Journal of the Korea Concrete Institute
Vol.18 No.2, pp.293~298 April, 2006

Strain Monitoring of Strengthened RC Beams with Hybrid Fiber Reinforced Polymer (FRP) Laminates by FBG Sensor

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(Received September 26, 2005 ; Accepted December 31, 2005)

ABSTRACT

The reinforced concrete(RC) structures strengthened with fiber reinforced plastic(FRP) has been accepted by the construction engineering community for rehabilitation. FRP composites can present many advantages like a corrosion resistance, strength-weight ratio, relatively short application time, and cost effectiveness. The beams under design load, however, are cracked and result in degrading the strength. It is difficult to recognize cracks and deflections on the surface of the concrete members retrofitted with FRP through the life cycle. For these reasons, if they result in the effects, which were below the expected strength, we must monitor the state of concrete structures all the time in order to take an appropriate measure. Fiber Bragg Grating(FBG) sensor excel as monitoring of investigating the stress state of the retrofitted beams with FRP. The main objective of this study is to measure strain by experiment and analyze the behavior of RC beams retrofitted with FRP using FBG sensor. The kinds of FRP which were used in research are carbon, glass and improved hybrid FRP(IFRP) that has capacity than any other FRP. Other variables are the length of FRP, the number of sheet.

Keywords: FRP, CFRP, GFRP, monitoring, FBG sensor

1. Introduction

During lifetime of reinforced concrete(RC) structures, strengthening or retrofitting is caused by the change of building usage and design code, increase of safety requirement and deterioration of structures. Flexural strength of RC beam can be increased by bonding a fiber reinforced polymer(FRP) plate to the tension face. Externally- bonded FRP composites has gained acceptance in the rehabilitation. The technique was recently used with success in field strengthening and rehabilitation. This technique has numerous advantages such as minimum increases in structural size and weight, ease of site handling, high strength-to-weight ratio, good corrosion resistance and good nonmagnetic property.

However, as the structural faces are wrapped with retrofitting material, it is not easy to figure out the visible defect like cracks on externally-bonded FRP strengthened beams. Monitoring is essential in order to investigate structural conditions for loading on structures after retrofitting. The selection of sensor is very important to get effective monitoring data for lifetime of structures. Electrical resistance gages are generally used to measure strains of structures for each loading in the laboratories. The electric gages are proved to have some problems in durability and not to be applicable to long-time measurement such as monitoring for building maintenance whose lifetime is at least fifty years. For these reasons, the measuring technology using optical fiber sensor has been studied since 1980s. Optical fiber sensors are proved to be safe in long term use, to make no noise by electromagnetic force and to have some advantages such as lightweight, easy handling and relatively lower price. Thus, the optical fiber sensor is effectively applied to monitoring strains in order to investigate structural conditions of retrofitted members through multi-measurement system and networking sys-

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measurement system and networking system.

This study is aimed to investigate the applicability of optical sensor to structural monitoring. For this purpose, two small-scale beams retrofitted with carbon fiber reinforced polymer(CFRP) laminates are tested. Then, monitoring by optical fiber sensor is applied to test beams. Fiber Bragg Grating(FRG) sensor of several optical fiber sensors is selected to be applied. To evaluate the application in the reinforced concrete(RC) flexural member retrofitted with combined CFRP and GFRP, the experimental results by FBG sensor under several levels of pre-loading are compared with those by electronic resistance gage installed at the same location with FBG sensor.

2. FBG sensor for monitoring

Fiber Bragg Grating(FBG) sensor and Fabry-Perot sensor of optical fiber sensors are generally used to measure strains. Fabry-Perot sensor is less used than Fiber Bragg Grating sensor because it is impossible to mass-produce due to its complex product process and also it is relatively expensive and hypersensitive to environment. For these reasons, the FBG sensor is selected in this study.

