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Author(s)	KIM, N.; KIM, Y.; SHIN, Y. et al.
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EXPERIMENTAL AND NUMERICAL STUDIES FOR EFECT OF TAPER LAYERED CFRPS ON STRENTHENING RC BEAMS

N. KIM[1], Y. KIM[1], Y. SHIN[2], and H.S. KIM[3*]

[1]*Graduate student, Department of Architectural Engineering, Ewha Womans University*

[2] *Professor, Department of Architectural Engineering, Ewha Womans University*

[3]*Assistant Professor, Department of Architectural Engineering, Ewha Womans University*

ABSTRACT

This paper focuses on evaluation of strengthening effect of taper layered CFRPs (Carbon Fiber Reinforced Polymers) used to strengthen RC (Reinforced Concrete) beams. Toward this goal, experimental studies are performed on RC beams strengthened with various layers and types of CFRP sheets. Also, moment capacities are investigated using equations suggested from existing design manuals such as ACI and ISIS, and the numerical results are compared with the experimental results. For the experiments, CFRPs are externally attached to the bottom surface of RC beams which sizes are 200mm×250mm×3200mm (width×height×length). Variables of this study are the number of CFRP layers and length of each layer, so two, three, or four layers of CFRPs are used for strengthening and different lengths of CFRP layers are prepared. As A type, RC beams are strengthened with same length of CFRPs, while RC beams for B type are strengthened with CFRPs which length of each layer becomes shorter as attached later. From four point loading tests, load-deflection relations of the beams and strain distributions of CFRPs are obtained. Experimental results shows that the RC beams with taper layered CFRPs show the better strengthening effect than the uniformly ended CFRPs, especially when the beams are strengthened with three or more layers of CFRPs. The reason is because taper layered CFRPs reduce stress concentration at the end of CFRPs layers and delay failure due to dobending of CFRPs. From numerical studies, it is found that the existing numerical models do not consider the strengthening effect due to taper layered CFRPs, and are not able to distinguish moment capacity of RC beams with taper layered CFRPs from RC beams with uniformly ended CFRPs.

Keywords: CFRP, Strengthening, RC beams, Debonding, Taper layered.

* Corresponding author: Email: hskim3@ewha.ac.kr

1. INTRODUCTION

CFRP sheets having high ductility and strengthening capacity is widely used for strengthening and repairing RC structures. Recent experimental and analytical studies has suggested configurations of CFRPs attachment and anchorage systems to delay debonding failures (Choi et al, 2012; Kim and Shin, 2011; El-Hacha and Rizkalla 2004; Gao et al, 2006; Bencardino et al, 2002). Also, moment capacities of RC beams strengthened with non-taper layered CFRP sheets can be found from design guides such as ISIS, fib, and ACI manual (ISIS Design manual no.4, 2008; fib bulletin 14, 2001; ACI concrete repair manual, 2008).

This study aims to present effect of taper layered CFRPs used for flexural strengthening of RC beams and evaluate existing design guides for RC beams with taper layered CFRPs. Toward these goals, experimental and numerical studies are performed on RC beams strengthened with different types of non-taper layered CFRPs and taper layered CFRPs.

2. METHOD

2.1. Experimental method

In order to examine strengthening effect of taper layered CFRPs, RC beams strengthened with different lengths of CFRPs are prepared as listed in Table 1. All specimens have dimensions of 200 x 250 x 3200 mm (width x depth x length) and 1~4 layers CFRPs are externally attached to bottom surfaces of tested beams except for CONT specimen. From material strength tests, concrete compressive and tensile strengths are measured as 29MPa and 3MPa, respectively. Material properties of CFRP and adhesives are provided from manufacturer as shown in Table 2. After cured, specimens are subjected to four-point bending as shown in Figure 1.

