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# Review of Brillouin Distributed Sensing for Structural Monitoring in Transportation Infrastructure

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**Abstract:** Distributed optical fiber sensing (DOFS) is an advanced tool for structural health monitoring (SHM), offering high precision, wide measurement range, and real-time as well as long-term monitoring capabilities. It enables real-time monitoring of both temperature and strain information along the entire optical fiber line, providing a novel approach for safety monitoring and structural health assessment in transportation engineering. This paper first introduces the fundamental principles and classifications of DOFS technology and then systematically reviews the current research progress on Brillouin scattering-based DOFS. By analyzing the monitoring requirements of various types of transportation infrastructure, this paper discusses the applications and challenges of this technology in SHM and damage detection for roads, bridges, tunnels, and other infrastructure, particularly in identifying and tracking cracks, deformations, and localized damage. This review highlights the significant potential and promising prospects of Brillouin scattering technology in transportation engineering. Nevertheless, further research is needed to optimize sensing system performance and promote its widespread application in this field. These findings provide valuable references for future research and technological development.

**Keywords:** distributed optic fiber sensing; brillouin scattering; structural health monitoring; damage identification

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## 1. Introduction

Transportation plays a foundational and strategic role in the national economy, serving as a critical driver of economic and social development. The construction and maintenance of transportation infrastructure are essential to enabling efficient and accessible networks [1,2]. However, long-term service conditions expose vital assets—including roads, bridges, and tunnels—to adverse environmental influences, growing traffic demands, and dynamic loading. These factors often lead to serious structural issues such as settlement, deformation, slope instability, and loss of protective systems, which can degrade performance or result in structural failure [3–5]. Ensuring the safe and stable operation of these systems requires real-time SHM [6–8], supported by advanced information technologies that provide robust tools for infrastructure evaluation and lifecycle management [9].

SHM technologies have steadily advanced over the years and have found applications across a wide range of civil infrastructure [10]. Conventional monitoring approaches, primarily relying on electronic sensors—including strain gauges, displacement transducers, and accelerometers—are often constrained by high cost, limited sensing coverage, low durability, and vulnerability to external interference. These limitations hinder their effectiveness in large-scale, long-term monitoring of transportation structures. In contrast, DOFS utilizes fiber as both a sensing and transmission medium, offering superior corrosion resistance, immunity to electromagnetic interference, and long service life [11]. It enables continuous, multi-parameter monitoring over extended distances and is well-suited for detecting temperature variations, deformation in auxiliary structures, and unauthorized disturbances [12]. By overcoming the inherent limitations of traditional sensing methods, DOFS significantly enhances risk detection capabilities and supports structural integrity in complex transportation environments. As a result, it has become a key technology in the monitoring of large-scale transportation infrastructure across diverse structural forms [13,14].

This paper provides a systematic review of DOFS technologies and their improved variants, focusing on the classification schemes and basic operating principles. It highlights representative applications of Brillouin scattering-based distributed fiber sensing in the SHM of transportation infrastructure, including roads, bridges, and tunnels. Additionally, this paper discusses current challenges faced by these technologies in large-scale structural monitoring and outlines future research directions and development prospects.

## 2. Overview of Fiber Optic Sensing Technology

### *2.1. Classification and Principles*

Over the past two decades, optical fiber sensing has rapidly evolved and found widespread application across diverse engineering fields [12]. Leveraging the unique physical properties of optical fibers, this technology employs the fiber itself as a sensing element. By analyzing the propagation characteristics of light signals within the fiber, it enables the measurement of key environmental parameters, including temperature, strain, and vibration. Optical fibers are ideal for harsh environments, characterized by corrosion, high temperatures, or humidity, thanks to their compact size, light weight, resistance to electromagnetic interference, and high radiation tolerance [15]. Moreover, optical fiber sensing supports simultaneous multi-parameter monitoring with high spatial resolution and scalability, providing an effective solution for large-scale, high-precision, real-time SHM [16,17].

As a sensing technique, optical fibers are broadly categorized into two types: quasi-distributed sensing based on fiber Bragg gratings (FBGs) and fully distributed sensing based on scattering mechanisms—DOFS. FBG is a point-based sensing method that measures localized strain or temperature by detecting wavelength shifts in reflected light [18–20]. While it offers high sensitivity at specific points, its ability to monitor global structural behavior is limited due to the discrete nature of its sensing. In contrast, DOFS enables continuous measurements over the entire length of the fiber, with thousands of sensing points created along the fiber axis. This approach analyzes variations in scattered light—specifically in intensity, frequency, or phase—to extract physical quantities [21]. These quantities depend on the optical properties of the fiber as well as the performance of signal demodulation systems and algorithms, and they typically represent average values over a certain segment of the fiber.

DOFS systems are further classified based on the type of optical backscattering generated during laser transmission through the fiber. As shown in Figure 1, the three main scattering mechanisms are Brillouin, Rayleigh, and Raman scattering [22,23]. Brillouin scattering is predominantly used for strain and temperature monitoring; Raman scattering is highly sensitive to temperature variations; and Rayleigh scattering is more applicable for acoustic and vibration sensing. Furthermore, depending on the signal interrogation method, DOFS can be categorized into time-domain and frequency-domain systems: optical time domain reflectometry (OTDR) and optical frequency domain reflectometry (OFDR).

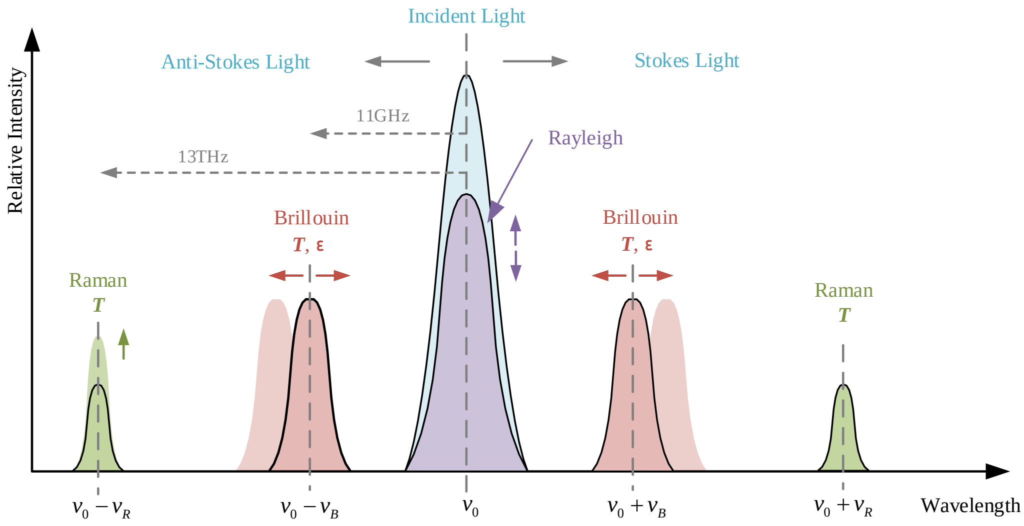



**Figure 1.** Backward-scattered light spectrum.

### 2.1.1. Rayleigh Scattering

Rayleigh scattering refers to the elastic scattering of light by particles much smaller than the incident light wavelength, where the frequency of the scattered light remains the same as that of the incident light. A continuous light source is modulated into narrowband pulses, which are coupled into the optical fiber via a circulator. As the light travels along the fiber, spatial fluctuations in the refractive index cause scattering in various directions, with the backscattered signal being captured by a photodetector [24,25]. By measuring the round-trip time of light between the emission and reception points, the distance to a specific location and the corresponding peak power can be calculated. The backscattered signal curve enables the extraction of local strain and temperature information, while the exponential attenuation of the signal strength reveals the loss profile along the fiber, thus allowing for the identification and localization of fiber faults, bending, and attenuation for system diagnostics and maintenance.

Rayleigh-based DOFS systems offer excellent spatial resolution and measurement accuracy, often achieving millimeter-level spatial resolution and high precision [26]. They provide continuous visualization of signal attenuation along the entire fiber, making them widely used in fiber link diagnostics. However, limited by the width of the optical pulse, these systems face constraints in both sensing distance and resolution, and they may contain blind spots. Consequently, they are less suited for large-scale or long-range SHM applications and are primarily used for short-distance fault detection, fiber breakage localization, intrusion monitoring in buildings, and vibration sensing in civil structures. In distributed strain and temperature measurements, the spatial resolution can reach 1 mm, with a sensing accuracy of up to 0.1 °C or 1.0 $\mu\epsilon$.

Common Rayleigh-based techniques include, but are not limited to, coherent optical time domain reflectometry (COTDR), phase-sensitive optical time domain reflectometry ($\varphi$-OTDR), Rayleigh optical time domain reflectometry (OTDR), and Rayleigh optical frequency domain reflectometry (OFDR) [27]. COTDR enhances sensing distance by using coherent detection to extract weak Rayleigh backscattering signals from strong noise, enabling multi-span, long-range fiber measurements. $\varphi$-OTDR, on the other hand, injects highly coherent light pulses into the fiber, generating interference among the backscattered signals from different fiber segments. This interference effect allows for the detection of weak signal disturbances that conventional OTDR systems cannot capture, thereby significantly improving sensitivity [28,29]. As a result, $\varphi$-OTDR has emerged as a primary technique for distributed monitoring of intrusions and vibrations. Additionally, distributed acoustic sensing (DAS) and optical backscatter reflectometry (OBR) also fall under this category, offering unique monitoring capabilities.

#### 2.1.2. Raman Scattering

Raman scattering refers to an inelastic scattering process caused by molecular vibrations. When incident light travels through the fiber, it interacts with optical phonons in the fiber material, resulting in a change in photon energy and a corresponding frequency shift—namely, Stokes and anti-Stokes shifts. Because Raman-scattered light carries temperature-related information, the intensity of anti-Stokes light varies with local fiber temperature, while the intensity of Stokes light remains largely unaffected by temperature changes [30]. Therefore, the temperature distribution along the fiber can be determined by analyzing the power ratio between Stokes and anti-Stokes components. This method effectively eliminates the influence of light source fluctuations and fiber bending, ensuring long-term temperature measurement accuracy.

