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LOAD IDENTIFICATION OF FLEXURAL RC STRUCTURES USING DISTRIBUTED FBG SENSING SYSTEM

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Abstract

In this paper, an experimental investigation for a flexural reinforced concrete (RC) beam based on distributed long-gage fiber optic sensors and strain gauges were carried out. Furthermore, an extended numerical study to identify the load level of the RC structures using static strain measurements from long-gage fiber Bragg grating (FBG) sensors or distributed strain gauges for structural health monitoring (SHM) was performed. A method of load level identification of flexural RC Structure from distributed strain measurements was proposed and verified here.

INTRODUCTION

Because of the advanced researches on health monitoring or maintenance for large scale civil engineering structures such as bridge, dam or tunnel etc. , various sensing systems are created and developed by researchers. Regarding the on-going development of available fiber optic sensing techniques, FBG sensor in nature holds the excellent ability to provide a measurement having higher precision and measuring stability. But one critical problem in this sensing technique lies in that the inherent gauge length of most commercially available FBG is on the order of a few millimeters and still difficult for distributed measurements. This research uses long-gage FBG sensor of which the effective sensing gauge length can be extended to several centimeters or meters through special packaging and broadening its application in civil engineering structures as a kind of distributed strain sensing technique by connecting a group of long-gage sensors in series.

As sensing systems were installed on the structures, large quantities of live data were obtained such as strain, deformation, velocity, acceleration etc. from monitored structures. Therefore, it becomes much more important for the managers of structure health monitoring to translate those live data to an identifiable parameter for the evaluation of

those structures. In this study, an experimental investigation for a flexural RC beam based on distributed long-gage fiber optic sensors and strain gauges were carried out. Furthermore, an extended numerical study to identify the load level of the RC structures using static strain measurements from long-gage FBG sensors or distributed strain gauges for SHM was performed. A method of load level identification of flexural RC Structure from distributed strain measurements was proposed and verified here.

EXPERIMENTAL INVESTIGATION

Fig.1 shows the outline of an experimental investigation. The specimen is a RC beam with rollers supported at two points. The load applied by loading machine is equivalently split into two parts, landing at two points with a distance of 600mm from each support. The progressively increasing load is applied continuously up to failure.

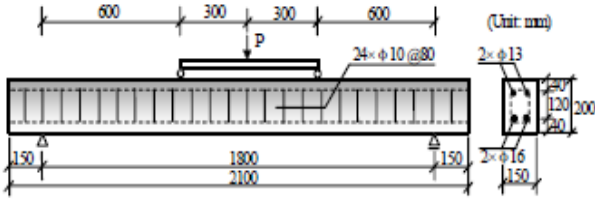


Fig. 1 Outline of RC beam

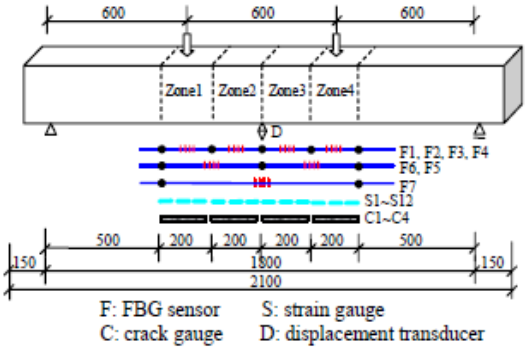


Fig.2 Arrangement of sensors

Fig.2 shows the detail of sensors placement. Four FBG sensors of 200mm gauge length (F1, F2, F3 and F4) are arranged onto the bottom surface of the specimen. The other two kinds of FBG sensors with respective gauge length of 400mm (F5, F6) and 800mm (F7) and a set of distributed traditional foil strain gauges (from S1 to S12) are attached in parallel.

