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Effects of mechanical and geometric properties of adhesive layer on performance of metal-coated optical fiber sensors

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ABSTRACT

The concept underlying metal-coated optical fiber sensors (MCOFSs) is to evaluate the maximum strains previously experienced by host structures from the residual strains induced by an elasto-plastic metal coating. The performances of MCOFSs are altered by the selection of an adhesive as well as the geometric parameters of the adhesive layer. To investigate their effects on sensor performance, a finite element (FE) model was proposed and verified by experiments involving three different adhesives using metal-coated fiber Bragg grating (FBG) sensors. The strain transfer coefficients, the residual strains, and the sensitivity coefficients for the strain level were calculated to examine the influence of the parameters through a finite element analysis (FEA). We found that the nonlinear and plastic properties of the adhesive should be considered to achieve accurate estimation when evaluating the maximum host strains from the residual strains. Moreover, small underlying adhesive thickness and short bonding length are favorable for a MCOFS with 10 mm gauge length. Finally, we presented a relationship (among the residual strain, bonding length of MCOFSs, and the maximum host strains) that helps to quantitatively evaluate the maximum host strains from the residual strains.

1. Introduction

Optical fiber sensors (OFSs) have been widely used for structural health monitoring (SHM) [1–5] because they offer various advantages such as light weight, small size, high reliability, immunity to electromagnetic interference, embedding capacity [6]. They linearly respond to external strain and temperature because they are made from pure silica glass (SiO_2). However, they show nonlinear and plastic behavior when an elasto-plastic metal is coated on the OFS. In a previous study [7] we showed that surface bonded metal-coated optical fiber sensors (MCOFSs) yield permanent residual strains due to the elasto-plastic characteristics of the metal coating when host structures are loaded and unloaded. We reported that MCOFSs have outstanding capability to remember the maximum strain previously experienced by composite structures.

However, the strains are not fully transferred from the hosts to OFSs, because the adhesive layers consume some energy for shear deformation when the host structures are strained. This is called the “shear lag phenomenon”. Many researchers have theoretically and numerically observed the effects of shear lag on strain transfer of OFSs [8–14], and showed that the strain transfer characteristics of OFSs depend on mechanical and geometric properties of the adhesive layers. For example, the strain transferred from the host to the OFS increases as the modulus and bonding length of the adhesive layer increase. On the other hand, the transferred strain decreases with increasing thickness of the underlying adhesive layer. In the case of MCOFSs, the quantity of residual strain is related to the maximum strain in the MCOFS, and it can quantitatively evaluate the maximum strain experienced by host structures through the strain transfer relations. Thus, the strain transfer characteristics should be examined to determine the maximum strain experienced by the host structures. In addition, the mechanical properties of the adhesive layer, which display material nonlinearity and plastic features, can influence the force equilibrium of a MCOFS system, and thus they can also alter the quantity of residual strains and strain transfer characteristics. Moreover, we cannot accurately predict the maximum host strain from the residual strains without consideration of mechanical and geometric properties of the adhesive layer.

This study examines the influence of mechanical and geometric properties of the adhesive layer on residual strain in surface-bonded MCOFSs, focusing on MCOFSs with 10 mm gauge length. Material property tests for three types of adhesive were undertaken to obtain their mechanical properties. A finite element (FE) model considering elasto-plastic characteristics of the metal

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coating and adhesive was proposed, and then experimentally verified using metal-coated fiber Bragg grating (FBG) sensors bonded on composite specimens. The finite element analysis (FEA) was performed using the commercial software ABAQUS/ Standard to investigate the effects of mechanical and geometric parameters on strain transfer coefficients, residual strains, and sensitivity coefficients of MCOFSs. Finally, we proposed a response surface model (RSM) that gives the relationships among the maximum strains experienced by composite hosts, the residual strains in MCOFSs, and the bonding length of sensors.

2. Mechanical property tests of adhesive

The stiffness of interlayer materials of OFS systems can significantly affect the strain transfer characteristics of OFSs. Taking into consideration the parameter of stiffness, we chose two kinds of stiff epoxy adhesives and a soft silicone adhesive to examine the effects of mechanical properties on the performance of MCOFSs. The specifications of these adhesives are listed in Table 1.

Adhesive ‘B’, adhesive ‘K’, and adhesive ‘M’ denote the epoxy adhesives BOND-IT 7040 and KFR-730 and the silicon adhesive MOS8, respectively. Material tests based on ASTM D638 were performed to obtain the tensile properties of the adhesives. Six specimens for each adhesive were fabricated according to different mixing ratios and curing conditions, as illustrated in Table 1. Fig. 1 shows the fabricated specimens and the dimensions of ASTM D638.

