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Structural Response of Reinforced Concrete Beams Strengthened with CFRP Rod

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ABSTRACT

Rod-type fiber reinforced polymer plastics(FRPs) similar to reinforcing steel bars have rarely been considered. In this study, an experiment was performed using beams strengthened with rod-type CFRPs and high-strength mortar overlay. The test results show that the strengthened beams not only had improved endurance limits but also improved load carrying capacities, stiffness values, and cracking loads as compared to a non-strengthened beam. Strengthened beams anchored with bolts throughout their entire span had more efficient structural behaviors, including composite behavior on the interface between the concrete and mortar, and load carrying capacity, than a strengthened beam anchored only on the end block.

Keywords: anchor bolt, composite action, fatigue test, fiber reinforced polymers, flexural test

1. Introduction

Many concrete structures have been used for over 30 years in South Korea and are now in need of replacement or rehabilitation. Fiber reinforced polymer plastic(FRP), carbon fiber sheet(CFS), and glass fiber sheet(GFS) are widely used to strengthen these deteriorated concrete structures, but sheet-type materials introduce some unavoidable problems.[1-5] The adhesives that are used for these materials can be weakened by fire or aggressive chemicals, and partial debonding of external strengthening materials can result owing to stress concentrations.[6-9]

If FRP composites are embedded in a concrete matrix, additional strengthening benefits are expected, such as crack-bridging effects and chemical and fire resistance, as well as improved load carrying capacity. Therefore, different types of rod composite FRP(RCFRP) materials have been tested as substitutes for reinforcing steel bars to either retrofit deteriorated concrete members or reinforce existing concrete members.

The surfaces of the RCFRPs used in this research were treated with artificial garnet particles which is similar with sand to increase the bond strength. The typical strengthening scheme is depicted in Fig. 1. The bond strength between the concrete matrix and the mortar used to repair and protect RCFRP from aggressive environments was also a factor to be considered. As the mortar overlay on concrete surfaces that have deteriorated owing to strain lag or strain concentration can be separated from the concrete matrix after flexural cracking, anchor bolts are required to confine the mortar to the concrete and to transfer the tensile stress in the RCFRP to the rod composite member. In this study, polymer mortar that requires only a few hours to harden was considered. This is an improvement over ordinary cement mortar, which requires a minimum of several days to harden.

This paper addresses the structural efficiency of reinforced concrete beams strengthened with RCFRP and subjected to monotonic and cyclic loads. The beam specimens were tested to assess the strengthening effect of different anchoring schemes. Two anchoring schemes were considered: one with 10 anchor bolts inserted into the concrete in a line throughout the entire span, and the other with 12 anchor bolts assembled in two lines in the

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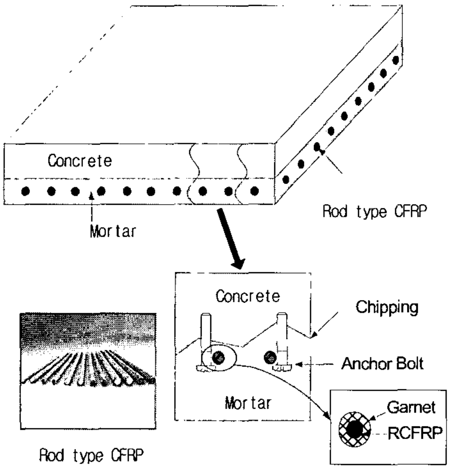


Fig. 1 Strengthening detail of RCFRP

end block of the beam. In addition, the load carrying capacity and failure patterns of the strengthened beams were experimentally assessed, and fatigue responses were examined.

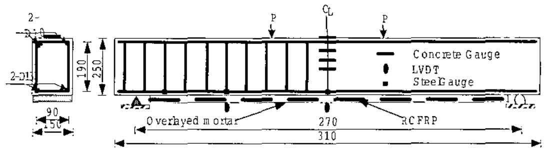
2. Experimental program

The properties of the materials used in the experimental program are summarized in Table 1, and the test variables and strengthening details for the static and fatigue tests are shown in Table 2 and Fig. 2. The amount of strengthening RCFRP was fixed to an area spanning only 2 × ϕ6 mm for each of the two anchor bolt reinforcing schemes. The end block of beam BS-EA was reinforced by 12 anchor bolts, arranged in two lines of six bolts.

