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Flexural Behavior of Concrete Beam Reinforced with Steel and FRP Re-bars

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Abstract. FRP composite materials are widely applicable in the construction industries as a load-bearing structural element or a reinforcing and/or repairing materials for the concrete. In this paper, we presented the flexural behavior of steel reinforced concrete beams reinforced with FRP re-bars manufactured by different fibers but the same vinylester resin. Experimental investigation pertaining to the load-deflection and load-strain characteristics of steel reinforced concrete beams reinforced with FRP re-bars with garnet coated surface is presented and the theoretical prediction is also conducted. In the investigation, the effects of FRP re-bar reinforcement in addition to the steel reinforcement are estimated. The experimental results are compared with theoretical predictions. Good agreements are observed.

Introduction

The FRP re-bars are gaining broad acceptance in the construction industries due to their superior physical and mechanical properties. In recent years, concrete structures including flexural members under service are severely deteriorated due to hazardous environmental effects.

To overcome such problems, flexural behavior of concrete beams reinforced with FRP re-bars has been investigated. Most of researches related to the structural behavior of concrete beams reinforced with FRP re-bars are reported by Nanni(1993)[1], ACI 440R(1996)[2], ACI 440(2000)[3], etc. In addition, a concise state-of-the-art review on the composite applications for construction in civil engineering is given by Bakis et al. (2002)[4].

In this paper we presented the results of experimental investigations pertaining to the flexural behavior of steel reinforced concrete beams reinforced with three different types of FRP re-bars. The FRP re-bars used in the experimental investigations are E-glass, carbon, and aramid fibers which are impregnated into the vinylester resin to form a FRP bar. The FRP re-bars discussed are produced by the pultrusion process and the surface of re-bars is coated with garnet to improve the bond strength between concrete or mortar and FRP re-bar surfaces.

The FRP re-bars used in this research may be utilized as a new construction material or a material for the repair of existing deteriorated concrete members. But, in the present study, we intended to use the FRP re-bars for the repairing and/or strengthening of the steel reinforced concrete flexural members.

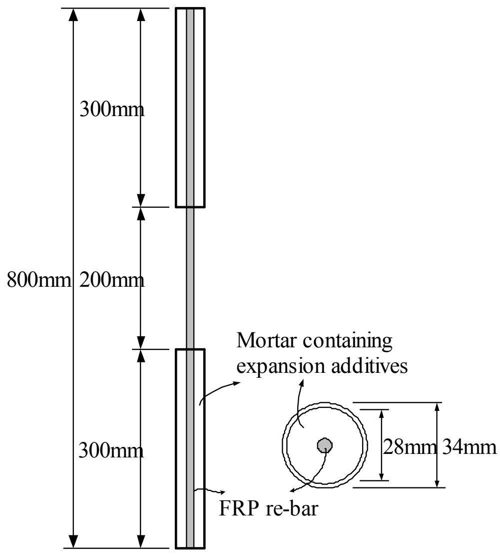
Mechanical Properties of Materials

FRP Re-bars. The FRP re-bars used in this investigation were manufactured by Reform System Co., Ltd., in Korea. Three different types of FRP re-bars, such as aramid (AFRP), carbon (CFRP), E-glass

(GFRP) fibers impregnated into the vinylester resin to form a FRP bar, are used. All FRP re-bars had 6mm in diameter and are coated with garnet to increase bond strength between the surfaces of concrete and FRP re-bar. The fiber volume ratio of AFRP, CFRP, and GFRP is 58%, 61%, and 66%, respectively.

Tensile tests of the FRP re-bars were carried out using a universal testing machine. In the preparation of tensile test specimens, to avoid gripping problems due to the low transverse strength of FRP re-bars, a gripping system based on embedding both ends of the FRP re-bar into a metal tube was adopted, and the bond between the FRP re-bar and the steel tube was assured by an injection of mortar containing expansion additives (Castro et al. 1998)[5].

A total of fifteen specimens, i.e., five for each type of fiber reinforced FRP re-bar, was prepared. Fig. 1(a) shows the detailed dimension of test specimens, and Fig. 1(b) shows the completely prepared test specimens with grip reinforcement with steel tubes, and thus the failure can occur within the gage length.