Table 1: List of specimens

Specimen	*CFRP length (mm)*			
	1st layer	*2nd layer*	*3rd layer*	*4th layer*
CONT	-	-	-	-
2A	1800	1800	-	-
3A	1800	1800	1800	-
4A	1800	1800	1800	1800
2B	1800	1500	-	-
3B	1800	1500	1200	-
4B	1800	1500	1200	900

Table 2: Material properties of CFRP and adhesives

Specimen	*Thickness (mm)*	*Elastic modulus (GPa)*	*Tensile strength (GPa)*	*Flexural strength (MPa)*
CFRP	0.5	245.2	4.5	-
Primer	3.2	2.46	0.055	82.4
Top-coat	3.2	3.11	0.063	99.3

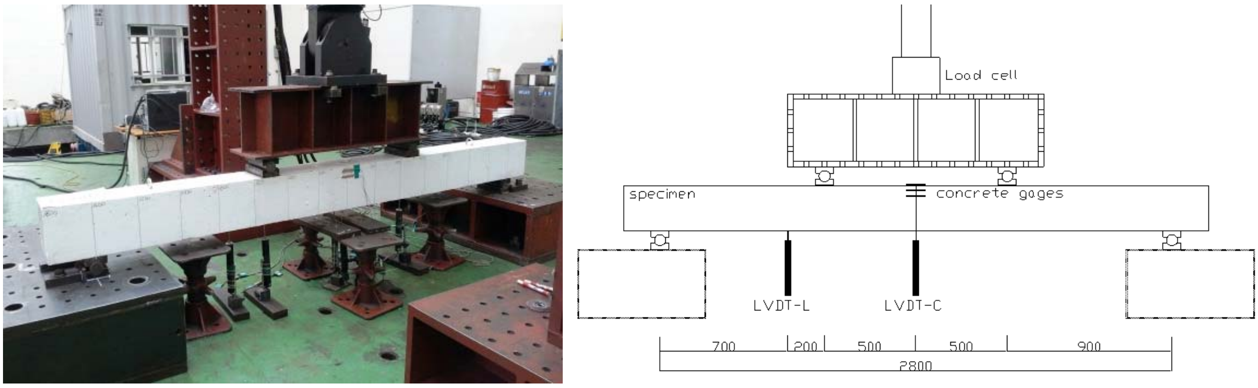


Figure 1: Test set-up

2.2. Numerical approaches for moment capacity of RC beams strengthened with FRPs

Equation (1), (2), and (4) are formulations for moment capacity of RC beams strengthened with FRP sheets suggested by ISIS, fib, and ACI manual (ISIS Design manual no.4, 2008; fib bulletin 14, 2001; ACI concrete repair manual, 2008), respectively. In these equations, M_r, M_{Rd}, and M_n denote moment capacities.

$$M_r = C_s\left(\frac{a}{2} - d'\right) + T_s\left(d - \frac{a}{2}\right) + T_{FRP}\left(h - \frac{a}{2}\right) \tag{1}$$

$$M_{Rd} = A_{s1} f_{yd}\left(d - \delta_G x\right) + A_f E_f \varepsilon_f \left(h - \delta_G x\right) + A_{s2} E_{s2} \varepsilon_{s2}\left(\delta_G x - d_2\right) \tag{2}$$

In equation (2), A_{s1}, A_f, and A_{s2} are section area of compressive rebar, CFRP, and tensile rebar, respectively. f_{yd} is tensile strength of compressive rebar. E_f and E_{s2} are elastic modulus of CFRP and tensile rebar. d is depth from upper surface of beam to compressive rebar, and d_2 is depth from upper surface of beam to tensile rebar. δ_G is constant depending on concrete strain at upper surface of beam, and calculated as 0.416. ε_f and ε_{s2} are strain of CFRP and tensile rebar. Parameter x used in equation (2) can be calculated using equation (3)

$$0.85\psi f_{cd} bx + A_{s2} E_{s2} \varepsilon_{s2} = A_{s1} f_{yd} + A_f E_f \varepsilon_f \tag{3}$$

$$M_n = A_s f_s\left(d - \frac{\beta_1 c}{2}\right) + \Psi_f A_f f_f\left(h - \frac{\beta_1 c}{2}\right) \tag{4}$$