DOFS based on Raman scattering is typically categorized into two techniques: Raman optical time domain reflectometry (ROTDR) and Raman optical frequency-domain reflectometry (ROFDR). Leveraging the temperature sensitivity of Raman scattering, these systems enable spatially resolved temperature measurements along the length of the fiber. By analyzing the frequency shift and intensity of the scattered signal, the temperature distribution around the fiber and attenuation along the sensing path can be accurately captured. This makes Raman-based sensing particularly suitable for temperature monitoring, fire detection, and other applications requiring real-time thermal tracking.

However, the inherent signal attenuation of Raman scattering imposes limitations on both sensing accuracy and spatial resolution. While temperature measurement accuracy can reach up to 0.1 °C, the best achievable spatial resolution is approximately 0.1 m. This limitation poses a challenge for detecting subtle temperature variations in complex environments using Raman-based distributed sensing systems. In contrast, distributed temperature sensing (DTS) offers a solution by providing higher spatial resolution and improved sensitivity, making it more effective for precise temperature measurements over long distances in challenging environments.

#### 2.1.3. Brillouin Scattering

Compared to Rayleigh and Raman scattering, Brillouin scattering-based optical fiber sensing has only recently been introduced into structural monitoring applications for strain and temperature [31]. Brillouin scattering refers to an inelastic scattering process caused by the interaction between optical and acoustic waves propagating within the fiber. This interaction leads to a shift in light frequency, known as the Brillouin frequency shift (BFS) [32,33], which is defined as follows:

$$v_{(B)} = 2nv_{(0)}\frac{V_{(A)}}{c}\sin(\frac{1}{2}\theta), \tag{1}$$

where $n$ is the refractive index, $v_{(0)}$ is the frequency of incident light, $V_{(A)}$ is the acoustic velocity in the fiber, $c$ is the speed of light in a vacuum, and $\theta$ is the scattering angle between the incident and scattered light.

The BFS variation exhibits a linear relationship with both strain and temperature. By using standard single-mode communication fibers as sensors, Brillouin-based systems can achieve long-range, high-resolution, and high-accuracy distributed strain and temperature monitoring. By detecting the backscattered Brillouin signal and demodulating the BFS, the strain distribution along the sensing fiber can be retrieved. Although temperature variations also influence the BFS, they can be neglected when the change is within 5 °C. The relationship among strain, temperature, and BFS is expressed as follows:

$$v_{(B)}(\varepsilon, T) = v_{(B)}(0) + \frac{dv_{(B)}(\varepsilon)}{d\varepsilon}\varepsilon + \frac{dv_{(B)}(T)}{dT}(T - T_0), \tag{2}$$

where $v_{(B)}(\varepsilon, T)$ is under zero strain and temperature, $v_{(B)}(0)$ denotes the reference Brillouin frequency shift under initial conditions (when $\varepsilon = 0$ and $T = T_0$), and $\frac{dv_{(B)}(\varepsilon)}{d\varepsilon}$ and $\frac{dv_{(B)}(T)}{dT}$ are the coefficients for strain and temperature sensitivity, respectively.

Brillouin scattering can be categorized into two types depending on the operating conditions [34]: spontaneous Brillouin scattering (SpBS) and stimulated Brillouin scattering (SBS).

1. Spontaneous Brillouin Scattering
   In SpBS, the incident photons undergo backscattering and generate lower-energy phonons. These interactions, resulting from thermal fluctuations due to Brownian motion in the fiber material, modulate the refractive index and induce spontaneous scattering. The frequency shift due to this Doppler-like effect constitutes the spontaneous Brillouin scattering.
   Brillouin optical time domain reflectometry (BOTDR) and Brillouin optical frequency domain reflectometry (BOFDR) are both distributed sensing techniques based on SpBS [35]. They launch pulsed light from one end of the fiber and detect the backscattered Brillouin signal using a demodulation system. The time and intensity of the return signal are used to infer the temperature and strain distribution along the fiber [36]. By analyzing the Brillouin frequency peak, localized strain or temperature variations can be extracted in real time.
   Compared to SBS-based systems, BOTDR exhibits lower signal-to-noise ratio (SNR), spatial resolution, and sensing range. However, its single-ended configuration significantly simplifies the field deployment and makes it more robust in scenarios where the fiber loop cannot be completed. Even if the fiber is partially damaged, measurements can still be carried out continuously [37,38]. BOTDR is thus suitable for structural health monitoring of bridges, buildings, tunnels, and pipelines, enabling real-time insight into temperature and strain evolution.
2. Stimulated Brillouin Scattering
   When the pump power exceeds a certain threshold, the interaction between incident light and coherent acoustic waves enhances the refractive index modulation and causes a strong backscattered signal [39], known as SBS.
   Brillouin optical time domain analysis (BOTDA), Brillouin optical frequency domain analysis (BOFDA), and Brillouin optical correlation domain analysis (BOCDA) are all distributed sensing methods based on SBS. These techniques measure strain and temperature by analyzing the acoustic wave velocity within the fiber, offering high spatial resolution and extended sensing ranges. By adjusting the pulse parameters, users can flexibly balance resolution and distance, enabling continuous profiles of strain and temperature [40].
   Unlike BOTDR, BOTDA requires a fiber loop configuration: a pulsed pump signal is injected from one end while a continuous probe wave is launched from the other [41], making the installation relatively more complex. Nevertheless, BOTDA provides significantly stronger backscattered signals, longer sensing range, and improved performance in terms of spatial resolution, SNR, and measurement accuracy. It has thus been widely applied in transportation, civil engineering, environmental monitoring, and aerospace systems.

Brillouin scattering is better suited for long-range distributed sensing than Rayleigh scattering, especially for simultaneous strain and temperature monitoring. It offers sensing distances ranging from tens to hundreds of kilometers and spatial resolution as fine as 0.5 m. Notably, Brillouin optical frequency domain analysis (BOFDA) can even achieve a spatial resolution of up to 2 cm [42]. Compared to Raman scattering, Brillouin-based methods offer greater stability against step-loss-induced errors and more reliable temperature readings due to the frequency-shift-based measurement mechanism [12].

### 2.2. Sensing Mechanisms

In DOFS, variations in the underlying physical principles lead to distinct differences in sensing performance—including measurement accuracy, sensing range, and environmental adaptability. Table 1 classifies various types of DOFS technologies and outlines their respective working principles. It provides a foundational understanding of how different scattering mechanisms—Rayleigh, Raman, and Brillouin—enable distinct sensing techniques based on their physical interactions and signal characteristics.

**Table 1.** Distributed optical fiber sensing techniques.

| Techniques | Scattering Type | Physical Mechanism | Sensing Technique | Sensing Principle | Access Configuration |
|---|---|---|---|---|---|
| Brillouin-based sensing | Inelastic scattering (Doppler effect) | Electrostriction, interaction between photons and acoustic phonons | BOTDA [43–45] | Stimulated Brillouin scattering in time domain | Dual-end injection |
| | | | BOCDA [46–49] | Stimulated Brillouin scattering with coherent detection | |
| | | | BOFDA [49–51] | Stimulated Brillouin scattering in frequency domain | |
| | | | BOTDR [52–54] | Spontaneous Brillouin scattering in time domain | Single-end injection |
| | | | BOFDR [55] | Spontaneous Brillouin scattering in frequency domain | |
| Raman-based sensing | Inelastic scattering (low optical intensity) | Photon–phonon interaction | ROTDR [56] | Spontaneous Raman scattering in time domain | Single-end injection |
| | | | ROFDR [57] | Spontaneous Raman scattering in frequency domain | Dual-end injection |
| Rayleigh-based sensing | Elastic scattering (high optical intensity) | Microscopic density fluctuations | OTDR [53,54,58] | Spontaneous Rayleigh backscattering with intensity detection | Single-end injection |
| | | | COTDR [59] | Coherent Rayleigh scattering detection in time domain | |
| | | | $\varphi$-OTDR [60,61] | Phase-sensitive coherent Rayleigh detection | |
| | | | OFDR [58,62] | Coherent Rayleigh interferometry in frequency domain | |

Table 2 presents a comparative overview of common DOFS techniques, summarizing their typical best-case performance in terms of sensing range, spatial resolution, temperature and strain accuracy, measurement frequency, and SNR. It is important to note, however, that these performance metrics are often mutually constrained in practical implementations. For example, enhancing spatial resolution or increasing sampling frequency typically leads to a reduction in sensing range or SNR. Consequently, not all listed values can be simultaneously achieved under the same experimental conditions or system configuration. These trade-offs should be carefully considered when selecting or designing a distributed sensing system.