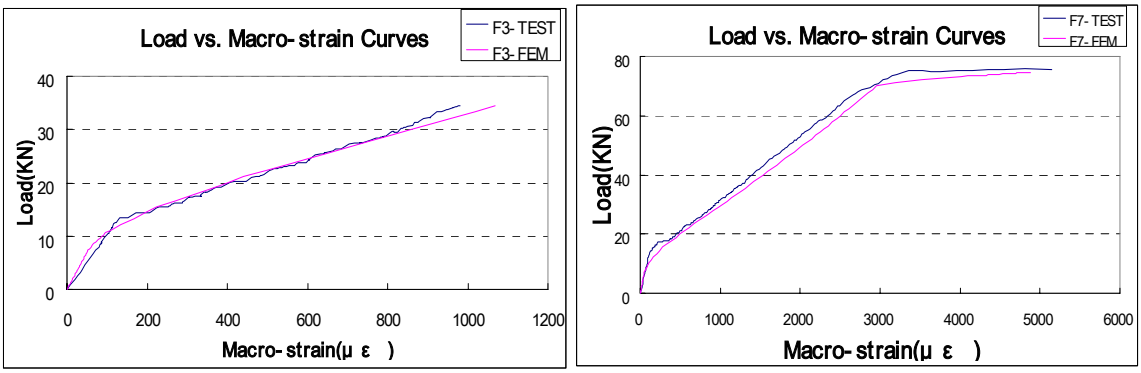


Fig. 3 Comparison of experimental results from FBG sensors and FEM analysis results

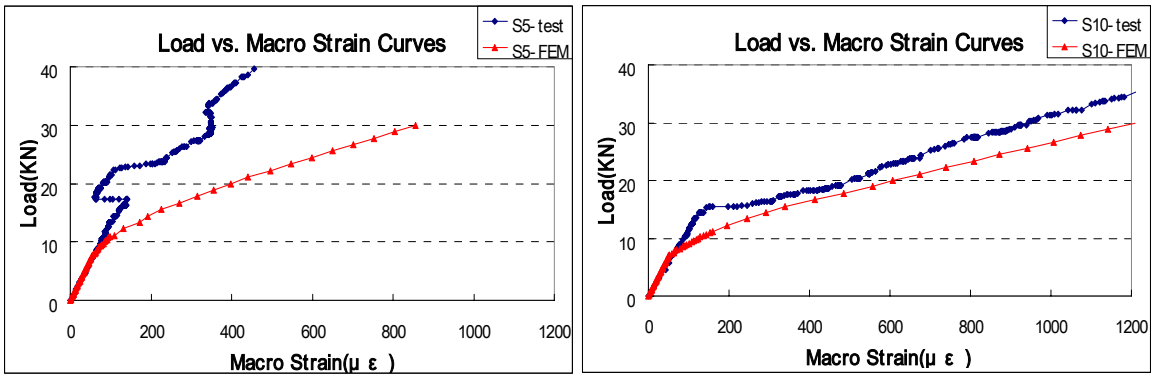


Fig. 4 Comparison of experimental results from strain gauges and FEM analysis results

Fig. 3 and Fig. 4 show a part of the experimental results and their comparisons with FEM analysis results[2]. It was confirmed that the experiment is finely implemented and the results are reasonable by means of comparison with the results using FBG sensors and using strain, displacement or crack gauges[1], also by means of a verification using nonlinear FEM analysis[2]. It is shown here that the strains measured by FBG sensors and the strains measured by strain gauges own different features respectively. Because the measured strain using FBG sensor is a macro strain within the length of fiber, it shows the macro behavior of concrete structure. Meanwhile, because the measured strain using traditional foil strain gauge is a micro strain at a point of structure, it shows the micro behavior of concrete structure. After concrete cracks, the measured strain using strain gauges is changing severely as shown in Fig. 4 compared with the results of FEM analysis, which means that the micro behavior of concrete structure after crack evaluated by traditional foil strain gauge is out of the range of theory of Continuum Mechanics. That is the upfront theoretical reason why the long-gage FBG sensors performed better than traditional foil strain gauges in the measurement of RC structures which was one of the main conclusions drawn at the end of this paper.

A METHOD OF LOAD IDENTIFICATION

The load identification scheme is illustrated in **Fig.5**. Here the load to be identified is the average moment for a section of structure shown in Fig.6. Suppose the structural physical parameters including material properties (concisely MP) and geometric properties (concisely GP) are known, the average curvature can be calculated based on the measured macro-strains at the bottom of the beam. Then from Equation (1) to Equation (10) based on the assumption of plane section, the average moment can be identified

