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Fiber optic smart monitoring of concrete beam retrofitted by composite patches

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Abstract. In order to extend the lifetime of buildings and civil infrastructure, patch type fibrous composite retrofitting materials are widely used. Retrofitted concrete columns and beams gain stiffness and strength, but lose toughness and show brittle failure. Usually, the cracks in concrete structures are visible to the naked eye and the status of the structure in the life cycle is estimated through visual inspections. After retrofitting of the structure, crack visibility is blocked by retrofitted composite materials. Therefore, structural monitoring after retrofitting is indispensable and self diagnosis method with optical fiber sensors is very useful. In this paper, we try to detect the peel out effect and find the strain difference between the main structure and retrofitting patch material when they separate from each other. In the experiment, two fiber optic Bragg grating sensors are applied to the main concrete structure and the patching material separately at the same position. The sensors show coincident behaviors at the initial loading, but different behaviors after a certain load. The test results show the possibility of optical fiber sensor monitoring of beam structures retrofitted by the composite patches.

Key words: fiber optic sensors; carbon sheet; repair; self diagnosis; delamination and self monitoring.

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1. Introduction

Patch type retrofitting composite materials are widely used for repairing civil infrastructure nowadays. There are several previous studies on strengthening effects of various kinds of composites (Garden *et al.* 1998, Lorenzis *et al.* 2001). Composite material increases load bearing capacity and confines crack openings. Fiber composites are several times stronger than ordinary repairing materials such as steels and have almost the same stiffness as steel. They are very effective for the repairing and retrofitting of reinforced concrete structures. They show elastic behavior up to near fracture and their specific gravity is much smaller than other repairing materials. Because the specific gravity is 1/5 of the specific gravity of steel, the fiber composites do not increase the dead load much and they are very easy to handle without special tools in very small working spaces. According to the locations of damage and the damaged conditions, we can increase or decrease the number of composite layers and control the load bearing capability of repaired structures.

For monitoring of the repaired structure with composite materials, optical fiber sensors are very convenient, because crack visibility is blocked by repair materials. The fiber sensors are very small and very similar to the fibers in the composite. They also have several merits such as electro-magnetic immunity, long signal transmission, good accuracy and multiplicity of one sensor line. Strain measurement technologies with fiber optic sensors have been investigated since 1980's (Lau *et al*. 2001, Mouring *et al*. 2001, Kim *et al*. 1993). We also investigated the possibilities of fiber optic sensor application in various fields such as composites, bridges, buildings and roads (Kim *et al*. 1996, 1997, Baek and Kim 1997). We expect that the fiber optic sensors replace electrical strain gauges. The commercial electric strain gauges show good stability and dominate the strain measurement market. However, they lack durability and long term stability for continuous monitoring of the structures. In order to apply the strain gauges, we only have to attach them to the surfaces of the structures. For optical fiber sensors, we can embed them inside the composites or interface between the composites and the concrete structure. We also can use various packages for evaluation of the structure (Kim *et al.* 1992, 1993). In this paper, we investigate the hybrid composites for repairing concrete and apply the fiber optic sensors to the reinforced concrete. We are trying find self diagnostic methods that will give an early warning of the separation of composites and the main structure, which is the most probable damage in retrofitted structures.

2. Principles of fiber optic sensors

Among typical fiber optic sensors, fiber Bragg grating sensors (FBGs) and fiber optic Fabry-Perot sensors are widely used. Fiber optic Fabry-Perot sensors are very sensitive but are very difficult to produce by automated mass production processes. Furthermore, their signal treatment is very complicated. On the other hand, fiber Bragg gratings can be produced by mass production equipment and they have very good reproducibility. Their signal processing is rather simple. Like many previous investigators, we choose FBGs as our structural monitoring sensors.

