- Technical Paper -

BOND STRENGTH OF CFRP RODS IN SIMPLY SUPPORTED RC BEAM WITH HANGING REGION

Rendy THAMRIN [*1] and Tetsuzo KAKU [*2]

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,

[*1] Doctor course student, Architecture and Civil Engineering Dept., Toyohashi University of Technology, JCI Member.
[*2] Professor, Architecture and Civil Engineering Dept., Toyohashi University of Technology, JCI Member.

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 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, ρ_{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, ρ_{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).

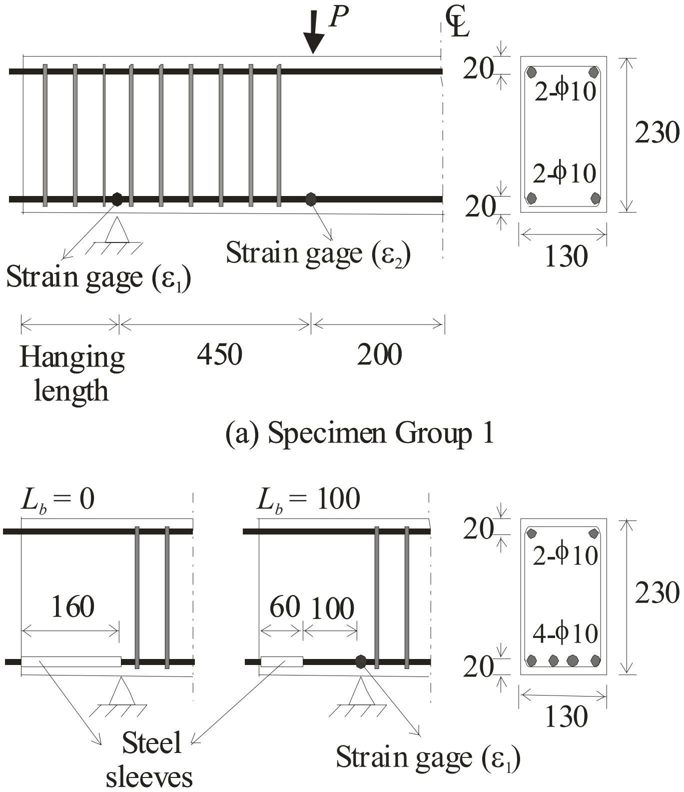


Fig. 1 Specimen detail and loading position.

Table 1 Detail of specimens and test results.

Beams	Concrete Comp. Strength fc' (MPa)	Longitudinal Reinforcement Tension Side (CFRP) ρ (%)	f_{fu} (MPa)	E_f (GPa)	Transverse Reinforcement Shear span ρ_{ws} (%)	Hanging region ρ_{wh} (%)	f_y (MPa)	Additional embedment length L_b (mm)	P_{exp} (kN)	Type of failure
G1-1	38.3	0.58	1725	153	0.67	0.73	850	160	96	Flexural
G1-2						0.54			84	Bond
G1-3						0.27			75	Shear
G1-4						0.73		220	89	Flexural
G1-5						0.54			92	Bond
G1-6						0.27			85	Bond
G1-7						0.54		280	91	Shear
G1-8						0.27			96	Flexural
G2-1	40.2	1.15	1906	164	0.97	0	550	0	73	Bond
G2-2					0.87				87	Bond
G2-3					0.78				73	Bond
G2-4					0.68				60	Bond
G2-5	48.5				0.97			100	95	Shear
G2-6					0.87				78.2	Shear
G2-7					0.78				78	Shear
G2-8					0.68				68	Shear

3. BOND STRESS

Experimental bond stress, τ, in the shear span can be calculated by measured strains at the support, ε_1, and at the loading point, ε_2, as follows:

$$\tau_s = \frac{E_f d_b}{4L_{bs}}(\varepsilon_2 - \varepsilon_1) \quad (1)$$

while bond stresses in the hanging region were determined by:

$$\tau_h = \frac{E_f d_b}{4L_b}\varepsilon_1 \quad (2)$$

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.

