FBG-BASED DISPLACEMENT AND STRAIN SENSORS FOR HEALTH MONITORING OF SMART STRUCTURES

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ABSTRACT

A series of FBG-based sensors were developed to use in a health monitoring system for a smart structure. Their performance tests have been extensively conducted. The FBG-based sensors have many advantages over conventional electric sensors. One of the most significant features is multiplexing capability and durability. A 12-story building equipped with panel dampers was chosen to install such sensors for ensuring the good performance of the building.

1. INTRODUCTION

Fiber Bragg grating (FBG) sensors are the most promising optical fiber sensors based on the state-of-the-art technologies. FBGs have initially begun to be used extensively in the telecommunication industry for dense wavelength division demultiplexing, laser stabilization and erbium amplifier gain flattening at 1,550nm wavelength range. In addition, the characteristics that an FBG reflects a specific wavelength that shifts slightly depending on the strain applied is ideal for mechanical sensing. The advantages of FBG sensors over conventional electric sensors include:

- environmentally more stable and durable (free from rust),
- immune to electromagnetic field (low noise),
- can be highly multiplexed (many sensing points in a single fiber cable),
- low fiber loss (transmission over several kilometers),
- can be used in the explosive atmosphere (in natural gas or oil).

The above features are perfect for structural health monitoring. A structural health monitoring system started getting strong attentions in Japan after the 1995 Hyogo-Ken Nanbu (Kobe) Earthquake in which more than 6,000 people were killed and 40,000 buildings were destroyed. In many damaged steel buildings, it was not possible to find the correct degree of the damages by a simple eye-inspection of the structure surface because there were no major visible damages on the surface of fire-protection material on structural members. This fact prompted strong demands in real-time nondestructive assessment systems for steel buildings.

In 1998, the Japanese Building Standards Act was changed to allow a performance-based design opposed to the conventional practice of a specifications-based design. This change accelerated the development of new structural systems such as base isolated buildings and damper-equipped buildings. A smart building is a final goal for development. It will be equipped with a health monitoring system to ensure the safety and performance.

Hence, the FBG-based sensors were recently developed focusing on using them in such a health monitoring system.

2. MECHANISM OF FBG

Mechanism of an FBG is described in Fig. 1. The wavelength of a reflected light is called “Bragg wavelength” and is dependent on the strain or the temperature applied to the FBG element. As an FBG element reflects only a narrow region of the light, it is possible to multiplex several sensors in a single fiber cable as shown in Fig. 2 (See [1], [2]). However, the number of FBGs depends on the wavelength bandwidth of input light and the required spacing between FBGs. If the spacing is not large enough, overlapping of the output signals should be observed as shown in Fig. 2. Therefore the number of FBG elements and the spacing should be carefully designed considering measuring range and the bandwidth of the input light source.

For a typical case of an erbium-doped laser light, the light source has enough strength in the wavelength range of 1520nm through 1570nm. Therefore bandwidth of about 50nm can be used for sensing.
3. FBG-BASED SENSORS

3.1 Displacement Sensor
An FBG-based displacement sensor has been developed to measure large displacement (Fig. 3). The mechanism of FBG-based displacement is depicted in Fig. 4. An FBG element is bonded to a metal bar of the spring constant $K_1$. The metal bar is connected to a soft spring of the spring constant $K_2$. As they are connected in a series the spring constant of the displacement sensor $K$ is given in the form

$$K = \frac{K_1 K_2}{K_1 + K_2} \quad (1)$$

The elongation $dx$ measured from the neutral position in the displacement sensor subject to the force $F$ can be obtained by

$$dx = \frac{K_1 + K_2}{K_1 K_2} F \quad (2)$$

The elongation of the metal bar $dx_1$ is obtained as

$$dx_1 = \frac{K_2}{K_1 + K_2} dx \quad (3)$$

From Eq. (3), it is clearly understood that the displacement caused in the metal bar becomes very small if the spring $K_2$ is small enough.