2.1 Strain measurement principle with fiber Bragg grating

Fiber Bragg gratings are produced by exposing ultraviolet laser through the phase mask which gives periodical patterns to the Ge doped core. As can be seen in Fig. 1, a broadband incident beam

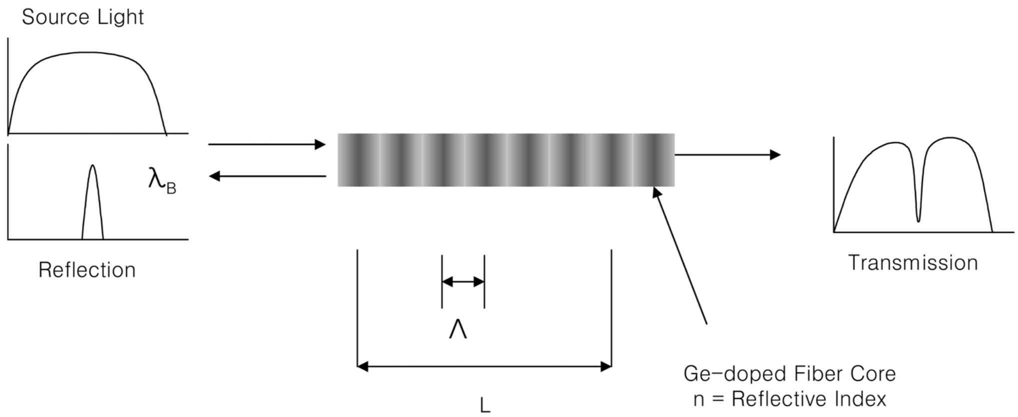

Fig. 1 Schematic diagram of FGB signal

is introduced to the grating and a specific narrow band wavelength beam is reflected. The wavelength of the reflected beam relates to the periodicity of the pattern in the core. Fig. 1 shows the schematic diagram of FBG. Only the part of the incident beam which satisfies the condition of Eq. (1) reflects from the FBG and rest of the incident beam is transmitted. We call the wavelength of the reflected beam, which is in Eq. (1), Bragg wavelength.

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

n : effective refractive index, Λ: grating period

Bragg wavelength which reflects from the grating is a function of the effective refractive index. Bragg wavelength is changed by temperature and strain variation. Therefore, we can measure the temperature and strain by measuring Bragg wavelength. The center wavelength shift of the grating according to applied strain change is described in Eq. (2) where P_e : photo-elastic constant, ε : applied strain to the grating

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

3. Evaluation of FBG sensors with steel reinforced concrete

3.1 Preparation of specimens

In order to characterize adhesion properties and the response of FBG sensors, steel reinforced concrete specimens with the dimensions $15 \times 25 \times 180$ cm are produced. The data from FBG sensors for applied tensile and compressive loads are compared to the electric strain gauges at the same location. The specifications and properties of the specimens are as shown in Table 1.

Table 1 Specification and material properties of test specimens

	Design purpose	Materials	
		Steel	Concrete
CTL I	Tensile strain	2@D13(Tension) 2@D10(Compression)	σ_{ck} = 270 kg/cm^2
CTL II	Compressive strain	2@D13(Tension) 2@D10(Compression)	σ_{ck} = 270 kg/cm^2

3.2 Testing procedure

In order to prevent breakage of the fiber optic sensors, two pieces of metal islands are attached to the specimen and the fiber sensor is attached to them. The gauge lengths of the sensors represent the distances between the two islands, which are 85 cm from the side of specimen and 75 cm from the bottom of the specimen. Strain gauges are attached at the locations that are the centers of the fiber sensors. To detect the compressive strain, the fiber sensor is stretched and prestressed by force. The responses of the sensors are observed while loads are applied by 4-point bending.

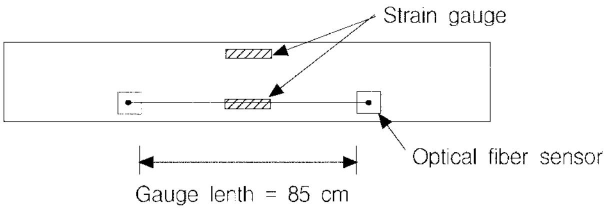

Fig. 2 Specimen for tensile test (CTL I)

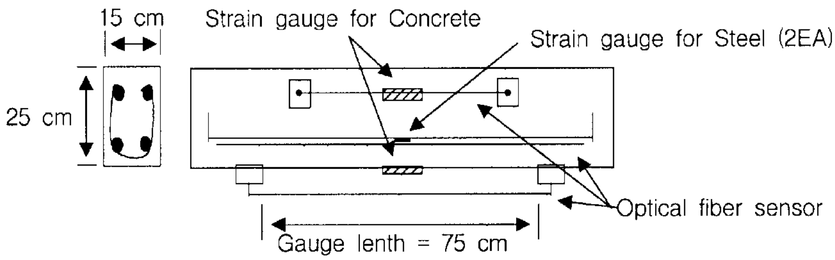

Fig. 3 Specimen for compressive test with embedded steel (CTL II)

3.3 Test results

Under cyclic loading up to 40% of the fracture strength, the optical fiber sensors in CTL I are almost identical to the strain gauges at the same location as shown in Fig. 4. Strain gauges show breakage due to cracking after a certain loading while fiber optic sensors show good responses as shown in Fig. 5. Fiber optic sensors show residual values after unloading while strain gauges cannot give any data due to failure (Fig. 6).

