Expert Profile

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Abstract

Distributed and quasi-distributed optical fiber sensors have attracted considerable attention in engineering structural measurement, intelligent health monitoring, and early warning systems owing to their advantages of low cost, high accuracy, and long-term stability in full-scale testing of long-distance, large-span, and super high-rise structures. Due to the silica material characteristics of slender optical fibers, encapsulation protection is required when continuously measuring parameters such as strain and temperature in practical engineering structures over the long term, so as to improve the effective service life of sensors. In static and dynamic deformation measurement, the measurement of structural strain by encapsulated optical fibers can be equivalent to a strain transfer model of a multilayer medium structure. Strain transfer theory can guide the encapsulation process design of optical fiber sensors and improve their measurement accuracy, long-term stability, and durability, thereby enabling accurate inversion of structural characteristic parameters. On the basis of accumulated high-quality massive monitoring information, structural theory and mathematical analysis methods need to be integrated to identify and diagnose global and local structural damage, and to develop safety and early warning assessment methods for service states, thereby providing scientific guidance for the intelligence and automation of structural health monitoring systems. Therefore, this study mainly introduces the design and application history of engineered optical fiber sensing devices and, based on more than ten years of research achievements by the research group in strain transfer theory, systematically, deeply, and comprehensively discusses the core ideas of durable design for point, quasi-distributed, and distributed optical fiber sensing devices as well as inversion analysis methods for measured structural parameters, thereby enabling accurate interpretation of characteristic parameters of engineering structures and diagnosis of structural health or safety states. Furthermore, this study reviews structural damage identification methods based on massive monitoring data processing and modal parameter estimation, as well as the current research status of structural state assessment based on multi-source monitoring information, and presents the current application status and trends of artificial intelligence algorithms in structural damage identification and state assessment. From the hardware and software perspectives, this study provides feasible, reliable, and effective scientific support for the optimized design of sensing devices and sensor network architectures in structural health monitoring systems, the functional upgrading of core damage identification and state assessment modules, and intelligent and lightweight operation.

Full Text

Expert Profile

Wang Huaping has long been engaged in research on the development of intelligent fiber-optic sensing devices, theoretical analysis of strain transfer, characterization of the service state of composite structures, structural damage identification and fault diagnosis, and full-scale monitoring of multilayer medium structures. She has won the Second Prize of the Science and Technology Award of the Gansu Society of Civil Engineering and Architecture, and the winning prize in the Western Division rematch of the 2nd "Yuan Chuang Cup" Innovation and Creativity Competition. As first/corresponding author, she has published more than 70 SCI/EI papers in authoritative journals such as *Composite Part B: Engineering* and *Journal of Lightwave Technology*, and has been granted 16 invention patents. She has led one Young Scientists Fund project of the National Natural Science Foundation of China, three foreign-expert projects of the Ministry of Science and Technology, one Longyuan Youth Innovation and Entrepreneurship Talent Team project of Gansu Province, one university-teacher innovation research project of the Gansu Provincial Department of Education, one key R&D program project of Gansu Province, one industry-support plan project of the Department of Education, one scientific and technological breakthrough project, and one SME innovation project; she has also led one Hong Kong–Macao–Taiwan cooperative research project and one CNOOC cooperative horizontal project. She serves as an editorial board member of the international SCI journal *Reviews on Advanced Materials Science*, an editorial board member of the EI journal *Structural Durability & Health Monitoring*, and a young editorial board member of journals including *Journal of Traffic and Transportation Engineering* and *Chinese Journal of Applied Mechanics*.

Research Progress on Fiber-Optic Sensing Information-Driven Methods for Structural Characteristic Parameter Inversion, Damage Identification, and Condition Assessment

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Abstract: Distributed and quasi-distributed fiber-optic sensors, owing to their advantages of low cost, high precision, and long-term stability in long-distance, large-span, and super-high-rise full-scale structural testing, have received great attention in engineering structural measurement as well as intelligent health monitoring and early-warning systems. Because of the material characteristics of silica in small-diameter optical fibers, encapsulation protection is required when continuously measuring parameters such as strain and temperature in actual engineering structures over the long term, thereby improving the effective service life of the sensors. In static and dynamic deformation measurement, the structural strain measured by an encapsulated optical fiber can be equivalent to the strain transfer model of a multilayer medium structure. Through the guidance of strain-transfer theory for the packaging-process design of fiber-optic sensors, the accuracy, long-term stability, and durability of fiber-optic sensor measurements can be improved, thereby realizing accurate inversion of structural characteristic parameters. On the basis of the accumulation of high-quality massive monitoring information, structural theory and mathematical analysis methods need to be integrated to identify and diagnose global and local structural damage and to develop service-state safety and early-warning assessment methods, thereby providing scientific guidance for the intelligentization and automation of structural health monitoring systems. Therefore, this study mainly introduces the design and application history of engineering fiber-optic sensing devices and, based on more than ten years of research achievements by the research group in strain-transfer theory, systematically, thoroughly, and comprehensively discusses the core ideas of durable design for point, quasi-distributed, and distributed fiber-optic sensing devices and inverse analysis methods for measuring structural parameters, thereby realizing accurate [[unclear: text continues on next page]]