**Table 2.** Performance comparison of common DOFS techniques.

| Sensing Technique | Maximum Sensing Range | Minimum Spatial Resolution | Best-Case Temperature Accuracy | Best-Case Strain Accuracy | Maximum Measurement Frequency | SNR | Sensing Parameters |
|---|---|---|---|---|---|---|---|
| BOTDA [43–45] | 200 km | 0.01 m | ±0.1 °C | ±2 με | 0.1 Hz | Moderate | Strain; Temperature |
| BOCDA [46–49] | 10 km | 0.01 m | – | ±1 με | 0.1 Hz | High | |
| BOFDA [49–51] | 100 km | 0.02 m | ±0.1 °C | ±2 με | 1 Hz | Moderate | |
| BOTDR [52–54] | 80 km | 0.5 m | ±0.1 °C | ±2 με | 0.01 Hz | Low | |
| BOFDR [55] | 50 km | 1 m | ±1 °C | ±20 με | 0.1 Hz | Moderate | |
| ROTDR [56] | 37 km | 0.1 m | ±0.1 °C | ±1 με | 0.2 Hz | Low | Temperature |
| ROFDR [57] | 30 km | 0.1 m | – | ±0.1 με | 0.1 Hz | Moderate | |
| OTDR [53,54,58] | 250 km | 1 m | – | – | 100 Hz | Low | Fiber breaks; Loss points |
| COTDR [59] | 50 km | 0.01 m | – | – | 20 kHz | Low | Acoustic waves; Vibration |
| φ-OTDR [60,61] | 250 km | 0.001 m | – | – | 20 kHz | Low | Fiber breaks; Damage points; Strain |
| OFDR [58,62] | 0.1 km | 0.01 m | ±0.1 °C | ±1 με | 100 Hz | High | Fiber breaks; Damage points; Temperature; Strain [12] |

The following tables provide a comparative overview of DOFS mechanisms and their key performance metrics. Rayleigh-based systems offer ultra-high spatial resolution and are well-suited for detecting localized dynamic responses, though their sensing range is limited. Raman-based techniques excel in temperature monitoring but suffer from lower spatial resolution and SNR. In contrast, Brillouin-based methods, particularly BOTDA and BOFDA, enable long-range strain and temperature sensing—up to 200 km—with high accuracy and strong environmental stability. BOTDA also demonstrates greater robustness to signal degradation compared to Raman-based systems. Overall, Brillouin-based DOFS offers a balanced combination of sensing range, accuracy, and multi-parameter capabilities, making it particularly advantageous for large-scale SHM in transportation infrastructure.

### *2.3. Advantages of Brillouin DOFS*

Among the various DOFS technologies, Brillouin scattering-based systems offer a particularly favorable combination of performance characteristics that make them well suited for SHM in transportation infrastructure [30]. These systems provide long sensing ranges, adequate spatial resolution, and dual-parameter capability for both strain and temperature measurement—features that are rarely combined in a single platform. Table 3 presents a comparative overview of the key attributes of Rayleigh-, Raman-, and Brillouin-based DOFS techniques, highlighting their respective strengths and limitations.

**Table 3.** Comparison of Rayleigh, Raman, and Brillouin DOFS technologies.

| Technique | Sensing Range | Spatial Resolution | Sensitivity (T,$\varepsilon$) | Signal Robustness | Deployment Ease | Application Suitability |
|---|---|---|---|---|---|---|
| Rayleigh [58] | Short to long (up to 100–200 km) | High (mm–cm) | $\varepsilon$ only (high) | Moderate to low | Easy | Vibration, acoustic sensing, perimeter security |
| Raman [56] | Medium (10–30 km) | Low ($\geq$1 m) | T only (moderate) | Low | Easy | Temperature or fire detection in cables, tunnels |
| Brillouin [51] | Long (up to 200 km) | Moderate (0.5 m–1 m) | T + $\varepsilon$ (high) | High | Moderate | SHM in transportation, pipelines, geotechnical systems |

In terms of sensing range, Brillouin-based systems can reliably operate over distances of up to 100–200 km using standard single-mode optical fibers, significantly exceeding the typical ranges of Rayleigh-based systems (usually less than 10 km) and Raman-based systems (typically below 30 km). This extended range is particularly advantageous for large-scale transportation applications such as bridges, tunnels, highways, and rail corridors, where centralized monitoring of widely distributed sensing points is required.

While Rayleigh-based systems are known for their exceptional spatial resolution, often reaching the sub-meter or even millimeter scale, they are generally constrained to short-range applications and are more susceptible to signal fading, environmental noise, and interference. Raman-based systems, by contrast, are primarily sensitive to temperature and exhibit limited spatial resolution—commonly in the order of meters—making them less suitable for detecting localized mechanical deformations. Moreover, Raman systems do not inherently support strain measurement, limiting their functionality in multi-parameter SHM contexts.

Brillouin DOFS offers a balanced trade-off between these extremes. With a typical spatial resolution ranging from 0.5 to 1 m, Brillouin systems can effectively detect distributed strain and temperature variations along extended structures while maintaining good signal stability over long distances. More importantly, the inherent ability of Brillouin scattering to simultaneously capture strain and temperature data enables discrimination between mechanical and thermal effects—an essential feature for accurate diagnostics in complex and dynamic transportation environments.

From a practical deployment perspective, Brillouin-based systems are compatible with conventional telecommunication-grade single-mode fibers, facilitating cost-effective integration into existing infrastructure. Furthermore, the use of passive optical fibers—devoid of any in-line electronic components—enhances their durability and resistance to harsh environmental conditions such as humidity, temperature extremes, mechanical stress, and electromagnetic interference. These factors contribute to reduced maintenance requirements and longer service lifetimes.

In summary, the unique combination of long-range coverage, simultaneous strain and temperature sensing, and strong environmental resilience makes Brillouin scattering-based DOFS particularly well suited for transportation infrastructure monitoring. These capabilities not only support the large-scale, continuous observation required in real-world engineering applications but also ensure reliable long-term performance under complex field conditions. As a result, Brillouin-based systems have become one of the most widely adopted and practically effective sensing solutions in transportation-related SHM.

## 3. Packaging and Deployment Methods of Optical Fibers

The performance and durability of DOFS systems largely depend on proper fiber packaging and deployment, especially in complex transportation environments. Given the combined effects of strain and temperature, careful design of packaging, connections, and installation is essential. Effective encapsulation protects the fiber from mechanical damage and environmental degradation, ensures efficient strain transfer and synchronized deformation with the host structure, and preserves sensing accuracy and reliability over the long term.

### *3.1. Packaging Technologies*

To improve the durability, survivability, and long-term stability of optical fiber sensors, multiple protective layers are typically applied around the fiber for encapsulation, forming a complete cable [36]. Figure 2 shows a schematic diagram of a typical encapsulation structure.

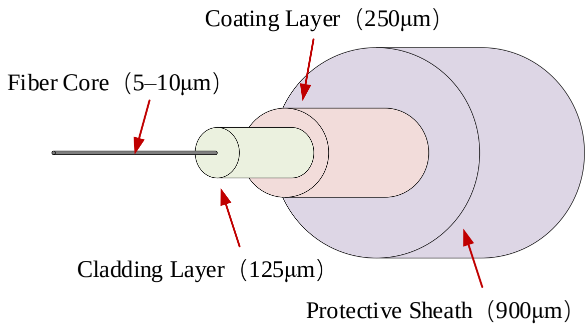



**Figure 2.** Typical fiber optic cable encapsulation structure schematic [21,63,64].

The long-term stability and sensing performance of optical fibers in harsh environments rely on the combined function of one or more protective layers, which not only provide mechanical protection but also ensure consistent signal transmission. These structural layers include both essential and optional components. The core, cladding, and primary coating are fundamental for light propagation and basic protection. Additional layers—such as buffer layers, strength members, jackets, armoring, and specialized functional coatings or filling materials—are selectively employed depending on the environmental conditions and specific performance requirements of the application. These layers collectively shield the fiber from direct environmental damage. A schematic representation of typical encapsulation structures is shown in Figure 3. In practice, not all of the listed layers are simultaneously present in every fiber configuration; an optical fiber or cable may contain only a subset of these layers, or it may incorporate additional functional components. The commonly used protective layers are outlined below.

1. Optical fiber core. The fiber consists of a core and cladding, typically made of silica ($SiO_2$). The cladding confines light within the core through total internal reflection, enabling efficient signal transmission.
2. Coating layer. A soft polymer coating is generally applied to protect the fiber core from minor mechanical damage and environmental stress, enhancing its durability, corrosion resistance, and mechanical robustness in harsh environments. Zhang et al. [65–67] applied

a polyurethane coating directly over the cladding, offering flexibility and elasticity to improve frictional contact with similar materials, thus enabling excellent strain transfer and coupling performance. Additionally, it is easy to mold and process, making it suitable for complex packaging requirements. Other studies have reported the use of polyimide [68,69] and acrylate-based materials [53,70] as alternative coatings.

3. Buffer layer. Typically made of soft plastic materials such as polypropylene or polyvinyl chloride (PVC), the buffer layer increases fiber flexibility and improves bonding with the protective coating, ensuring efficient strain transfer—crucial for high-precision strain measurements. Gomez et al. [63] used epoxy resin for its strong adhesion to the fiber, facilitating stress transfer and enabling coordinated deformation. Gue et al. [54] employed a gel-filled core to prevent the transmission of external mechanical strain from the sheath while also enabling temperature sensing.
4. Strengthening layer. This layer typically consists of aramid fibers like Kevlar or glass fibers, designed to enhance the cable's tensile strength and protect it from damage caused by stretching or pulling forces.
5. Armoring layer. Employed chiefly in long-term structural health monitoring applications, this layer safeguards the fibers against abrasion, compression, and mechanical intrusion in demanding environments such as concrete or soil. Armoring can be classified into metal and non-metal types. Metal armoring, usually made of stainless steel, aluminum, or other alloys, provides superior resistance to compression, impact, and rodent damage while maintaining a certain level of flexibility to accommodate structural deformation [71]. Non-metal armoring, composed of high-strength materials such as braided glass fibers or aramid yarns, offers reduced weight, moderate compression resistance, and immunity to electromagnetic interference. Gutierrez et al. [72] applied both glass fiber and corrugated steel armor, which, through a compact buffer structure, improved the mechanical integrity between the inner fiber and other cable components.
6. Outer jacket. The outermost protective layer, often made from polyethylene [73], polyvinyl alcohol [74], PVC, or other durable plastics, protects the fiber from water, corrosion, and ultraviolet (UV) exposure. Van et al. [75] used a nylon jacket that provided superior strength but was prone to slip between layers, which could affect strain localization. Monsberger et al. [76] applied a polyamide jacket to shield the fiber from mechanical impact.
7. Special coatings or filling materials. In extreme environments with high humidity or elevated temperatures, additional materials like waterproof gels, flame retardants, corrosion-resistant coatings, or moisture-proof compounds may be incorporated to enhance environmental resilience. According to [53], thermoplastic polyester elastomer (TPEE) jackets exhibit strong resistance to moisture ingress, making them particularly suitable for applications in water-rich soil environments.