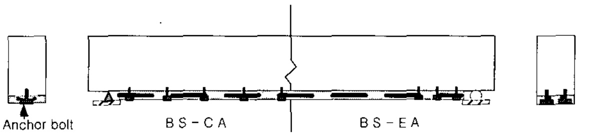
The 10 anchor bolts used in the beam specimen BS-CA were inserted into the mortar along the centerline of the lower beam section through the entire span. In the fatigue tests, the stress levels of the reference and strengthened specimens were set to 60, 70, and 80% of the ultimate loads obtained from the static test results summarized in Table 2.

The specimen details and strengthening schemes are illustrated in Fig. 2. For all of the specimens, the clear span of beam was 2.7 m, and the section of beam was 150 × 250 cm. The depth of the mortar overlay was 2.5 cm, and the reinforcement ratio of the flexural reinforcing steel bars was ρ = 0.139 (A_s / bd).

The shear-span to depth ratio (a / d) was set to 3.5. An actuator with a 1000-kN capacity was used for the static and fatigue tests. An automated data acquisition system acquired the test data such as strain and displacements. Displacement transducer(LVDT) were used to record the beam deflections at the midpoint and 1/4 point of the span to obtain the beam deflection profiles. Electrical resistance strain gages(120Ω) were bonded to the tensile rebars and RCFRPs to measure the strain profiles.



(a) Specimen detail



(b) Anchoring scheme

Fig. 2 Strengthening and anchoring scheme

Table 1 Material properties

	Diameter	Strength (MPa)		Ultimate strain (%)	Elastic modulus (MPa)
		Yield	Ultimate		
Concrete		-	22.5	-	0.232×10^5
Mortar			45.0	-	0.108×10^5
Rebar	13, 10mm	400	550	-	2.00×10^5
RCFRP	6mm	-	2,352	1.15	1.20×10^5

Table 2 Test variables and results

Specimen	Static test			
	Failure attern	Yield load (kN)	Failure load (kN)	(2)/(1)
BC	a)	40	48(1)	1.00
BS-EA	b)	43	68(2)	1.42
BS-CA	c)	44	75(2)	1.56

Specimen	Fatigue test		
	Stress level	Failure pattern	Endurance limit
BC	60%, 70%, 80%	a)	58% (29 kN)
BS-EA	60%, 70%, 80%	b)	60% (44 kN)

a) Flexural failure, b) Flexural failure and partial interface debonding at mid point of beam after yielding of rebars, c) Flexural failure and horizontal crack in interface of concrete and mortar overlay

3. Test results and discussion

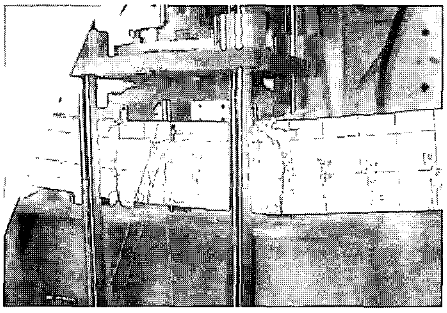
3.1 Static test

Failure patterns

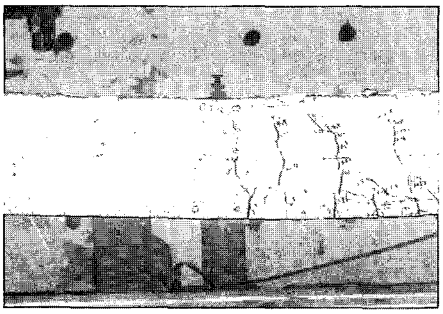
Fig. 3 shows the crack patterns of each specimen. The yield strength of specimen was estimated from the load-strain relationship of the tensile rebar.

The unstrengthened BC specimen exhibited a typical flexural failure, as shown in Fig. 3(a). After the development of the initial crack at 15 kN, the tensile reinforcement yielded at 40.6 kN, and finally failed at 48 kN. As the load increased, major flexural cracks propagated to the compression side and the crack width expanded until the beam failed completely. The maximum crack width at failure was 12 mm.

