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A review of DFOS sensors installation methods for curved surfaces in tunnels

Examen des méthodes d'installation des capteurs DFOS pour les surfaces courbes dans les tunnels

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ABSTRACT: This paper reviews previous published articles on structural health monitoring (SHM) of tunnels using distributed fibre optic sensing (DFOS). The installation of DFOS sensors onto curved surfaces in tunnels, such as the transverse cross section of a tunnel, is a major challenge for the effectiveness of SHM of tunnels. The state-of-the-art DFOS sensors installation methods currently used for monitoring surface strains in tunnels are summarized, with emphasis on evaluating the applicability scenario of each method and their advantages and disadvantages.

RÉSUMÉ: Ce document est un recueil d'articles publiés précédemment sur le contrôle de la santé structurelle (SHM) des tunnels au moyen de la détection distribuée par fibre optique (DFOS). L'installation de capteurs DFOS sur des surfaces courbes dans les tunnels, telles que la section transversale d'un tunnel, est un défi majeur pour l'efficacité du SHM des tunnels. Les méthodes d'installation des capteurs DFOS actuellement utilisées pour contrôler les contraintes de surface dans les tunnels sont résumées, en mettant l'accent sur l'évaluation du scénario d'applicabilité de chaque méthode et sur leurs avantages et inconvénients.

Keywords: Distributed fibre optic sensing; tunnel engineering; structural health monitoring

1 INTRODUCTION

Tunnel engineering has been one of the most vital aspects of underground infrastructure over recent decades, serving an important function in the urban transportation network. By the end of 2020 in China, there were already 16,789 tunnels in operation, with a total length of about 19,630km; 2,746 tunnels under construction, with a total length of about 6,083km; and 6,354 tunnels under planning, with a total length of about 16,255km (Tian et al. 2021). With the increase of construction and service time, tunnel defects are unavoidable (e.g. settlement deformation, lining cracking and tunnel leakage) due to adverse factors such as extreme weather and material deterioration. Recently, distributed fibre optic sensing (DFOS) is emerging as an innovative monitoring tool for measuring continuous strain development by a single fibre optic cable in civil infrastructures (Li et al., 2018). However, DFOS sensors need to be closely attached to the monitored structure so that they can deform simultaneously with the monitored structure and provide accuratemeasurement. Such close attachment can be easily achieved in monitoring flat operational structures such as piles, pipelines, and bridge decks, but it is rarely seen on curved surfaces. The lack of suitable methods for installing DFOS sensors on curved surfaces has been a major obstacle to promoting this innovative technology in tunnel engineering. This paper presents the state-of-the-art methods for installing DFOS sensors on curved surfaces, mainly by comparing the advantages and disadvantages of each method and briefly suggesting improvement measures. It aims to promote the further application of DFOS in tunnel engineering and beyond.

2 EMBEDDED INSTRUMENTATION

Regarding tunnels under construction, DFOS sensors are mainly embedded in the monitored structure, which ensures that DFOS sensors deform simultaneously with the monitored structure by a solid bond, allowing reliable deformation to be transmitted to the sensitive glass fibre core (Monsberger and Lienhart, 2017). Figure 1 shows the typical embedding positions of DFOS sensors.