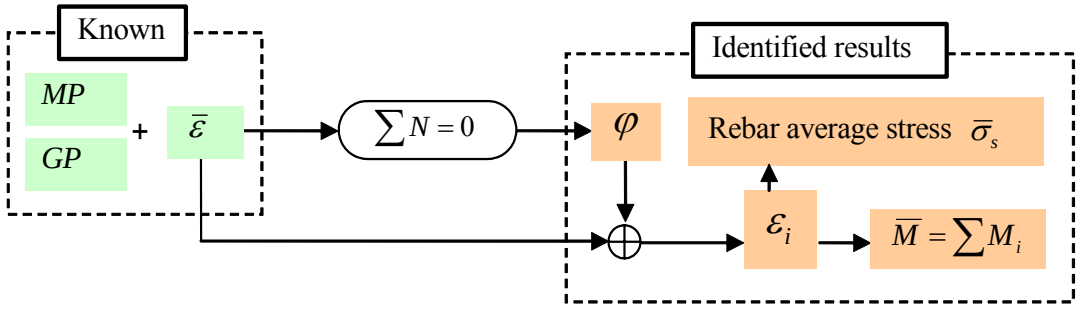


Fig. 5 Load identification scheme

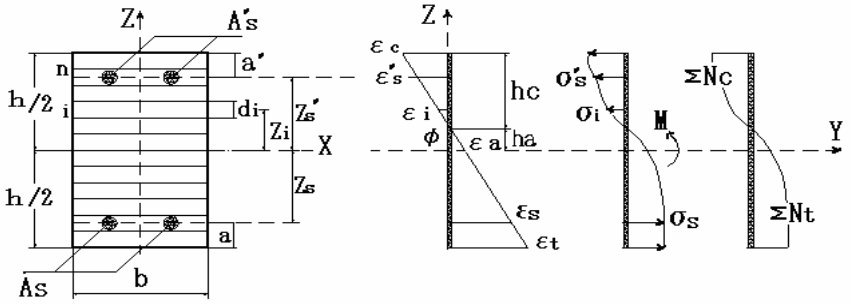


Fig.6 Section of fiber model

$$h_a + h_c = h/2 \tag{1}$$

$$\varphi = \varepsilon_t/(h/2 + h_a) = \varepsilon_a/h_a = \varepsilon_c/h_c \tag{2}$$

$$\varepsilon_s = \varepsilon_t(Z_s + h_a)/(h/2 + h_a) \tag{3}$$

$$\varepsilon'_s = \varepsilon_t(-Z'_s + h_a)/(h/2 + h_a) \tag{4}$$

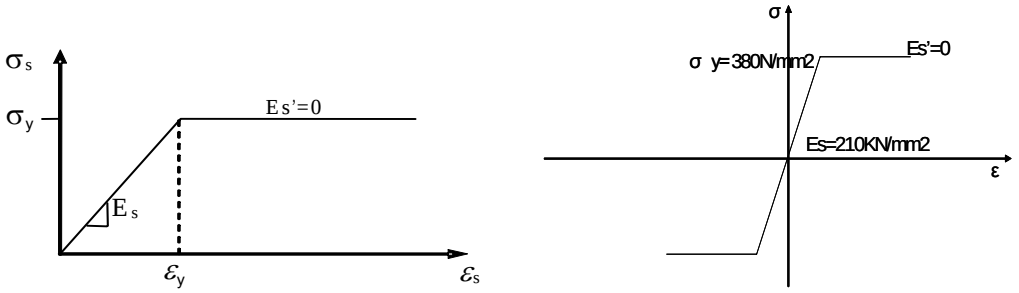


Fig.7 The stress-strain relationship for reinforcements

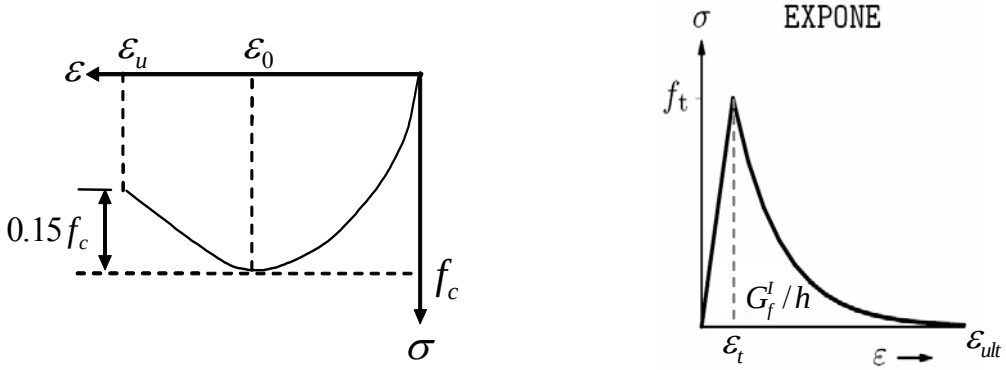


Fig.8 The stress-strain relationship for concrete

$$\sigma = \begin{cases} f_c\left[\dfrac{2\varepsilon}{\varepsilon_0} - \left(\dfrac{\varepsilon}{\varepsilon_0}\right)^2\right] & \text{if } \varepsilon_0 < \varepsilon \le 0 \\ f_c\left[1 + \dfrac{0.15(\varepsilon - \varepsilon_0)}{\varepsilon_0 - \varepsilon_u}\right] & \text{if } \varepsilon_u \le \varepsilon < \varepsilon_0 \\ 0 & \text{if } \varepsilon \le \varepsilon_u \end{cases} \tag{5}$$