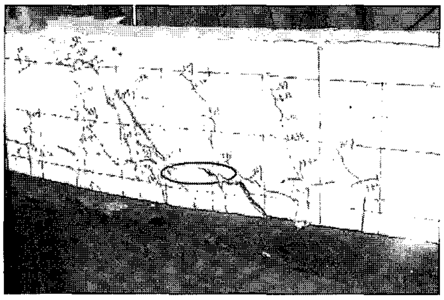
The beams strengthened with RCFRP developed numerous flexural cracks in the mortar on the tension side of the beam until interface debonding occurred between the concrete surface and mortar. The interface debonding patterns differed slightly between beams BS-EA and BS-CA. Beam BS-EA, which was anchored only in the end block, exhibited either a separation or spalling of the mortar overlay only at the mid-point of the beam after the tensile rebar yielded. The composite action of the RCFRP and mortar overlay was diminished by the pull-out failure of the RCFRP. Beam BS-CA, which was anchored along the entire beam length, developed horizontal cracks in the concrete and mortar overlay interface along the entire span, but the mortar overlay, as shown in Fig. 3(c), did not fully separate from the bottom of the beam. These facts indicate that the anchor bolts inserted in the mortar contributed to the stress distribution and the composite action between the overlay material and the concrete.



(a) BC



(b) BS-EA



(c) BS-CA

Fig. 3 Failure patterns of specimens under static loads

Load-displacement relationship

Fig. 4 shows the load-displacement relationships of non-strengthened and strengthened specimens with different anchoring schemes. The load-displacement relationship of the strengthened BS-EA and BS-CA specimens showed identical behaviors to that of the BC specimen before the reinforcing bars yielded. However, after the yielding point of the reinforcing steel bars in the BS series, the stiffness and yield load of the strengthened beams were slightly greater than those of the BC specimen. Whereas the stiffness of specimen BS-EA after yielding was slightly higher than that of specimen BS-CA, the ultimate strength of specimen BS-EA was relatively lower. This specimen had anchor bolts installed only in the end block of the mortar. The strengthened specimen BS-CA failed owing to a ductile failure mode that is more often compared to beam BS-EA; this was caused by a gradually progressive debonding of the RCFRP in the mortar overlay after post-peak region. The failure loads for the strengthened specimens are shown in Table 2. Even though the same amount of RCFRP was applied, the BS-EA and BS-CA specimens increased in strength by 42% and 56%, respectively. These results indicate that the anchoring scheme that spanned the entire specimen (specimen BS-CA) was more effective than the scheme in which only the end block was anchored (specimen BS-EA).

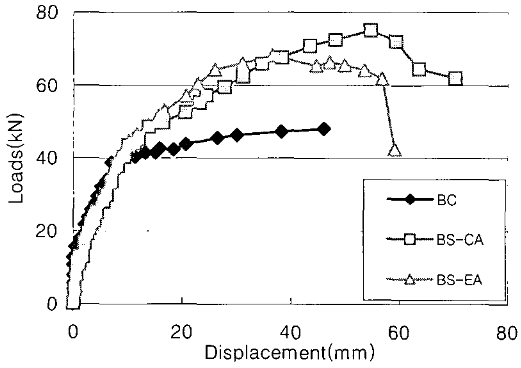


Fig. 4 Load-displacement relationship

Load-strain relationships of the rebar and RCFRP

The load-strain relationships of the RCFRP are shown in Fig. 5. The strain profiles of the strengthened beams BS-EA and BS-CA were very similar to the strain profiles of the rebar up to the yield loads. An initial noticeable deformation of the RCFRP in beam BS-EA was observed 20 kN after flexural cracking. Then the strain of the strengthening material abruptly increased. This differed from the strain of the RCFRP in beam BS-CA, which increased proportionally from the initial loading state. Thus the anchoring scheme of beam BS-CA adequately resisted external loads without introducing the mid-span pull-out failure of the strengthening material that was observed for beam BS-EA.

Strain profile in the beam section

Experimentally obtained strain profiles of the concrete, rebar, and RCFRP in the mid-span beam section are shown in Fig. 6 to examine the relative effectiveness of the composite action in the strengthened beam. Since the strengthening materials were assumed to be perfectly bonded to the mortar overlay, the discrepancy between the linearity of the strain profile and the strain compatibility for each load resulted from either cumulative slips that existed in the interface between the strengthening materials and their surrounding materials or the stress concentrations in the strengthening materials. Beam BS-EA, which was initially perfectly bonded to the mortar overlay, showed a strain lag after the rebar yielded, which was caused by the pull-out failure of the RCFRP. For beam BS-CA, the rebar strain was relatively small as compared to the deformation of the RCFRP from the initial loading state. This phenomenon originated from the stress concentration at the mid-span of the beam. Therefore, the anchoring scheme of beam BS-EA was more effective and would ensure better composite action up to the yield load of the reinforcing bars. However, when the purpose of the strengthening is either to increase the ultimate strength or to control the failure mode, the anchoring scheme adopted in beam BS-CA would be more effective.

