Experimental Study for Evaluating Structural Behavior of RC Beams Strengthened by Different Width of FRP Layers

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***Abstract*—This paper reports experimental studies of reinforced concrete (RC) beams strengthened by carbon fiber reinforced polymer sheet (CFRPs) having different width. The objective of this study is to evaluate effect of different width of CFRPs on structural behaviors of RC beams and investigate most effective height of CFRPs on the side surfaces of RC beams for flexural strengthening. Toward this goal, five RC beams are fabricated and strengthened with different width of CFRPs, and then four-point bending tests with the simply supported beams are performed. Results of this study show that the width of strengthened CFRPs on RC beams has a significant influence on structural behaviors of RC beams.**

***Index Term*—CFRPs, CFRP width, RC beams, strengthening effect**

I. Introduction

Fiber reinforced polymer (FRP) is widely used for reinforcing structural members due to its high strength, light weight, and simple installation. For evaluating strengthening effect of FRP, many studies have been performed using experimental and analytical methods [1]-[10]. Because early debonding of FRP sheet (FRPs) from structural members is one of the significant factors to determine strengthening effect of FRPs, previously reported studies have suggested methods to delay early debonding using anchorage system or proper configuration of FRPs [11]. About configurations of FRPs, length, thickness, and width of CFRPs have been reported as influencing parameters on structural behaviors of RC beams [12]-[14]. Among them, experimental study about width of CFRPs shows that CFRPs is able to delay debonding failure of RC beams that is similar to case of using anchorage system in RC beams strengthened with FRPs [15]. In addition, effect of CFRPs width on structural behaviors of RC beams is investigated by Brena and Macri [16]. In their experiments, it is seen that load capacity of beam increases with CFRPs width.

In this study, an effect of width of CFRPs on structural behavior of RC beams is investigated. Four-point bending tests are performed using RC beams strengthened with two layers of CFRPs, which variables are width of CFRPs. For the experiment, width of the CFRPs are same as or wider than beam width in order to investigate strengthening effect according to covered area of beam side surfaces by CFRPs. To analyze strengthening effect, maximum load, load-deflection curves, stress distributions of CFRPs, ductility and failure modes are examined from the experiments.

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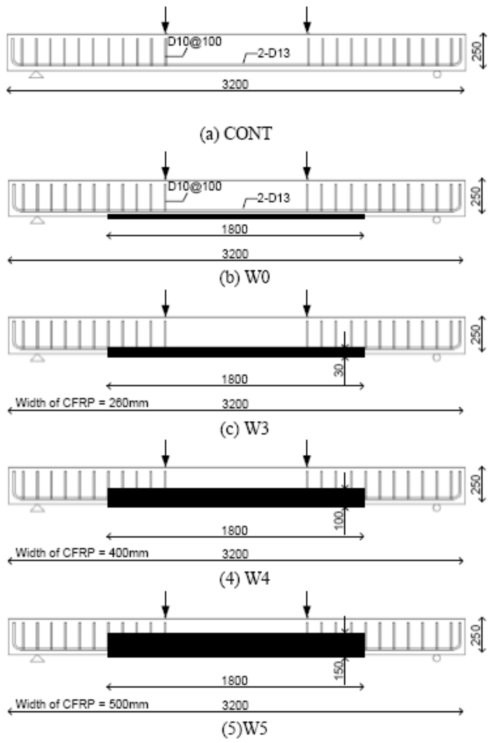

Fig. 1. Details of specimens

II. Experimental Program

A. Details of Tested Beams

Notation and variables of specimens are listed in Table I. Five RC beams are fabricated with dimensions of 200mm × 250mm × 3200mm (width × depth × length), and all beams are internally reinforced with reinforcing steel bars of 13mm diameter at an effective depth 203.5mm, as illustrated in Figs. 1. Also, all beams are reinforced with stirrups of 10mm diameter for preventing beams from being governed by shear failure prior to flexural failure. CFRPs are externally attached on the bottom surface of RC beams. Length of CFRPs and numbers of CFRPs layers are same for all specimens, but widths of CFRPs are 200mm, 260mm, 400mm, and 500mm for W0, W3, W4, and W5 specimens, respectively. CONT specimen denotes a control beam, which is not strengthened with CFRPs. Attaching CFRPs is conducted after curing for 21 days by professional technicians. Surfaces of RC beams to

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attach CFRPs are sanded, primer and top-coat are applied in orders, followed by impregnating CFRPs with epoxy. The impregnated CFRPs are attached to the bottom surfaces of RC beams such that direction of CFRPs is same as longitudinal direction of RC beams.

TABLE I: LIST OF SPECIMENS

Specimen	CFRPs width (mm)	CFRPs length (mm)	Number of layers
W0	200	1800	2
W3	260	1800	2
W4	400	1800	2
W5	500	1800	2
CONT		No CFRPs	

B. Material Properties

Mixing proportion is based on Table II for fabricating regular strength concrete, and compressive strength is obtained as 29MPa from compressive test after curing for 28 days in room temperature. Also, tensile strength of concrete is measured as 3MPa from material tests.

