Experimental Study on Measurement of Strain Distribution on Simply Supported Steel Beam Using FBG Strain Sensors

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ABSTRACT

Monitoring of individual member is necessary and important in light of structural safety especially in building structure. To obtain information on health status of a member, the critical process is to find the maximum stress or strain which can be compared with allowable stress or stiffness through design codes. This means a proper data processing must be included when monitoring members. Thus, experimental study for measurement of strain distribution from scattered and limited data is presented in this research to determine accuracy and possibility for estimating strains which were not measured. The analytical (mechanical) and approximate (numerical) approaches are adopted as the means of estimation.

INTRODUCTION

As time passes, fatigue is accumulated on the structure and it goes through the process of aging. It is even exposed to unexpected loads sometimes. Therefore, the life-safety of the building can be guaranteed through periodic assessment of the performance and the measure according to it. Moreover, as structural health is directly related to the financial value, research on the Structural health monitoring (SHM) was conducted actively, and several countries carried out SHM targeting various different structures in practice[1,2]. In SHM in respect of member unit, judgment of the structural health is initiated by comparing and assessing the maximum stress of each structural member with allowable stress of the material. If the maximum stress is bigger than allowable stress, it means the structural safety is under a threat [3].

As Fiber Optic Sensors (FOS), which supplemented the weakness of existing electric signal based sensors, are evaluated as the reasonable alternative, many researches and applications of SHM utilizing the Fiber Optic Sensor were carried out. In SHM utilizing the Fiber Optic Sensor, the status of the structure is mostly

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comprehended by measuring strain and FBG(Fiber Bragg Grating) strain sensor is most widely in use currently. Especially, since FBG strain sensor is multiplexing available and in addition, there is almost no loss during the transmission process, it is suitable to compose the system with multiple sensors. Therefore it would be easy to apply a number of sensors on a single member if necessary [4,5]. This characteristic is a great strength of FBG in the member level monitoring thus FBG strain sensor was selected as the strain measurement sensor for the experiment in this research.

However, Because the measured value does not directly display the stress level of the member, the maximum strain (or maximum stress) should be drawn through the measured data [6]. In some circumstances, an exact stress status of the member should be figured by applying multiple sensors. According to this, this paper has carried out an experimental study on the accuracy and possibility of estimation of strain distribution through the measured value as a basic study to estimate the maximum stress of the member. Analytical and approximate methods to estimate the strain distribution using the data measured by the FBG strain sensors at arbitrary locations on simply supported steel beam were conducted and the accuracy and possibility of the estimation were studied through two-point concentrated loading experiment. Both approaches vary in application whether the rest of load information except the magnitude (e. g, load type, loading point) of the load applying to the targeted beam is available or not.

FBG STRAIN SENSOR

FBG sensor is realized by utilizing Bargg grating formed inside the optical fiber. Bragg grating is a type of interference fringe being formed when the phase mask, which is the diffractive optical element included in inside of optical fiber, is being exposed to ultraviolet rays. If the broadband light source collide against the Bragg grating, a component satisfying the relationship with the Bragg wavelength (l_B) has a characteristic of being reflected. The principle of FBG sensor is utilizing the character of Bragg grating being altered by the influence from change of temperature and pressure, and elongation. The change of Bragg wavelength can be figured out by detecting the change of light wavelength being returned after it projecting the Bragg grating then reflected and through this finding the strain can be figured. The characteristics of FBG sensor is displayed as Table 1.

Table 1. Characteristics of FOS and FBG sensor.

Fiber Optic Sensors (VS conventional sensors)	FBG sensors (VS other FOS)
Immunity to EMI	Low cost
Light weight, small dimension	Good linearity
Single end connection	Wavelength multiplexing capacity
Excellent resolution and range	Resistance to harsh environments
Water and corrosion resistance	

ANALYTICAL APPROACH

This chapter will present the analytical approach to estimate the strain distribution of a member when the strain was measured at arbitrary location of simply supported linear-elastic beam by FBG sensor but the information on the applied load except the magnitude is available. Multi-load is regarded as a sum of multiple single load according to the principle of superposition. From this finding, estimation of strain distribution on multi-load can be figured by utilizing superposition on estimated strain distribution curve on the beam which created the elastic deformation by a single load. Mathematically the minimum number of sensors required for the estimation is equal to the number of applied loads. Ultimately, the maximum strain on the targeted beam can be found through the estimated strain curve. In this approach, if values from structural analysis are completely identical to the measured values, error of the estimation will become zero. But, resulting completely identical values is difficult due to error of the sensors and environmental factors.