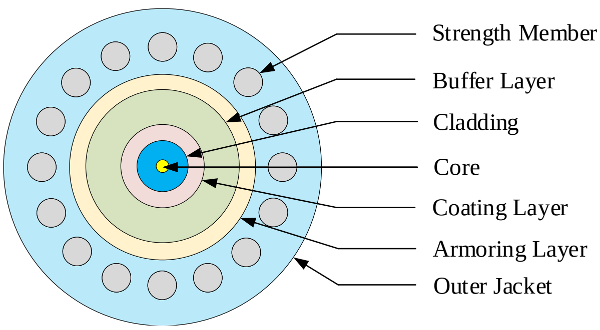
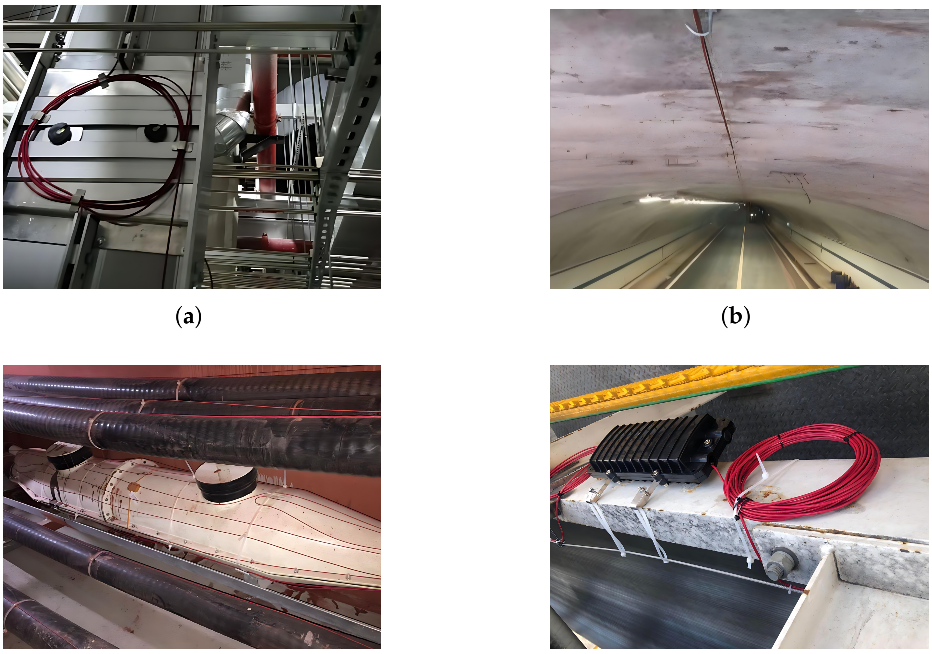



**Figure 3.** Schematic diagram of encapsulation materials for each layer of optical fiber [21].

*3.2. Deployment Methods*

Depending on the contact interface between the sensing cable and the monitored structure, optical cable deployment can generally be categorized into externally bonded and internally embedded.

1. Externally bonded deployment is commonly used for existing structures, where optical cables are attached to the structural surface using adhesives, anchors, clamps, or cable ties. Alternatively, cables can be laid along structural elements like bridge girders or tunnel walls through protective conduits, or placed in precut grooves on components like precast piles or anti-slide piles to achieve better integration. Among these, surface bonding using epoxy resin or similar adhesives is frequently employed. However, due to direct exposure to environmental conditions, surface-mounted installations require careful consideration of durability under harsh environments, making them more suitable for laboratory tests or small-scale monitoring. Common surface-mounted configurations are illustrated in Figure 4.
2. Internally embedded deployment is generally adopted during construction. In this approach, the fiber is incorporated directly into structural elements by embedding it within roadbeds, ducts, or trenches, or inserting it into concrete or asphalt layers during casting. It may also be installed inside ducts before grouting [77]. This configuration ensures close coupling between the fiber and the surrounding material, enabling effective strain transfer and structural compatibility. Embedded deployment is particularly suitable for pavements, subgrades, and tunnel linings. Examples are shown in Figure 5.

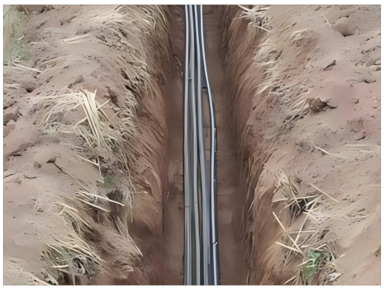


(**a**) (**b**) (**c**) (**d**)

**Figure 4.** Common attached fiber placement methods: (**a**) Paste on surface. (**b**) Mounted on top of the tunnel using hooks. (**c**) Clamping with metal fixtures. (**d**) Secure with plastic ties.

In road infrastructure monitoring, optical fibers are generally installed using internally embedded methods. Cables are pre-positioned beneath pavement layers—typically through slotting, drilling, or trenching—allowing for flexible deployment across various structural components, such as the subgrade and pavement. To improve sensing performance, researchers have proposed diverse layout strategies. For instance, Zeng et al. [78]

introduced a spiral array configuration to increase the fiber length per unit area, thereby enhancing spatial resolution and localization accuracy. Dong et al. [79] implemented a horizontal zigzag layout by aligning the fiber using utility poles; this method was later applied by [80] for crack detection in bridge structures. While simple in structure and suitable for linear layouts, this approach offers limited improvements in positional accuracy. To broaden sensing coverage, researchers like [81,82] introduced grid-patterned layouts. Wei et al. [83] developed a bidirectional zigzag layout capable of capturing both strain and localized settlement. Bao et al. [84] embedded U-shaped fiber sensors within concrete slabs, enabling the identification of closely spaced cracks. In response to complex soil stratigraphy and large vertical variability, Meng et al. [85] proposed multilayered deployment, with each layer featuring staggered grids—typically spaced less than 1 m apart—to enhance strain sensitivity. According to [66,86], vertical drilling was used to embed fibers, enabling the monitoring of subsurface deformation at various depths. In some cases, helical or serpentine layouts have been employed to further improve strain sensitivity or increase the monitoring area. Gutierrez et al. [72] implemented a dual-layer loop configuration within trenches, achieving full-area coverage for regional sensing.



(**a**)

(**b**)

**Figure 5.** Common embedded fiber placement methods: (**a**) Directly buried fiber optics. (**b**) Embedded fiber optic fabrics.

In bridge applications, fiber sensors are typically installed on key structural components, including main girders, decks, bearings, and cable stays, to monitor strain and stress under traffic loads, displacement at critical points, and crack formation. These fibers are often internally embedded along the longitudinal axis of the girder or within the deck concrete using slotting techniques. When monitoring deck loading is a priority, fibers can also be externally bonded to the supporting beams through adhesive-based methods.

Tunnel monitoring involves three main deployment approaches: (i) Circumferential layout. Fibers are arranged along the circular cross-section of the tunnel lining and fixed using grooving, bonding, or pre-embedding before concrete casting. Depending on monitoring needs, fibers may be positioned at different heights, like the crown, sidewalls, and invert. They can also be installed across various tunnel sections, such as the portal, midsection, and exit, to assess the stress distribution across key regions. (ii) Longitudinal layout involves deploying one or more fibers continuously along the tunnel axis and fixing them to structural surfaces, including the crown, walls, or base, using either internally embedded or externally bonded methods. (iii) Helical layout. Fibers are arranged in a helical path along the inner or outer surface of the lining, either covering the entire structure or focusing on specific zones. In a few cases, trapezoidal layouts have been adopted, where fibers follow a stepwise path along the tunnel wall to capture stress and deformation at various vertical positions.

These deployment strategies are selected based on the structure type, monitoring objectives, and surrounding conditions. Ultimately, the goal is to ensure strong coupling between the fiber and the host material, enabling reliable and accurate acquisition of structural health data.

## 4. Applications of Brillouin Scattering-Based DOFS in Transportation Engineering

During its long-term service, transportation infrastructure undergoes gradual structural changes and degradation, which can compromise its safety and stability. Therefore, SHM is crucial to ensure structural integrity and enable timely maintenance and repair. DOFS has demonstrated great potential in real-time monitoring of the structural health of various transportation engineering infrastructures [16]. Figure 6 provides an overview of DOFS applications in transportation infrastructure. SHM systems typically measure structural and environmental parameters such as temperature, strain, pressure, deformation, vibration, and acceleration.