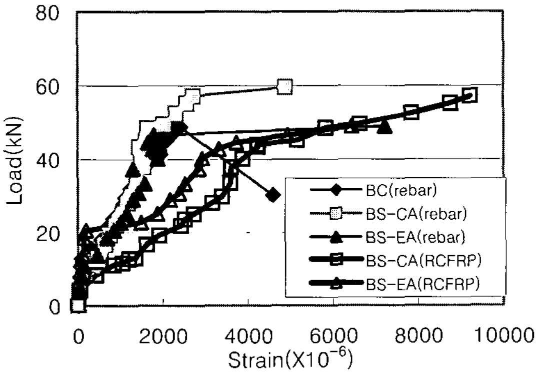


Fig. 5 Load-strain relationship of reinforcing steel bar and RCFRP

3.2 Fatigue response

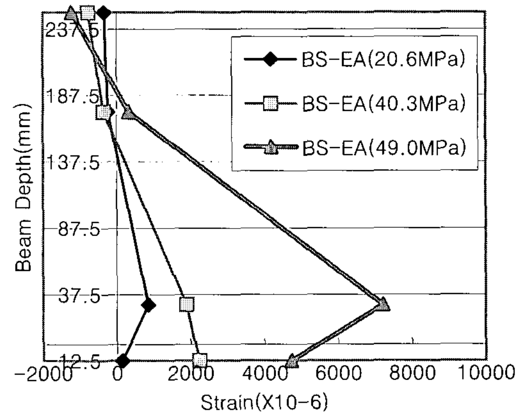
Failure patterns

A summary of the test results is shown in Table 2, and the failure patterns of each specimen at a stress level of 60% are illustrated in Fig. 7. The non-strengthened specimens (BC-60, -70 and -80) developed flexural cracks similar to the crack patterns of beam BC under static loads, and finally failed after the macro-flexural cracks widened at the mid-span.

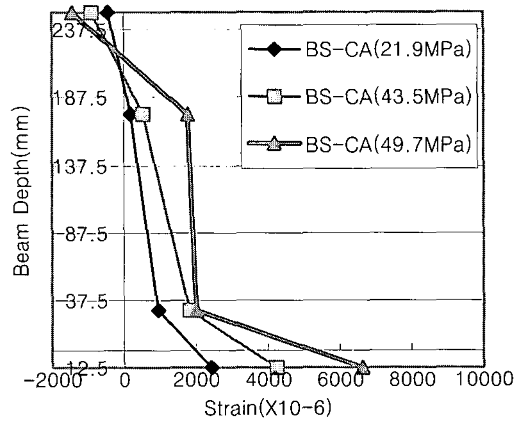
Horizontal interface cracks were not observed in beam series BS-CA, unlike beam BC-CA which was subjected to monotonic loads, as shown in Fig. 7. Horizontal debonding cracks between the concrete/mortar interface were widely propagated in beam series BS-EA.

Load-displacement relationship according to load cycle

Load-cumulative displacement relationships corresponding to the load cycles of the beams at a stress level of 70%