$$\begin{cases} \sigma = E \cdot \varepsilon & \text{if } \varepsilon \le \varepsilon_t \\ \dfrac{\sigma}{f_t} = \left(1 + \left(c_1 \dfrac{\varepsilon - \varepsilon_t}{\varepsilon_{ult} - \varepsilon_t}\right)^3\right) \exp\left(-c_2 \dfrac{\varepsilon - \varepsilon_t}{\varepsilon_{ult} - \varepsilon_t}\right) & \\ \quad - \dfrac{\varepsilon - \varepsilon_t}{\varepsilon_{ult} - \varepsilon_t}(1 + c_1^3)\exp(-c_2) & \text{if } \varepsilon_t < \varepsilon \le \varepsilon_{ult} \\ \sigma = 0 & \text{if } \varepsilon > \varepsilon_{ult} \end{cases} \tag{6}$$

Where $\varepsilon_{ult} = \varepsilon_t + 5.136 \dfrac{G_f^I}{h f_t}$

Tensile fracture energy: $G_f^I = 100 N/m$

C_1=3, C_2=6.93.

$$\sum N_c = \sigma'_s A'_s + \sum \sigma_{ci} A_i \tag{7}$$

$$\sum N_t = \sigma_s A_s + \sum \sigma_{ti} A_i \tag{8}$$

$$\sum N_c + \sum N_t = 0 \tag{9}$$

$$\sum M = \sum_{i=1}^{n} \sigma_i A_i Z_i + \sigma'_s A'_s \left(\frac{h}{2} - a'\right) + \sigma_s A_s \left(\frac{h}{2} - a\right) \tag{10}$$

Fig.9 shows a method of load identification from identified moment distribution using above scheme. The moment distribution $M_1, M_2, \ldots M_i, \ldots M_n$ caused by P_1, P_2,……, P_i,……, P_n can be expressed as a sum of $\boldsymbol{M_{i,j}}$ caused by P_i shown in Equation (11). In view of the classic bending theory based on plane section assumption, it has linear relationship between $\boldsymbol{M_{i,j}}$ and P_i, so that Equation (11) can be rearranged as Equation (12), where $\alpha_{i,j}$ is a known parameter which can be calculated by the position of load.

Using Equation (12), the load distribution P_1, P_2,…, P_i,……, P_n can be determined by the identified moment distribution.

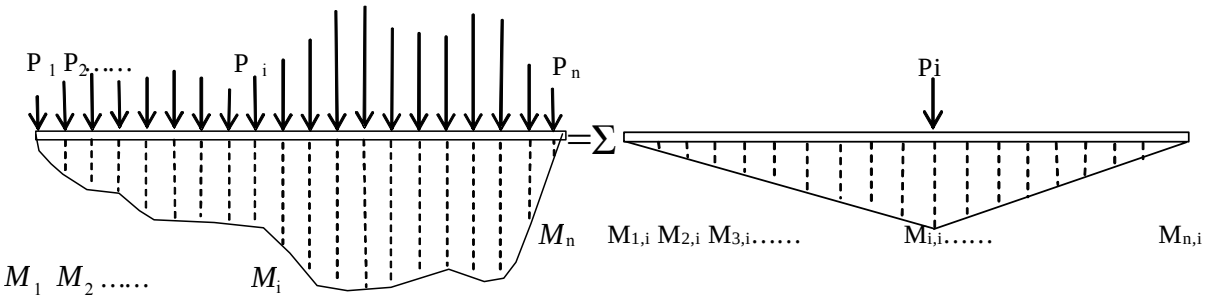


Fig.9 Load distribution identification

$$\begin{cases} M_{1,1}+M_{1,2}+M_{1,3}+.....+M_{1,j}+....M_{1,n}=M_1 \\ M_{2,1}+M_{2,2}+M_{2,3}+.....+M_{2,j}+....M_{2,n}=M_2 \\ \quad \ldots\ldots \\ M_{i,1}+M_{i,2}+M_{1,3}+.....+M_{i,j}+....M_{i,n}=M_i \\ \quad \ldots\ldots \\ M_{n,1}+M_{n,2}+M_{n,3}+.....+M_{n,j}+....M_{n,n}=M_n \end{cases} \tag{11}$$

