

## DEVELOPMENT LENGTH EVALUATION OF REINFORCED CONCRETE BEAM WITH CFRP BARS

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### ABSTRACT

This paper presents a study designed to evaluate the anchorage length in hanging region (i.e. the outside part of the support) of reinforced concrete beam. Totally 32 simple supported beams longitudinally reinforced with CFRP bars were tested to failure. The main test variables were development length and stirrup ratio. Test results indicate that, the beams with insufficient development length were failed prematurely in bond even though the beam had high stirrup ratio. From the test results, a model to predict the tension force at the support due to the diagonal shear crack was proposed and the provisions of AIJ, JSCE, ACI 318-05, and ACI 440.1R-03 codes on the development length were evaluated.

### KEYWORDS

Development length, reinforced concrete beam, CFRP bars, bond failure, tension shift.

### INTRODUCTION

Due to the occurrence of diagonal cracks in the shear span of simple supported beam, the tension forces of longitudinal reinforcement shift to the support region and the additional tensile forces exist at the support. This fact shows that a certain quantity of additional embedment length is needed pass through the support to anchor the additional force. AIJ (1999), JSCE (1997), and ACI 318-05 codes recommend some additional embedment length over the support. However the codes do not explicitly explain the relationship of the additional embedment length and the shifted tensile force at the support.

Theoretical equations based on the truss mechanism for evaluating the tension force at the support can be found in references (e.g. Park and Paulay 1975, CEB Design Manual on Cracking and Deformation 1985, and Ueda *et al.* 2002). But, as far as the authors concern, experimental studies evaluating quantitatively the relationship of the tension shift and the additional embedment length is still few. The object of this paper is to fill up this blank by focusing the study on the hanging region of simply supported RC beams experimentally.

Previous studies have shown that the bond strength of CFRP bar is lower than that of the conventional steel bar (Komiya *et al.* 1999). In addition, CFRP bars have higher tensile strength and non-plastic behavior (no yield phenomena). Hence, the CFRP deformed bars were used in this study as the longitudinal tension bars instead of the conventional steel bars to realize the expected bond splitting failure.

Based on the experimental data and statistical procedure the tension force model of longitudinal reinforcement at the support was proposed, which was expressed as a function of the shear force and the additional embedment length. Then, the accuracy of the model was verified by the experimental results.

### EXPERIMENTAL SET-UP

Totally 32 simple supported beams (130 mm wide and 230 mm deep) longitudinally reinforced (tension reinforcement) with deformed CFRP bars were tested to failure. CFRP bars used in this study were produced by Fukui Fibertech, Co. Ltd. in year 2002 until 2005 with the same type of resin (epoxy) and percentage of carbon fiber (60%). The tensile strength,  $f_u$ , of CFRP bars was averagely 1800 MPa with modulus of elasticity  $E_f = 160$  GPa. The compression longitudinal reinforcements for all of the beams were ordinary deformed steel bars (D-10) with yield strength,  $f_y = 403$  MPa. Since the main focus of this study is to observe the tension force shifted to hanging region due to the diagonal cracks as well as bond behavior of longitudinal reinforcement in shear span

and in hanging region, the steel stirrups were used instead of FRP stirrups. The stirrups were closed type with diameter 6 mm and yield strength averagely 800 MPa. Additionally, the concrete compressive strength was range between 35 MPa to 48 MPa.

As stated in the reference (Park and Paulay 1975), the flexural failure may be occurred in beam with shear span-effective depth ratio,  $a/d$ , more than 2.5. The quantity of the tension shift at the support also might become smaller. On the other hand, when  $a/d$  less than 1.5 the diagonal compression strut will be developed towards the support and the loading point. Consequently, the mechanism of tension shift may not be occurred. Therefore, in this study, the beams were designed with  $a/d = 2.1$  in order to ensure the occurrence of diagonal shear cracks and mechanism of the tension shift. The beam was subjected to two-point loads with 450 mm shear span as shown in Fig. 1(a).