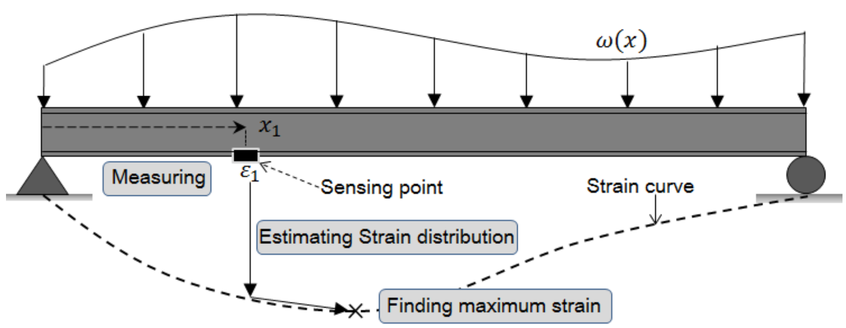


Figure 1. Measuring strains and Estimating maximum strain.

Strain distribution under single-loading condition

The minimum number of sensor required for a single load is one. If the sensor is installed on certain location except the spot where the moment becomes zero due to the load, the estimation of strain is possible. This relationship can be drawn from the relation between moment and strain. If a certain load ω is applied on the beam, moment $M(x)$ will be created and the relation between the strain and moment at the location where the distance is x far from the ends is given by the following equation (1).

$$\varepsilon(x) = \frac{M(x)}{EZ} = f(x, \omega, L, a, E, Z) \tag{1}$$

Where ω is magnitude of applied load, a is the location of the load, L is the length of the beam, and E and Z are each elastic modulus and section modulus. After the estimated value of strain (x_1, ε_1) is substituted into the equation (1) and it is being arranged for ω, it will be written as

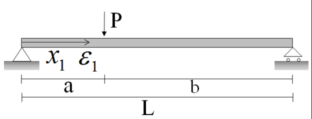
$$\omega = g(x_1, \varepsilon_1, L, a, E, Z) \tag{2}$$

As equation (2) is re-substituted to equation (1), the approximate calculation of strain can be generalized as follow;

$$\varepsilon(x) = f(x, x_1, \varepsilon_1, L, a) \tag{3}$$

The values ω, E, Z , which are parameters in equation (1), are being cancelled. When the strains are estimated, the magnitude of the load, section properties, and actual value of elastic modulus are difficult to figure out. Therefore, the distribution of strain can be assumed with these details as an exemption. Table 2 displays the example of analytical model for estimated strain distribution under the concentrated loading.

Table 2. example of estimated strain distribution.

Loading condition	Number of sensor	Sensing location	Estimation of strain distribution $\varepsilon(x)$	
			Estimating location	Estimation formula
	1	$0 < x_1 \le a$	$0 < x \le a$	$\varepsilon(x) = \frac{\varepsilon_1}{x_1} x$
			$a \le x < L$	$\varepsilon(x) = \frac{\varepsilon_1}{x_1}\frac{a}{b}(L-x)$
		$a \le x_1 < L$	$0 < x \le a$	$\varepsilon(x) = \frac{\varepsilon_1}{L-x_1}\frac{b}{a} x$
			$a \le x < L$	$\varepsilon(x) = \frac{\varepsilon_1}{L-x_1}(L-x)$

Strain distribution under multi-loading condition

General load can be assumed as a sum of several individual loads. According to the type and number of individual loads composing the combined load, the number of combination can be considerably large. Though, the estimation of the combined load can be figured as a simple process by applying the weight concept through the principle of superposition. In case of two-point concentrated loading in this experiment, equation for estimation is given as follow;

$$\varepsilon(x) = a\varepsilon^{P_1}(x) + (1-a)\varepsilon^{P_2}(x) \tag{4}$$

Where ε^{P_1} and ε^{P_2} are estimated strain curves made by first data (x_1, ε_1) to two loads under the assumption that two loads (P_1, P_2) have independently applied on the beam. Through the substituting the second data (x_2, ε_2) into equation (4), the weight a can be found.

APPROXIMATE APPROACH

Mechanical (analytical) approach is sufficiently effective in estimating the strain curve under the condition where types of loads and points of action can be predicted such as removing the temporary bent during construction. However, there are many cases where there is no actual information on the load. In these cases, the strain distribution should be estimated approximately through the measured data. This paper adopts a polynomial interpolation technique as a numerical scheme.