The relation between applied displacement and resulting output wavelength shift is shown in Fig. 5. The linearity of the sensor is well confirmed.
the problem is to use a base metal as shown in Fig. 6. The size of the base metal is described in Fig. 7. In our prototype, the base metal is made of stainless steel. An FBG element is glued to this base metal in a factory. At the construction site, this fabricated sensor is glued or welded to a structural member. The size and the thickness of the metal is modified depending on the material used for the structural member.

3.3 Temperature Sensor

An FBG element is sensitive not only to the strain but also to the temperature. For most applications, compensation for the temperature is necessary. To measure the temperature of a structural member, an FBG-based temperature sensor was developed as shown in Fig. 8. To assure good heat conductivity, an aluminum plate was chosen. An FBG element is glued to the plate as shown in Fig. 9. The outer portion of the plate is glued or welded to the structural member. However, the inner portion of the plate is not glued to the structural member to be free from the deformation.

In Fig. 9, the temperature versus wavelength shift is shown for the test pasted to a steel beam. The strain level during the test was kept constant. In Fig. 10, the wavelength shift is plotted versus strain applied to the steel beam. This time, the temperature was kept constant during the test. From the figure, it is clear that the temperature is measured with no influence of strain induced in the structural member.
4. APPLICATION TO A SMART STRUCTURE

4.1 Structural System
A 12-story steel building was chosen to install FBG-based sensors. The perspective view of the structural system is depicted in Fig. 11. The structural system consists of conventional moment-resistant frames with a series of panel dampers for the safety against large earthquakes.

A panel damper is made of a low-yielding steel plate that is welded to a beam-column joint. The bending motion of the building induces large deformation in this panel so that the plate reaches to the plastic deformation. By doing so, the vibration energy is suppressed from the building.

The capacity of the panel damper has been designed to be large enough for extremely large. However, to ensure the safety of the building, installation of a health monitoring system was decided.

4.2 Performance of Panel Damper
A number of panel dampers were tested to evaluate their energy absorption capacity. An example of test specimen is shown in Fig. 13. Two FBG-based displacement sensors were attached to the panel damper to measure diagonal displacements of the panel. The test setup is shown in Fig. 14. Large cyclic deformations were applied to the panel to reach its rapture. An example of displacement measurement is given in Fig. 15. From this test, it was verified that the FBG-based displacement sensor could correctly measure in the wide displacement range. In addition, enough durability of the sensor was confirmed.

Fig. 11 12-story steel moment-resistant frame structure

Fig. 12 Mechanism of panel damper

Fig. 13 Panel damper specimen

Fig. 14 Panel damper test

Fig. 15 Wavelength shift versus applied force
4.3 Sensor Network

Utilizing the multiplexing capability of FBG-based sensors, six sensors were installed in a single optical fiber cable in average. A portion of the sensor network configuration is depicted in Fig. 16.

5. CONCLUDING REMARKS

A series of FBG-based sensors were developed to measure displacement, strain and temperature. They were designed to use in building and civil structures for monitoring their health condition. Thorough tests to evaluate the performance of the developed sensors were conducted. All developed sensors exhibited good accuracy and durability.

The FBG-based sensors have many advantages over conventional electric sensors. One of the most significant features is multiplexing capability. The feature is ideal for deploying the sensors to large structures.

A 12-story building was chosen to install a structural health monitoring system consisting of FBG-based sensors. The sensors were multiplexed in a single optical fiber cable. The maximum number of sensors in single fiber cable is eight. By this multiplexing configuration, cabling labor was significantly reduced.

The FBG-based sensors are concluded to be ideal for long time monitoring of a large building structure or a large civil structure. They are durable and reliable, and require less labor for installation.

ACKNOWLEDGEMENT

This research was partially supported by the university-industry Collaborative project, “Smart Material and Structure System (Health Monitoring)”, directed by Prof. Takeda at University of Tokyo and coordinated by New Energy Development Organization (NEDO) and R&D Institute of Metals and Composites for Future Industries (RIMCOF). The authors are grateful to Mr. Yokoi, president of Tokyo Sokushin Co., Ltd. for his technical supports and to Mr. Kabashima at Mitsubishi Electric Corp. for collaboration on the temperature sensor.

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