In equation (3), Ψ is invariant constant, and can be replaced by 0.8. f_{cd} is compressive strength of concrete. In equation (4), c is distance from upper surface of beam to neutral axis and can be calculated using equation (5). A_s is a section area of tensile rebar. f_s and f_f are tensile strength of tensile rebar and CFRP. Parameters γ and β_1 are associated with the Whitney stress block, calculated as 0.85. Finally, a constant 0.85 is used for a reduction factor, Ψ_f,

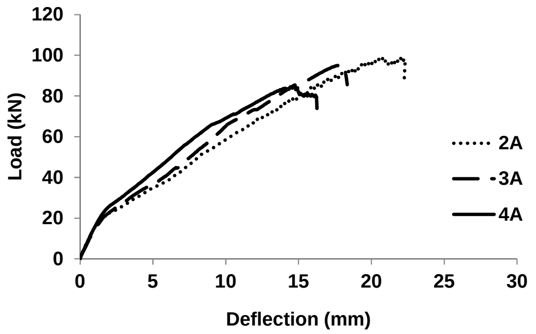
$$c = \frac{A_s f_y + A_f f_{fe}}{\gamma f_c^{'} \beta_1 b} \qquad (5)$$

3. RESULTS

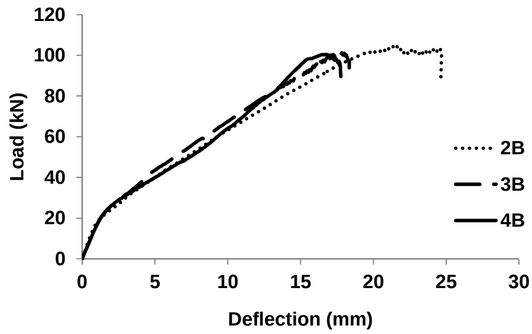
3.1. Experimental results

3.1.1. Load-deflection curves

From experiments, load-deflection curves are obtained as shown in Figures 2(a) and (b). Commonly, maximum load capacities decrease as number of CFRP layers increase. However, ratio of maximum load decrease reduces in B series compared with A series. Especially, maximum load of 4B is about 25% larger than maximum load of 4A. The main reason is because taper layered CFRP is able to reduce high stress concentration occurred at the end of FRP sheets and delay early beam failure due to FRP debonding.



(a) A series

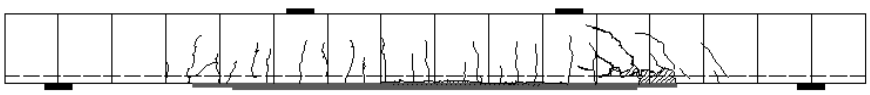


(b) B series

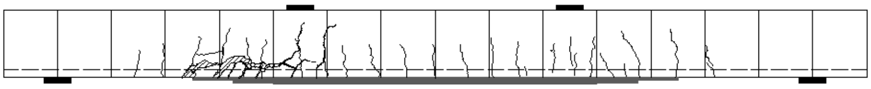
Figure 2: Load-deflection curves, (a) A series, (b) B series

3.1.2. Failure modes

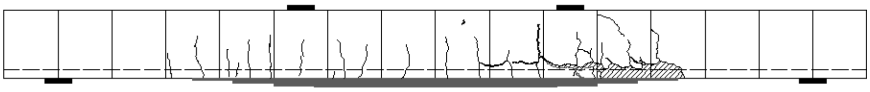
Figures 3(a)~(c) illustrate crack configurations observed at the end of loading tests. All tested beams show failure due to debonding of CFRP sheets and separation of concrete cover from the RC beams. As layer of CFRP sheets increases, intervals between flexural cracks increase and the larger area of concrete cover is separated from RC beams. There is no significant difference of failure mode between A and B series.