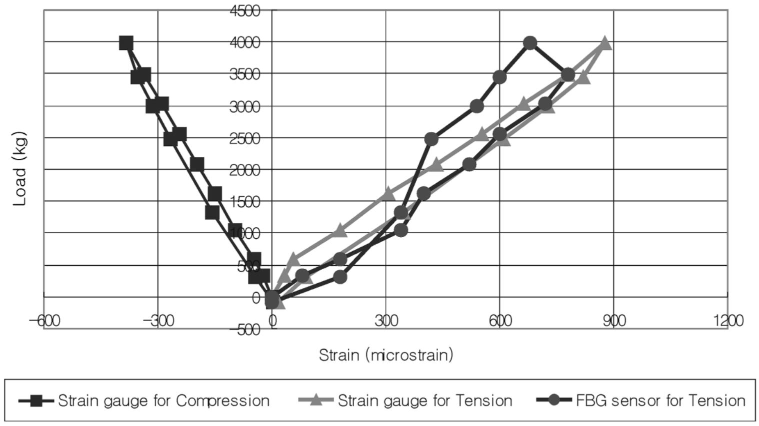

Fig. 4 Results from strain gauge & FBG sensor for tensile test (CTL I)

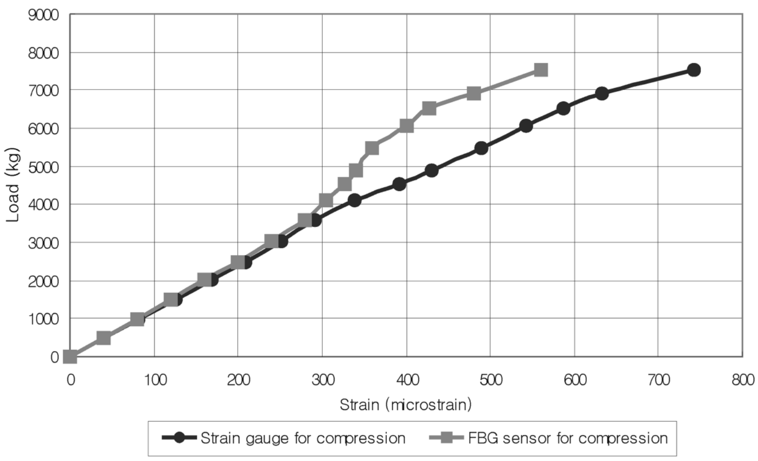

Fig. 5 Results from strain gauge & FBG sensor for compressive test (CTL II)

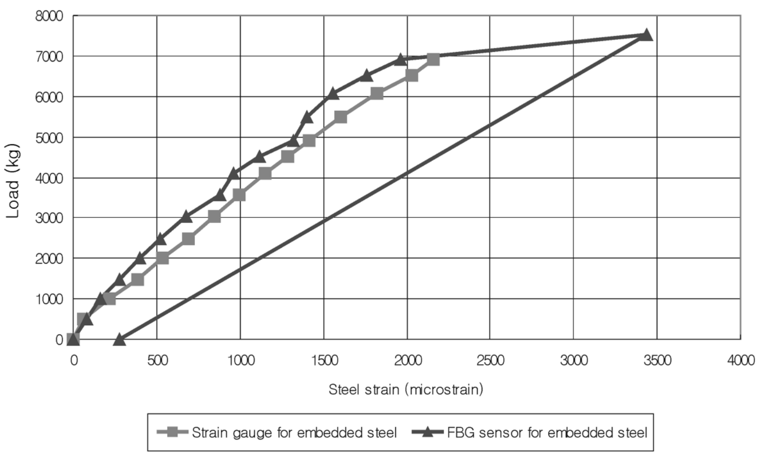

Fig. 6 Results from strain gauge & FBG sensor for embedded steel (CTL II)

4. Design and evaluation of retrofitting method using FBG sensors

4.1 Preparation of specimens

A 15 cm × 25 cm section of reinforced concrete beam with effective depth of 21 cm and 240 cm length was manufactured for bending tests as shown in Fig. 7. It was designed with a maximum ratio of reinforcement (ρ_{max} = 0.75, ρ_b = 0.01466), using compression bar of 2-D10, tension bar of 2-D13s, length 2.8 m, rectangular form double layered reinforced beam, the effective span length of which is 2.4 m. The composite sheets of 13 cm × 196 cm to retrofit the beam were applied to the structure while the distance between the two supporting points in the bottom is 196 cm. The distance between the two supporting points on the top of the specimen is 50 cm. Tests were performed with 4 point bending.