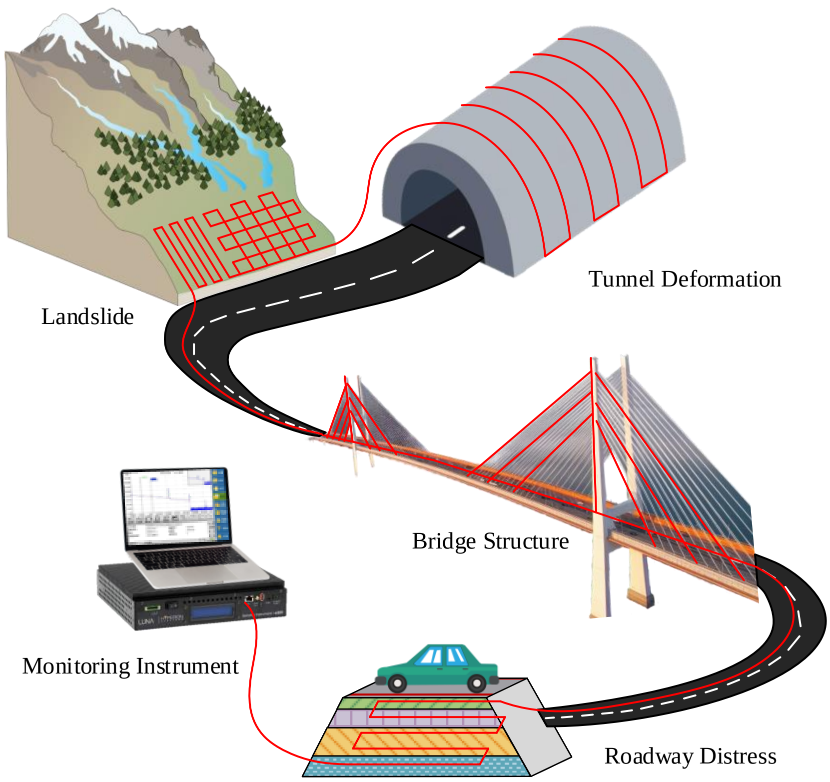



**Figure 6.** Distributed fiber optic sensing technology for transportation applications.

Compared to conventional sensing technologies, optical fiber sensing offers significant advantages for structural health monitoring (SHM), including high sensitivity, all-solid-state construction, no moving parts, and long service life. Among these, Brillouin scattering-based distributed optical fiber sensing (DOFS) stands out for its ability to perform real-time, distributed measurement of both strain and temperature by leveraging advanced electronic signal processing. This enables continuous and accurate monitoring of key structural parameters. Moreover, its compatibility with passive optical communication networks allows for wide-area deployment and remote infrastructure management, which is particularly valuable in transportation systems. Given its long sensing range, dual-parameter capability, and high reliability in harsh environments, Brillouin-based DOFS has emerged as a leading solution for infrastructure monitoring in the transportation field. Its comparative advantages over Rayleigh- and Raman-based techniques—such as broader coverage, better mechanical robustness, and applicability to standard single-mode fibers—provide a clear rationale for its widespread adoption in roadway, bridge, tunnel, and rail monitoring [37].

### 4.1. Roadway Monitoring

DOFS can be broadly categorized into two key areas for roadway monitoring: road structure monitoring and road traffic monitoring. This paper primarily focuses on using Brillouin optical fibers for road structure monitoring to identify various deformations, like settlement, subsidence, and cracks in the roadbed and pavement, along with analyzing slope stability. In contrast, road traffic monitoring involves tracking traffic flow, vehicle speed, and related indicators, typically achieved using Rayleigh scattering-based DOFS.

#### 4.1.1. Subgrade Settlement

Subgrade settlement occurs when the roadbed sinks due to factors like loose soil structure or prolonged vehicle loads. This movement can trigger a range of additional problems, including further subsidence and cracking, potentially compromising traffic safety and the road's longevity. Hence, real-time monitoring of subgrade settlement is crucial to maintaining road traffic safety and ensuring the functionality of the road.

Traditional measurement techniques often rely on manual measurements or fixed sensor setups, which face challenges such as low monitoring efficiency, limited coverage, and incomplete data collection. Even so, new monitoring technologies have introduced more effective solutions, though certain limitations still exist in practical applications [87], as shown in Table 4. DOFS technology enables real-time monitoring across the entire road section, offering a low-cost solution and providing robust technical support for accurate subgrade settlement monitoring.

Liu et al. [88] proposed a solution for monitoring subgrade settlement based on BOTDR technology, using finite element analysis to understand the deformation patterns and main influencing factors of new and old roadbeds. Their study verified the feasibility of DOFS for monitoring soil and gravel settlement. To eliminate stress transfer errors between the optical fiber and road materials, Jiang et al. [89] used armored cables to protect the fibers and employed epoxy resin clamping blocks to ensure stress transfer between the optical fiber and the road structure. They also applied both BOTDA and BOTDR to monitor subgrade strain distribution in freeze–thaw regions, proving the effectiveness of optical fiber sensing in detecting internal structural changes and early road damage. Still, due to the extremely low temperatures outdoors, only surface temperature compensation was applied, which led to some uncertainties in the data.

To improve measurement accuracy, Tom et al. [90] used temperature-compensated optical cables and steel strand strain sensing cables to obtain strain and temperature data. Using inverse calculation, they derived subgrade settlement values and conducted monitoring on the highway roadbed. However, this study lacked comparison with other measurement devices at different locations. Wang et al. [91] employed BOTDA to monitor subgrade settlement, and the analysis of strain variations confirmed the feasibility of using a zigzag fiber deployment configuration. Xu et al. [92] proposed a long-distance subgrade settlement localization and quantitative monitoring method for high-altitude permafrost regions, using longitudinally and fixed-point embedded strain-sensing cables. The effectiveness of this method was validated through inverse analysis based on local and regional strain measurements, further confirming the applicability of DOFS for settlement monitoring in complex environments.

**Table 4.** Roadbed settlement monitoring techniques.

| Categories | Monitoring Technique | Working Principle | Applicable Settlement Type | Limitations |
|---|---|---|---|---|
| Traditional surveying techniques [93] | Accelerometer | Measures changes in vertical acceleration | Static settlement | Cannot capture vibration or temperature; weak electromagnetic resistance; susceptible to interference |
| | Strain gauge | Measures strain variation | Dynamic settlement | |
| | Inclinometer compass | Monitors tilt angle and rotation of structures | Lateral settlement | |
| | Monitoring pile method | Monitors pile height variation (periodic measurement) | Surface settlement | Labor-intensive, not suitable for continuous or automated monitoring |
| | Hydrostatic leveling system | Water level-based inference | | Complex installation, limited accuracy in uneven soil conditions |
| | Settlement plate method | Measures vertical displacement via a reference plate | Surface settlement; shallow settlement | Not suitable for hard soils |
| | Multipoint settlement gauge | Monitors settlement at multiple depths | Layered settlement | Complex installation; costly |
| | Cross-sectional settlement gauge | Detects variations in cross-sectional profile | Cross-sectional settlement | Complex operation; limited scope |
| | Horizontal inclinometer | Measures horizontal tilt changes | Lateral settlement; tilt deformation | Sensitive to vibration |
| Advanced or semi-automated techniques | Vehicle-mounted ground penetrating radar [94] | Electromagnetic reflectometry and GPS correction monitoring | Surface settlement; subgrade anomalies | Increased cost and complexity; limited to surface deformation |
| | Interferometric synthetic aperture radar [95] | Derives settlement displacement from radar image phase difference | Large-area settlement | Technically demanding and costly for long-term monitoring |
| | Distributed optical fiber sensing [21] | Measures strain/displacement via changes in optical signal | Layered settlement; cross-sectional settlement | Requires pre-embedded optical fiber layout |
| | 3D laser scanning [96] | Reconstructs displacement field using 3D point cloud | Surface settlement; structural settlement | Sensitive to reflectivity; limited by obstructions |
| | Satellite-based differential interferometric synthetic aperture radar [97] | Analyzes settlement via multitemporal synthetic aperture radar image differencing | Large-scale differential settlement | Long revisit time; limited timeliness |

Although traditional BOTDR and BOTDA technologies have application value for long-distance strain and temperature distribution measurements, their spatial resolution is limited, making it difficult to achieve synchronous detection of small, localized strains. To address this issue, Kishida et al. [98] first proposed the pulse pumped Brillouin optical time domain analysis (PPP-BOTDA) technique, which uses a long-duration pulse to stimulate phonons in the fiber before a narrow-bandwidth pulse arrives, improving the precision of Brillouin frequency recognition. This advancement enhances both strain and temperature measurement accuracy and spatial resolution. In this method, a long-duration pre-pump pulse excites phonons before a short-duration pump pulse, improving Brillouin frequency shift accuracy, strain and temperature precision, and spatial resolution [99,100]. Based on this breakthrough, Wei et al. [83] introduced a novel zigzag fiber layout method to simulate subgrade settlement at regular intervals in highway monitoring areas. Experimental results demonstrated that this new layout method significantly improved monitoring accuracy, providing more reliable technical support for subgrade settlement monitoring.

#### 4.1.2. Pavement Cracking

Pavement cracking, one of the most common forms of distress in road infrastructure, significantly reduces the performance and service life of roads. In the field of crack monitoring, surface detection technologies like laser scanning, digital image processing, and video measurement are predominantly used. Although the measurement accuracy of these methods is often influenced by factors like ambient lighting and surface texture, they are still widely used. Moreover, traditional monitoring techniques, which rely on sensors like strain gauges or vibration extensometers, require dense sensor arrays, leading to high monitoring costs and limited economic benefits. In contrast, DOFS provides several advantages, with the ability to measure continuously along the fiber path and be embedded within road structures. This has demonstrated significant potential in the field of pavement crack monitoring [21,77].

In the research of distributed optical fiber crack monitoring technology, several innovative methods have been proposed. One approach suggests deploying distributed optical fibers at an angle to intersect with concrete cracks. This method requires minimal fibers and can monitor cracks over a large area without prior knowledge of the crack's position, demonstrating the feasibility of using oblique optical fiber networks for crack monitoring in concrete [80]. A method for crack analysis based on Brillouin scattering spectra (BSS) data was introduced [101]. This method, which analyzes the maximum strain variations within the spatial resolution range of each measurement point along the fiber, allows for precise crack localization. The experimental results indicate that it can accurately locate and evaluate narrow cracks smaller than 23 mm, addressing the spatial resolution limitations of traditional techniques. Cui et al. [102] developed a new asphalt pavement crack monitoring method by introducing polymer materials into the crack modulator. They established a quantitative relationship between crack parameters and optical power loss based on the bending characteristics of the optical fiber at the crack site. Their study confirmed that the bending radius of the fiber and optical loss are positively correlated with crack width, providing a theoretical basis for pavement crack prediction. Liu et al. [103] developed a Brillouin distributed optical fiber-based crack monitoring sensor for roadbed structures and successfully applied it to an experimental section of a highway in Dalian. Field tests demonstrated that the sensor offers high survival rates, exceeding 9%, as well as high detection accuracy with a margin of error of ±0.1 mm. Additionally, it provided precise quantification of structural changes, fully validating its practicality and reliability for monitoring pavement structural performance.

