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# Improving the durability of the optical fiber sensor based on strain transfer analysis

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ABSTRACT

To realize the reliable and long-term strain detection, the durability of optical fiber sensors has attracted more and more attention. The packaging technique has been considered as an effective method, which can enhance the survival ratios of optical fiber sensors to resist the harsh construction and service environment in civil engineering. To monitor the internal strain of structures, the embedded installation is adopted. Due to the different material properties between host material and the protective layer, the monitored structure embedded with sensors can be regarded as a typical model containing inclusions. Interfacial characteristic between the sensor and host material exists obviously, and the contacted interface is prone to debonding failure induced by the large interfacial shear stress. To recognize the local interfacial debonding damage and extend the effective life cycle of the embedded sensor, strain transfer analysis of a general three-layered sensing model is conducted to investigate the failure mechanism. The perturbation of the embedded sensor on the local strain field of host material is discussed. Based on the theoretical analysis, the distribution of the interfacial shear stress along the sensing length is characterized and adopted for the diagnosis of local interfacial debonding, and the sensitive parameters influencing the interfacial shear stress are also investigated. The research in this paper explores the interfacial debonding failure mechanism of embedded sensors based on the strain transfer analysis and provides theoretical basis for enhancing the interfacial bonding properties and improving the durability of embedded optical fiber sensors.

## 1. Introduction

The structural safety of civil infrastructures, ocean platforms and aerospace structures has received increasing attention, because the failure of those important structures usually leads to large abundant of casualties and economical loss. To characterize the structural performance, structural health monitoring (SHM) technology has been recognized as one of the most effective and intelligent measures [18,19,1,23,22,10,7]. By the use of smart sensors and components, the real-time, long-term and continuous information of the in-situ structures can be provided for the damage identification, disaster forecasting and warming, and safety and life-time assessment [35,17,20,16,26]. Among these smart sensing elements, optical fiber based sensors are the most popular in civil engineering for the unique advantages of high sensitivity and precision, corrosion resistance, anti-electromagnetic interference, good stability, geometrical shape-versatility, absolute measurement and convenient integration of network [25,34,32,12].

For the brittle material properties of silica fiber, bare optical fiber is weak to resist the shear or torsion force in structural construction and operation. Especially for the embedded case, the packaging technique is the most critical factor to guarantee the survival and enhance the durability of optical fiber based sensors. However, the existence of the protective layer introduces the intermedium between the sensing fiber and the monitored structure, which makes the strain measured by the sensor not entirely represent the actual strain of host material [2]. The error between the measured strain and the actual strain is attributed to the strain loss in the transferring path. To eliminate the strain transfer error and improve the measurement accuracy of optical fiber based sensors, strain transfer theory has been developed to establish the quantitative relationship of strains between the host material and the optical fiber [13,33,9,28].

Considerable attempts have contributed to studying the strain transfer mechanism of optical fiber sensors. The earliest research started from the 1990s, and the strain relationship between the

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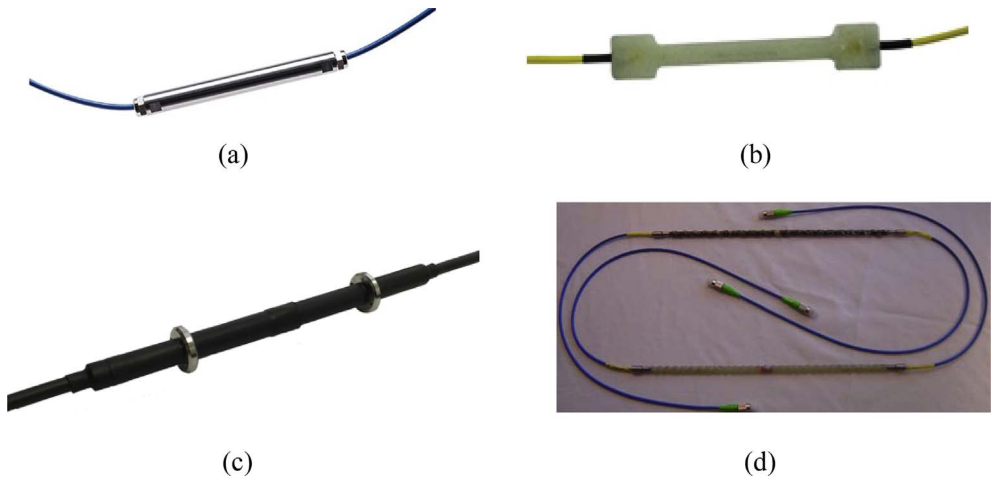