(a) 2B



(b) 3B



(c) 4B

Figure 3: Crack configurations, (a) 2B, (b) 3B, (c) 4B

3.2. Results from numerical models

Table 3 shows moment capacities of tested beams calculated by formulations provided from ISIS, fib, and ACI repair manual. As shown, numerical models are not able to capture effect of taper layered CFRP sheets, therefore moment capacities of A and B types are identical. In addition, moment capacities of RC beams with CFRPs increase with number of CFRP layers because early beam failure due to debonding of CFRPs is not considered in the numerical models. Between the models, ISIS gives the largest, while ACI repair manual gives the smallest moment capacities.

Table 3: Results from numerical models

Specimen	*ISIS*	*fib*	*ACI repair manual*
2A, 2B	76.7 *kN*m*	74.7 *kN*m*	65.2 *kN*m*
3A, 3B	85.8 *kN*m*	83.6 *kN*m*	72.9 *kN*m*
4A, 4B	92.3 *kN*m*	90.0 *kN*m*	78.5 *kN*m*

4. DISCUSSION

In this section, results from experiments and numerical models are compared. As shown in Figure 4, all formulations underestimates moment capacities of the tested beams. From Table 4, it is found that ISIS predicts moment capacity of 2A, 3A, 2B, and 3B specimens with high accuracy, while ACI show accurate prediction for 4A specimen. For 4B, fib shows good agreements with experimental results.

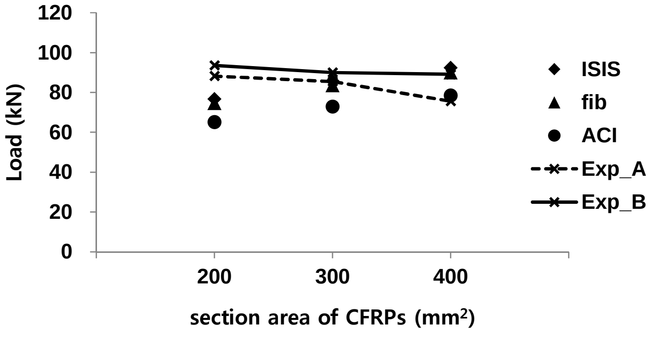


Figure 4: Moment capacities from experiments and numerical models

Table 4: Comparison between experimental results and numerical models

Specimen	*experimental results (kN*m)*	*Moment capacities from numerical models (kN*m) (Ratio of experimental results to numerical model (%))*		
		ISIS	*fib*	*ACI manual*
2A	88.2	76.7 (87.0%)	74.7 (84.7%)	65.2 (73.9%)
3A	85.5	85.8 (100.4%)	83.6 (97.8%)	72.9 (85.3%)
4A	75.6	92.3 (122.1%)	90.0 (119.0%)	78.5 (103.8%)
2B	93.6	76.7 (81.9%)	74.7 (79.8%)	65.2 (69.7%)
3B	90.0	85.8 (95.3%)	83.6 (92.9%)	72.9 (81%)
4B	89.1	92.3 (103.6%)	90.0 (101.0%)	78.5 (88.1%)

5. CONCLUSION

In this paper, strengthening effect of taper layered CFRPs is investigated using experimental and numerical methods. From experiments, RC beams with taper layered CFRPs show higher maximum loads compared to RC beams with non-taper layered CFRPs, because taper layered CFRPs delay debonding of FRP sheets. In addition, improved strengthening effect of tapered layered CFRPs becomes significant as number of CFRP layers increase. Unlike experimental results, moment capacities calculated from existing design guides increase as number of CFRP layers increases. Besides, the formulations are not able to capture effect of taper layered CFRPs, therefore, further modifications are needed in order to take account of strengthening effect of taper layered CFRPs.

6. ACKNOWLEDGMENTS

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