Where

$$M_{1,1}=\alpha_{1,1}\cdot P_1;.....;M_{i,1}=\alpha_{i,1}\cdot P_1;.....;M_{n,1}=\alpha_{n,1}\cdot P_1$$

$$M_{1,j}=\alpha_{1,j}\cdot P_j;.....;M_{i,j}=\alpha_{i,j}\cdot P_j;.....;M_{n,j}=\alpha_{n,j}\cdot P_j$$

$$M_{1,n}=\alpha_{1,n}\cdot P_n;.....;M_{i,n}=\alpha_{i,n}\cdot P_n;.....;M_{n,n}=\alpha_{n,n}\cdot P_n$$

$$\begin{cases} \alpha_{1,1}\cdot P_1+\alpha_{1,2}\cdot P_2+.....+\alpha_{1,j}\cdot P_j+.....+\alpha_{1,n}\cdot P_n=M_1 \\ \alpha_{2,1}\cdot P_1+\alpha_{2,2}\cdot P_2+.....+\alpha_{2,j}\cdot P_j+.....+\alpha_{2,n}\cdot P_n=M_2 \\ \quad \ldots\ldots \\ \alpha_{i,1}\cdot P_1+\alpha_{i,2}\cdot P_2+.....+\alpha_{i,j}\cdot P_j+.....+\alpha_{i,n}\cdot P_n=M_i \\ \quad \ldots\ldots \\ \alpha_{n,1}\cdot P_1+\alpha_{n,2}\cdot P_2+.....+\alpha_{n,j}\cdot P_j+.....+\alpha_{n,n}\cdot P_n=M_n \end{cases} \tag{12}$$

MOMENT IDENTIFICATON AND ACCURACY EVALUATION

The comparisons of experimental moment distribution and identified moment distribution by different sensing system are shown in the following figures from Fig. 10 to Fig. 14. Because two equivalent loads were performed on the middle span of bending beam as shown in Fig. 2, the loading moment distributed equivalently along that loading span (see test loading moment in the figures). The horizontal axis of those figures shows the loading span position of the specimen. The comparisons were performed in different load levels such as before crack (M=1710 KN□mm), cracking (M=4680 KN□mm & M=6030 KN□mm), after crack (M=8160 KN□mm & M=10350 KN□mm) respectively.

Fig. 15 gives the changing curves for ratios of averaged identified moment from the measurements by FBG sensors and strain gauges vs. test loading moment. Table 1 gives an accuracy evaluation for the moment identification using strain measurements from long-gage FBG sensors and distributed strain gauges.

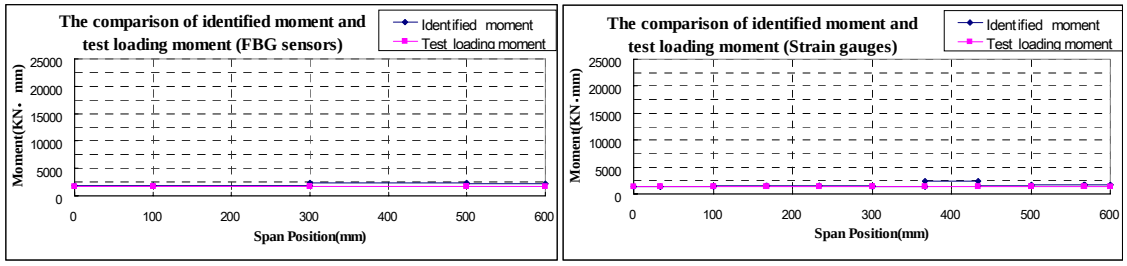


Fig. 10 Comparisons of experimental moment distribution and identified moment distribution by FBG sensors' measurement and strain gauges' measurement(M=1710 KN□mm)