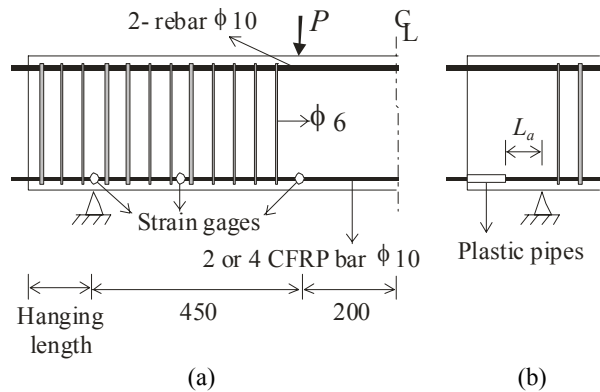


Figure 1 Beam detail and loading position

The main test variables were stirrups ratio and additional embedment length. In order to observe the stress distribution on the longitudinal reinforcement, strain gages were attached at the support and at the loading point (see Fig. 1(a)). Strain gages were also attached at the middle point of shear span in selected ten beams. Effect of additional embedment length ( $L_a$ ) to the bond stresses was investigated using ten different lengths (i.e. 0, 25, 50, 100, 105, 150, 160, 210, 220, and 280 mm) and plastic pipes were used to eliminate bond between concrete and reinforcement as shown in Fig. 1(b). The effect of stirrup in the shear span was examined using nine different reinforcement ratios,  $\rho_{ws}$ , ranging from 0.48% to 1.74%, while in the hanging region using four different ratios,  $\rho_{wh}$ , (i.e. 0, 0.27%, 0.54%, and 0.73%).

## REVIEW OF DEVELOPMENT AND ADDITIONAL EMBEDMENT LENGTH

The role of development length ( $L_d$ ) is to transfer the flexural tension force from the peak stress point to the actual cutoff point as shown in Fig. 2(a). Table 1 shows the basic development length equations for conventional steel and for FRP reinforcements suggested in the codes (Eq. (1) ~ (4)). ACI 440.1R-03 also provides a more conservative estimation than Eq. (4) for FRP bars as

$$L_d = \frac{d_b f_{fu}}{18.5} \quad (5)$$

where:  $d_b$  is bar diameter and  $f_{fu}$  is the design tensile strength of FRP, considering reduction for service environment.

Longitudinal reinforcement also must be embedded pass through the support, known as the additional embedment length ( $L_a$ ), to avoid bond splitting failure due to the tension shift. In AIJ code (1999), the additional embedment length must be equal or greater than the effective depth of the beam (see Fig. 2(b)), while in ACI 318-05 code Sec. 12.11.1 the reinforcement shall be extend over the support at least 150 mm (see Fig. 2(c)). Also, it is mentioned in JSCE code (1997) that at least 1/3 of the tension reinforcement in beams shall be anchored with a distance equal to the effective

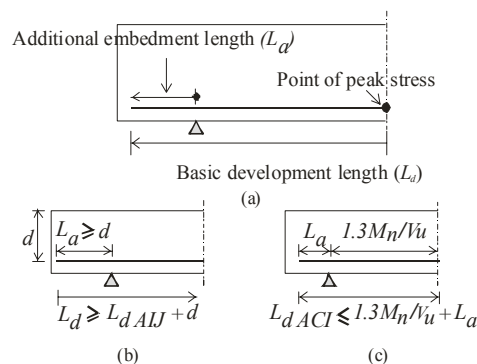


Figure 2(a) Description of development and additional embedment length in reinforced concrete beam as suggested in (b) AIJ Code, (c) ACI 318-05

Code

Table 1 The basic development length equations of reinforced concrete beam

AIJ (1999) <sup>1</sup>	$L_d = \frac{\sigma_t A_s}{K f_b \phi}$	(1)
ACI 318-05 <sup>1</sup>	$\frac{L_d}{d_b} = \frac{12}{25} \frac{f_y}{\sqrt{f'_c}} \frac{\alpha \beta \gamma \lambda}{c + K_{tr}} \frac{1}{d_b}$	(2)
JSCE (1997) <sup>2</sup>	$L_d = \alpha_1 \frac{f_d}{4 f_{bod}} d_b$	(3)
ACI 440.1R-03 <sup>2</sup>	$L_d = K_2 \frac{d_b^2 f_{fu}}{\sqrt{f'_c}}$	(4)

<sup>1</sup> Code for conventional steel reinforcement

<sup>2</sup> Code for FRP reinforcement

depth of the beam from the center of the support. Meanwhile, no information could be found from ACI 440.1R-03 related to the additional embedment length.