The loads being directly applied on the single beam member can be divided into loads through the slab and nodal loads being applied at ends. Since the loads through the slab will be functionally distributed and transmitted when being delivered to the beam, the loads on beam can be assumed as a consecutive polynomial function throughout whole of the member. In case where the concentrated loads will be applied on slab, it is reasonable to set the load function above cubic. Thus, function of the strain distribution with the consideration of relation between load and strain will be assumed as 5th order polynomial like equation (5) then estimated approximately.

$$\varepsilon(x) = ax^5 + bx^4 + cx^3 + dx^2 + ex + f \quad , \quad \left(0 \le x \le L\right) \tag{5}$$

Where a, b, c, d, e, f are coefficients which determine the strain curve. However, six sensors are required per each member to figure out the coefficient in the equation (5), so that there is a necessity to reduce the number of the sensor by applying the boundary condition. In case of continuous beam, the conditions where the values of strain at the adjacent beams are equal can be given as a boundary condition, but in case of simply supported beam the convenient condition of strain on both ends are zero can be applied. According to this, equation (5) is changed as equation (6), which is prepared to estimate the strain of simply supported beam with 4 sensors.

$$\varepsilon(x) = ax\left(x^4 - L^4\right) + bx\left(x^3 - L^3\right) + cx\left(x^2 - L^2\right) + dx(x - L) \tag{6}$$

If function order in presumed load is reduced due to necessity, the high order term in equation (6) is deleted as the correspondence. Thus, the required number of sensors is reduced.

TEST OF THE MODEL ON A STEEL BEAM

To verify the accuracy of strain estimation through FBG sensor measurement, an experiment of sensing strains under the condition of two-point concentrated load was conducted to simply supported beam of 4m span, Steel for Marine as Figure 2 and 4. The results were displayed in Table 3. FBG strain sensors used in the experiment are MSS-1700 of FIBERPRO and a package type with the protective case to simplify the application on the actual structure. The strain distribution on the beam was estimated by the analytical approach through the data acquired from two FBG sensors. The accuracy of analytical estimation was verified by comparing the measured values acquired from ESGs at certain points. Because of the limitation that strains of several locations were measured by only ESGs as condition of the experiment, the approximate estimation was inevitably carried out through the strains acquired by ESGs.

Table 3. Strains measured by ESGs and FBG sensors.

Load Step	Sensor	strain $(\mu\varepsilon)$						
		500mm	1000mm	1500mm	2000mm	2500mm	3000mm	3500mm
0.3 kN	FBG	-	-	-	86	-	83	-
	ESG	39	66	76	88	97	82	39
0.6 kN	FBG	-	-	-	179	-	169	-
	ESG	78	133	150	176	196	168	76
0.9 kN	FBG	-	-	-	269	-	253	-
	ESG	119	203	227	264	293	252	114

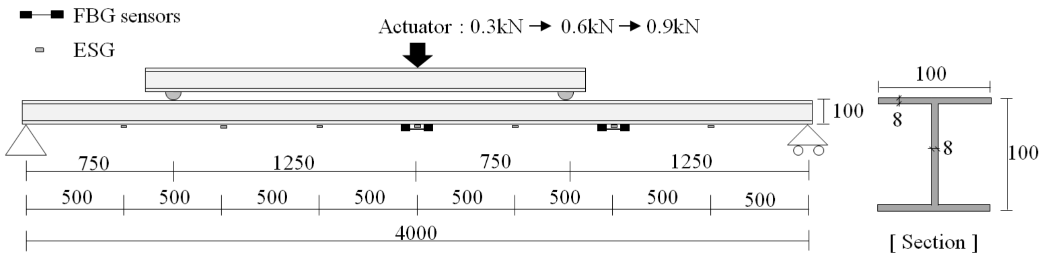


Figure 2. Test setup.

Strain distribution estimated analytically

Fig 3 is a graph comparing the curve estimating the strain distribution by the analytical approach through the measured values from FBG sensor with values measured by ESGs in every 500mm. Each line of the graph describes the estimation of strain distribution at step 1, 2, 3 and the finding was compared to the strain values measured by ESGs on the corresponding locations. Cross marks below the graph display the average value of errors on strain estimation on 3 steps. As the result of estimation, the general margin of error to actual measured value was 3.85%.