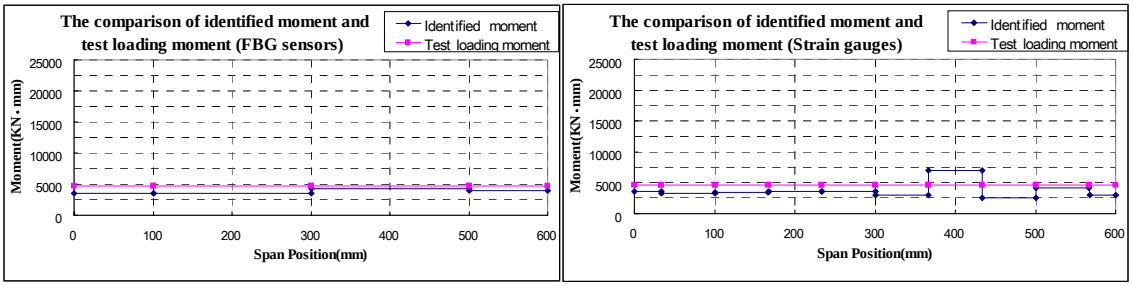


Fig. 11 Comparisons of experimental moment distribution and identified moment distribution by FBG sensors' measurement and strain gauges' measurement(M=4680 KN□mm)

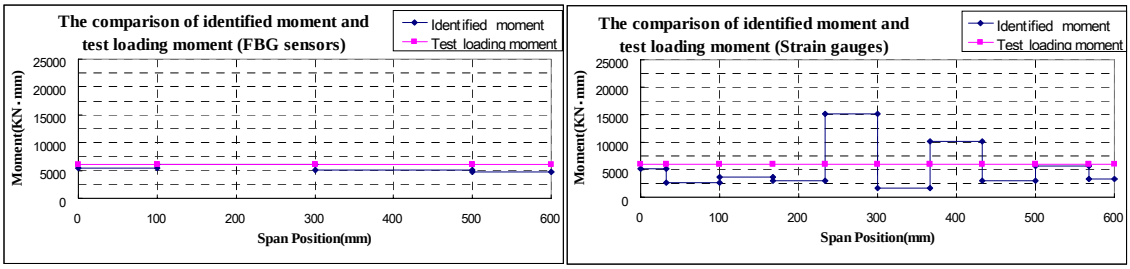


Fig. 12 Comparisons of experimental moment distribution and identified moment distribution by FBG sensors' measurement and strain gauges' measurement(M=6030 KN□mm)

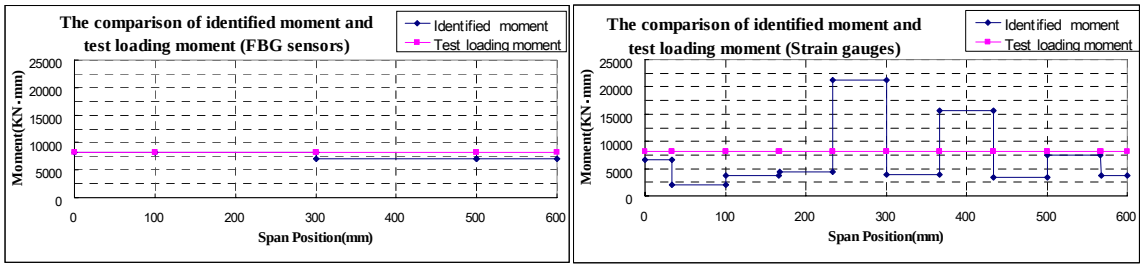


Fig. 13 Comparisons of experimental moment distribution and identified moment distribution by FBG sensors' measurement and strain gauges' measurement(M=8160 KN□mm)

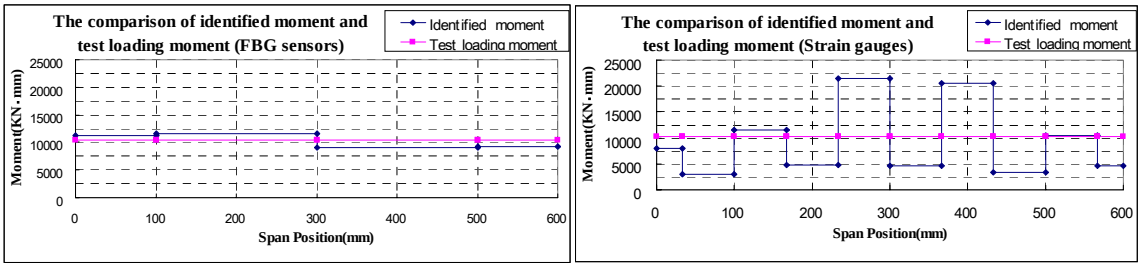


Fig. 14 Comparisons of experimental moment distribution and identified moment distribution by FBG sensors' measurement and strain gauges' measurement(M=10350 KN□mm)