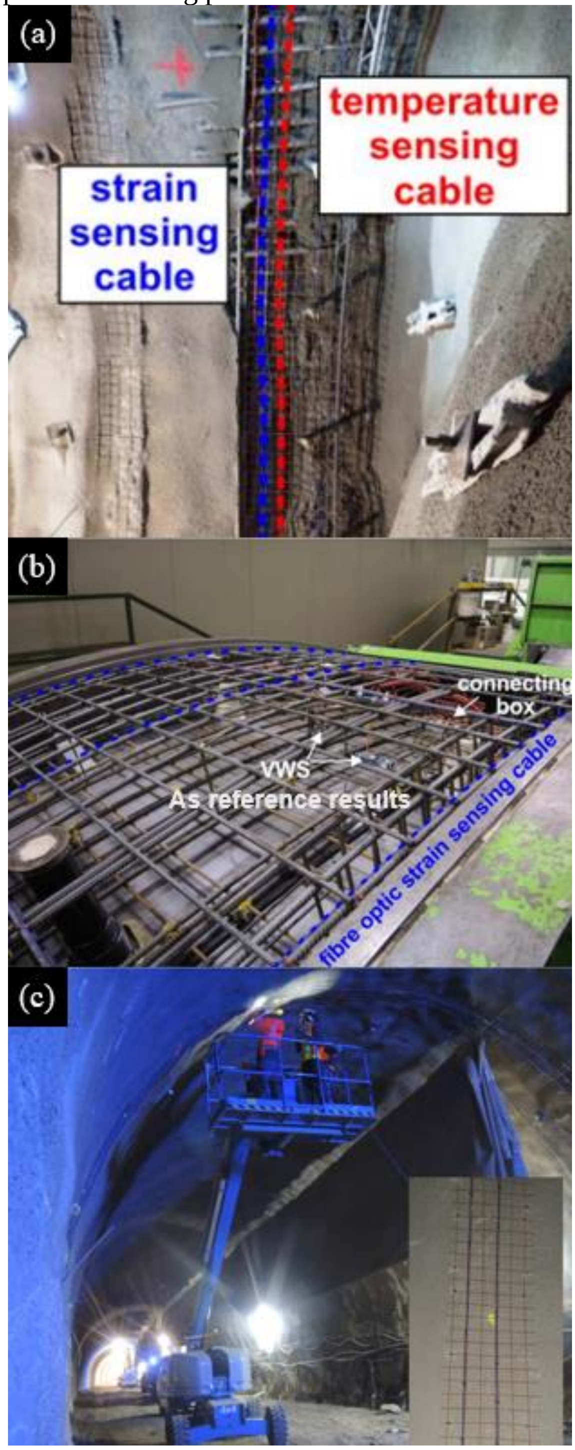

Figure 1. Typical embedding position of DFOS sensors, (a) in shotcrete lining , (b) in tunnel segments and (c) along the shotcrete lining.

Regardless of the tunnel construction methods used (e.g., the New Austrian Tunneling Method (NATM) or prefabricated tunnel segments, as shown in Figure 1(b)), embedding DFOS sensors into the monitored structure in tunnels generally involves two steps:

1) The sensors are first attached directly to the monitored structure at regular intervals (15-20 cm) along the reinforcement bars using some fixing materials, including epoxy resins, eye-bolts, buckles and cable ties.
2) A solid bond between DFOS sensors and the monitored structure is obtained by concrete.

Pre-tension of DFOS sensors has also been shown to be not necessary in a demonstration case reported by Monsberger et al. (2018). A comparative analysis of tunnel lining deformation measurements using vibrating wire sensors (VWS) and non-prestrained DFOS demonstrated that the data obtained from both methodologies exhibited a high degree of congruence in terms of their magnitude and geometric profiles. This finding underscores the reliability and compatibility of non-prestrained DFOS in parallel with traditional vibrating wire sensor measurements for assessing tunnel lining deformations.

For existing tunnels, embedding DFOS sensors directly into the structure at the initial stage is often not possible. In these scenarios, the attachment of DFOS sensors to the cross-section of the tunnel can be achieved via a supplementary structure applied to the tunnel lining, utilizing elements like custom-designed clamps (Muley et al., 2011; Monsberger et al., 2021). After the DFOS sensors installation, additional shotcrete is applied to the area of the secondary structure to ensure a solid bond between the DFOS sensors and the existing tunnel lining. A major limitation of this DFOS sensors installation method is the robustness of DFOS sensors since the DFOS sensors are placed in harsh tunnel construction environment by workers in limited working space. For example, in a NATM construction project, shotcrete is often sprayed onto reinforcement grids under high pressure, the DFOS sensor has to be able to withstand the high pressure and the grid vibrations caused by the high pressure to avoid partial dislodgement of the DFOS sensors from the reinforcement bars. Therefore, DFOS sensors often require additional protective layers and corresponding experimental investigation in the laboratory to examine the influence of site construction on the DFOS robustness and measurement accuracy.

The absence of a requirement for pre-tensioning the DFOS sensors and the ability to accurately track the monitored structural deformations stand as the principal advantages of the embedment instrumentation. However, the construction phase presents a significant risk of damages the DFOS sensors, resulting post-embedment repairs or replacements changelling without significant intervention in the structure. Consequently, the implementation of supplementary protective measures is advocated to safeguard the integrity of DFOS sensors during installation.

3 SURFACE INSTRUMENTATION

For most existing tunnels, the installation of DFOS sensors on the surface of the monitored structure is more popular due to feasibility, tunnel integrity and serviceablity. The DFOS sensors can be either installed onto tunnel surface using a continuous bonding method or a fixed-point method. Figure 2 summarises the common materials and tools used to attach the DFOS sensors to the surface of the monitored structure.