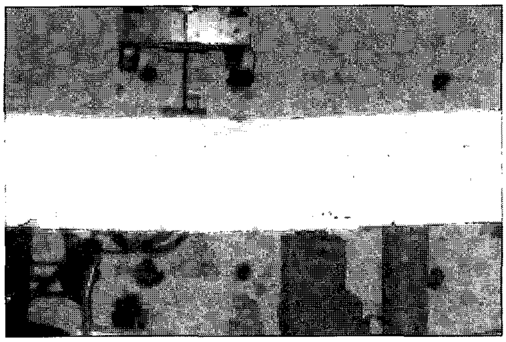


(a) Beam BS-EA

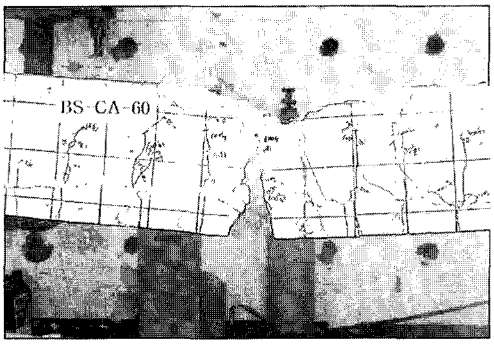


(b) Beam BS-CA

Fig. 6 Strain profile in strengthened beam section

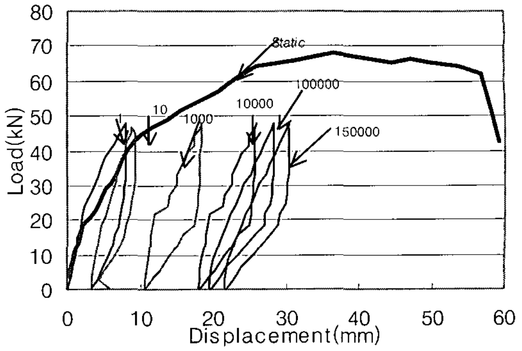


(a) BS-EA-60

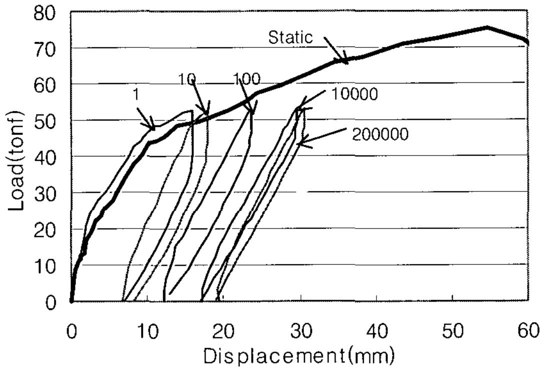


(b) BS-CA-60

Fig. 7 Typical fatigue failure patterns



(a) BS-EA-70(Nf =158,241)



(b) BS-CA-70(Nf=236,869)

Fig. 8 Cyclic load-displacement relationship

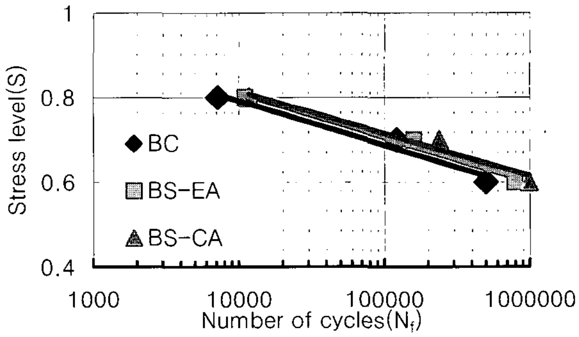


Fig. 9 S-N relationship

are illustrated in Fig. 8. Strengthened beams BS-EA-70 (N_f= 158,241) and BS-CA-70 (N_f= 236,869) had longer life cycles than did beam BC-70 (N_f= 121,426).

The maximum accumulation displacements of specimens BC-70, BS-EA-70, and BS-CA-70 subjected to cyclic loads were 30, 21.6, and 30.6mm, respectively. The beams strengthened with RCFRP displayed similar behaviors under the other stress levels.

S-N relationship

The strengthened beams had an improved endurance limit as well as load carrying capacity for cyclic loads. When the fatigue limit cycles were regarded as 10^6 cycles, the endurance limit of the BC specimen was 58%, while the endurance limits of the strengthened specimens BS-EA and BS-CA were 60 and 62%, respectively. The endurance limit of BS-CA series beams was 4% higher than that of an unstrengthened beam. The S-N relationship of the beams based on the test results is shown in Fig. 9.

4. Conclusions

The results presented in this paper lead to the following conclusions. Beams strengthened with RCFRP can have a substantially increased load carrying capacity and flexural stiffness, but the cracking patterns and failure mode of the strengthened beams depend on the anchoring scheme. From the static test results, the strengthened specimens showed a 40-50% improvement in their ultimate strength. Beam BS-CA, which was anchored through its entire span length, proved to be efficient from the viewpoint of strength, crack control, and energy dissipation. Also, the fatigue tests suggested that the strengthened beams were more efficient at fatigue resistance as compared to BC beams. At the same stress level, the BA-CA beam series showed a remarkable structural enhancement that resisted fatigue loads, because the stress was more effectively distributed in the beams under the service load state. The test results showed that the structural behavior of beams strengthened with RCFRP largely depended on the anchoring scheme.

Acknowledgements

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