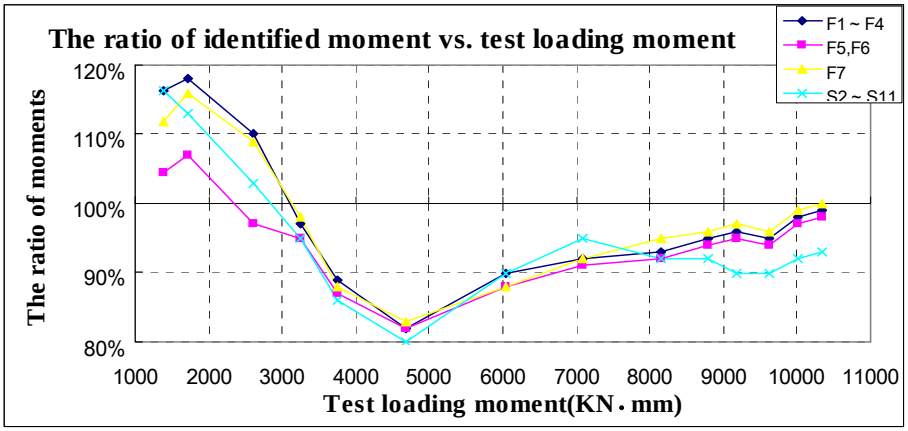


Fig. 15 The ratio of averaged identified moment vs. test loading moment

Some basic features about the results of loading moment identification by proposed method can be drawn from above comparisons.

(1) The dispersion of identified result by FBG sensors is relatively small. Furthermore, the identified moments by FBG sensors are consistent well with the test loading moments.

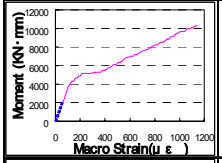
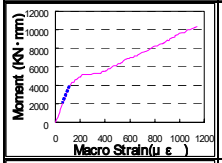
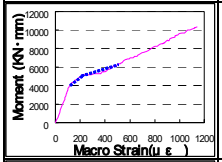
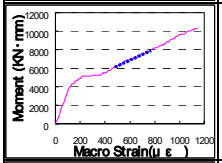
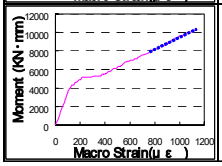
(2) If mean values of identified moments by FBG sensors or strain gauges along loading span are taken respectively, both averaged values are coincided well with the test loading moments.

(3) As shown from Fig. 10 to Fig. 14, because the dispersion of identified results by traditional foil strain gauges is very large, it is not recommendable to identify load by strain gauges. If only measurements by strain gauges can be obtained, using the mean value of a certain length of structure to identify load is somewhat effective to improve the accuracy of identification.

(4) The stiffness of specimen is changed when test load moment is about 5000 KN□mm. The accuracy of identification by both FBG sensors and strain gauges becomes relatively coarse around this changing time. Because the stiffness changing of real structure is a transient process which rarely can be measured by any sensing system, this feature of a little coarse accuracy almost has no influence on application of proposed identification method.

(5) After cracking, the accuracy of identified results by FBG sensors is much better than that by strain gauges even though the mean value of strain gauges' measurements is compared.

Table 1 Accuracy evaluation for the moment identification using the measurements from FBG sensors and distributed strain gauges

State of structure	By strain gauges		By FBG sensors	
	Difference from test loading	Dispersion of identified results	Difference from test loading	Dispersion of identified results
	10%～20%	small	0%～20%	small
	0%～10%	middle	0%～10%	small
	10%～20%	large	10%～20%	small
	5%～10%	large	5%～10%	small
	10%	large	0%～5%	small

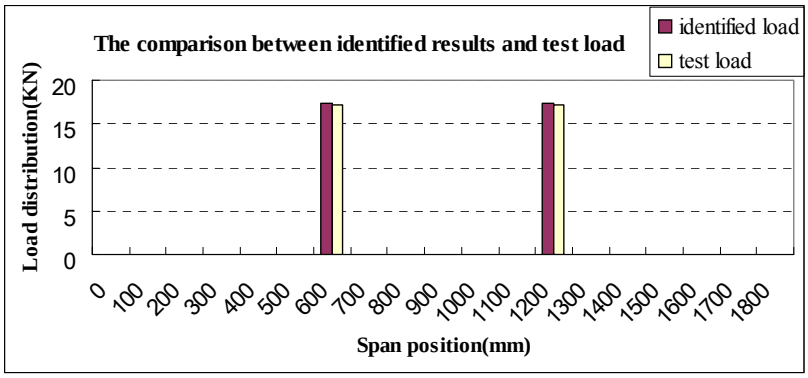
According to above discussions focused on the accuracy of identification of test loading moment by FBG sensing system and strain gauge sensing system, we can conclude that distributed FBG sensing system is really suitable for load identification of RC structure since it gives good accuracy of identification in both elastic range and failure zone besides the dispersion of identified results is small.