FBG is an optical fiber grating element that reflects the lights with specific wave length, whose cycle of grating changes the reflective index by periodically applying ultraviolet rays to optical fiber core added Ge (germanium) as shown Fig. 1. Wavelength that satisfies the formula (1) is reflected by FBG when the light comes in. The rest passes through and appear the optical spectrum analysis appliance.

$$\lambda_B = 2n\Lambda \tag{1}$$

where, n : a effective refractive index
Λ : grating period

Bragg wavelength reflected from grating is a function of effective refractive index and grating interval. The length is changed by physical conditions like temperature and pressure. Therefore the physical changes can be measured from the change of Bragg wavelength. The formula (2) shows the change of Bragg center wavelength to the change of strains.

$$\Delta\lambda_B = \lambda_B(1 - P_e)\varepsilon \tag{2}$$

where, P_e: optical elastic constant
ε : the strain of FBG grating

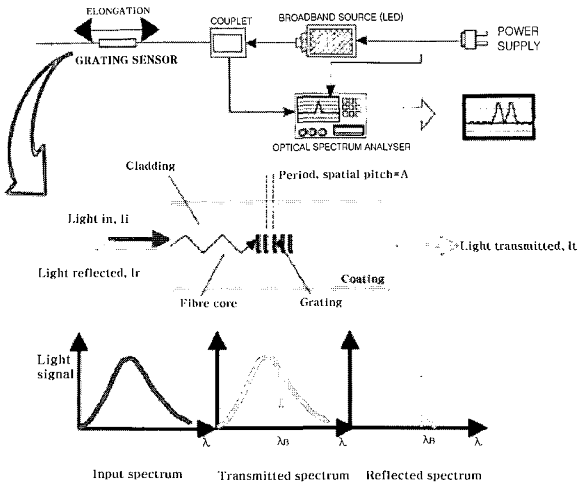
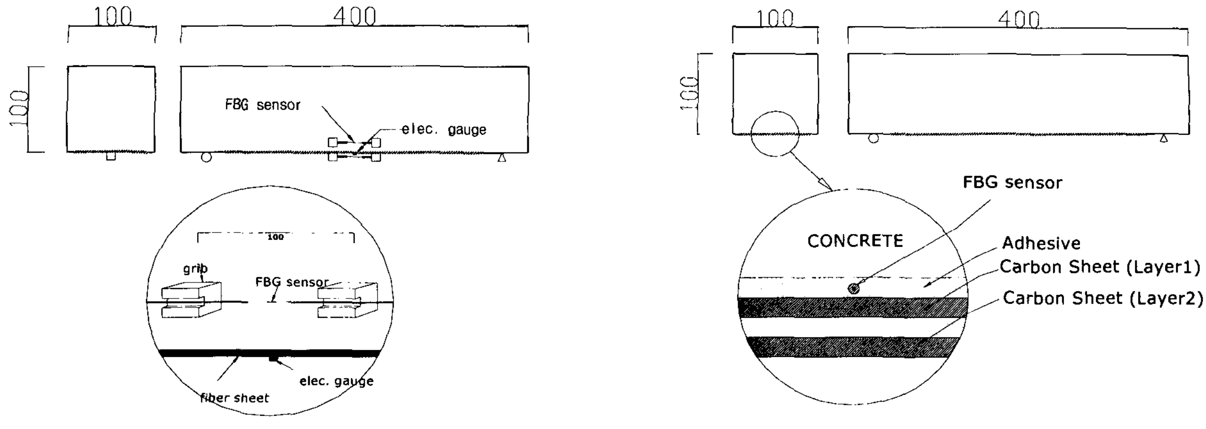


