Health Monitoring of Steel Structures using Fiber Bragg Grating Sensors

ABSTRACT

A fiber Bragg grating (FBG) sensor is considered to be the most promising sensor for health monitoring system installed in building and civil engineering structures among advanced sensors. We have conducted tensile tests on FBG sensors to evaluate their mechanical and optical properties. It is shown that the FBG sensor expresses excellent linearity up to the large strain level which is enough for covering a yielding strain of steel material. Coefficients of thermal extension and contraction are obtained in the thermal extension test. Some steel plates to which FBG sensors were glued were loaded to investigate applicability of the sensors to real steel buildings. Under certain conditions, the FBG sensors could deliver precise strain outputs which are well correlated to those obtained from resistive foil strain gauges.

INTRODUCTION

Many steel building structures were damaged by the Northridge Earthquake in 1994 and the Hyogo-Ken Nanbu Earthquake in 1995. Though most of them were broken brittly, their residual displacements were very small. In both cases, it was time-consuming and expensive to remove interior and fire-resistance materials for inspection of damages. After the inspection, many civil engineers realized that they did not have tools for detecting such damages without conducting expensive human inspections by experienced engineers.

One of solutions to overcome it is to install a lot of sensors in a structure for monitoring conditions. In order to build such a system, compact, simple, durable and

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low-cost sensors are desirable. Some fiber optic sensors have been considered as promising candidates. Especially, a fiber Bragg grating (FBG) sensor is suitable for monitoring strain.

In this paper, we describe some recent results of our fundamental experiments of FBG sensors conducted for civil structure applications.

FIBER BRAGG GRATING SENSOR

An FBG sensor is a kind of interferometric sensor. A short diffraction grating is written in a portion of a single-mode optical fiber. When broad band light rays enter the fiber, a light of specific frequency which is dependent on the interval of grating is reflected by the gratings. If the fiber with the grating is extended by external forces, the reflected light frequency shifts. In this way, the grating fiber works as a strain sensor. It is easy to multiplex sensors on the single fiber by writing different intervals in each grating.

The major advantages of FBG sensors over resistive foil strain gauges include (1) narrowband with wide wavelength operating range (can be highly multiplexed), (2) nonconductive (immune to electromagnetic interference), (3) environmentally more stable (glass compared to copper), (4) low fiber loss at 1550nm (for remote sensing).

EXPERIMENTS

Some experiments were conducted to study mechanical properties of FBGs. Optical fibers and the FBGs were manufactured by a Japanese cable fabricator. A diameter of core of the optical fiber is 9.3µm and that of clad is 125µm. The length of the grated portion is about 10mm. We tested two types of optical fibers with polyimide coating and with ultraviolet (UV)-cured epoxy acrylate coating. An analyzing system of FBG sensors is FBG Interrogation System (FBG-IS) made by Micron Optics Inc.

Tensile Test

The tensile strength of FBG were measured. Both sides of the fiber are held with Teflon adhesive tape for grip ping. The free length of the fiber between grips (gauge length) is 200mm. The maximum capacity of tensile load machine is 50N.

Loads were measured by a load cell in the tensile load machine and displacements were measured by a displacement transducer (DT). Strains were calculated as the ratio of the extension to the gauge length. As the fiber was connected to FBG-IS, strain data are captured by the FBG-IS. A schematic diagram of the experiment sys-
tem is shown in FIGURE 1.

FIGURE 2 shows results of the tensile tests. The tensile strength of polyimide coated fiber is 14N (1.1GPa) and the maximum strain is 1.5%. That of UV-cured epoxy acrylate coated fiber is 17N (1.4GPa) and maximum strain is 1.8%. As 0.2% is a boundary of elastic to plastic deformation of common steel, FBGs of both coating systems are considered to have enough measuring ranges. Their linearities are also excellent. There are some discrepancies between DT data and FBG data in FIGURE 2 (a). They might be caused by inaccurate setting of the DT.
Figure 4. Power Loss in Bending Tensile Test.

- (a) polyimide coated fiber
- (b) UV-cured epoxy acrylate coated fiber

Figure 3. Experiment System for Bending Tensile Test
Power Loss in Bending Tensile Test

A power loss of FBGs in bending tensile tests was studied. For comparison, the loss of a plane optical fiber was also measured. A schematic diagram of the experiment system is shown in FIGURE 3.