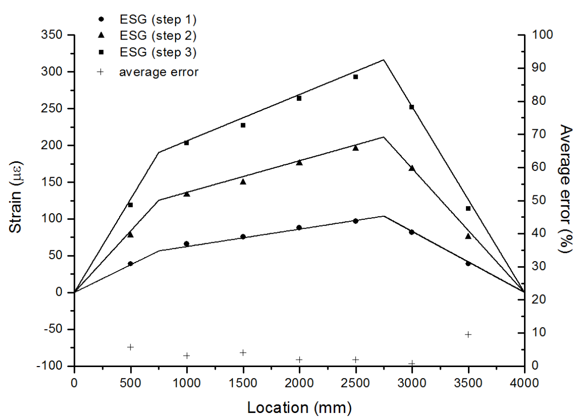


Figure 3. Strain distribution estimated analytically.

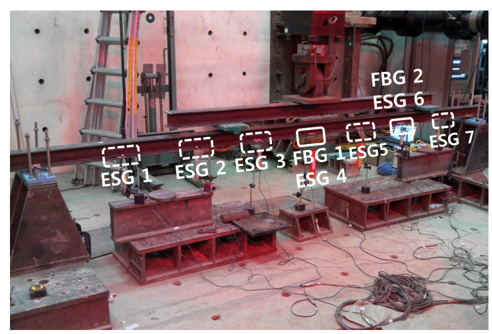


Figure 4. Installment of sensors.

Strain distribution estimated numerically

Fig 5 displays the average error between the estimated values of locations where sensors were installed but exempted from the selection and the measured values through the approximated strain distribution by selecting each 4,5,6 ESGs installed on the beam with an equal interval. The selection of the number of sensors in every cases, which mean ${}_7C_n$ amount of cases were considered in n number of selection and the average error according to the selection of the number of sensors were determined as the average value of representative errors. Where representative error is defined as the average of errors between measured values and estimated values at the locations where the sensors were installed but were not included during the process of drawing estimated curve. The estimated curve used the data of loading condition in step 1 and Fig 6 displays the example of strain distribution estimation according to the selection of sensors. According to the results of the experiment, the accuracy of strain distribution evaluated from sensors installed with equal interval was insufficient and the limitation was found when particularly estimating the magnitude of maximum strain and exact location of occurrence.

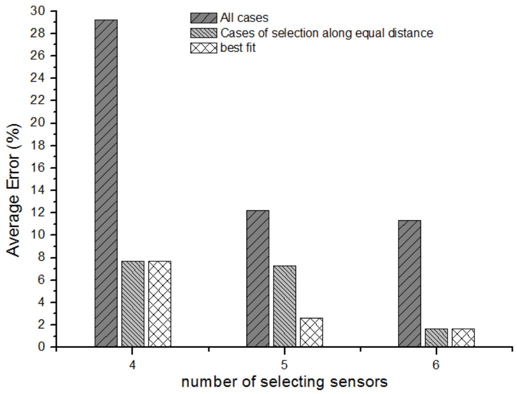


Figure 5. Average error according to number of sensor selection.

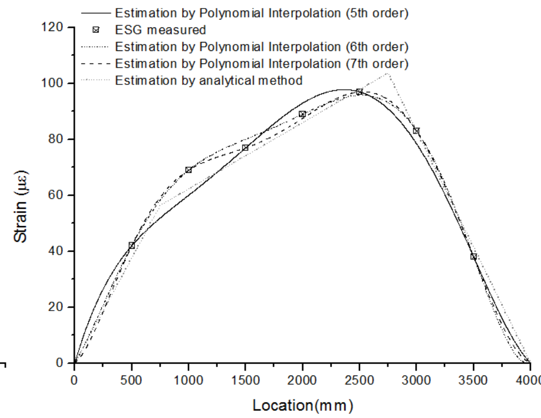


Figure 6. Example of approximate estimation.

CONCLUSION

This paper is a basic study of estimating the maximum stress of individual member through the research of strain distribution estimation by utilizing FBG. The target of the experiment was a simply supported beam and proposal of strain estimation algorithm and its verification were executed. As the finding of the experiment, estimation of strain distribution was possible with a small margin of error when the type of loads and points of action were available whereas the magnitude of the loads was not. However, if the information of the load was not given, the accuracy of the estimation was insufficient. Thus, the future studies on the process to estimate the distribution of strain to secure the safety of general structural members when the information of the loads is unavailable are necessary.

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