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Characteristics of strain transfer and the reflected spectrum of a metal-coated fiber Bragg grating sensor

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ABSTRACT

Previous researchers have simulated strain transfer and spectrum of normal fiber Bragg grating (FBG) sensors with a polymer coating bonded on the structure. They only considered the shear stress in a polymer coating for the simulation. However, for metal-coated FBG sensors, not only shear stress but also axial stress in the metal coating should be reflected into the calculation because its axial stiffness is no longer negligible. Thus, the author investigated the strain transfer and reflected spectra of metal-coated FBG sensors by considering both shear stress and axial stress. The strain transfer analysis involved evaluating the strain profiles along the sensor by plotting an analytical solution, and validating the evaluated profiles with the results obtained by a finite element analysis (FEA). The solution was also verified by the experiments that used aluminum-coated FBG sensors bonded on a carbon fiber reinforced polymer (CFRP) composite specimen. A transfer-matrix (T-matrix) formulation and coupled mode theory were used to simulate the reflected spectra of metal-coated FBG sensors for the evaluated strain profile. In addition, the effect of mechanical and geometric parameters of the sensor was examined. The findings revealed that the strain transfer characteristics and reflected spectra deteriorated with increases in the thickness and Young's modulus of the metal coating due to the consideration of axial stress. It is the opposite results for the normal FBG sensor with a polymer coating. Furthermore, the results also indicated that the decrease in bonding thickness resulted in improved strain transfer and signal characteristics. Moreover, a bonding length of 14 mm was suitable in suppressing an asymmetric shape of the reflected spectrum and in achieving an accurate measurement. The results of the parametric study are expected to contribute to improve the measurement accuracy of metal-coated FBG sensors in actual applications. The analytical methodology can be usefully employed in the design of a metal-coated FBG sensor system.

1. Introduction

A fiber Bragg grating (FBG) sensor exhibits excellent capabilities for structural health monitoring (SHM) and damage detection because it possess significant advantages [1] including small size, light weight, excellent sensitivity, immunity to electromagnetic interference (EMI), and multiplexing capability. However, unexpected loads can easily break FBG sensors since they are composed of a fragile material, i.e., pure silica glass (SiO_2). Thus, several materials, such as polymers, acrylates, or metals, are coated on the surfaces of FBG sensors to protect the sensors [2], to monitor the corrosion [3], and/or to increase their sensitivity [4,5]. One type of intermediate layers includes a conventional coating, such as a polymer coating, with a thin thickness and/or low mechanical properties. This intermediate layer with low mechanical properties affects strain transfer and the reflected spectrum of the sensors owing to the shear lag phenomenon wherein the strain acting on a host structure is not completely transferred to the surface-attached FBG sensors. Meanwhile, the other intermediate layer involves an adhesive layer used for bonding the sensor. This layer further decreases the strain transfer efficiency and varies the reflected spectrum. Analytical calculations in previous studies only considered shear stresses in the intermediate layers with low mechanical properties to evaluate the strain transfer characteristics for surface-attached FBG sensors [6,7]. This was because the Young's moduli of the intermediate layers were relatively much smaller than those of the FBG sensors and host structures. However, with respect to a metal coating, it is important to consider both shear stress and axial stress in the calculations as the axial stiffness of the metal coating is no longer negligible. This implies that the strain transfer characteristics and corresponding reflected spectrum can vary depending on the extent of thickness of a metal coating or the types of materials that are used for the coating.

Researchers proposed a metal-coated FBG sensor for improving the

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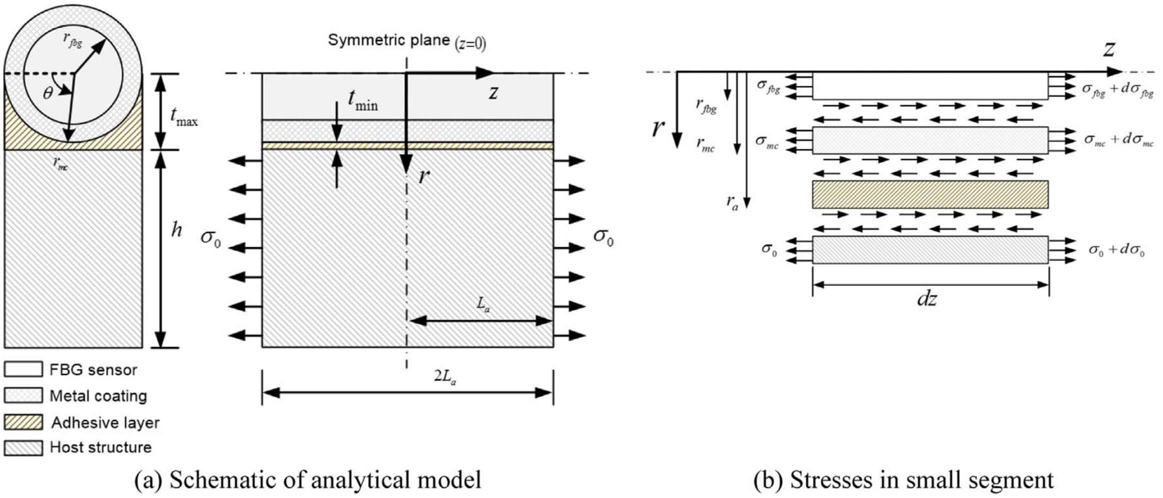