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interpretation and structural health or safety-condition diagnosis. Furthermore, it reviews the current status of research on structural damage identification methods based on massive monitoring-data processing and modal-parameter estimation, and on structural condition assessment based on multi-source monitoring information, and presents the current status and trends in the application of artificial-intelligence algorithms to structural damage identification and condition assessment. From both hardware and software perspectives, this study provides feasible, reliable, and effective scientific support for the optimized design of sensor components and sensing-network architectures in structural health monitoring systems, as well as for the functional upgrading, intelligentization, and lightweight operation of core damage-identification and condition-assessment modules.

Keywords: optical fiber sensor; strain transfer theory; measurement mechanism; characteristic-parameter estimation; damage identification; condition assessment

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Optical fiber sensing information driven structural feature parameter reflection, damage identification and state assessment: a review

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Abstract: Distributed and quasi-distributed optical fiber sensors have attracted great attention in the field of structural measurement, smart health monitoring and warning system due to their outstanding advantages such as low cost, high precision, and long-term stability in full-scale testing of long-distance, large-span, and super high-rise structures. Owing to the silica material and slender diameter of optical fibers, packaging and protection measures are required during long-term continuous measurement of strain and temperature parameters of actual engineering structures, so as to improve the effective service life of the sensors. The strain measurement of the structure using the packaged optical fiber can be equivalent to a strain transfer model of a multi-layer medium structure. Therefore, strain transfer theory plays a critical role in guiding the packaging process design, thereby realizing accurate inversion of structural characteristic parameters, preventing interface damage between the packaged optical fiber sensor and the measured structure, and improving the accuracy, long-term stability, and durability of distributed and quasi-distributed optical fiber sensors in engineering structure measurement. Based on the accumulation of high-quality and massive monitoring information, it is necessary to integrate structural theory and mathematical analysis methods to identify and diagnose damage in both the overall and local structures. This approach aims to develop safety and early-warning assessment methods for the service condition, thereby providing scientific guidance for the intelligent and automated operation of structural health monitoring systems. Therefore, this review aims to mainly introduce the design and application course of engineering optical fiber sensors. Based on over a decade of research by our group on strain transfer theory, we will systematically and comprehensively discuss the core ideas related to the durable design of point-type, quasi-distributed, and distributed optical fiber sensors as well as the inversion analysis methods for measuring structural parameters, so as to realize an accurate interpretation of engineering structural characteristic parameters and the diagnosis of structural health or safety status. Furthermore, this review summarizes the structural damage iden-

tification methods based on massive monitoring data processing and modal parameter estimation, as well as the current research on structural condition assessment using multi-source monitoring information. It also discusses the application status and trends of AI algorithms in the fields of structural damage identification and condition assessment. The review provides feasible, reliable, and effective scientific support for optimizing the design of sensor devices and sensing network architectures in structural health monitoring systems, upgrading the core damage identification and condition assessment modules, and achieving intelligent and lightweight operation at both hardware and software levels.

Key words: optical fiber sensor; strain transfer theory; measurement principle; feature parameter recognition; damage identification; state assessment

Large-volume oil and gas storage tanks, long-span bridges, long-distance high-speed railways, pipelines, tunnels, and other energy and transportation infrastructure structures, when subjected to harsh service environments such as wind loads, earthquake actions, temperature and humidity, and foundation settlement, may undergo degradation of structural performance. To avoid casualties and economic losses caused by sudden structural failure, health monitoring of such important structures is of paramount importance. Structural health monitoring (SHM) is an intelligent method that tracks and monitors structural performance throughout the service process, identifies damage, evaluates health status, and, through the identification of early defects, carries out timely maintenance, extends structural service life, reduces maintenance costs, and provides warning of potential safety hazards; it has been widely recognized in the industry[^1-^8]. A complete SHM system includes core links such as target-parameter sensing technology, data acquisition and transmission, big-data-based system identification and damage diagnosis, modal analysis and model updating, structural-state interpretation, structural safety and integrity maintenance management, remaining service-life prediction, and disaster early warning[^9-^14]. Among these subsystems, advanced sensors are the most fundamental and critical component; their performance directly determines the accuracy and reliability of structural observation information, as well as the validity of structural condition assessment results[^15-^19].