Fig. 1 Flow of FBG sensor

3. Pre-evaluation of applicability of FBG sensor to flexural member

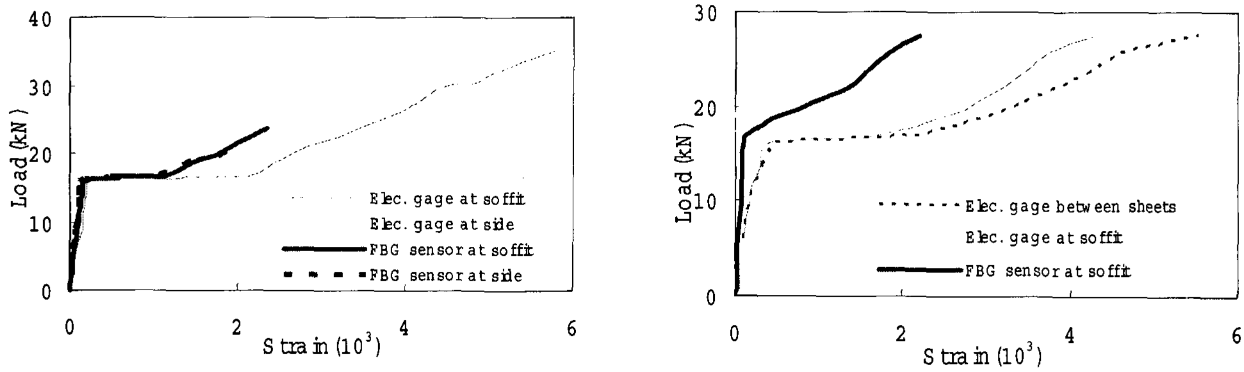
To pre-evaluate the applicability of FBG sensor to flexural member, non-reinforced small-scale beams(100mm in width, 100mm in height and 400mm in length) are fabricated and CFRPs are bonded at the soffit of them. The beams are loaded to the failure at the center of the beam as three-point loading. Electric strain gages and FBG sensors are installed at the same location to grasp the interrelationship between two sensors and to evaluate the measured results of FBG sensor by comparing with those of electric strain gages.

To investigate the effect of the setting method of FBG sensor on change of strains, two methods are selected. One is embedding the FBG sensors between retrofitted material and concrete and another is using the grip accessories to place the sensors. For specimen CC-OA, the 60mm long FBG gages are installed at the side and soffit of the beam by using the grip accessories as shown in Fig. 2(a). The electric strain gages are installed on the face of same position. For specimen CC-OE, FBG sensors are embedded between CFRP and concrete as shown in Fig. 2(b) and electric gages are placed in each layer. Details of the specimen are shown in Table 1. The load-strain curves are shown in Fig. 3. As shown in Fig. 3, both curves of CC-OA and CC-OE show similar shape except near failure. However, the tendency of the results is much similar with that of electric resistance gage. FBG sensor is applicable to monitoring strains RC beams retrofitted with FRPs. As compared Fig. 3(a) and (b), the position of FBG sensor and setting method are proved to affect less on the structural monitoring.



(a) CC-OA (b) CC-OE

Fig. 2 Specimen configuration and position of FBG sensors



(a) CC-OA (b) CC-OE

Fig. 3 Load-strain curves

Table 1 Summary of small-scale specimens

Description	Size (mm)	No. of CFRPs	Retrofitting material	Setting method of FBG sensor
CC-OA	100×100×400	2	Carbon Fiber	embedding
CC-OE	100×100×400	3	Carbon Fiber	Using grip accessories

4. Evaluation of the applicability of RC beam retrofitted with FRPs

4.1 Experimental program

As the results of pre-evaluation, FBG sensor is confirmed to be usable to monitoring the RC structure. To investigate the applicability of FBG sensor to real RC structures, eleven test beams including a control beam are fabricated. Main test variables are the levels of sustaining load, the length of FRPs and the FRP of combined retrofitting material where FBG sensors are installed. All beams have the same dimensions, that is, 150 mm wide, 250 mm high and 2400 mm long. Two 13 mm-diameter steel bars with a sectional area of 127 mm^2 are used as the main flexural reinforcement for each beam, which correspond to reinforcing ratio 0.0077. This reinforcing ratio is used to ensure that total reinforcing ratio after strengthening be less than the maximum reinforcement ratio of $0.75\rho_b$. Two steel bars of 10mm diameter with a sectional area of 71 mm^2 are placed for all beams as top reinforcement. Top and bottom bars have yield strength of f_y=443MPa and 531MPa, respectively. The stirrups of 10mm diameter bars are spaced