3.1 Continuous bonding method

In theory, the continuous bonding method shown in Figure 2(a) is the most effective method for attaching the DFOS sensors on the surface of the monitored structure to exploit the continuous strain sensing capacities of DFOS sensors (Sui et al., 2021). Gue et al. (2015) attached the DFOS sensors via continuous gluing to obtain a continuous strain profile along the entire cross section for a cast iron tunnel over a period of 11 months and representative strains of the behaviour of the cast iron ring were measured. However, in order to achieve effective bond between the DFOS sensors and the surface of the monitored structure, a comprehensive treatment of the surface is necessary, including fluting, smoothing, grinding, cleaning, bottoming, sticking, checking etc. These installation techniques severely limit the application of the continuous bonding method. Also, the performance of adhesive (usually a thin layer of epoxy resin) in the long term is vital since the effective contact between the DFOS sensors and the surface of the monitored structure are achieved mainly by the adhesive. According to Gomez et al. (2020), additional protective measures could be taken to avoid possible damage of the DFOS sensors as shown in Figure 2(b).

3.2 Fixed-point method

In many practical situations, a major challenge is that the continuous bonding method can not be used due to the constraints of the construction and service environment. In response to this challenge, the fixed-point method has been advocated. This approach acknowledges the inherent limitation that strain measurements are only representatively for the gauge length. Consequently, rigorous consideration of gauge length is necessary as the computation of deformation hinges on the product of strain and this precisely defined interval length. The hook-and-pulley system shown in Figure 2(c) is currently the most widely reported fixed-point method for installing DFOS sensors (Mohamad et al., 2012). Briefly, the hooks are fixed at different locations on the surface of the monitored structure, with the DFOS sensors passing along the pulleys. Zhu et al. (2022) reported that fixing clamps, designed for installation on tunnel linings through the use of external expansion screws as illustrated in Figure 2(d), are also efficacious in gripping the DFOS snesors. Regardless of the tool used to fix the DFOS sensors to a number of discrete points on the surface of the monitored structure, the DFOS sensors need to be pre-strained to avoid any slack sections. The selected fixation kit should have a suitable curvature to avoid excessive optical signal loss and minimize the distance between the DFOS sensors and the surface of the monitored structure.

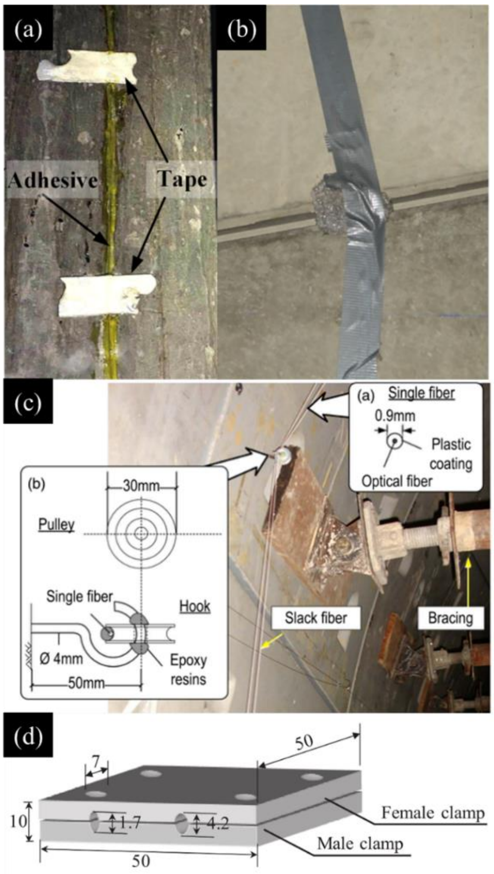

Figure 2. Common materials and tools for attaching the DFOS sensors to the surface of the monitored structure.

Compared with embedded instrumentation, surface instrumentation provides a straightforward and minimally invasive method for structural health monitoring, offering better flexibility for sensor maintenance, adjustments, and replacements without compromising structural integrity. However, deploying DFOS sensors on the curved surfaces introduces unique challenges, particularly in maintaining consistent contact between the sensors and the curved surfaces, which is crucial for accurate deformation measurement. The complexities introduced by curved surfaces need to be addressed by emphasizing the need for careful method selection, development of innovative attachment solutions and data correction techniques.

4 CONCLUSION

In recent years, a large number of field monitoring projects have been conducted to successfully demonstrate the great potential of DFOS in structural health monitoring. Nevertheless, the capability of DFOS for monitoring structures with curved surface has always been restricted by the reliable DFOS sensor installation method. The present work summarized the DFOS sensors installation method for curved surface, aiming to enhance the applicability of this innovative monitoring technology in tunnel engineering and beyond.

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