(a) Specimen dimension with grip details

(b) FRP re-bar test specimens

Fig. 1 Tension test specimen of FRP re-bars

Tensile test results of FRP re-bars are summarized in Table 1. In the table mechanical properties of steel re-bar are also included for comparison purposes. From the test it was confirmed that the stress-strain relation of FRP re-bars is linear up to the specimen failure.

Table 1 Mechanical properties of FRP and steel re-bar

Type of Re-bar	E_f, E_s MPa (kgf/cm^2)	R_E	f_{fu}, f_y MPa (kgf/cm^2)	R_y
AFRP	71,834 (733,000)	0.37	1,666 (17,000)	4.25
GFRP	53,704 (548,000)	0.27	1,205 (12,300)	3.08
CFRP	99,176 (1,012,000)	0.51	2,009 (20,500)	5.13
Steel	196,000 (2,000,000)	1	392 (4,000)	1

E_f : elastic modulus of FRP re-bar f_{fu} : ultimate strength of FRP re-bar $R_E = E_f / E_s$
E_s : elastic modulus of steel re-bar f_y : yield strength of steel re-bar $R_y = f_{fu} / f_y$

Polymer Mortar. To repair or reinforce the concrete structures using FRP re-bars effectively, polymer mortar must be used in this system. The required properties of polymer mortar are high strength, good bond strength, workability, etc. In this research, the average compressive strength of polymer mortar used to reinforce the flexural test specimens was determined by the standard compression test with 50.8×50.8×50.8mm cubes. The average compressive strength of polymer mortar was more than 39.0MPa (400kgf/cm^2).

Design and Preparation of Beam Specimens

Three sets of steel reinforced concrete beams reinforced with AFRP re-bars, CFRP re-bars, and GFRP re-bars, respectively, were prepared to test under the 4-point bending test set-up. Each set of beam specimens is comprised of three steel reinforced concrete beams with a different quantity of reinforcement of FRP re-bars. The FRP re-bars are used in addition to steel re-bar to simulate the repair of deteriorated steel reinforced concrete beams. All steel re-bar reinforced concrete beams before reinforced with FRP re-bars were designed to fail due to yielding of tensile re-bars, i.e., under reinforced beam.

A beam specimen is disignated with a certain number as B-0, B-A, B-C, and B-G, respectively, in which B indicates beam specimen, and 0, A, C, and G after hyphen stand for the reinforcement with no FRP re-bar, aramid FRP re-bar, carbon FRP re-bar, and glass FRP re-bar reinforced, in addition to steel re-bar, respectively.

A schematic view of the 4-point bending test specimen with cross-section is shown in Fig. 2. The span length of beam is 3,000mm and the both ends are simulated as simply supported, as illustrated in Fig. 2. All test specimens are intended to estimate the flexural moment strength to find the effects of FRP re-bar reinforcement. Therefore, all beam specimens are designed to fail by bending not by shear. The compressive concrete strength of beam specimens at the time of testing was 37.3MPa (380kgf/cm^2), and the yield strength of steel re-bar (f_y) was 392.0MPa (4,000kgf/cm^2). In the design of beam specimens, strength design method suggested by the ACI 440 with slight modification is used. In this method the design strength of FRP re-bar (f_{fd}) which is equivalent to yield strength of steel re-bar should be determined. In this experimental investigation, we determined $f_{fd} = \alpha f_{fu}$ with α=0.5, where f_{fd} and f_{fu} are the design and ultimate strengths of FRP re-bar, respectively. The multiplication factor α was determined by the experiment. The stress at the FRP re-bars, when the beam specimen failed, was about 1/2 of the ultimate strength of FRP re-bar.