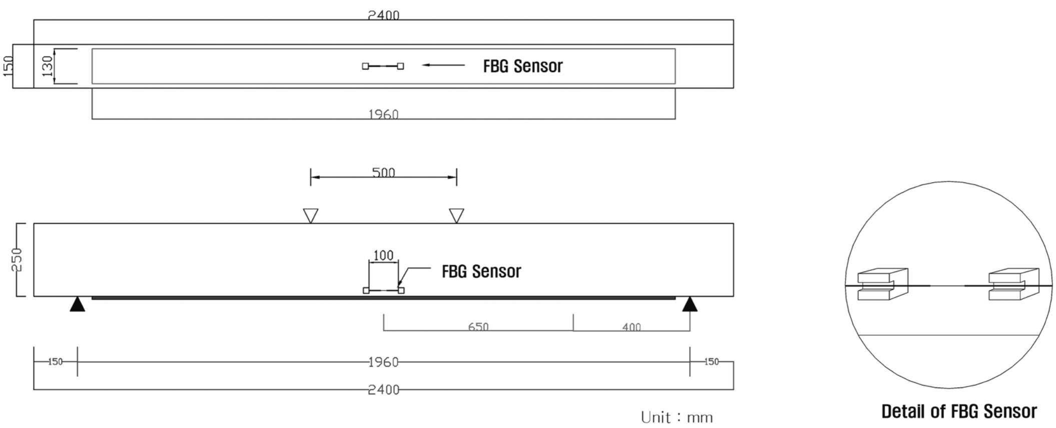

Fig. 7 Dimensions of bending test specimens and details of FBG sensors

4.2 Testing method

While carbon fiber has better performance characteristics than most other fibers, carbon fiber sheets are weak in fire. Glass fiber has fire protecting performance and less detachment than carbon fiber. Therefore, in case of reinforcement with a combination of these two fibers, reinforcement performance and the most efficient mixture of composite material was investigated. We try to find the most effective mixture of the retrofitting composite material by mixing glass fiber and carbon fiber (presented in Fig. 8). In this paper, bending tests of GCO (mixture of glass fiber and carbon fiber) and GGO (mixture of glass fibers) are conducted and new monitoring techniques are developed, which can give a warning of peel out at early stages. Peel out is a shortcoming of general retrofitting composite materials. The strain differences between the side and the bottom of reinforced concrete beam with retrofitting materials are compared. In the tests, as shown in Fig. 9, FBG sensors are protected by using small steel pipe in the interval of composite materials and also between reinforced concrete beams and retrofitting composite materials, then for the warning of peel out, monitoring of strain differences at that point is tried.