Despite the high spatial resolution of Brillouin-based DOFS, which allows for the measurement of surface strain distribution, there are still some limitations in crack detection applications due to the relatively low SNR in measurements. To address this issue, Song et al. [104] proposed a micro-crack detection method based on deep learning. By analyzing strain measurement data across a wide range of scales, they successfully extracted high-precision micro-crack features from low SNR distributed strain measurements, significantly improving detection performance.

In practical applications, Bao et al. [84] developed a crack detection system for highway pavements based on PPP-BOTDA. They embedded the distributed PPP-BOTDA sensor in a U-shaped configuration within a concrete slab and conducted strain and crack detection under truck load conditions. This further demonstrated the feasibility and reliability of embedded distributed optical fiber sensors in structural health monitoring.

#### 4.1.3. Surface Subsidence

Surface subsidence, also known as ground sinking or surface depression, refers to the vertical displacement of the ground caused by the compaction of loose underground layers, either due to natural factors or human activities. This geological disaster poses a serious threat to road infrastructure and the safety of public life and property. The DOFS technology, with its wide coverage and real-time monitoring advantages, provides an effective solution for early warning and damage prevention of surface subsidence, playing a critical role in ensuring transportation safety.

In coastal cities with water-saturated soil structures, significant subsidence occurs under external loadings, a process mainly caused by water drainage and soil consolidation. This subsidence can be quantified through vertical displacement measurements [105]. One study [64] demonstrated this by deploying three types of optical fiber sensors—polyurethane-sheathed cable, metal-reinforced cable, and fixed-point cable—in a borehole. Using BOTDR and FBG technologies, the researchers monitored surface subsidence in Suzhou. Their study showed that vertical displacement could quantify the subsidence caused by drainage consolidation, allowing for precise strain analysis in water-saturated layers. Shi et al. [106] took into account the coupling between optical cables and soil deformation. Using drilling technology for full-section fiber monitoring, their approach effectively monitored soil deformation and subsidence at a lower cost. Based on these findings, studies like [86,107] applied BOTDR technology in different regions, combining analyses of engineering loads and soil microstructure to refine subsidence monitoring in coastal areas. This approach improved the tracking of movement, deformation, and subsidence trends across various soil layers.

In addressing the key scientific issue of fiber coupling with soil layers and backfill materials, Liang et al. [108] developed a land subsidence prediction model. Their drilling-based full-section fiber monitoring system allowed for continuous deformation monitoring of different road structure layers, providing effective evaluation and prediction of subsidence in areas with severe uneven subsidence. Zhang et al. [109] carried out long-term subsidence deformation monitoring in Suzhou, establishing a strain transfer model to study the impacts of soil, backfill materials, and fiber optics, thereby offering valuable theoretical support for precise distributed fiber monitoring in drilled soil profiles.

Futhermore, Hauswirth et al. [110] first achieved high-precision measurement of horizontal strain through fiber optic embedding. They also explored a displacement evaluation and prediction method based on strain measurement, verifying the significant advantages and application prospects of optical fiber sensing technology in underground engineering monitoring. In the development of a cement concrete pavement vibration distributed sensing system, Zeng et al. [78] realized the fusion analysis of multi-dimensional data in time, space, and frequency domains. In another study, Lu et al. [111] used BOFDA technology to construct a distributed monitoring model for soil subsidence deformation. By comparing and analyzing the collapse processes of different types and thicknesses of soil, they demonstrated the feasibility of this technology. One study [112] combined FBG and BOTDR technologies to propose a multi-layer pavement structural health monitoring system design, achieving real-time monitoring of subgrade settlement and rutting information. Cheng et al. [113] successfully validated the effectiveness of distributed optical fiber strain sensing technology in monitoring ground subsidence caused by underground voids in indoor model experiments, using BOFDR technology combined with the sequence-to-sequence (Seq2Seq) strain–displacement conversion method. In [114], a two-dimensional deformation monitoring method based on BOTDA technology was proposed. The researchers conducted indoor simulation experiments on horizontal displacement and subsidence data in geotechnical environments, demonstrating the superior performance of this method in soil deformation monitoring.

In the field of asphalt pavement monitoring, Xiang et al. [115] developed an innovative flexible asphalt–resin encapsulated fiber optic sensor. This sensor optimizes the protective layer design to effectively eliminate strain transfer errors and allows for comprehensive monitoring of distributed strain, temperature, and the effects of traffic loads on pavement performance. Field applications demonstrate that this sensor accurately detects the distributed strain on asphalt pavements and quantitatively analyzes the impacts of temperature and traffic loads, providing reliable technical support for the health monitoring and performance evaluation of large-span pavements.

Regarding karst collapse monitoring, Jiang et al. [116] conducted large-scale physical simulation experiments to study the application of optical fiber sensing technology. The study revealed that the optical fiber strain peak could precisely locate the collapse position; strain variations at different depths reflected the vertical soil layer disturbance process, and time-series strain trends could reveal the development of horizontal disturbances. These findings confirmed the feasibility of optical fiber sensing technology in karst collapse monitoring. However, many critical technical challenges arising from the principles of optical fiber sensing technology, combined with the concealed and sudden nature of karst collapses, still need to be addressed. Meng et al. [85] proposed solutions from three perspectives: environmental temperature interference, fiber–soil synchronous deformation, and prediction models. By innovatively using a multi-layer grid deployment method and establishing a strain peak model, they significantly improved monitoring accuracy. Futhermore, Gutierrez et al. [72] successfully monitored the rapid subsidence of a sinkhole using BOTDA technology, with fiber optic strain data aligning well with level measurement results in both time and spatial dimensions.

Building upon conventional techniques, Chai et al. [117] developed a three-dimensional numerical model based on the Mohr–Coulomb criterion. They employed PPP-BOTDA to reveal the three-phase surface deformation characteristics in coal mining subsidence areas—namely initiation, gradual deformation, and sudden collapse. This work demonstrates the technical superiority of this method for ground surface monitoring. Dong et al. [79] further proposed a novel approach for subsidence monitoring using PPP-BOTDA. By deploying the optical fiber in a zigzag configuration, they achieved a transformation of horizontal strain data into vertical displacement information, effectively addressing the challenge of vertical displacement measurement in DOFS systems. This method demonstrated high precision, efficiency, and long-distance capability, highlighting its strong application potential.

#### 4.1.4. Slope Instability

Slope stability monitoring is a crucial part of highway safety. Because of complex geological conditions and frequent engineering activities, slope deformation and failure have become one of the most severe hazards affecting road infrastructure. Monitoring slope deformation and stress is of great significance for understanding rock mass evolution, determining displacement patterns, directions, and rates of unstable slopes, and for effectively preventing landslides and collapses, providing scientific support for taking protective measures. One of the urgent technical challenges in monitoring practice is how to optimize sensor placement at key and sensitive locations.

In terms of monitoring technology, Wang et al. [81] applied fiber-optic temperature sensors in slope model experiments, achieving temperature compensation and strain calibration using a grid layout. Although this method is easy to operate, it is limited by the spatial resolution of the sensing technology and the inability to detect stress accumulation, which results in certain measurement errors in practical applications. Iten et al. [118] proposed a novel landslide boundary positioning technology based on BOTDA. By embedding improved fiber-optic sensors beneath the asphalt surface and analyzing data using truncated average and convolution methods, they effectively solved the problem of nonlinear strain–frequency response.

To address the limitations of traditional techniques, Song et al. [119] used an improved PPP-BOTDA technology to monitor distributed deformation fields in a slope model under localized loading at the top of the slope and excavation along the slope face. They established a numerical model to analyze the deformation patterns of the soil under loading and excavation conditions, verifying the feasibility of using this technology for slope deformation field monitoring.

#### 4.1.5. Summary

Brillouin scattering-based DOFS technology has demonstrated unique advantages in the field of roadway structural health monitoring. Numerous studies have shown that this technology, by capturing Brillouin frequency shift characteristics, effectively monitors the integrity of road structures under traffic load, especially in identifying and locating roadbed and pavement issues such as settlement, cracks, and subsidence. Brillouin scattering-based distributed sensing enables real-time detection of strain changes in road structures while continuously tracking the development of microcracks and deformations. By simultaneously sensing the temperature and strain distributions over long distances, this technology can effectively detect and prevent structural damage caused by temperature fluctuations, material aging, corrosion, and overloading, thus providing reliable technical support for extending road lifespan and enhancing safety.

In contrast, there are still several issues that need to be addressed in current research. Firstly, most optical fiber sensor studies are limited to laboratory experiments or closed road sections, lacking long-term monitoring data in real-world traffic environments, which restricts the practical application of the technology. Consequently, it is necessary to conduct long-term monitoring in real traffic conditions to obtain actual data on roadway structural responses, improve fiber survival rates, and optimize measurement accuracy, thereby providing more reliable support for preventive maintenance decisions. Secondly, Brillouin scattering-based fiber optic sensing technology is sensitive to environmental conditions, and the coupling effect between temperature and strain can affect the accuracy of measurement results. To address this, researchers have proposed several compensation and correction methods, including the following: (i) Dual-fiber method. Using the primary fiber to measure strain and temperature, and the compensation fiber to measure only temperature; (ii) Dual-wavelength method. Using different wavelengths of light signals to distinguish between strain and temperature effects; (iii) Fiber strain gauge-assisted method. Independently measuring temperature to correct strain data. These methods have improved measurement reliability to a certain extent.

In practical applications, DOFS technology still faces challenges such as insufficient standardization and complex data processing. The large volumes of data generated during monitoring require efficient data storage, processing, and analysis systems to accurately identify structural anomalies. Furthermore, the integration of multiple sensors poses higher demands on the speed and accuracy of data fusion. Despite these challenges, as Brillouin scattering technology continues to mature and optimize, it shows tremendous application potential in roadway structural health monitoring, with promising prospects for future development.