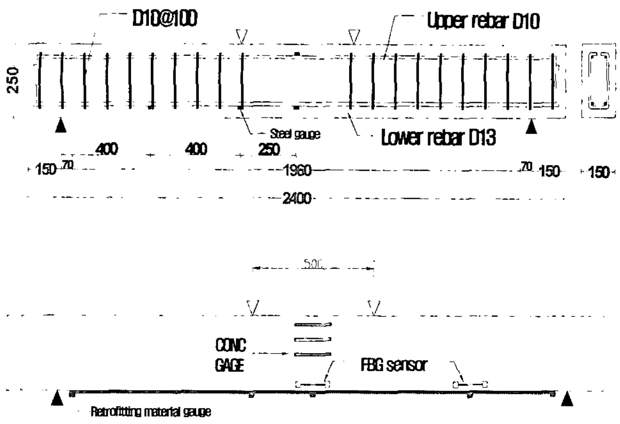
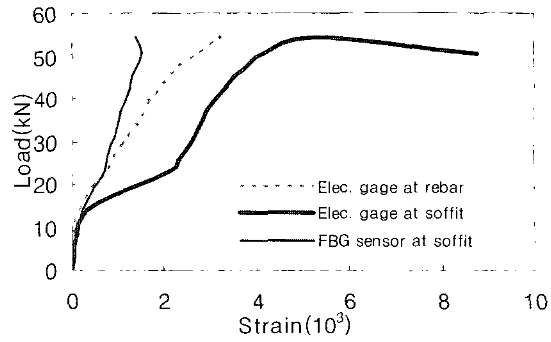
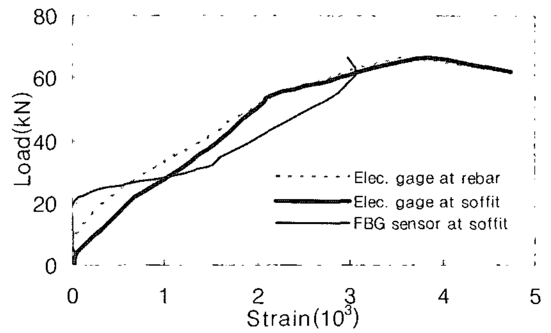


Fig. 4 Specimen layout and sensor location

at 100mm along the beam length for all specimens. For external strength-ening, the CFRP and glass fiber reinforced polymer(GFRP) are combined and the materials have the same properties and thickness. The strengthening lengths of FRPs are determined as 1960mm and 1200mm to investigate the effect of strengthening length on monitoring by FBG sensor. Fig. 4 illustrates the reinforcement arrangement, strengthening length and the position of gages and FBG sensors. The test specimens are summarized in Table 2. Specimens are labeled as CGn where C, G and n stand for CFRP, GFRP, percent of nominal flexural strength of non-strengthened RC beam, respectively. CG also means



(a) CCLS



(b) GGLS

Fig. 5 Strain monitoring by strengthening length

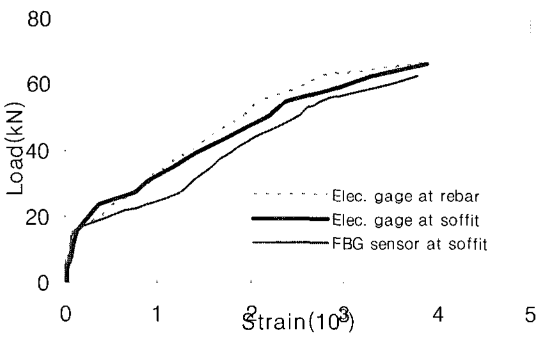
CFRP is bonded to concrete face prior to GFRP.