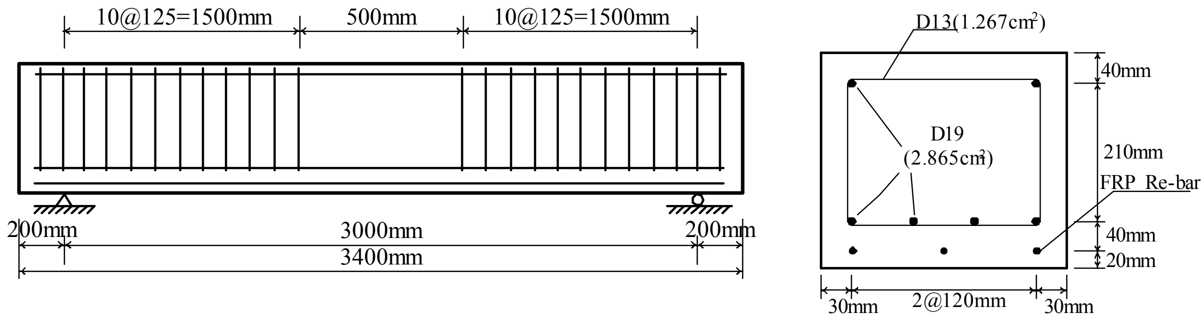
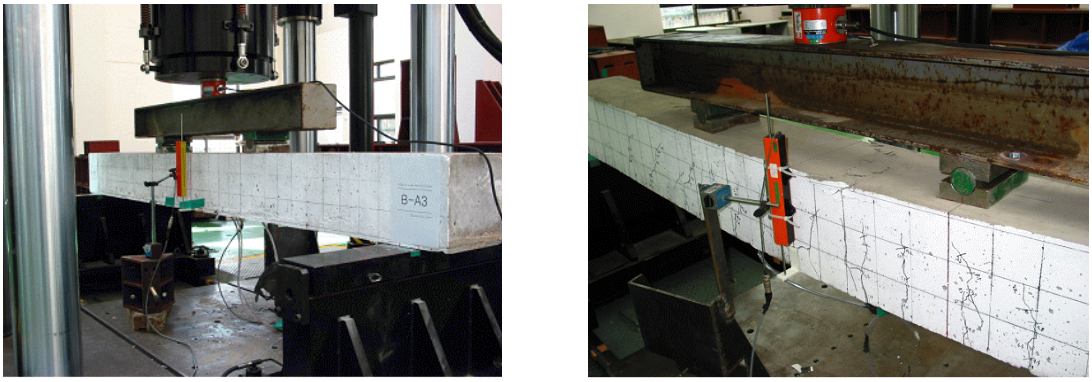


Fig. 2 Detail dimension and reinforcement of beam specimen

Flexural Test Results

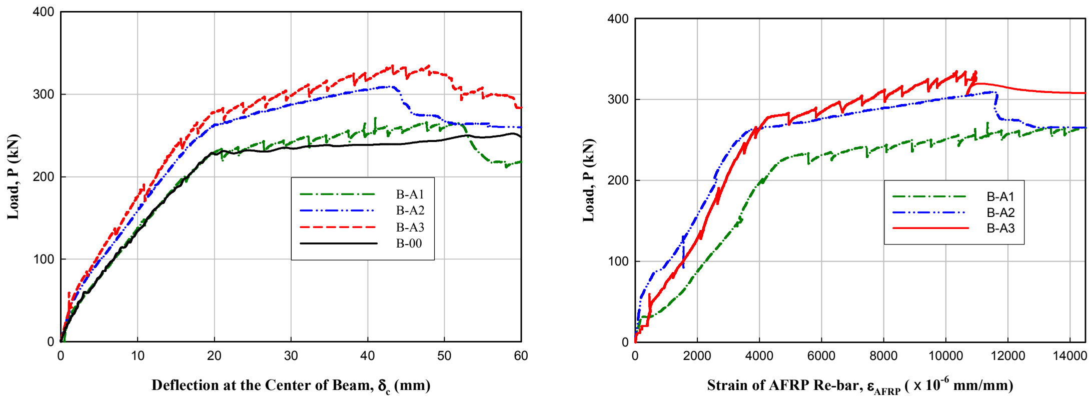
All beam specimens were loaded monotonically up to failure. Fig. 3(a) shows the 4-point bending test set-up and Fig. 3(b) shows one of the tested beam specimens. The applied lateral load and mid-span deflection were measured with a load cell and linear variable differential transformers (LVDTs), one at each side of the beam, respectively. Also, the strain gages were installed at the tension side of steel and FRP re-bars which are embedded in the concrete beam. All experimental data are measured and recorded through a computer controlled data acquisition system.

From the test results, load-deflection and load-strain curves are plotted as shown in Figs. 4 to 6. As can be seen in the load-deflection curves, slope of the curves changes significantly if the steel re-bar yields but still maintains increasing trend. This increasing trend can also be found in the load-strain curves.