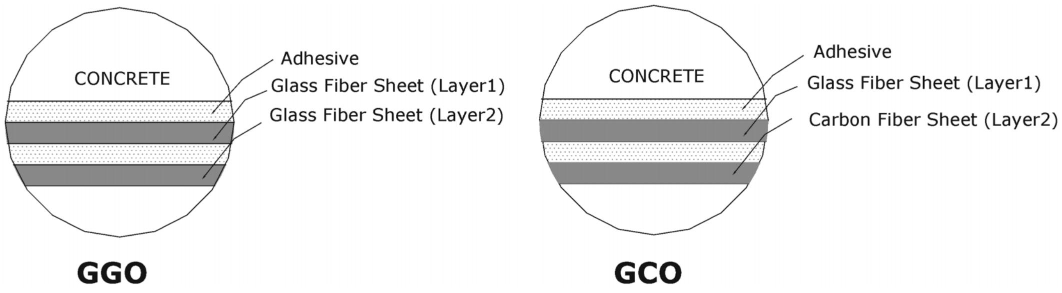

Fig. 8 Combinations of lay-ups in hybrid type repairing patch

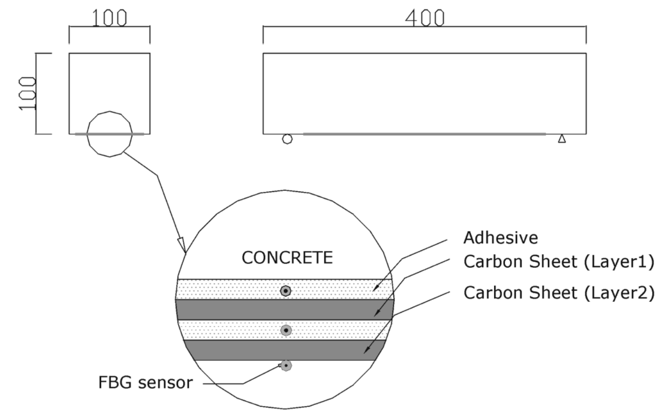

Fig. 9 Embedded FBG sensors between the lay-ups

4.3 Test results

In two cases of bending tests, it is estimated that GCO (Fig. 11) is more efficient than GGO (Fig. 10) because GCO of physically high strength has less danger of sudden brittle failure. As you see in Fig. 11, the curves show discontinuity points around the strain level of 1500 micro strain. The reason is that the carbon fibers have less elongation capability and higher strength than glass fibers. Therefore, we can give an alarm when carbon fibers break and we can prevent the brittle failure. Then, both GGO and GCO have the strain differences between the side and the bottom and these are proven to be effective monitoring of peel out effects.

The strains of side and bottom represent the strains of concrete material and repairing composite. The strain in concrete must be smaller than the strain of composite because the sensor in the concrete is closer to the central axis than the sensor in the repairing composite. However, the data in Figs. 11 and 12 show higher strain in concrete than the strain in composite sheets at the same load level. The difference in strain between concrete and composite becomes larger with increases in load increment. That means the shear between the concrete and the repairing composites becomes larger. Eventually, the structure has failure between concrete and composites as shown in Fig. 12.

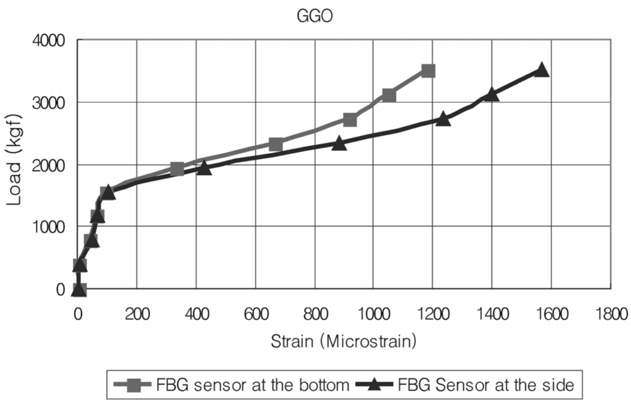

Fig. 10 Bending test result from the beam strengthened with two glass fiber sheets

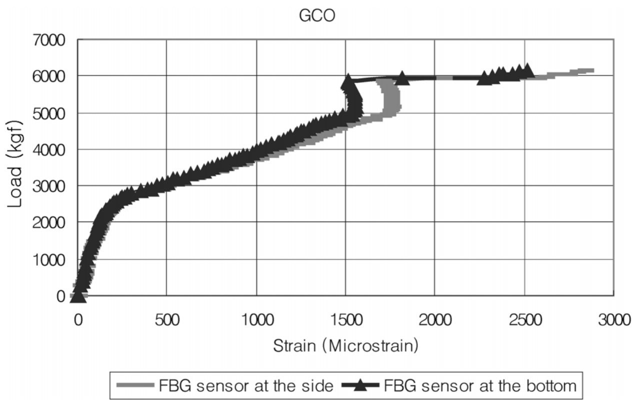

Fig. 11 Bending test result from the beam strengthened with one glass fiber sheet and one carbon fiber sheet