Fig. 1. Analytical model.

sensitivity [4] or building damage detection and evaluation systems [8,9]. With respect to metal-coated FBG sensors, it is not possible to accurately evaluate the strain transfer characteristics by only considering the shear stress in the coating. That is, the axial stress in the metal coating should be considered because its high stiffness provides the coating layer with a load-carrying capacity in the axial direction. Evidently, the axial stress in the adhesive layer is still negligible because its mechanical properties are relatively smaller than those of the FBG sensors, metal coating, and host structure.

Additionally, given the peak detection of reflected light, the narrow bandwidth and high reflectivity of FBG sensors are extremely advantageous when a normally used peak detection algorithm is employed. Therefore, it is necessary to examine the strain transfer and reflected spectrum to achieve an accurate measurement of the physical strain. This study investigated the strain transfer and reflected spectrum characteristics for a metal-coated FBG sensor bonded on a host structure by using an analytical approach. The strain profiles along the core of the metal-coated FBG sensors were first evaluated and validated with the numerical results obtained from a finite element analysis (FEA) by using commercial software, ABAQUS/CAE. Furthermore, the analytical solutions were verified by an experiment involving aluminum-coated (Al-coated) FBG sensors bonded on a carbon fiber reinforced polymer (CFRP) composite specimen. A transfer matrix (T-matrix) formulation and coupled mode theory were used to subsequently simulate the reflected spectrum for the evaluated strain profile [10–12]. The effect of the mechanical and geometric parameters of the metal coating and adhesive layer were also discussed. Finally, the findings indicate that a required bonding length for a metal-coated FBG sensor with an aluminum coating of 18 µm thickness and a Bragg grating with a length of 10 mm were necessary to achieve an accurate strain measurement.

2. Strain transfer analysis

2.1. Review of strain transfer analysis

The strains of the host structure induced by external loads are not completely transferred to FBG sensors because the intermediate layers, i.e., the coating and adhesive layer, convert the energy into shear deformation. Thus, previous studies investigated the strain transfer by developing theoretical models that replicate optical fiber sensors (OFS) with protective coatings. Several researchers focused on the strain transfer characteristics of embedded FBG sensors that are actually installed inside host structures [13–16]. Li et al. [13,14] proposed an analytical model to estimate the sensing strain of embedded FBG sensors in composite structures. They examined the parameters affecting the strain transfer efficiency and verified the theoretical results through experiments. Lau et al. [15] presented a theoretical model for embedded FBG sensors to evaluate the differential strains between the host materials and bare fiber. Their findings revealed that a sufficient embedding length of the FBG sensor is required to reduce measurement errors. Additionally, Zhou et al. [16] examined the effect of the adhesive and coating on the strain transmission for an embedded OFS. Meanwhile, some researchers performed strain transfer analysis for surface-attached FBG sensors [6,7]. Wan et al. [6] investigated the strain transfer of surface-attached OF strain sensors by using a classical shear lag model and 3D-FEA. Their results revealed that the strain transfer was dominantly affected by two geometric parameters of the adhesive layer: (1) bond length, and (2) bonding thickness. Her et al. [7] also proposed a theoretical model for a surface bonded OFS and validated the model with numerical results by using FEA. They verified the theoretical solution by using Mach-Zehnder interferometric type OFS, and found that increased bonded length and the increased stiffness of the coating materials resulted in the transfer of increased strain to the OFS. However, previous studies examining surface-attached FBG sensors focused on the strain transfer characteristics of the OFS with a protective coating with low mechanical properties. Therefore, the models proposed by these studies were unable to accurately evaluate the strain transfer characteristics of the surface-attached FBG sensors coated by a metal with a high stiffness. This study used an analytical model that replicated a surface-attached FBG sensor coated with a metal with high material properties or a relatively large thickness.

2.2. Theoretical model

The theoretical model employed in this study was based on a previously proposed analytical model [17] for a surface-attached metal-coated OFS. The model was based on a theoretical model developed by Her et al. [7]. Fig. 1 shows the analytical model used for the strain transfer analysis. As shown in Fig. 1(a), the analytical model is composed of four components, namely a FBG sensor, a metal coating, an adhesive layer, and a host structure. Only an axial external stress (σ_0) was applied to both sides of the host structure. A cylindrical coordinate system was used given the cylindrical shape of the FBG sensor and metal coating. Fig. 1(b) shows the stresses acting in the small segments of the four components that satisfy the following assumptions [7,15,17]:

i) All materials used in the analysis behaved in a linear and elastic manner.