1(b).

![Fig. 1 Specimen detail and loading position.](image)

### Table 1 Detail of specimens and test results.

<table>
<thead>
<tr>
<th>Beams</th>
<th>Concrete Comp. Strength( f_{c'} ) (MPa)</th>
<th>Longitudinal Reinforcement( \rho ), ( f_y ) (MPa), ( E_y ) (GPa)</th>
<th>Transverse Reinforcement( \rho_{ws} ), ( \rho_{wh} ), ( f_y ) (MPa)</th>
<th>Additional embedment length ( L_b ) (mm)</th>
<th>( P_{\text{exp}} ) (kN)</th>
<th>Type of failure</th>
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<tr>
<td>G1-1</td>
<td>38.3</td>
<td>0.58</td>
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<td>153</td>
<td>0.73</td>
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<td>164</td>
<td>0.97</td>
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<tr>
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<td>164</td>
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<tr>
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<td>164</td>
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3. BOND STRESS

Experimental bond stress, $\tau$, in the shear span can be calculated by measured strains at the support, $\varepsilon_1$, and at the loading point, $\varepsilon_2$, as follows:

$$\tau_s = \frac{E_f d_b}{4L_{bs}} (\varepsilon_2 - \varepsilon_1)$$

while bond stresses in the hanging region were determined by:

$$\tau_h = \frac{E_f d_b}{4L_b} \varepsilon_i$$

where $E_f$ is the elastic modulus of FRP, $d_b$ is the diameter of longitudinal reinforcement, $L_{bs}$ is the shear span length, and $L_b$ is the additional embedment length in hanging region.

Discussion on beam group 1

In order to investigate the effect of transverse reinforcement ratio in hanging region, shear forces are plotted versus bond stresses in hanging region as shown in Fig. 2. Figure 2 (a) and (c) show that even though with increase of transverse reinforcement ratio in hanging region from $\rho_{wh} = 0.27\%$ to $0.73\%$, there is no significant difference of bond stresses in hanging region. Although Fig. 2(b) shows a little difference, the variation is not proportional to $\rho_{wh}$. Therefore, there is no influence of $\rho_{wh}$ on bond stress in hanging region.

Discussion on beam group 2

Figure 4 show the test results of beams G2-5 to G2-8. These figures point out that as transverse reinforcement ratio in shear span ($\rho_{ws}$) increases, bond stresses in both hanging region and shear span decrease. Thus, bond stresses are considerably affected by $\rho_{ws}$.

4. TEST RESULTS AND DISCUSSION

The maximum load capacity and failure mode for each specimen are shown in Table 1. Specimens failed in different failure mode with specimens G1-2, G1-5, G1-6 failed in corner splitting bond, specimens G2-1 to G2-4 failed in side splitting bond and the others failed in flexure or shear failure mode.

Based on experimental results, two main points will be discussed: (1) the effect of transverse reinforcement ratio in hanging region and shear span, and (2) the influence of additional embedment length in hanging region.
Figure 5 shows the effect of additional embedment length on bond stresses in shear span. As can be seen, these figures show bond stresses in shear span without additional embedment length are higher than those with additional embedment length.

Moreover, in the experimental test, the beams without additional embedment length (G2-1 to G2-4) failed in bond splitting failure mode, while beams with additional embedment length (G2-5 to G2-8) failed in shear with higher ultimate load carrying capacity due to the contribution of anchorage length to the bond splitting capacity of the beams.

Figure 6(a) and (b) show bond strength in shear span calculated using Fujii-Morita ($\tau_{FM}$) and ACI-440 ($\tau_{ACI}$) equations respectively compared with the maximum experimental bond stress of specimens failed in bond. It is noted that, at the maximum load, the shear span length in Eq. (1)
could be assumed as $L_{bs} = a - d$, due to the diagonal cracks occurred in shear span. These figure shows that predicted values using Fujii-Morita and ACI-440 equations are higher than test results.

5. PROPOSED TENSION FORCE MODEL

Figure 7(a) shows the relationship between shear force and additional tension force at the support developed after diagonal shear crack. Only the representative specimens G1-2 and G2-5 were presented in this paper. Corresponds to the explanation in the previous section related to the bond stress in hanging region, it is demonstrated that the tension force at the support also significantly increases after the diagonal shear crack occurred.

Furthermore, statistical analysis has been conducted using strain data after diagonal shear crack of each specimen (see Fig 7(a)). Based on the results of linear regression, an equation $\Delta T = \alpha V - B$ was obtained.

In addition, the diagonal shear cracking force in Eq. (5) suggested by Niwa [8] were used to check the shear force carried by concrete, $V_c$. The results show that coefficient $B \approx V_c$, therefore it is reasonable to replace the coefficient $B$ to $V_c$.

$$V_c = 0.2\left(\rho_w f'_{c}\right)^{\frac{1}{3}}\left(d^{-\frac{1}{8}}\right)\left(0.75 + 1.4\frac{d}{a}\right)h_w d$$

where $\rho_w$ is the longitudinal reinforcement ratio, $d$ is the effective depth, $b_w$ is the web width, and $a$ is the shear span length.

Then a model to illustrate the additional tension force, $\Delta T$, of longitudinal reinforcement at the support due to the tension shift can be proposed as follows:

If $V \leq V_c$ : $\Delta T = 0$  \hspace{1cm} (6)

and if $V > V_c$ : $\Delta T = \alpha(V - V_c)$  \hspace{1cm} (7)

where $\Delta T$ is the additional tension force, $V$ is the shear force, and $\alpha$ is the coefficient as a function of the additional embedment length.

A simple statistical analysis was conducted to find the coefficient $\alpha$. It is found that, when $L_b$ smaller than $0.68d$, the tension force increases as the embedment length increases and it become constant when $L_b$ greater than $0.68d$ as shown in Fig 7(b). Finally, the following expression could be expressed:
for $L_b \leq 0.68d$: \[ \alpha = 1.5 \frac{L_b}{d} \] (8)

and for $L_b > 0.68d$: \[ \alpha = 1.0 \] (9)

In order to apply the proposed model, the authors suggest to use the minimum shear capacity, $V_{\text{min}}$, between $V_{\text{flexure}}$, $V_{\text{bond}}$, and $V_{\text{shear}}$ i.e. shear capacity calculated from flexural, bond, and shear capacity respectively.

Figure 7(c) shows the comparison between predicted maximum tension forces using proposed model with experimental results. It is shown that the proposed model predicts well the maximum tension force at the support.

6. CONCLUSIONS

Totally 16 beams have been tested to investigate the bond behavior of RC beams with hanging region using CFRP rods and the results led to the following conclusions:

1. AIJ and ACI codes conservatively provide development length at hanging region.
2. ACI-440 and Fujii-Morita equations a little overestimate the bond strength of CFRP rods in the beams without additional embedment length.
3. Transverse reinforcement ratio in hanging region has no influence on bond stress in hanging region while transverse reinforcement ratio in shear span significantly affects bond stress in both hanging region and shear span.
4. Additional embedment length has significant influence on improving bond-splitting capacity of the beams.
5. The proposed model predicts well the maximum tension force at the support and it also could be used to evaluate the additional tension force at the support.

REFERENCES

1. ACI 318-95 (1995), Building Code Requirements for Structural Concrete, American Concrete Institute.
2. ACI Committee 440 (2000), Guide for the Design and Construction of Concrete Reinforced with FRP Bars, American Concrete Institute.