Material properties of CFRP, primer, and top-coat are provided from manufacturer as listed in Table III.

C. Instrumentation and Testing

RC beams strengthened with CFRPs are simply supported for performing four point bending test as shown in Fig. 2. After beam is placed, load is applied as displacement control until beam failure.

During tests, vertical deflections of RC beams are measured at bottom surface of mid span using linear variable displacement transfer (LVDT). To measure strain of concrete, electric strain gages are attached upper and side surface. The strains of rebar and FRP are measured in longitudinal span using electrical strain gages as shown in Fig. 3.

TABLE II: MIXING PROPORTIONS FOR CONCRETE

Compressive strength	w/c (%)	s/a (%)	Weight per unit Volume (kg/m3)				
			W	C	S	G	AD
29MPa	44.2	46.9	165	373	837	966	1.87

TABLE III: MATERIAL PROPERTIES OF CFRPS AND ADHESIVES

Type	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

III. RESULTS

A. Load-Deflection Relationships

Load-deflection curves of all specimens are illustrated in Fig. 4. As shown in Fig. 4, maximum loads of specimens strengthened with CFRPs generally increase as width of CFRPs increases. Exceptionally, W3 specimen results lower maximum load than W0, which width of CFRPs for W0 is narrower than CFRPs for W3. Therefore, it is interesting to note that strengthening effect of attaching CFRPs up to side surfaces of RC beam can be improved depending on the CFRPs area covering beams.

Also, stiffness of RC beams strengthened with CFRPs increases with CFRP width. For RC beams strengthened with CFRPs wider than beam width (W3, W4, and W5), deflection at beam failure are smaller than deflection of W0 at beam failure. Among W3, W4, and W5, deflection at beam failure increase with width of CFRPs.

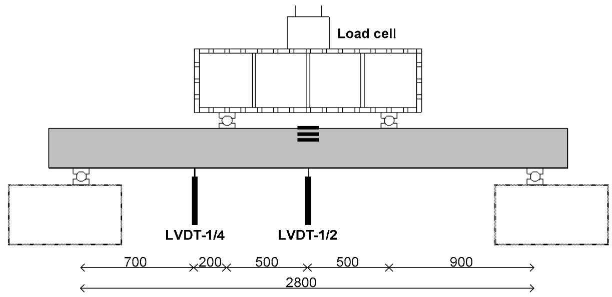

Fig. 2. Test set-up and Instrumentation

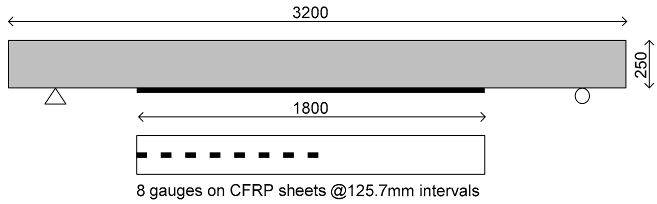

Fig. 3. Location of CFRP strain gages

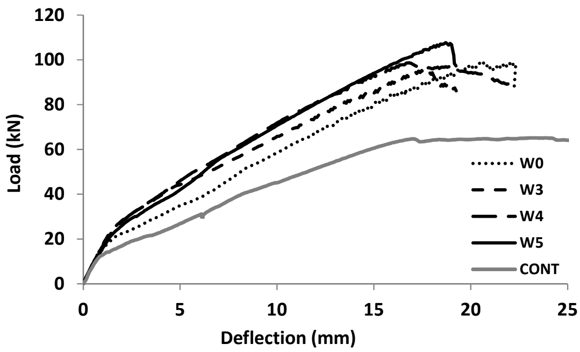

Fig. 4. Load-deflection relationships

B. Interfacial Stress Distributions

Interfacial shear stress, τ , is one of the important factors for analyzing structural behaviors, since it determines beam failure by initiating debonding of CFRPs. Therefore, interfacial shear stresses are calculated using (1), where, t_P and E_P are thickness and elastic modulus of CFRPs, respectively. Strains of CFRPs are measured using gages attached on CFRPs with intervals of 125mm in longitudinal direction and used to calculate interfacial shear stresses.

$$\tau = t_P \, E_P \frac{d\varepsilon}{dx} \tag{1}$$

Interfacial shear stress between CFRPs layers and bottom surfaces of concrete is illustrated in Fig. 5. For most specimens, maximum interfacial shear stresses occur at the end of CFRPs layers, where debonding of CFRPs is initiated. W5 specinmens show largest interfacial shear stress at the end of CFRPs compared to all the specimens, while W0 shows the smallest. Also, maximum interfacial shear stress is not observed at the end of CFRPs for W0, may be because debonding is initiated from the end of CFRPs when measured at 95%of maximum load level.