Since the bond provision of AIJ is based on the Fujii-Morita proposal, the test results were compared with Fujii-Morita equation [7]. The equation can be written as follows:

$$\tau_u = \tau_{co} + \tau_{st} \quad (3)$$

where τ_u is the bond strength, τ_{co} is the bond strength carried by concrete, τ_{st} is the bond strength carried by stirrups.

Furthermore, a basic development length (L_d) for FRP rod, provided by ACI Committee 440 [2], was also used as a comparable one with Fujii-Morita equation and could be written in term of bond strength as follows:

$$\tau_{ACI} = \frac{T}{L_d \phi} = \frac{A_f f_{fu}}{L_d \phi} = \frac{\sqrt{f_c^{'}}(MPa)}{4K_2 d_b} \quad (4)$$

where T is the tension force of longitudinal reinforcement, ϕ is the perimeter of longitudinal reinforcement, f_c' is the concrete compression strength, A_f is area of longitudinal reinforcement, f_{fu} is the ultimate tensile strength of the FRP rod, K_2 is a constant taken 1/40 [5], and d_b is the diameter of longitudinal reinforcement.

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.

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 ρ_{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 ρ_{wh}. Therefore, there is no influence of ρ_{wh} on bond stress in hanging region.

Figure 3 shows the influence of additional embedment length in hanging region on bond stress in shear span. With increase of additional embedment length in hanging region from 160 mm to 280 mm, there is no significant decrease of bond stresses in the shear span.

Hence, additional embedment length greater than 160 mm, which is still shorter than effective depth of the beam (d = 210 mm), has no further effect on the beam.

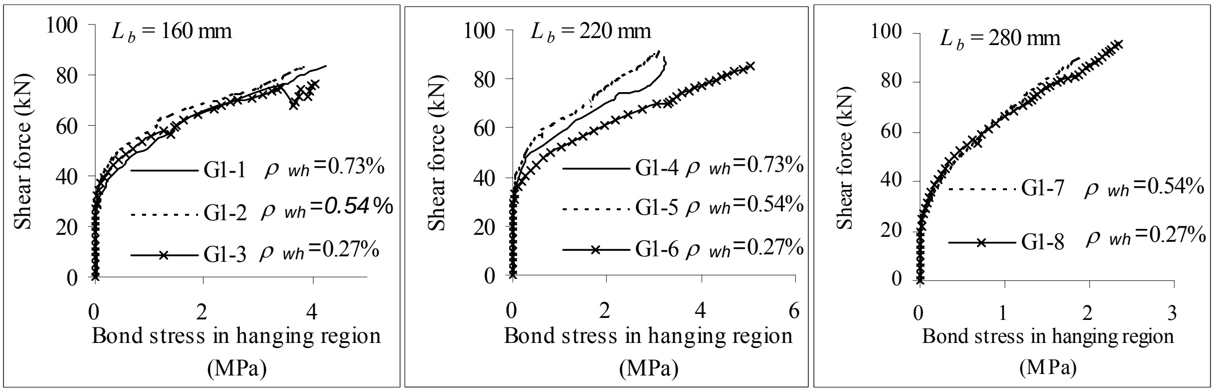
As a result, the recommendation in AIJ and ACI codes, which suggested that the additional embedment length in hanging region should be equal or greater than the effective depth of the beam and should be extend from the support at least 150 mm, may be conservative.

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 (ρ_{ws}) increases, bond stresses in both hanging region and shear span decrease. Thus, bond stresses are considerably affected by ρ_{ws}.