Tensile tests were carried out using a universal testing machine (INSTRON 4482; INSTRON Corp.) at room temperature. Based on the ASTM standard, the specimens using adhesives ‘B’ and ‘K’ were loaded with a loading speed of 5 mm/min, and the specimen using adhesive ‘M’ was subjected to a load with a speed of 50 mm/min. A SDA-810C measured the voltage signals from two-axis electrical strain gauges (ESGs) installed on the specimens.

The material properties obtained by tensile tests are presented in Table 2. The values of yield strength are the 0.1% offset yield strength. In the case of yield points, the yield strength of adhesive ‘M’ is observed to be smaller than that of the others. In this study, the measured nonlinear and plastic properties of the adhesives were used in the FEA. However, in the case of adhesive ‘M’, the elongation and strength at breakage could not be measured since the ductile silicone adhesive stretched more than the sensing limitation of ESGs, and therefore the material properties observed in the sensing region were used.

Table 1
Description of adhesives.

Adhesive	Abbreviation	R-H mixing ratio (wt.%)	Curing condition	Manufacturer
BOND-IT 7040	Adhesive ‘B’	100:30	48 h. at RT	Cotronics Corp.
KFR-730	Adhesive ‘K’	100:37	48 h. at RT	Kukdo Chemical Corp.
MOS 8	Adhesive ‘M’	100:100	48 h. at RT	Konishi Co., Ltd.

R-H, resin-hardening; RT, room temperature.

3. Metal coated optical fiber sensors

Generally, OFSs behave linearly when they are loaded and/or unloaded. However, OFSs present plastic characteristics when they are coated by elasto-plastic metals. Thus, permanent residual strains are induced by metal coatings after the stretched MCOFSs are unloaded. The quantity of residual strains induced in MCOFSs is directly correlated with the maximum strains experienced by composite structures under limited conditions such as small variations of temperature and strain rates. MCOFSs exploit these characteristics to remember the maximum host strains previously experienced by composite structures [7]. In this study, metal-coated fiber Bragg grating (FBG) sensors, a type of MCOFS, were used to investigate the material and geometric parameters of the adhesive layer. The sensors were bonded on carbon fiber reinforced polymer (CFRP) composites. The principle of the metal-coated FBG sensor is illustrated in Fig. 2.

The principle of a FBG sensor is based on measuring the shift of reflected light with a certain wavelength that satisfies the Bragg condition as follows [15]:

$$\lambda_{Bragg}=2n_e\Lambda_{Bragg}, \tag{1}$$

where λ_{Bragg}, n_e ($=1.48$), and Λ_{Bragg} are the Bragg wavelength, effective refractive index, and the period of the Bragg grating, respectively. The OFSs with metal coating yield residual strains due to the elasto-plastic property of the coating when external loads are applied and removed. The permanent residual strain (ε_r) can be obtained by measuring the quantity of the wavelength shift

Table 2
Material properties of adhesives.

Adhesive		Adhesive ‘B’	Adhesive ‘K’	Adhesive ‘M’
Young's modulus (MPa)	Mean	2150	3260	206
	SD	99	199	37
Elongation at yield (%)	Mean	0.998	0.867	0.574
	SD	0.119	0.038	0.116
Yield strength (MPa)	Mean	19. 2	25.0	0.9
	SD	1.9	1.5	0.1
Elongation at breakage (%)	Mean	3.394	2.044	–
	SD	1.144	0.493	–
Strength at breakage (%)	Mean	40.3	40.5	–
	SD	5.5	3.4	–
Poisson's ratio	Mean	0.426	0.393	0.452

SD standard deviation.

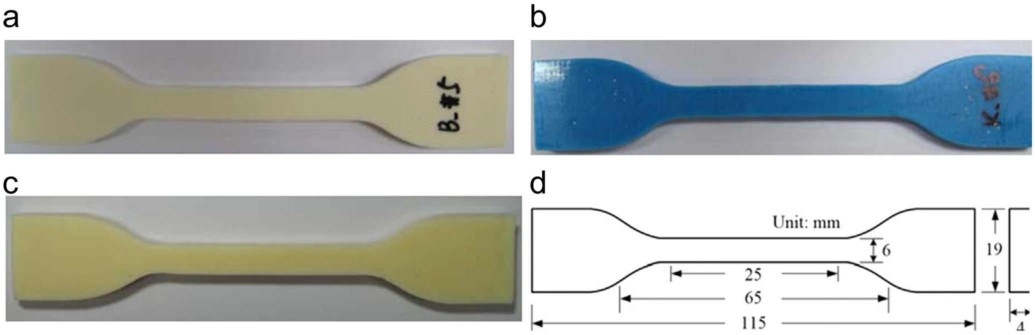

Fig. 1. Dimension of ASTM D638 and fabricated specimens. (a) BOND-IT 7080 (adhesive ‘B’), (b) KFR-730 (adhesive ‘K’), (c) MOS 8 (adhesive ‘M’), (d) dimension.