Fiber-optic sensors are among the most promising sensing technologies. Compared with electronic sensors such as piezoelectric sensors, capacitive sensors, and strain gauges, they have many outstanding advantages: small volume, light weight, corrosion resistance, immunity to electromagnetic interference, good electrical insulation, low cost, suitability for absolute measurements, high sensitivity, flexible and diverse geometries, multiplexing capability, low transmission loss, and the ability of a single optical fiber to realize multipoint sensing; moreover, during construction they can be conveniently embedded and integrated into the host material[^20-^26]. Among them, distributed optical fiber sensors for full-scale measurement and fiber Bragg grating (FBG) sensors for local measurement are the two most widely used classes of sensors. They have been extensively applied to monitor parameters such as strain, temperature, pressure, displacement, and acceleration in engineering structures[^27-^30]. With the development of new demodulation technologies, distributed acoustic sensing (DAS) systems can convert vibration or acoustic-wave signals in the environment along a distributed optical fiber into changes in optical intensity or phase, thereby realizing the perception of vibration or acoustic-wave information[^21]. Because DAS systems are highly sensitive to environmental noise, and because the large data volumes brought by high sampling frequencies are often used independently for perimeter security monitoring or underwater structural and biological information detection. Distributed and quasi-distributed fiber-optic sensing technologies have received great attention in the field of engineering structural health monitoring owing to their low cost at large scales and high-precision measurements. Since the optical fibers used in sensing are mainly composed of silicon dioxide, this brittle characteristic makes bare fiber-optic sensors difficult to withstand the harsh construction environments and service conditions encountered in engineering. Therefore, when measuring actual engineering structures, in order to achieve effective and long-term testing of structural strain and temperature, fiber-optic sensors must be packaged and protected so as to improve their effective service life. The protective layer must have the capacity to withstand shear, torsion, or extrusion, ensuring that the sensor can operate normally after installation. At the same time, sufficient bonding strength must be guaranteed to prevent measurement failure caused by debonding of the sensing fiber at the interface[^31-^34]. For special structures such as multilayer asphalt pavements, the protective layer must also withstand the high temperature and high pressure during construction[^35-^37]. For installation methods such as surface bonding and embedding, the main characteristics of the packaging layer also need to be differentially designed according to the features of the measured structure[^38-^40]. Overall, by packaging sensing optical fibers with different materials, measurements of multiple target parameters can be realized, and the potential applications of packaged fiber-optic sensors in various engineering projects will continue to attract more attention and recognition.

In deformation measurement, the essence of measuring structural strain with packaged optical fibers can be equivalently regarded as a strain-transfer model of a multilayer medium structure. Therefore, strain-transfer theory can be used to guide the packaging process and application design of point-type, quasi-distributed, and distributed fiber-optic sensors under different measurement conditions (such as static strain, dynamic strain, and temperature), thereby achieving accurate inversion of structural characteristic parameters. Because packaging methods differ, the methods for converting fiber-optic measurement signals into structural characteristic parameters through parameter-inversion analysis also differ. At the same time, local damage (such as debonding or warping) at the contact interface between the packaged fiber-optic sensor and the measured structure will also affect measurement accuracy. By understanding the interfacial action mechanism and related influencing factors, one can, in the packaging application design of fiber-optic sensors, focus on how to avoid interfacial debonding damage as much as possible, so as to maintain the long-term validity and reliability of fiber-optic sensor measurement data.

