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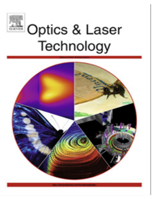

Full length article

Priority design parameters of industrialized optical fiber sensors in civil engineering

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ABSTRACT

Considering the mechanical effects and the different paths for transferring deformation, optical fiber sensors commonly used in civil engineering have been systematically classified. Based on the strain transfer theory, the relationship between the strain transfer coefficient and allowable testing error is established. The proposed relationship is regarded as the optimal control equation to obtain the optimal value of sensors that satisfy the requirement of measurement precision. Furthermore, specific optimization design methods and priority design parameters of the classified sensors are presented. This research indicates that (1) strain transfer theory-based optimization design method is much suitable for the sensor that depends on the interfacial shear stress to transfer the deformation; (2) the priority design parameters are bonded (sensing) length, interfacial bonded strength, elastic modulus and radius of protective layer and thickness of adhesive layer; (3) the optimization design of sensors with two anchor pieces at two ends is independent of strain transfer theory as the strain transfer coefficient can be conveniently calibrated by test, and this kind of sensors has no obvious priority design parameters. Improved calibration test is put forward to enhance the accuracy of the calibration coefficient of end-expanding sensors. By considering the practical state of sensors and the testing accuracy, comprehensive and systematic analyses on optical fiber sensors are provided from the perspective of mechanical actions, which could scientifically instruct the application design and calibration test of industrialized optical fiber sensors.

1. Introduction

Optical fiber based sensors have been extensively used to measure the strain and temperaure information in civil engineering for the unique advantedges of absolute measurement, good geometrical shape-versatility, debonding and corrosion resistance, anti-electromagnetic interference, small size, light weight and convenient integration of sensor network [1–4]. However, for the immature design method and imperfection standard, most of the industrialized optical fiber sensors prevailed in the market have low measurement accuracy, poor durability, bad stability and weak robustness [5–9]. This case becomes more serious in the long-term monitoring of structures in field. Issues related to temperature-strain discrimination, demodulation of the amplitude spectrum during and after the curing process as well as connection between the embedded optical fibers and the surroundings were carefully reviewed [10,11]. How to accurately select and design the optical fiber sensors suitable for engineering structures is still an important problem that needs to be further studied. One of the important reasons is that the designers usually come from the optical electric engineering and are short of understanding the mechanical action between the sensors and the monitored structures in civil engineering. For example, if the designer doesn't know how the deformation of the host material is transferred to the sensing fiber, it is difficult to conduct the fine design or reinforcement in key positions of optical fiber sensors.

It is well known that bare optical fiber is weak to bear the shear and bending forces and resist the harsh service environment in civil engineering. To enhance the survival rate and durability of optical fiber based sensors, the packaging measure is particularly important. Therefore, an intermediate medium (i.e., packaging layer for protecting optical fiber and adhesive layer for fixing optical fiber) is introduced between the sensing fiber and the monitored structure, which makes the strain sensed by optical fiber not completely represent the actual strain of host material. For strain sensors, to ensure the durability and robustness of the optical fiber

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sensing system and realize the reliability and effectiveness of the long-term monitoring, the mechanical interaction between the attached sensor and the structure should be considered. To improve the measurement accuracy of sensors and reflect the actual deformation of host material, strain transfer theory is then established to quantitatively describe the strain relationship between the sensing fiber and the host material [12–14]. Except for providing the strain transfer error modification function, the strain transfer analysis of optical fiber sensors can also explain the mechanical action and instruct the application design.

Considering the structural properties and measurement requirements of a given structure, optical fiber based sensors can be mainly divided into two categories due to the installation modes: surface-bonding case and embedding case. For the different layout techniques, the parameters to be particularly considered in the design are also distinguished. For embedded sensors, the fundamental capacity of the packaging layer is to resist the compaction forces during the construction, guarantee the survival of sensing elements, cause no perturbation to the strain field of the monitored structure and ensure a relatively high strain transfer ratio. For surface-bonding sensors, the packaging layer should bear the environmental action (i.e., moisture, sunlight and water erosion) and the influence to the structural integration can be ignored. According to the different paths for transferring the deformation of host material, the optical fiber sensors can be further divided into three types, which will be discussed in detail in Section 2. It can be noted that the design of a sensor is closely correlated with the installation modes, material and geometrical properties of the monitored structure, constraint condition, static (or dynamic) load types, and so on.

The objective of this paper is to develop the optimization design method and priority design parameters for industrialized optical fiber sensors in civil engineering through the strain transfer theory. This paper gives an instruction and detail analysis on how to design optical fiber sensors for a given structure (especially for asphalt pavements) and what kind of factors should be firstly considered in the design of an optical fiber sensor. Based on the analysis, improved calibration test is put forward.