FIGURE 4 shows the power loss in the bending tensile test. When the bending radius $\rho$ is $10\text{mm}$ for the polyimide coated FBG, the power loss increase with increasing load. But the increase in the power loss is not so significant for UV-cured epoxy acrylate coated and polyimide coated plane fibers. The difference between polyimide and UV-cured epoxy acrylate is caused by stiffness of the coating. The hard polyimide coating results in large stresses in the fiber. In addition, as the grating has a different refraction index, lights may become easy to escape from the fiber. When $\rho$ is $5\text{mm}$, the power loss for both coating fibers becomes large.
FIGURE 5 shows FBG-IS outputs in the experiments. It shows fine linearities. At \( \rho = 10 \text{mm} \), the maximum observable strain becomes almost one third to half compared with that in regular tensile tests (see FIGURE 2). When \( \rho \) is 5mm, the observable strain becomes fatally small.

The experiments show that FBG sensors are not suitable for using with a large curvature, for example a corner of column-beam joint.

**Thermal Extension Test**

We installed FBGs in a thermostatic chamber and observed the strain of FBGs at various temperatures; from -40 °C to 250 °C. The room temperature was 25 °C. The results are shown in FIGURE 6. Both polyimide coated fibers and UV-cured epoxy acrylate coated fibers show almost identical features versus temperature. The extension rate of temperature looks linear and it is different from the compression rate. The extension rate is 9.8\( \mu \varepsilon / ^\circ \text{C} \) and the compression rate is 6.5\( \mu \varepsilon / ^\circ \text{C} \).

**Adhesive Test in Cyclic Stress**

A purpose of this experiment is to investigate durability of adhesives under cyclic load. Before this experiment, we had tried to measure strains of a beam by FBG sensors and resistive foil strain gauges (see PICTURE 1). But FBGs slipped and they showed the value less than 50% of the correct strain value. The main reason was a problem in adhesives. From this experience, we evaluated many kinds of adhesives to choose appropriate ones[1].

Two types of adhesives were tested; epoxy and polyester. Four specimens were made of a regular steel for building structures in Japan. FBGs were glued on the
specimens that were loaded by cyclic tension. Two resistive foil strain gauges were glued on the same and opposite sides of each specimen and outputs of them are compared with those of FBG sensors. If the fiber slips, it makes a difference of the outputs. The load range was approximately from 0 to 70MPa. 70MPa is equivalent to 0.15% of strain that is close to the elastic limit of the steel. The loading frequency is approximately 3Hz. A schematic diagram of the experiment system is shown in FIGURE 7.

After 200,000 cycles, three FBGs were survived. FIGURE 8 is one of the results. The average amplitude of strain in 180 cycles (1 minute measurement) is plotted against the number of cycles. As the sampling rate of FBG-IS is 20Hz, six or seven points are measured in a cycle. It is not enough to measure the correct amplitude. According to the probability calculation, the ratio of the average and correct ampli-
tude is 0.96. Data of FBG-IS is compensated in FIGURE 8, but it is little smaller than data of strain gauges. The reason is not clear but it may be the accuracy of the FBG and strain gauges or the setting of them. In any case, the sampling rate should be increased for dynamic strain observations.

One FBG slipped in a polyester adhesive specimen at nearly 40,000 cycles. After the experiment, we inspected the adhesive part to find no exfoliation of the adhesive.

One of two fibers slipped in polyester adhesives and no fiber slipped in epoxy adhesives. But we have to increase the number of specimens to derive our conclusion.

CONCLUSION

Series of fundamental experiments to evaluate mechanical properties of fiber Bragg grating (FBG) sensors and durability of adhesives for applying FBG sensors to civil structures were conducted. The experiments verify the attractive features of the FBG sensors for building and civil structures. The results are summarized as below.

1. The tensile strength is enough to cover the elastic strain ranges of steels.
2. When a tension loads on a bending polyimide coating FBG, power loss becomes large.
3. Thermal extension and compression rate are 9.8 µε/°C and 6.5 µε/°C, respectively.
4. FBG sensors indicate slightly smaller strain compared with values obtained by resistive foil strain gauges when they are glued on steel specimens.

The data provided in this paper should be very useful for developing a health monitoring system for building and civil structures.
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REFERENCE