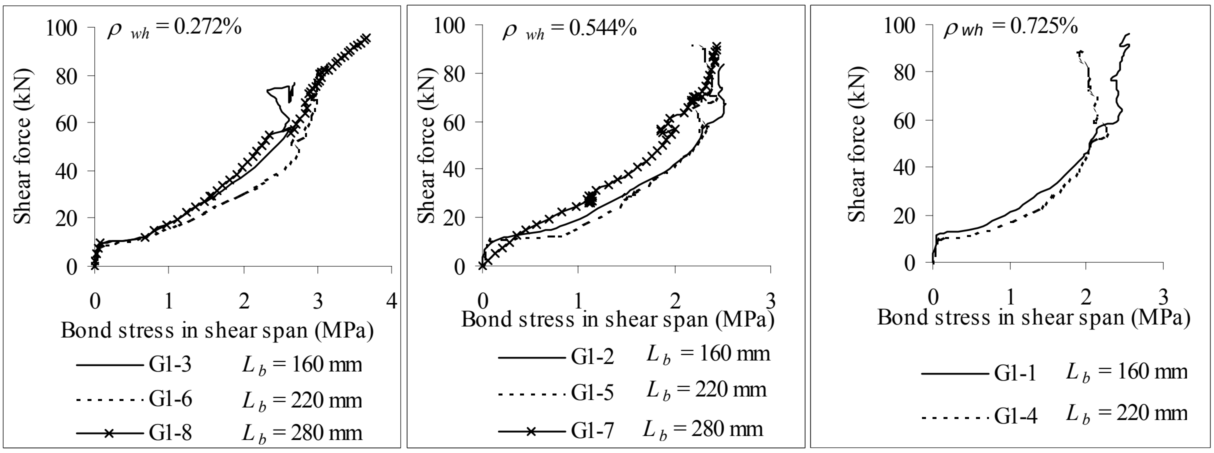
Figure 4(a) shows a considerable increase of bond stress in shear span after the occurrence of flexural crack. At this load level, bond stresses in hanging region remains zero as shown in Fig. 4(b). With further loading, diagonal shear crack occurred in the shear span and additional tension forces were transferred from shear span to hanging region (tension shift occurs). Consequently, bond stress in hanging region start to increase.

From this stage, bond stress in hanging region increases, see Fig. 4(b), while bond stress in shear span does not increase with additional loading until failure as shown in Fig. 4(a).



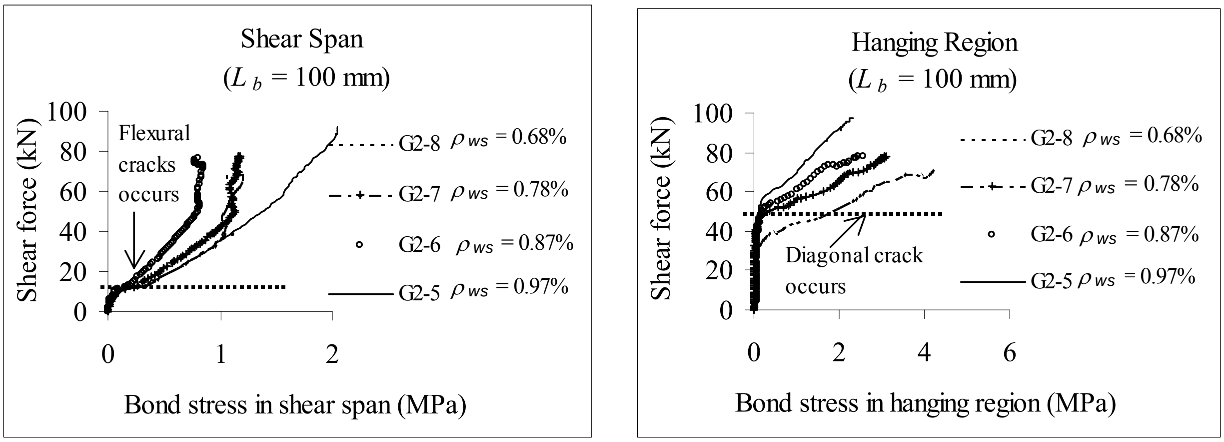
(a) (b) (c)

Fig. 2 The effect of transverse reinforcement in hanging region on bond stress in hanging region.