Figure 3(a) and (b) were plotted in order to compare the development length adopted in the experiment,  $L_{d\ exp}$ , to that calculated using Eq. (3) and Eq. (5),  $L_{d\ codes}$ , and the minimum development length requirement,  $L_{d\ min.}$ , from the codes. It is shown that  $L_{d\ exp}$  shorter than  $L_{d\ codes}$ . All beams have the same shear span length (450 mm) which was the shortest development length in the experiment, however as shown in Fig. 3(b) this length is still longer than the minimum requirement length recommended in the JSCE (1997) and ACI 318-05 codes i.e.  $L_{d\ min.} > 20d_b$  and 300 mm, respectively.

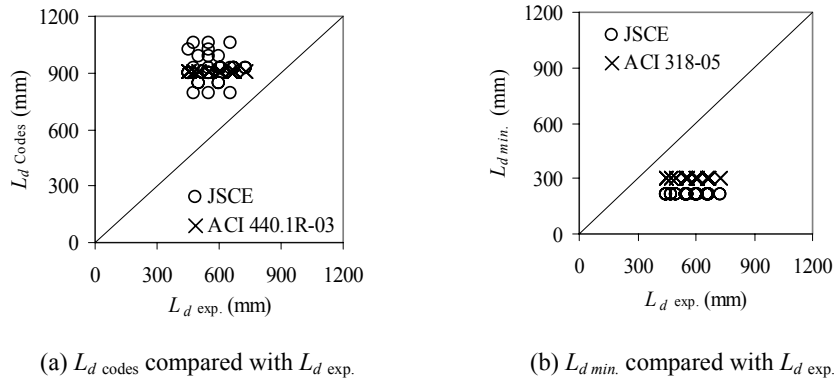


Figure 3 Comparison between calculated basic development length and minimum requirement length to that used in experiment

## TEST RESULTS AND DISCUSSIONS

### Failure Mode of the Beams

Three type of failure mode observed from the test were: bond splitting failure showed by the occurrence of splitting cracks propagated toward the support, shear failure showed by concrete crushing at the loading point (shear compression), and flexural failure showed by concrete crushing at the maximum compression zone under the elastic state of tension bar. Additionally, due to the small shear span effective depth ratio ( $a/d = 2.1$ ), the diagonal shear crack was observed in all of the beams at the load level from 25 to 45 kN.

Bond splitting failure mode was clearly observed from beams without and with short additional embedment length ( $L_a = 0, 25$  and  $50$  mm). The failure mode of the beams with  $L_a$  from 100 to 210 mm was scattering (bond, shear, or flexural failure), while beams with  $L_a$  longer than 210 mm, which was equal to the effective depth of the beam, were failed in shear and flexural failure depends on the stirrup ratio used in the beams.

### Effect of Additional Embedment Length and Stirrup Ratio on Beam Capacity

The experiment showed that the diagonal shear cracks developed in the shear span with the distance averagely equal to the effective depth of the beam,  $d$ , from the loading point. As a results, the tension forces on longitudinal reinforcement shift to the support region. Since all of the beam fulfil the minimum requirement development length, hence it will be more appropriate to consider the additional embedment length ( $L_a$ ) rather than the development length ( $L_d$ ).

Figure 4 shows the effect of additional embedment length and stirrup ratio on shear capacity (only the representative beams are presented in this paper). It is shown that as the  $L_a$  increases, the shear capacity increases. Two beams with  $L_a$  equal to the effective depth ( $L_a = 210$  mm,  $\rho_{ws} = 0.72\%$  and  $1.09\%$ ) were

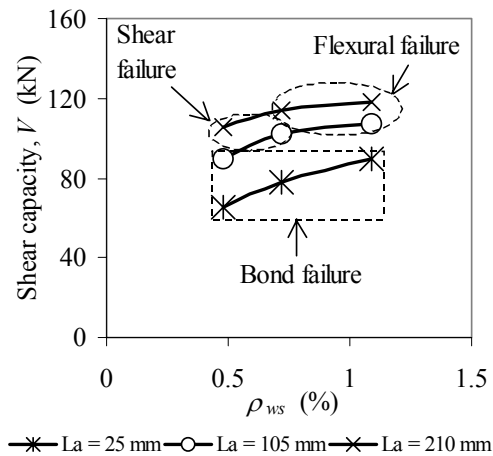


Figure 4 Effect of additional embedment length and stirrup ratio on shear capacity

failed in flexure while one beam ( $L_a = 210$  and  $\rho_{ws} = 0.48\%$ ) was failed in shear due to the low stirrup ratio.