**Fig. 1.** The optical fiber based sensors used in practical engineering: (a) Steel packaged FBG sensor developed by HBM; (b) GFRP packaged FBG sensor developed by SCAIME; (c) Stainless steel packaged FBG sensor developed by MOI (d) CFRP/GFRP packaged FBG sensor developed by TELL.

concrete and sensing fiber was studied with a polymer-to-glass modulus ratio of 1/200 given [21]. Host material with optical fiber sensor embedded was then simplified to infinite elastic cylinder model, and plane-strain theory was adopted to explore the strain transfer mechanism [24]. However, the simplified model in the two theories couldn't be used to accurately determine the strain transfer relationships for various host materials with non-elastic behavior. In 1998, a systematic strain transfer theory of a three-layered structure embedded with optical fiber sensor was established [3]. To analyze the effects of a local interfacial slippage on the strain transfer ratio, a two-layered mechanical model consisted of host material and optical fiber was discussed [13]. For a multi-layered structure with various packaging layers, the unified strain transfer formula was conducted [33]. The improved strain transfer deduction of a three (multi)-layered sensing model by the use of simplified geometrical and physical functions was proposed [15]. Strain transfer analysis was also extended to special cases for considering the viscoelastic material properties of the monitored structure [30]. For surface-attached point optical fiber sensors, the strain transfer mechanism and sensitivity of influencing parameters was studied [27]. The strain transfer of surface-attached distributed optical fiber sensors with one crack in host material was explored [6]. Besides, the dynamic strain transfer relationship of the sensing model under fatigue load was investigated [31]. In general, most of the existing strain transfer theory mentioned above is based on the non-destructive models, and limit consideration focuses on the damaged model. Besides, the current studies are confined to the strain transfer error modification. The strain transfer theory has yet been adopted to explore the failure mechanism and application design of optical fiber based sensors.

In practical engineering, the premature failure of optical fiber based sensors becomes a common phenomenon. Many installed sensors are out of service in 5 years, the life cycle of which is quite shorter than that of the monitored structure. For embedded cases, it is usually difficult for rehabilitation or replacement, which threats the real-time performance monitoring of on-site structures. Therefore, the durability and long-term performance of optical fiber based sensors draws considerable attention [29]. When the rehabilitation is not so convenient and the sensor is claimed to work normally, strain transfer error modification with the damaged cases considered becomes particularly significant. The interfacial debonding between the embedded sensor and host material is one of the most common failure modes that should be carefully studied, for it associates with the reliable use and measurement accuracy of optical fiber sensors in practical application. If the local interfacial debonding exists in the embedded sensing model, the strain transfer error modification is also demanded to ensure the effective measurement. For this reason, the interfacial damage identification and measurement accuracy requires further investigation through the strain transfer analysis between the packaged sensor and host material.

Given the analysis above, the possible failure modes of optical fiber sensors available in the market for the embedment in structures are discussed by considering the strain transfer mechanism. Analysis on the influence of local interfacial debonding between the embedded sensor and host material is studied theoretically. The perturbation of the embedded sensor on the strain field of the structure is discussed. Based on the strain transfer analysis, theoretical approach to diagnose the occurrence of interfacial debonding and debonding length is proposed. Furthermore, the sensitive parameters influencing the interfacial bonding properties are discussed and suggestions on the application design of embedded sensors are provided for improving the durability of the sensor.

## 2. Optical fiber based sensors with enhanced performance

The optical fiber based sensors have been prevailed for decades, and optical fiber has been packaged with various materials to enhance the performance and the robustness of the sensors in practical engineering. Available sensors used for the inside strain detection of concrete (or composite) structures in market majorly contains the following four types presented in Fig. 1, which are separately developed by four internationally famous companies. Steel, glass fiber reinforced plastic (GFRP), carbon fiber reinforced plastic (CFRP) and stainless steel have been separately used as the packaging materials to protect the sensing fiber. It can be noted that the strain of the structure is majorly transferred to the sensor by interfacial shear force. Therefore, the interfacial bonding strength is particularly important to guarantee an effective measurement. Besides of the embedded FBG sensor provided by HBM, the surface of the other three sensors separately developed by SCAIME, MOI and TELL have been polished to increase the roughness. This measure partially improves the interfacial bonding state and finally benefits the long-term effective measurement of the embedded sensors. However, how to quantitatively assess the interfacial bonding strength and scientifically enhance the roughness of the packaged sensor still requires reliable theoretical investigation. For this reason, the strain transfer theory is adopted to explore the interfacial failure mechanism of the three-layered sensing model.