TABLE IV: EXPERIMENTAL RESULTS

Specimen	Load at failure (kN)	Mid-span deflection at failure (mm)	Steel strain at failure (10^{-3})	CFRP strain at failure (10^{-3})	Concrete strain at failure (10^{-3})
W0	99	22	2.135	2.337	-1.136
W3	95	18	3.045	3.441	-1.402
W4	99	17	2.590	2.992	-1.351
W5	108	19	3.151	3.456	-1.331
CONT.	69	76	7.119	-	-1.219

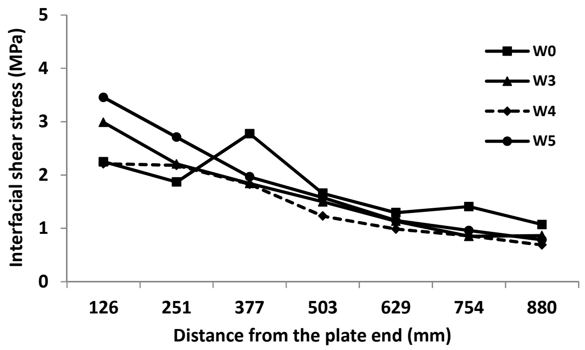

Fig. 5. Interfacial shear stress measured at 95% of maximum load level

C. Ductility

It is important to examine ductility, since RC beams strengthened with CFRPs often show brittle behaviors and sudden failures unexpectedly. In this study, deflection ductility (μ_D) and energy ductility (μ_E) are calculated based on yield of reinforcing steel bars using (2) and (3), and listed in Table V.

μ_D = (midspan deflection at maximum load)/(midspan deflection at tension steel yield) (2)

μ_E = (area of load-deflection curve up to maximum load)/(area of load-deflection curve at tension steel yield) (3)

For RC beams strengthened with wider CFRPs than beam width (W3, W4, and W5), ductility increases with CFRPs width. However, ductility for W3, W4, and W5 are smaller compared to ductility of W0 and CONT. These results mean that CFRPs covering side surfaces of RC beams contributes to resist against loads even after yielding of reinforcing steel bars for W3, W4, and W5.

D. Failure Modes

Failure modes and crack propagations of all the tested specimens are observed as illustrated in Figs. 6(a)-(e). As shown in Fig. 6(a), CONT specimen shows flexural cracks and failure in compressive zone. From strain gauges attached to reinforcing steel bars of CONT specimen, it is seen that reinforcing steel bars yield prior to failure in concrete compressive zone. RC beams strengthened with CFRPs shows sudden failure due to debonding of CFRPs. At beam failure, CFRP layers and part of concrete covers are separated from RC beams, initiated from one end of CFRP layers. Also, CFRPs inW5 specimen show debonding without concrete cover separation, because stresses are distributed throughout wide area of CFRPs covering side surfaces of RC beams. Since CFRP layers cover both compressive and tensile zone of concrete side surfaces in W5 specimen, debonding of CFRP is induced from combined mechanism of compressive and tensile stresses developed on side surfaces of RC beams.

TABLE V: DUCTILITY OF SPECIMENS

specimens	Deflection ductility		Energy ductility	
	μ_D	Ratio to CONT.	μ_E	Ratio to CONT.
CONT	4.98	1.0	8.16	1.0
W0	2.43	0.49	2.98	0.37
W3	1.41	0.28	1.77	0.22
W4	1.42	0.29	1.76	0.22
W5	1.59	0.32	2.17	0.27

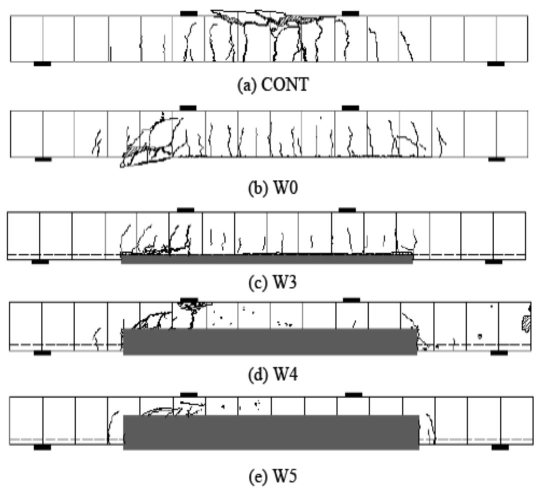

Fig. 6. Failure modes and Crack propagations

IV. CONCLUSION

This study investigates strengthening effect of CFRP width on structural behaviors of RC beams. From experiments, load-deflections curves, interfacial shear stress distributions, ductility, and failure modes are analyzed. The results show that RC beams strengthened with the wider width CFRPs has the higher load capacity and ductility. Also, it is recommended to have wider width of CFRPs than beam width such that CFRP sheets ends at higher level than location of reinforcing steel bars.

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