It is also shown from Fig. 4 that the increase of stirrups ratio increases the shear capacity. The considerable results illustrated clearly the effect of stirrup ratio on the shear capacity are shown from beams with  $L_a = 105$  mm ( $\rho_{ws} = 0.48\%$ ,  $0.72\%$  and  $1.09\%$ ), which were failed in bond, shear and flexure, respectively. However, as explain above, all of the beams with  $L_a = 25$  mm were failed in bond and in this case the stirrup ratio has no significant effect to the failure mode of the beams even though the shear capacity increase.

These results indicate that  $L_a$  and  $\rho_{ws}$  influence the shear capacity of the beam. Moreover, the additional embedment length provision suggested in AIJ ( $L_a \geq d$ ) and ACI 318-05 ( $L_a \geq 150$  mm) codes may be conservative even though the beam reinforced with CFRP bar.

### Typical Behavior Tension Force at the Support

From the strain gages data of the longitudinal reinforcement, it is shown that the tension forces at the loading point and the middle point of the shear span significantly increase just after the first flexural cracking. With further loading, the diagonal shear crack occurred in the shear span and the tension force at the support,  $\Delta T$ , starts to increase.

Typical behavior of  $\Delta T$  is shown in Fig. 5. Figure 5(a) and (b) show the relationship between shear force,  $V$ , and  $\Delta T$  with the effect of stirrups ratio in the hanging region  $\rho_{wh}$ , and in the shear span,  $\rho_{ws}$ , respectively. It is shown that  $\rho_{wh}$  has no significant effect on  $\Delta T$  but  $\rho_{ws}$  shows a considerable effect on  $\Delta T$ . Figure 5(c) shows the effect of  $L_a$  on  $\Delta T$ . It is shown that with the same amount of  $\rho_{ws}$ , the tension force increases as  $L_a$  increases.

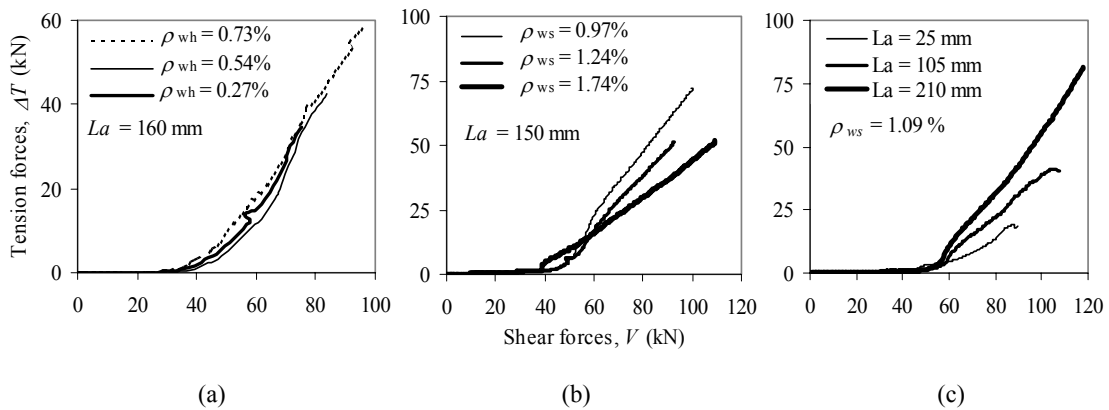
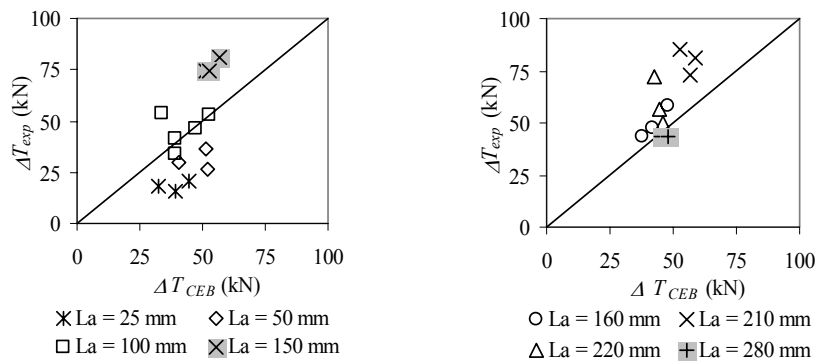


Figure 5(a) Effect of  $\rho_{wh}$ , and (b) effect of  $\rho_{ws}$ , and (c) effect of  $L_a$ , on  $\Delta T$



(a)  $L_a$  shorter than 150 mm (b)  $L_a$  longer than 150 mm  
Figure 6 Comparison between calculated tension forces by Eq. (5) with experiment

In order to check the amount of  $\Delta T$  analytically, the tension force formula suggested by CEB (1985) was used. The equation could be written as follows:

$$\Delta T = \frac{V}{2}(\cot\theta - \cot\alpha) \quad (6)$$

where  $V$  is the shear force,  $\theta$  is the inclination of diagonal shear cracks, and  $\alpha$  is the inclination of stirrups.