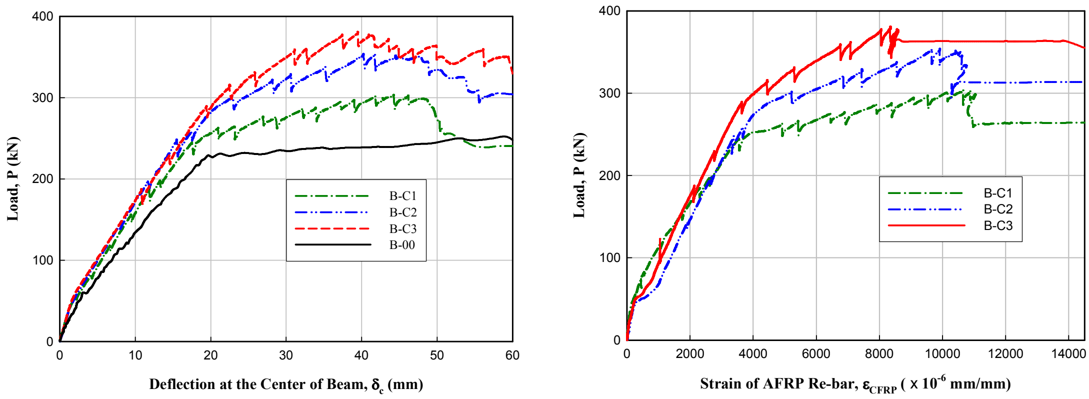
(a) 4-point bending test (b) Tested specimen

Fig. 3 Flexural test



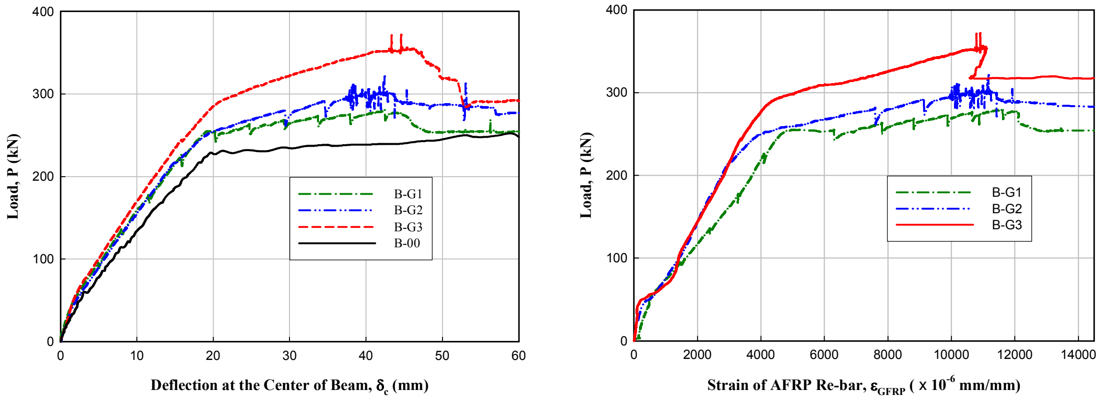
(a) Load-deflection curves (b) Load-strain curves

Fig. 4 Flexural test results of AFRP re-bar reinforced specimens



(a) Load-deflection curves (b) Load-strain curves

Fig. 5 Flexural test results of CFRP re-bar reinforced specimens



(a) Load-deflection curves (b) Load-strain curves

Fig. 6 Flexural test results of GFRP re-bar reinforced specimens

Comparison of Results

From the test results, the cracking moment when the concrete under tension cracks (M_{cr}), the moment when the steel re-bar yields (M_{ny}), and the maximum moment calculated at the ultimate load (M_{max}) are estimated, respectively. In addition, the nominal moment predicted by the strength design method is also presented. These results are summarized as shown in Table 2.