(a) (b) (c)

Fig. 3 The effect of L_b in hanging region on bond stress in shear span.



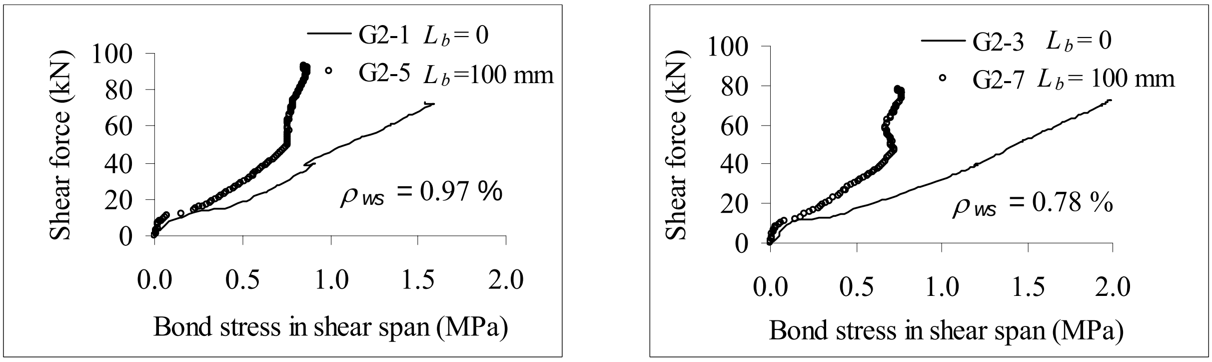
(a) (b)

Fig. 4 The effect of transverse reinforcement in beam group 2.

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.

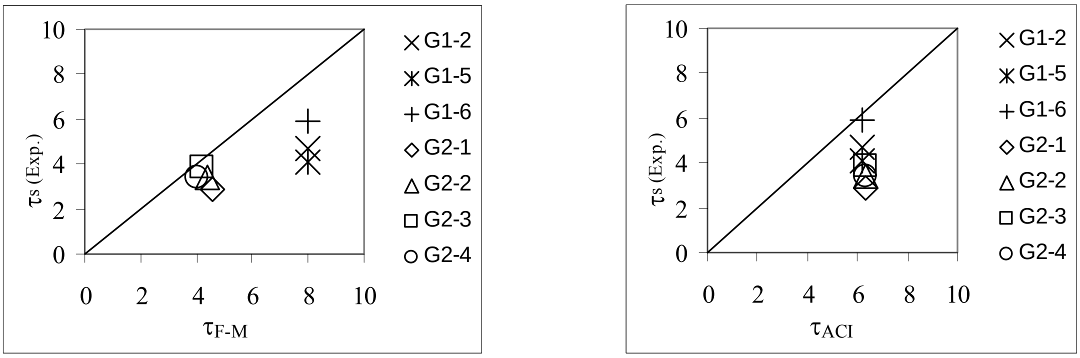
Moreover, in the experimental test, the beams without additional embedment length (G2-1 to G2-4) failed in bond splitting failure mode, while beams with additional embedment length (G2-5 to G2-8) failed in shear with higher ultimate load carrying capacity due to the contribution of anchorage length to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

Figure 6(a) and (b) show bond strength in shear span calculated using Fujii-Morita (τ_{F-M}) and ACI-440 (τ_{ACI}) equations respectively compared with the maximum experimental bond stress of specimens failed in bond. It is note that, at the maximum load, the shear span length in Eq. (1)



(a) (b)

Fig. 5 The influence of additional embedment length on bond stress in shear span.



(a) (b)

Fig. 6 Comparison between bond strengths predicted using Fujii-Morita ($\tau_{F\text{-}M}$) and ACI-440 (τ_{ACI}) equations with maximum experimental bond stress.