The comparison of experimental tension force at the support,  $\Delta T_{exp}$ , and that calculated with Eq. (6) is shown in Fig. 6 ( $\theta$  was assumed  $45^\circ$ ). As can be seen from Fig. 6 the calculated values predict well  $\Delta T_{exp}$  for the specimens with  $L_a$  longer than 150 mm. But, for the specimens with shorter  $L_a$ , the prediction does not show a good agreement. This result indicates that this equation is not appropriate to predict  $\Delta T$  of beam with insufficient additional embedment length.

### PROPOSED TENSION FORCE MODEL

As explained in the previous section, the tension force at the support,  $\Delta T$ , is mainly affected by the additional embedment length,  $L_a$ , and stirrup ratio in the shear span,  $\rho_{ws}$ . In addition,  $\Delta T$  increases after the diagonal shear crack occurs. Hence, it is reasonable to express the tension force at the support as the function of shear force and diagonal cracking load (Thamrin, R. and Kaku, T. 2005). Based on the statistical procedure, a model to illustrate the tension force,  $\Delta T$ , of longitudinal reinforcement at the support due to the tension shift can be proposed as follows (see Fig. 7(a)):

$$\text{If } V \leq V_c : \quad \Delta T = 0 \quad (7)$$

$$\text{and if } V > V_c : \quad \Delta T = \lambda(V - \gamma V_c) \quad (8)$$

where  $\Delta T$  is the tension force,  $V$  is the shear force,  $\lambda$  is the coefficient as a function of the additional embedment length,  $V_c$  is the diagonal cracking load, and  $\gamma$  is a coefficient intended to represent the effect of stirrup ratio in the shear span and could be expressed as:

$$\gamma = 1 + 5\rho_{ws} \quad (9)$$

It is found from statistical procedure that the coefficient  $\lambda$  could be expressed as follows:

$$\text{for } L_a \leq 0.5d : \quad \lambda = 2.0 \left( \frac{L_a}{d} \right) \quad (10)$$

$$\text{for } L_a > 0.5d : \quad \lambda = 1.0 \quad (11)$$

To evaluate the shear capacity of the beam, authors suggest to use the minimum shear capacity,  $V_{min}$ , between  $V_{flexure}$ ,  $V_{bond}$ , and  $V_{shear}$ , i.e. shear capacity calculated from flexural, bond, and shear capacity respectively. The diagonal cracking load in Eq. (12) proposed by Niwa *et al.* (1987) were used to determine the shear force carried by concrete,  $V_c$ .

$$V_c = 0.2(\rho_w f_c')^{1/3} (d^{-1/4}) \left( 0.75 + 1.4 \frac{d}{a} \right) b_w d \quad (12)$$

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.

Figure 7(b) and (c) show the comparison between predicted tension force of longitudinal reinforcement at the support using proposed model,  $\Delta T_{Model}$ , with the experimental tension forces,  $\Delta T_{exp}$ . It is shown that the proposed model predicts the tension force at the support quite well.