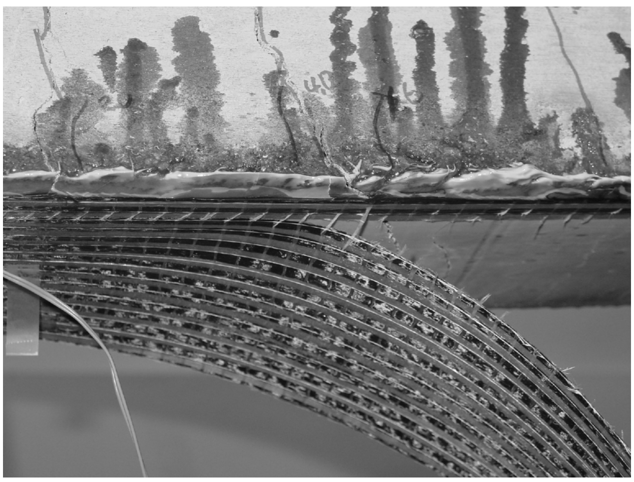

Fig. 12 A failure of the structure retrofitted by composite sheets

5. Conclusions

In this paper, experiments on concrete beams retrofitted by composite sheets are performed and during the experiment strain gauges and fiber optic sensors are applied. The data from optical fiber sensors are almost identical to those from the strain gauges. While strain gauges show breakage due to cracking after a certain loading, fiber optic sensors show good continuous responses without breakage. The fiber optic sensors even show residual values after unloading while strain gauges cannot give any data due to failure.

The fiber optic sensors in the specimen retrofitted by mixed composite with carbon and glass fibers show discontinuity points because the carbon fibers have less elongation capability than glass fibers. With this phenomenon, we can give an alarm when carbon fibers break and we can prevent the brittle failure.

The fiber optic sensor measuring technology can be applied to predict peel out effect for retrofitted structures. In particular, strain patterns of FBG sensor at the bottom of concrete and the carbon fiber sheet show coincident behaviors at the initial loading, but different behaviors after a certain load. The difference in strain between concrete and composite is the shear of the interface between concrete and the repairing composites. The shear between the concrete and the repairing composites increases after a certain load. Eventually, the structure has failure in the interface between concrete and composites. If we monitor the strain behaviors of main material and retrofitting material, we can monitor peel out effects.

Using these results, the warning of brittle failure and the time of additional retrofit can be estimated, and expenses can be reduced through regular diagnosis of structural safety for maintenance of structures. To establish more systematic and quantitative standards, it is clear that the advance of optical fiber measuring technology and accumulation of experimental sources of retrofitting composite materials is needed.

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References

Baek, S.H. and Kim, K.S. (1997), "Optical fiber monitoring system of bridge in Korea", *Proc. of the 1st Health Monitoring Workshop*, 555-563, Stanford Univ.

Garden, H.N., Quantrill, R.J., Hollaway, L.C., Thorone, A.M. and Parke, G.A.R. (1998), "An experimental study of the anchorage length of carbon fibre composite plates used to strengthen reinforced concrete beams", *Construction and Building Materials*, **12**, 203-219.

Kim K.S., Kollar, L. and Spring, G.S. (1993), "A model of embedded fiber optic Fabry-Perot temperature and strain sensors", *J. Composite Materials*, **27**, 1618-1662.

Kim, K.S., Ryu, J.U., Lee, S.J. and Choi, L. (1997), "In-situ monitoring of Sungsan Bridge in Han River with a optical fiber sensor system", SPIE, **3043**, 72-76.

Kim, K.S., Breslauer, M. and Spring, G.S. (1992), "The effect of embedded sensors on the strength of composite laminates", *J. Reinforced Plastics and Composites*, **11**, 949-958.

Kim, K.S., Segall, A. and Springer, G.S. (1993), "The use of strain measurement for detecting delamination in composite laminates", *Compos. Struct.*, **23**, 75-84.

Kim, K.S., Yoo, J.W., Kim, S.K. and Kim, B.Y. (1996), "Embedded intrinsic Fabry-Perot optical fiber sensors in the cement concrete structure", SPIE **2718**, 218-231.

Lau, K.T., Yuan, L., Zhou, L.M., Wu, J. and Woo, C.H. (2001), "Strain monitoring in FRP laminates and concrete beams using FBG sensors", *Compos. Struct.*, **51**, 9-20.

Lorenzis, L.D., Miller, B. and Nanni, A. (2001), "Bond of fiber-reinforced polymer laminates to concrete", *ACI Mat. J.*, May-June.

Mouring, S.E., Barton, O., Academy, N. and Simmons, D.K. (2001), "External retrofit of R/C beams using carbon fiber reinforced polymer laminates", Stanford Univ, USA. Structural Faults & Repair conference.