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.

$$V_c = 0.2\left(\rho_w f_c^{'}\right)^{1/3}\left(d^{-1/4}\right)\left(0.75 + 1.4\frac{d}{a}\right)b_w d \quad (5)$$

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

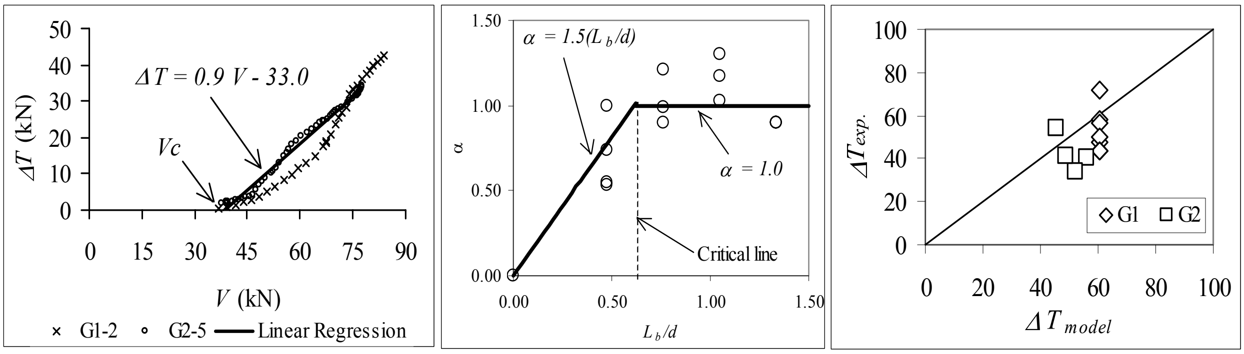
Then a model to illustrate the additional tension force, ΔT, of longitudinal reinforcement at the support due to the tension shift can be proposed as follows:

If $V \leq V_c$: $\quad \Delta T = 0$ (6)

and if $V > V_c$: $\quad \Delta T = \alpha(V - V_c)$ (7)

where ΔT is the additional tension force, V is the shear force, and α is the coefficient as a function of the additional embedment length.

A simple statistical analysis was conducted to find the coefficient α. 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:



(a) (b) (c)

Fig. 7 (a) Relationship between shear force and tension force at the support, (b) Critical additional embedment length based on proposed model, and (c) Comparison between experimental tension force with proposed model.

for $L_b \leq 0.68d$: $$\alpha = 1.5\frac{L_b}{d} \quad (8)$$

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

In order to apply the proposed model, the 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.

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. CONCLUSSIONS

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.
3. AIJ (1999), Standard for Structural Calculation of reinforced Concret Structures – Based on Allowable Stress Concept, Japan, (in Japanese).
4. Comité Euro-International du Béton (1985), *CEB Design Manual on Cracking and Deformation*, Ecole Polytechnique Fédérale de Lausanne.
5. Ehsani. M. R., and Saadatmanesh, H. (1996), "Design Recommendations for Bond of GFRP Rebars to Concrete", Journal of Structural Engineering, Vol. 122, No. 3, pp. 247-254.
6. Komiya, I., Kaku, T., Kutsuna, H., (1999), "Bond Characteristic of FRP Rods (No. 3)", Proc. of AIJ Annual Conf. 1999, pp. 623-624.
7. Morita, S. and Fujii, S. (1982), "Bond Capacity of Deformed Bars Due to Splitting of Surrounding Concrete, Bond in Concrete", edited by Bartos. P., Applied Science Publisher, pp. 331-341.
8. Niwa, J., Yamada, K., Yokozawa, K., and Okamura, H. (1987), "Revaluation of the Equation for Shear Strength of Reinforced Concrete Beams without Web Reinforcement", Concrete Library of JSCE, No. 9, pp. 65-84.
9. Park, R., and Paulay T. (1975), "Reinforced Concrete Structures", John Wiley & Sons, New York.