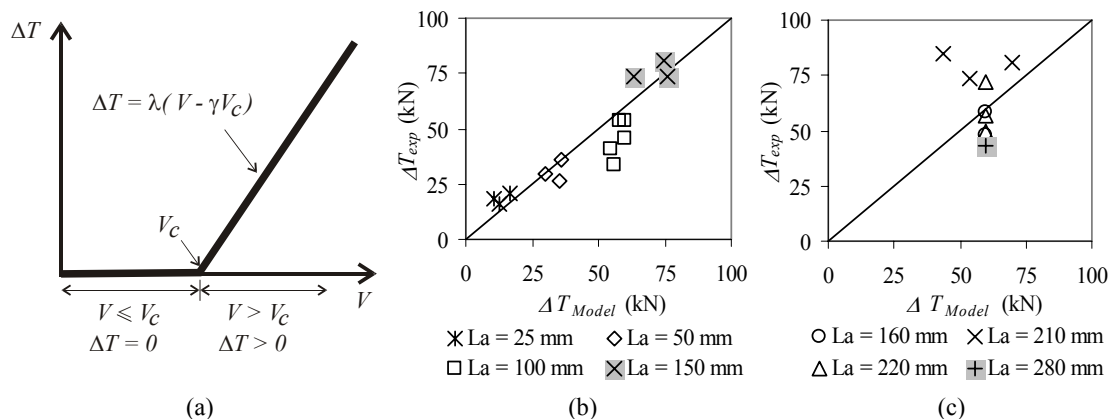


Figure 7(a) Tension force model of longitudinal reinforcement at the support, (b) Comparison between experimental tension forces for  $L_a$  shorter than 150 mm and, (c)  $L_a$  longer than 150 mm

Figure 8 shows the relationship between coefficient  $\lambda$ ,  $L_a/d$  ratio, and failure mode of the beams. It is shown that the position of the critical point of  $L_a$  is equal to  $0.5d$ , which is smaller than suggested additional embedment length provided in the codes. Furthermore,  $L_a/d$  ratio can be divided into three zones based on the possibility of failure mode of the beams summarized in Table 2. It is found that the possibility of failure mode in beam with  $L_a/d > 0.5$  considerably depends on the amount  $\rho_{ws}$ . From 32 beams tested in this study, the amount of  $\rho_{ws}$  affected the failure mode of the beams could be found and also presented in Table 2. It is noted that these range only valid for the beam with  $a/d$  ratio more than 1.5 and less than 2.5 as used in this study. In addition, more study is still needed to provide more appropriate amount of  $\rho_{ws}$  expressed in Table 2.

Table 2 Possibility of failure mode based on  $L_a/d$  ratio

$L_a/d$ ratio	Possibility failure mode
$0 < L_a/d \leq 0.5$	Bond
$0.5 < L_a/d \leq 1.0$	Bond <sup>(1)</sup> , Shear <sup>(2)</sup> and Flexure <sup>(3)</sup>
$L_a/d > 1.0$	Shear <sup>(4)</sup> , and Flexure <sup>(5)</sup>

<sup>(1)</sup>  $0.4\% < \rho_{ws} \leq 0.8\%$ ; <sup>(2)</sup>  $0.8\% < \rho_{ws} \leq 1.2\%$ ; <sup>(3)</sup>  $\rho_{ws} > 1.2\%$   
<sup>(4)</sup>  $0.6\% < \rho_{ws} \leq 1.0\%$ ; <sup>(5)</sup>  $\rho_{ws} > 1.0\%$

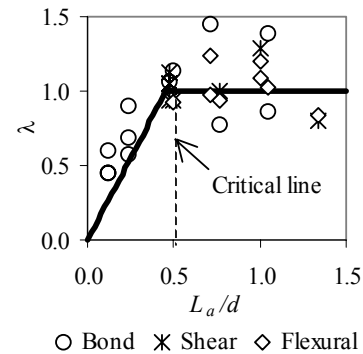


Figure 8 Relationship between coefficient  $\lambda$ ,  $L_a/d$  ratio, and failure mode of the beams

## CONCLUSIONS

Thirty-two simple supported beams longitudinally reinforced with CFRP bars were tested to failure in order to evaluate the anchorage length in hanging region. The test variables were development length and stirrup ratio. The results led to the following conclusion:

1. Additional embedment length has significant influence on improving the capacity of the beams.
2. Stirrup ratio in the hanging region,  $\rho_{wh}$ , has no influence on the tension force at the support,  $\Delta T$ , while stirrup ratio in the shear span,  $\rho_{ws}$ , shows a considerable effect on the tension force at the support. In addition  $\rho_{ws}$  has no effect on the failure mode of the beam with insufficient development length.
3. JSCE and ACI 440.1R-03 codes conservatively provide the development length,  $L_a$ , of beam with FRP reinforcement.
4. AIJ and ACI 318-05 codes properly recommend the additional embedment length,  $L_a$ , for simple supported beam and this provision also can be used in beam reinforced with FRP bars.
5. A model to calculate the tension shift,  $\Delta T$ , due to the diagonal shear crack was proposed and the model predicts the maximum tension force at the support quite well.
6. The failure mode of the beams with  $L_a/d \leq 0.5$  were always bond regardless the amount of  $\rho_{ws}$ , but in the case of  $L_a/d > 0.5$ , the failure mode is depends on the amount of  $\rho_{ws}$ .

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