2. Optimization design method of optical fiber based sensors

The ultimate goal of the optimization design of industrialized optical fiber sensors is to accurately measure the deformation of host material and simultaneously guarantee the long-term stability and effective measurement of the applied sensors, so as to satisfy the monitoring requirements of engineering.

2.1. Design based on strain transfer theory at the elastic stage

In practical engineering, the sensors are usually installed during the construction so as to monitor the structural performance in the whole process. Structures usually go through a much long time before stepping into the damaged stage. Therefore, the strain transfer theory at the elastic stage is majorly adopted to instruct the optimization design method of sensors. The implementation majorly contains the following steps: (1) establish the quantitative relationship between the average strain transfer coefficient and relative error based on the proposed strain transfer theory; (2) build up the control function with the relative error smaller than specified values and the variables contain geometrical and physical parameters; (3) solve the optimal solution by mathematical tool.

2.1.1. Surface-attached optical fiber sensors

According to the different deformation transferring paths, the commonly used optical fiber sensors can be mainly divided into two categories: (1) one type is that deformation of host material is transferred by interfacial shear force; (2) another type is that deformation of host material is transferred by the distance change between the two anchor pieces at the two ends of the sensing fiber [15,16]. The two kinds of sensors separately numbered S-OF1 and S-OF2 are displayed in Fig. 1. L means half of the gauge length.

(1) The sensor numbered S-OF1 in Fig. 1(a) measure the strain transferred by interfacial shear forces, which can be fabricated to detect the point and distributed testing and widely used in practical engineering. When the sensing model contains four layers (i.e., optical fiber, protective layer, adhesive layer and host material) as the Fig. 2 in Ref. [17], the correlated average strain transfer coefficient has been deduced in Ref. [12]and the relative error w can be accordingly obtained as

$$w = \frac{\varepsilon_m - \varepsilon_{test}}{\varepsilon_m} = \frac{\varepsilon_m - \beta_{av}\varepsilon_m}{\varepsilon_m} = \frac{\sinh(\lambda L)}{\lambda L \cosh(\lambda L)} \tag{1}$$

where ε_m is the actual strain of host material, ε_{test} is the measurement strain of host material, and $\lambda^2 = \frac{2}{E_f} \Big/ \left[\frac{r_p(r_p - r_f)}{G_p} + \frac{h_a(\pi r_p + h_a)}{G_a}\right]$. The physical meaning of parameters in the expression of λ are described as below: E_f and r_f are the elastic modulus and radius of optical fiber; G_p and r_p are the shear modulus and radius of the protection; G_a and h_a indicate the shear modulus and thickness of the adhesive layer.

The relative measurement error permitted in civil structures should be controlled in 5%. An equation then can be obtained by using Eq. (1)

$$\frac{\sinh(\lambda L)}{\lambda L \cosh(\lambda L)} \leqslant w \tag{2}$$

As the elastic modulus and radius of the sensing fiber are fixed values, it can be known that the geometrical and material parameters that influence the measurement error mainly contain: bonded length, radius and shear modulus of protective layer, thickness and shear modulus of bonding layer.

For surface-bonding sensors, the main capacity of the protective layer is to prevent the optical fiber from the environmental actions (i.e., moisture, temperature and sunlight), and that of the bonding layer is to fix the optical fiber continuously and durably on the monitored structure. Therefore, the protective and bonding materials should have the properties of good durability, stability, corrosion resistance and anti-aging, and then the polymer composites (i.e., epoxy resin, FRP and silicone rubber) can be optional. The corresponding geometrical parameters (i.e., bonded length, radius and thickness) can be optimized by Eq. (2).

When silicone rubber material ($G_p = 6.65 \times 10^7$ N/m^2) is selected as the protective layer, and rigid glue ($G_a = 2 \times 10^9$ N/m^2) is as the bonding material, one of the optimal values satisfied the control function can be calculated out by Eq. (3):

$$r_p = 0.15\ \text{mm}, \quad h_a = 0.4\ \text{mm}, \quad L = 0.06\ \text{m} \tag{3}$$

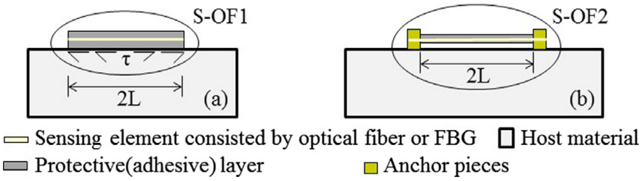

Fig. 1. The two surface-attached optical fiber sensors: (a) S-OF1; (b) S-OF2.