Concretes with compressive strengths of f_c=32MPa are

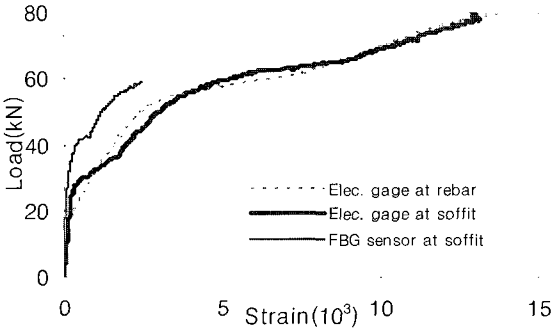
Table 2 Summary of test specimens

	Beam (mm)			Fiber reinforced polymer					Sustaining load at strengthening (kN)	Parameters of test
	Width (mm)	Depth (mm)	Length (mm)	Width (mm)	Thickness (mm)		Length (mm)	No. of plies		
					CFRP	GFRP				
CONTR	150	250	2400	130	-	-	-	2	-	Control
CCLS	150	250	2400	130	0.22	-	1200	2	-	FRP Length
GGLS	150	250	2400	130	-		1200	2	-	FRP Length
CC	150	250	2400	130	0.22		1960	2	-	FRP combination (CFRP only)
GG	150	250	2400	130	-		1960	2	-	FRP combination (GFRP only)
CG	150	250	2400	130	0.22		1960	2	-	FRP combination (CFRP+GFRP)
GC	150	250	2400	130	0.22		1960	2	-	FRP combination (GFRP+CFRP)
CG50	150	250	2400	130	0.22		1960	2		FRP combination and sustaining load
GC50	150	250	2400	130	0.22		1960	2		FRP combination and sustaining load
CG70	150	250	2400	130	0.22		1960	2		FRP combination and sustaining load
GC70	150	250	2400	130	0.22		1960	2		FRP combination and sustaining load

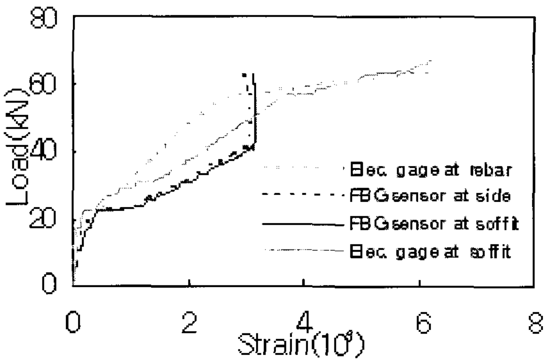
* C: Carbon fiber G: Glass fiber LS: Shortly retrofitted
** All beams have 2-D13 at bottom, 2-D10 at top of beams and D10@100 as stirrups.