RESULT OF LOAD IDENTIFICATON

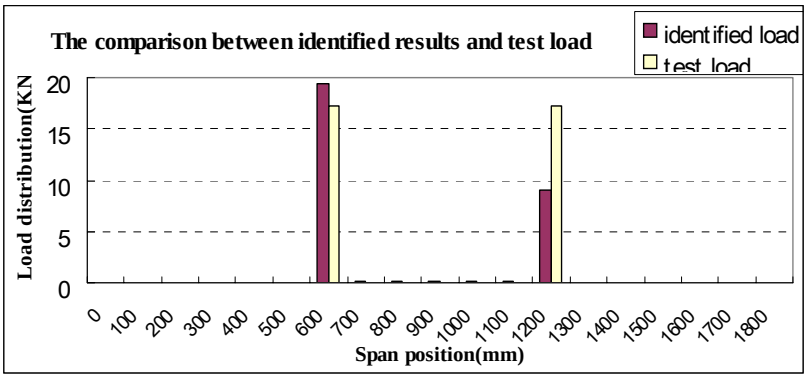
As an application using the proposed Equation (12) to identify the real load on structure, simple verification to identify the real load level and it distribution from identified load moment by FBG sensors for RC specimen of the experiment was performed here. Table 2 and Fig. 16 show the results of the identification and their comparisons with test load.

Table 2 Comparison of identified load by the measurements of FBG sensors and test load

Test loading moment(KN· mm)		Test load (KN)	Fiber F7		Fiber F5～F6		Fiber F1～F4	
			Identified load(KN)	Ratio with test load	Identified load(KN)	Ratio with test load	Identified load(KN)	Ratio with test load
Before crack	3240.0	10.8	10.542	97.6%	10.238	94.8%	10.542	97.6%
After crack	9630.0	33.0	30.906	96.3%	30.213	94.1%	30.788	95.9%
After crack	10350.0	34.5	34.598	100.3%	33.681	97.6%	33.948	98.4%



(a) The identified loads by fiber 7



(b) The identified loads by fibers F1 to F4

Fig. 16 Results of load identification by FBG measurements and their comparisons with test load

It is obvious that proposed method gives a good identification of both load level and load distribution for the flexural RC structure. It is also can be seen that accuracy of identification by longer fiber is better than that of shorter ones in this experiment.

It shows almost same accuracy between load level identification and loading moment identification by measurements of distributed FBG sensors.

It is also verified that identified moment results by traditional foil strain gauges can not be applied to load level identification because of their large dispersion.

CONCLUSIONS

In this paper, a method of load level identification of flexural RC Structure from distributed strain measurements was proposed and verified by means of an experimental investigation for a flexural RC beam based on distributed long-gage fiber optic sensors and strain gauges. Furthermore, a detail comparison and discussion for the accuracy of identifications by the measurements from long-gage fiber Bragg grating sensors or distributed strain gauges was performed.

Main conclusions about the application of proposed method of load identification can be drawn as follows.

(1) Proposed method gives a good identification of both load level and load distribution for the flexural RC structure.
(2) Distributed FBG sensing system is suitable for load identification of RC structure since it gives good accuracy of identification in both elastic range and failure zone.

(3) Because the dispersion of identified results by traditional foil strain gauges is very large, it is not recommendable to identify load by strain gauges. If only measurements by strain gauges can be obtained, using the mean value of a certain length of structure to identify load is a little effective to improve the accuracy of identification.

It is known that not enough researches for load identification by FBG sensors' measurement were accumulated till now, many further studies are necessary to be done in the near future by means of this kind of experiment and numerical approach. Such works may include the investigations of technique to identify the distribution of complicated load, the identification method for dynamic load, etc.

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2. Kejian YANG, Hideaki ARAKI, Akito YABE, Zhishen WU, Suzhen LI□The optimum length of long-gage FBG sensors for structural health monitoring of flexure RC members□The Proceeding of 4th China-Japan-US Symposium on Structural Control and Monitoring Oct.16-17, 2006