### 4.2. Bridge Monitoring

As a vital component of transportation infrastructure, bridge health monitoring has become a crucial field for the application of optical fiber sensing technology. Brillouin scattering-based distributed optical fibers have demonstrated unique advantages in this domain. These systems help prevent catastrophic failures, significantly reduce downtime and maintenance costs, and optimize operational efficiency while enhancing public safety. In contrast to traditional monitoring techniques—such as using seismometers, anemometers, accelerometers, velocimeters, global positioning systems (GPS), displacement meters, and tuned mass dampers (TMD)—which often face challenges in long-term continuity, measurement precision, and environmental sensitivity, Brillouin scattering-based DOFS has steadily become the preferred solution for long-term monitoring of large-scale bridges over the past two decades.

#### 4.2.1. Applications

Glisic et al. [120] were among the first to apply Brillouin-based DOFS systems for bridge monitoring, utilizing a combination of SMARTape distributed strain sensors and DTS cables to detect cracking along critical load-bearing girders, covering a length of approximately 5 km. This work laid the foundation for subsequent studies. For example, Enckell et al. [69] further advanced the crack detection system by developing a system based on the distributed temperature and strain monitoring system with SMARTape's layered mechanism. This innovation enabled the SMARTape sensors to automatically detect micro-cracks of 5 mm or more. Another significant contribution was made by [121], who used BOTDR technology to measure the strain distribution in steel beams during load testing, validating the technology's effectiveness for bridge structural assessments. Minardo et al. [122] employed stimulated Brillouin scattering in optical fibers to measure the deformation and temperature of the supporting beams along a bridge. By comparing the adhesion effects of two different adhesives—epoxy resin and single-component polyurethane—they validated the effectiveness of the BOTDA method in monitoring large-scale structural deformations.

To address the issue of signal attenuation in long-term monitoring, Glisic et al. [73] embedded both BOTDA and FBG sensors into bridge concrete during construction. Comparative analysis revealed a high level of consistency between the two technologies in non-defective areas. Still, due to the superior spatial resolution and higher temperature sensitivity of Brillouin scattering, BOTDA demonstrated better overall monitoring performance. Further validation was provided by [123], who conducted a three-year SHM campaign on the Salmon Falls Bridge. Their results confirmed the long-term stability and reliability of BOTDA, with significantly lower standard deviation values compared to BOTDR, highlighting its superior precision in sustained monitoring applications.

Van et al. [75] employed a Brillouin scattering-based system for static and dynamic loading tests on a steel truss bridge, confirming its effectiveness in assessing component behavior and connection performance. Nevertheless, they noted limitations in detecting local strain under dynamic loading. Strasser et al. [124] introduced a novel approach that combines DAS with Brillouin scattering technology, enabling comprehensive monitoring of bridge vibrations and deformations.

In addition to traditional DOFS, researchers have explored improved Brillouin-based sensing methods for bridge applications. Xu et al. [125] were the pioneers in applying the differential pulse-width pair Brillouin optical time domain analysis (DPP-BOTDA) technique to monitor kilometer-scale suspension bridges, marking a significant breakthrough in high-density strain and temperature measurements for large-scale infrastructure. Furthermore, ref. [92] further developed a slope-assisted differential pulse-width pair Brillouin optical time domain analysis (SA-DPP-BOTDA) system to monitor dynamic strain in pile foundations and long-span suspension bridges.

In terms of sensor deployment methods, there is currently no direct comparative study between the two primary optical fiber deployment strategies. Despite this, most existing bridges typically use surface bonding techniques, where optical fibers are fixed to the structure's surface with epoxy resin adhesives, followed by appropriate surface treatments. For bridges still under construction, the embedded deployment method is more commonly applied. Table 5 summarizes the specific deployment methods and related parameters for Brillouin scattering-based distributed optical fiber systems in bridge monitoring.

#### 4.2.2. Summary

Brillouin scattering-based distributed optical fiber sensing technology has proven to be an effective solution for long-term bridge health monitoring. This technology offers high spatial resolution and real-time data on strain, temperature, and stress distribution across key bridge components, enabling precise tracking of deformation, cracks, and displacement. Compared to traditional methods, it provides significant advantages in monitoring large-scale structures with enhanced accuracy and non-invasive capabilities.

In contrast, challenges remain, particularly with signal attenuation over long distances and environmental factors like temperature fluctuations, which can affect sensor accuracy. Despite improvements in sensor design and data processing techniques, there is still a need for further advancements to enhance sensitivity and precision, especially in complex or harsh environments. Future developments should focus on optimizing sensor deployment strategies, improving spatial resolution, and integrating real-time data analytics, which could lead to more accurate and proactive bridge health assessments. With these advancements, Brillouin scattering-based sensing technology has the potential to transform bridge monitoring, ensuring safety, performance, and longevity of infrastructure.

**Table 5.** Summary of Brillouin-based DOFS applications in bridge SHM.

| **Installation Type** | **Sensor Type** | **Monitoring Purpose** | **Sensor Deployment Method** | **Performance Metrics** | **Sensed Variables** | | |
|---|---|---|---|---|---|---|---|
| | | | | | **V** | **T** | $\varepsilon$ |
| Externally bonded | BOTDA [120] | Structural response and crack detection | Optical fibers adhered to steel beams; three SMARTape sensors arranged in series in a straight line; 20 basic loops set on both bridge ends. | Spatial resolution: 1 m<br>Sampling interval: 0.1 m<br>Strain accuracy: ±21 με<br>Sensing range: 5 km | | ✓ | ✓ |
| | BOTDR [121] | Structural response | Optical fibers and temperature-sensing cables glued on the top and middle of web plate with epoxy resin, laid continuously along stiffeners. | Spatial resolution: 1 m<br>Sampling interval: 0.4 m<br>Strain accuracy: ±40 με<br>Monitoring coverage: 150 m | | ✓ | ✓ |
| | BOTDA [69] | Crack detection | Sensors adhered to upper flange of steel beams prone to cracking; clamped at 1 m intervals with metal clips bonded to painted surface. | Spatial resolution: 1 m<br>Sampling interval: 0.1 m<br>Strain accuracy: ±20 με<br>Sensing range: 5 km | | ✓ | ✓ |
| | BOTDA [105] | Crack detection | Standard single-mode PVC-coated fiber adhered to outer side of I-beam; fibers also glued around four strain gauges. | Sampling interval: 0.5 m<br>Strain accuracy: ±50 με<br>Sensing range: 27 km | | | ✓ |
| | DPP-BOTDA [92] | Structural response | Fiber glued with epoxy resin to the inner deck surface along the longitudinal axis of steel box girder. | Spatial resolution: 0.2 m<br>Sampling interval: 0.1 m<br>Strain accuracy: ±2 με<br>Sensing range: 5 km | | ✓ | ✓ |
| | BOCDA [70] | Structural response | Tight-buffered fiber adhered along the steel rail and beams using PET film. | Spatial resolution: 0.31 m<br>Strain accuracy: ±15 με<br>Monitoring coverage: 40.3 m | | | ✓ |

**Table 5.** *Cont.*

| Installation Type | Sensor Type | Monitoring Purpose | Sensor Deployment Method | Performance Metrics | Sensed Variables | | |
|---|---|---|---|---|---|---|---|
| | | | | | V | T | $\varepsilon$ |
| Externally bonded | BOTDA BOTDR [123] | Structural response | Fiber sewn into reinforced fabric forming U-shaped sensor; installed beneath the non-riveted area of the bridge underside. | Spatial resolution: 1 m<br>Sampling interval: 0.1 m | | ✓ | ✓ |
| | BOFDA [124] | Structural response | Fibers vertically adhered across three bridge spans. | Spatial resolution: 0.2 m<br>Sensing range: 80 km | | ✓ | ✓ |
| Internally embedded | BOTDA [73] | Structural response | Two strain and two temperature-sensing fibers embedded in deck cross-section top and bottom, parallel to elastic line. | Strain accuracy: ±40 με | | ✓ | ✓ |
| | BOTDA [126] | Structural response | Fibers embedded in textiles and filled into beam using epoxy resin; laid in U-shaped fiber layout. | Spatial resolution: 1 m<br>Monitoring coverage: 91 m | | | ✓ |

### *4.3. Tunnel Monitoring*

During long-term tunnel operation, various structural issues arise due to the combined effects of complex geological conditions, climate changes, and dynamic traffic loads. Traditional methods, such as inductive sensors, total stations, and high-precision leveling instruments, have proven insufficient for evaluating modern tunnel safety and durability [127]. In contrast, Brillouin scattering-based DOFS technology enables comprehensive monitoring by capturing Brillouin frequency shift characteristics in real-time. This technology allows for the identification of structural defects and design flaws during construction and provides real-time health monitoring during operation, making it widely applicable for tunnel structural health assessment.

#### 4.3.1. Differential Settlement

Differential settlement refers to uneven subsidence along the tunnel structure caused by factors such as uneven foundation or geological conditions, layer deformation, traffic loads, or construction impacts. This results in local deformations in the tunnel structure, affecting its stability and safety.

In practical applications, Li et al. [128] incorporated optical fibers into the tunnel's top lining to monitor subsidence and deformation during the removal of temporary supports. Meanwhile, Zhu et al. [68] utilized BOFDA technology, securing optical fibers to the tunnel lining with fixed fixtures to accurately monitor the longitudinal and axial strain distributions caused by adjacent excavations. In another study, Yao et al. [129] employed BOTDR technology to monitor the health of the tunnel floor structure in expansive rock tunnels, leading to significant improvements in both monitoring performance and system durability. Additionally, Li et al. [130] introduced a diagnostic method that relies on the spatial correlation of high-density strain measurement points, which was validated through numerical simulations and experiments; however, some limitations remain regarding the calculation of actual subsidence.