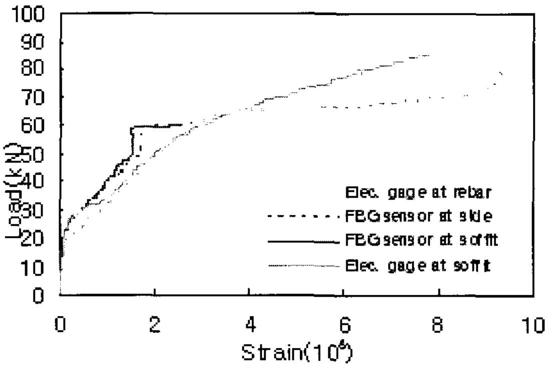
(a) CC



(b) GG

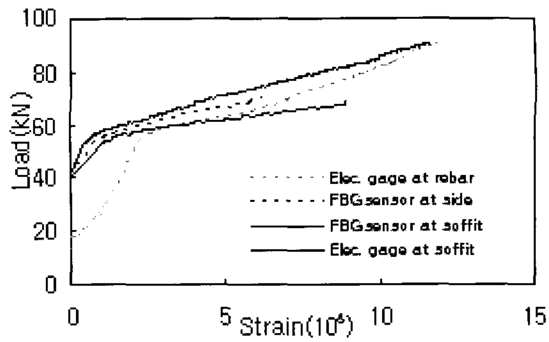


(c) CG

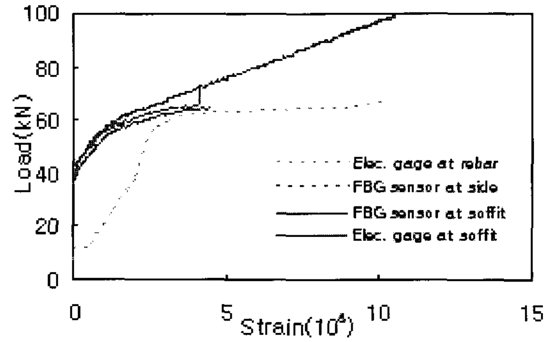


(d) GC

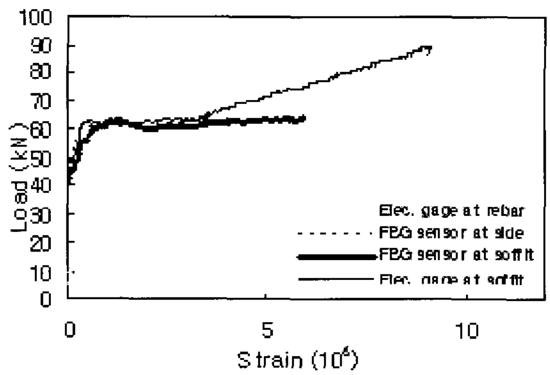
Fig. 6 Strain monitoring by retrofitting materials



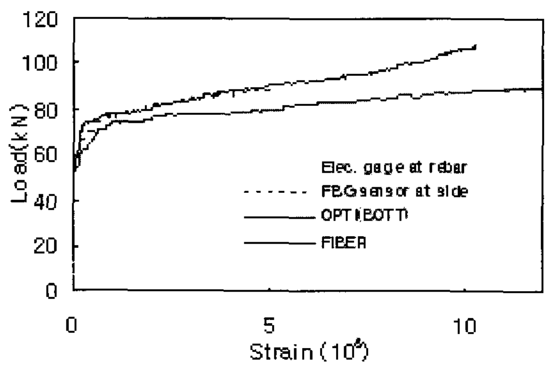
(a) CG50



(b) GC50



(c) CG70



(d) GC70

Fig. 7 Strain monitoring by levels of sustaining load used and CFRP and GFRP have 2.3×10^5MPa and 7.1×10^4MPa in elastic modulus and 851MPa and 649MPa in ultimate strength. All specimens are retrofitted with two plies combined with CFRP and GFRP laminates. The 100 mm long FBG sensor is installed at the position of main reinforcement with grip accessories as tested in the small-scale specimen CC-OA.

4.2 Results and discussion

4.2.1 Effects of strengthening length

The load-strain curves of the specimens with short strengthening lengths are shown in Fig. 5. These curves are comparable with Fig. 6(a) and (b). As shown in Fig. 5(a) and (b), the measured strains by the FBG sensor are much similar to those by the electric strain gages. Prior to peeling of at the end of retrofitting material, the strains of the FBG sensor are decreased. From this, peeling may be predicted by FBG sensor. From the curves, monitoring by FBG sensor may be applicable to the retrofitted beams with any FRP and strengthening length.

4.2.2 Effects of combination of retrofitting materials

The load-strain curves by combination of retrofitting materials are shown in Fig. 6. The strain tendency at each load step is much similar until failure although there are small differences. The strains at each load step by FBG sensor show much similar ones to those by electric gages at rebar. The strain by FBG sensor may be applicable to predict the structural condition without regard to FRP.

4.2.3 Effects of the levels of sustaining load

The load-strain curves of the specimens strengthened at different levels of sustaining load at strengthening are shown in Fig. 7. Two levels of sustaining load are selected. As shown in Fig. 7, the strains by FBG sensor show similar results to those by electric resistance gage without regard to different levels of sustaining load.

5. Conclusion

Independently of FRP combinations and pre-loading levels, strains measured by FBG sensor are similar to those by electrical resistance gage under low level of load. As the applied loads are increased, the measured strains tend to have different values. This is caused by cracks that have developed across the FBG sensor. The beams with short strengthening length show strain reversal in the load-strain curve prior to peeling at the curtailment of FRPs. From monitoring by FBG sensor, peeling and delaminating of FRP, may be predictable and retrofitting performance can be evaluated.

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