Table 2 Summary of results

Specimen No. (No. of re-bars)	Experiment			Predicted nominal moment M_{py} kNm (tonfm)	M_{ny}/M_{py}
	Cracking moment M_{cr} kNm (tonfm)	Moment at steel re-bar yielding, M_{ny} kNm (tonfm)	Maximum moment M_{max} kNm (tonfm)		
B-00 (0)	13.73 (1.40)	114.74 (11.70)	114.74 (11.70)	101.80 (10.38)	1.13
B-01 (0)	16.18 (1.65)	113.76 (11.60)	113.76 (11.60)		1.12
B-02 (0)	17.65 (1.80)	124.84 (12.73)	124.84 (12.73)		1.23
B-A1 (3)	20.59 (2.10)	115.72 (11.80)	132.79 (13.54)	118.66 (12.10)	0.98
B-A2 (6)	25.50 (2.60)	131.81 (13.44)	154.75 (15.78)	135.04 (13.77)	0.98
B-A3 (9)	25.50 (2.60)	136.51 (13.92)	167.01 (17.03)	150.83 (15.38)	0.91
B-G1 (3)	23.54 (2.40)	124.35 (12.68)	139.95 (14.27)	114.06 (11.63)	1.09
B-G2 (6)	23.54 (2.40)	131.90 (13.45)	151.71 (15.47)	126.02 (12.85)	1.05
B-G3 (9)	24.03 (2.45)	146.32 (14.92)	178.39 (18.19)	137.79 (14.05)	1.06
B-C1 (3)	21.09 (2.15)	126.41 (12.89)	155.83 (15.89)	122.10 (12.45)	1.04
B-C2 (6)	24.03 (2.45)	130.83 (13.34)	176.43 (17.99)	141.61 (14.44)	0.92
B-C3 (9)	25.50 (2.60)	147.79 (15.07)	189.77 (19.35)	160.44 (16.36)	0.92

M_{cr} : cracking moment at concrete under tension M_{ny} : moment when tensile re-bar yields
M_{max} : ultimate moment strength M_{py} : predicted nominal moment

The experimental results, estimated at the time of the steel re-bars yielding, and the predicted nominal moments are shown in Fig. 7. The experimental results are ranged from -9% to +9% of predicted values. In addition, the maximum moments are 11% to 29% higher than the predicted nominal moments. Therefore, it can be said that the beam designed by this approach may have at least more than 11% reserved moment strength without consideration of load and strength reduction factors.

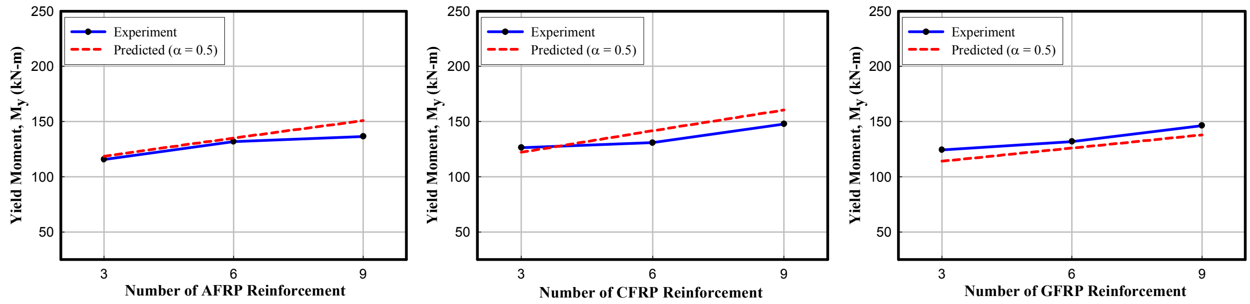


Fig. 7 Comparison of predicted and experimental results

Conclusions

From the experimental investigations following conclusions are drawn.

(1) All steel reinforced concrete beams were failed due to yielding of tensile re-bars but when the FRP re-bars are used as an additional reinforcement at the tension zone of the specimen the failure of specimens was the crushing of concrete under compression.

(2) The flexural strength of beam specimens was increased after yielding of steel re-bars but the increasing trend was significantly lessened.

(3) The flexural strength of beam specimens is increased when the quantity of FRP re-bar reinforcement is increased.

(4) The experimental moment strengths were -9% to +9% of theoretically predicted nominal moment strengths. The maximum moment strengths were 11% to 29% higher than the theoretically predicted nominal moment strengths.

(5) The effect of FRP re-bar reinforcement depends largely upon the FRP re-bar quantity, in general, but the final effect of FRP re-bar reinforcement will be affected by the compressive strength of concrete because the beam fails due to crushing of concrete under compression.

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