For shield tunnels, which are typically built in soft or high-moisture content soils, subsidence and soil collapse are more common. Yi et al. [131] embedded distributed optical fibers in a circumferential configuration within the tunnel segment during the segment prefabrication phase. By studying the continuous strain distribution, they verified the safety of structural forces by monitoring segment displacement, internal forces, and external load distribution. Further, Shen et al. [132] introduced an improved conjugate beam method for detecting settlement and lateral displacement in shield tunnels. Li et al. [133] deployed optical fibers in a "Z" shape along the tunnel sidewalls, using BOFDA technology to monitor structural damage in shield tunnels. Wang et al. [134] enhanced DOFS technology by adding plastic tubing protection to the sensors, solving the problem of fiber breakage and successfully enabling long-term monitoring of tunnel structure convergence and subsidence.

In practical engineering applications, tunnels often cover extensive distances and large scales, where localized strain measurements may not accurately reflect the deformation caused by structural damage. To effectively detect tunnel damage, a large number of strain measurement points are necessary, yet this is often impractical. Consequently, enhancing the sensitivity of strain to tunnel damage becomes essential. Liu et al. [135] introduced a tunnel damage detection method based on high-density section curvature, which converts structural strain into tunnel cross-sectional curvature, thereby improving sensitivity and addressing the challenge of insufficient strain sensitivity to structural damage in operational tunnels.

#### 4.3.2. Lining Deformation

In concrete-lined tunnels, shield tunnels, and immersed tube tunnels, various factors such as ground pressure, foundation settlement, rock mass loosening, or external loads can induce deformation in the tunnel lining. Prolonged deformation of the lining may lead to structural failure, affecting normal traffic and operation. Traditional tunnel construction typically relies on continuous face excavation and flexible surface support to ensure short-term stability of the surrounding strata. Therefore, structural monitoring of concrete linings at different stages is essential to minimize disturbances.

During tunnel construction, optical fibers are typically embedded to assess the structural state [64]. Gue et al. [54] applied BOTDA technology in the construction of a tunnel. By embedding optical fibers longitudinally along the tunnel, they successfully achieved precise monitoring of the lining cross-section and continuous longitudinal strain at different stages of construction. Their experiments demonstrated that this method had a relative advantage over traditional displacement measurement using automatic total stations. Following this, the integration of tunnel bolt strain gauges with BOTDR technology was used [136] to further study the overall and local impact of newly constructed tunnels on existing tunnels. Fajkus et al. [137] applied BOTDR technology to monitor structural loads in a highway tunnel for five months. By embedding optical cables in secondary lining support beams with shotcrete, they were able to continuously monitor and analyze Brillouin frequency shifts associated with tunnel loading over time. In another study, Seo et al. [138] employed embedded BOTDR technology to monitor a newly segmented concrete tunnel lining, focusing on the evolution of strain and circumferential loads under different excavation techniques. Hou et al. [139], on the other hand, embedded BOFDA optical fibers onto the concrete surface of the tunnel lining, uncovering the boundary effects of strain transfer between the embedded fibers and the lining itself, which provided valuable insights for optimizing the sensor layout.

Subsequently, scholars proposed a distributed fiber optic sensing method for tunnel cross-sectional deformation, utilizing neural networks to directly obtain the shape strain curve of tunnel sections, effectively avoiding cumulative errors in distance monitoring [127]. Monsberger et al. [140] combined BOTDA fiber optics with geodetic displacement readings to achieve centimeter-level high-resolution monitoring of the tunnel's bent shape. Both [71] and [76] validated the effectiveness of BOFDA technology for assessing strain distributions within tunnel linings. Wu et al. [141] further used finite element analysis to verify the monitoring results of longitudinal and circumferential strains under repeated loading in tunnel linings.

After a tunnel becomes operational, the embedding method is no longer applicable, and optical fibers can be installed on the inner surface of the tunnel lining in two ways—discrete point fixation [142] and continuous bonding.

1. Discrete point fixation. This method is widely used in shield tunnels to effectively monitor localized deformations [143]. Mohamad et al. [144] fixed BOTDR sensors at the top of a tunnel using a tensile meter, successfully monitoring the circumferential strain in a circular tunnel lining. Acikgoz et al. [145] proposed a “hook-pulley” method, offering a new solution for securing optical fibers on masonry surfaces.
2. Continuous bonding. This method provides a continuous strain curve along the entire cross-section, making it particularly valuable for monitoring damaged linings [146]. Sui et al. [142] fixed optical fibers using adhesives, successfully monitoring the lining cracks and circumferential strains caused by adjacent tunnel excavations for one year. Cheung et al. [143] used BOTDR technology to capture joint movement in the concrete lining of the London Underground tunnel, with results highly consistent with traditional strain gauge measurements. Wang et al. [147] bonded optical fibers continuously to the surface of a lining, monitoring the performance of composite material linings.

#### 4.3.3. Joint Displacement

During the long-term operation of tunnels, structures made up of multiple segments, such as those in immersed tube tunnels, shield tunnels, and cut-and-cover tunnels, are susceptible to joint displacement. This displacement can cause stress concentration between adjacent segments, which may lead to cracks, damage, and other structural issues. In severe cases, it can result in local structural instability, compromising the overall safety of the tunnel.

In immersed tube tunnels, it is crucial to monitor the differential settlement of both the immersed and expansive joints for deformation [148]. Zhang et al. [149] developed a combined monitoring system based on DOFS, utilizing a triangular sensor layout to simultaneously measure the horizontal opening and vertical uneven settlement at both types of joints. Through laboratory experiments, they established a quantitative relationship between fiber optic strain and joint deformation. Later, the team optimized the layout by extending the optical cables along the tunnel’s axis [65], enabling precise measurement of seasonal joint deformations in the tunnel and specifically revealing the impact of seasonal temperature fluctuations on joint opening and uneven settlement. In the same year, Kindler et al. [150] embedded distributed Brillouin optical fibers in the ceiling of the Munich subway tunnel for long-term crack monitoring, demonstrating the feasibility of this technology for large-scale continuous crack detection. Moreover, Zhang et al. [151] found a negative correlation between joint opening in immersed tube tunnels and temperature changes, and they showed that distributed fiber optic sensors can be used to perform high-frequency monitoring at 30-minute intervals.

In shield tunnel monitoring, Zhang et al. [152] monitored strain at the circumferential joints of the Chengdu metro tunnel, successfully providing early warnings of joint displacement and accurately identifying the direction of crack propagation. Wang et al. [67] used BOFDA sensor technology to monitor the joint sections of the Suzhou metro tunnel with high precision, providing reliable data to support the health assessment of tunnel structures.

#### 4.3.4. Summary

In terms of practical application, Brillouin scattering-based DOFS has been used effectively to monitor ground subsidence, structural deformation, and strain variations during tunnel construction and operation. It has proven to be valuable in detecting potential hazards such as cracks and misaligned joints, with an ability to capture subtle changes over extended periods and under harsh conditions. Additionally, it provides accurate monitoring for a variety of tunnel types, including shield tunnels and immersed tube tunnels, where traditional methods might struggle. However, challenges remain in addressing factors like signal attenuation and achieving high spatial resolution over long monitoring distances. Further research is needed to improve the technology's capability in monitoring fine-scale deformations, such as those that occur due to minor shifts in tunnel sections. In particular, optimizing sensor deployment and improving data processing algorithms are key areas for future advancement.

## 5. Conclusions

This paper provides a systematic review of the classification and working principles of DOFS technology, with a focus on the application progress of Brillouin scattering-based DOFS in the structural health monitoring of transportation infrastructure. By analyzing typical monitoring cases of roadways, bridges, and tunnels, it is shown that Brillouin scattering-based DOFS plays a key role in infrastructure deformation monitoring by precisely detecting structural strain changes. In recent years, significant breakthroughs have been achieved in sensing distance, measurement accuracy, and spatial resolution, leading to the development of various improved sensing technologies, which are widely applied in transportation engineering and structural health monitoring. With the rapid development of artificial intelligence and big data technologies, DOFS technology is evolving towards greater intelligence and precision.

Based on the current state of research both domestically and internationally, the challenges and future development directions of Brillouin scattering-based DOFS in large-scale structural health monitoring are as follows:

1. The monitoring accuracy of distributed optical fiber sensors is closely related to parameters such as the modulus of the encapsulation material and the fiber embedding location. Currently, there is a lack of unified fiber installation standard guidelines. In practice, reliable fiber bonding technologies and installation plans are relied upon [63]. In the future, it is necessary to establish standardized encapsulation and installation protocols to ensure that sensors accurately reflect the true health status of structures.
2. Temperature, strain, and vibration can all cause signal variations in optical fiber sensors, requiring the elimination of temperature and vibration effects on strain measurement data. Typically, multiple optical fiber sensors are set up to differentiate strain and temperature effects. One fiber sensor simultaneously measures both temperature and strain, while another is only sensitive to temperature and not influenced by strain. By simultaneously measuring the signal changes of these two fibers, the temperature effect on strain measurement can be effectively compensated for and eliminated. For vibration signals, frequency-domain analysis or signal processing techniques, such as bandpass filters and Fourier transforms, can be used to separate high-frequency vibration signals from low-frequency strain signals. Additionally, wavelet transformation can be used to de-noise environmental noise, further eliminating its interference with strain data, thereby improving the precision and reliability of structural monitoring data.
3. In terms of data processing, it is essential to conduct in-depth research on multi-source data fusion and inversion analysis methods to comprehensively assess structural responses, moving beyond the analysis of single strain or temperature data. With ongoing technological advancements, key future research directions include improving data management and processing technologies, achieving real-time automated moni-

toring of infrastructure, developing real-time Brillouin frequency shift demodulation techniques, constructing intelligent data management platforms, and promoting the implementation and application of the "smart infrastructure" concept.

4. Compared with other scattering types, Brillouin scattering-based DOFS offers significant advantages such as long measurement distances, high accuracy, and dual-parameter sensing. Nevertheless, a key challenge that remains is how to further improve spatial resolution while achieving long-distance, continuous monitoring in order to enable higher precision detection over long distances. Future research should focus on optimizing sensor design and data processing methods to balance the relationship between measurement range and resolution, enhancing the overall performance of the system and expanding its application areas.

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