Since the 1990s, scholars have carried out extensive investigations into the strain-transfer mechanism of fiber-optic sensors[^41]. Early studies focused on the case in which the modulus ratio between polymer and quartz glass was 1/200, and explored the strain relationship between concrete and sensing optical fibers[^42]. The embedded fiber-optic sensing model was simplified into an infinitely elastic cylindrical model, and the strain-transfer mechanism was analyzed using plane-strain theory[^43–45]. However, these simplified theoretical analyses involve assumptions that differ from actual models, making it difficult to determine the strain-transfer relationship accurately. Until 1998, based on the stress-transfer theory for fiber-reinforced composites[^46], relevant scholars established the systematic strain-transfer theory for embedded three-layer structures[^47]. Thereafter, for multilayer fiber-optic sensing models under different damage types and loading modes, scholars conducted a series of strain-transfer analyses: to account for the influence of local interfacial slip on strain-transfer efficiency, they investigated the strain-transfer relationship of a two-layer matrix-material-optical-fiber model[^48]; studied the uniform strain-transfer relationship of multilayer structures with different coating layers[^49]; proposed an improved strain-transfer analysis method for a three-layer sensing model by simplifying the geometry and physical functions[^50]; established the strain-transfer relationship of a four-layer sensing model by considering the pure shear deformation of the protective layer and adhesive layer[^51]; extended strain-transfer analysis to the special case of considering the viscoelastic material properties of monitored structures[^52]; for surface-bonded fiber-optic sensors, investigated their strain-transfer mechanism and the sensitivity of influencing parameters[^53]; and explored the strain-transfer mechanism of distributed fiber-optic sensors when a single crack exists in the matrix material[^54]. In addition to static models, some studies have examined the dynamic strain-transfer relationship of surface-bonded three-layer fiber-optic sensing models under fatigue loading[^55] and the strain-transfer law under thermal loading[^56]. Moreover, strain-transfer analysis has also been extended to parameter analysis of distributed fiber-optic sensors and flexible functional-material sensors considering variations in strain gradient[^57-58].

Based on the effective information obtained from massive monitoring data using advanced fiber-optic sensing technology, structural physical parameters must be accurately identified in order to diagnose the service state of structures and assess structural safety. Structural parameter identification can be divided into static and dynamic characteristic identification[^6]. The former is commonly used to identify local damage: measuring points are arranged on the structure, a static load is applied, the structural performance is measured, and, combined with corresponding optimization algorithms, parameter information under the actual structural state is obtained; through comparative analysis, the damage location of the structure is identified. The identified damage locations are usually within the measurement points and their surrounding regions. For damage in test blind zones, further identification must rely on structural theory, reconstruction algorithms, or numerical simulation analysis[^59]. The latter generally determines whether damage has occurred in the overall structure based on modal frequencies, then locates damage based on modal mode shapes, and constructs appropriate damage-identification indices to diagnose the severity of structural damage.

With regard to static characteristic identification, scholars at home and abroad have conducted extensive research. Cui Fei et al.[^60] developed a structural-parameter identification method based on static strain and displacement measurements, in which the identified stiffness parameters of steel-frame structures could accurately locate structural damage. Ghrib et al.[^61] used measured static deflection to develop two computational methods for reconstructing the stiffness distribution of Euler-Bernoulli beams and identifying damage; however, methods based on equilibrium gap functions were closer to the actual damage state than those based on data differences. Abdo[^62] studied the relationship between changes in structural displacement curvature under static loading and structural damage, and approximately calculated changes in displacement curvature using the central-difference method to identify damage in cantilever beams and two-span continuous beams. Caddemi et al.[^63] used static loading and closed-form solutions of transverse displacement caused by general boundary conditions to propose an inverse damage-identification method that can be used to identify the number, locations, and severity of cracks in simple straight beams and frame structures; however, the monitoring effectiveness is strongly related to sensor placement. Wu et al.[^64] proposed a static damage-identification method for beam structures based on L1 regularization, accurately identifying damage in concrete beams. Deng et al.[^65] proposed a method for identifying local damage in bridge structures based on quasi-static-information probability distribution equations, which can effectively identify the location and severity of damage such as cracks in beam structures. It can therefore be seen that research on static identification is mainly concentrated on bridge or truss structures to which static loads can readily be applied in laboratories or in the field.

The core of structural damage identification based on dynamic response information is that changes in the structural health condition cause changes in the physical characteristics of the structure. By establishing functional relationships between structural modal parameters—such as natural frequency and modal mode shapes—and structural physical parameters—such as mass, damping, and stiffness—structural damage identification can be achieved. Many scholars at home and abroad have studied detection methods for damage identification using dynamic approaches. Peeters et al.[^66] discussed the influence of excitation and temperature on modal parameters and developed a structural damage-identification method that removes temperature effects. Bayissa et al.[^67] proposed a statistical moment of the energy-density function based on vibration response in the time–frequency domain, transforming wavelet coefficients in the spatial domain into a new damage-identification parameter, and accurately measured damage in concrete slabs and steel-plate girders. Cao et al.[^68] reviewed methods for identifying structural damage using damping as a dynamic characteristic. Zhang et al.[^69] improved the Bayesian computational method and enhanced its effectiveness in structural damage identification. Hou et al.[^70] and Khodadoost et al.[^30] reviewed the research status and challenges of structural damage-identification methods based on vibration information. It can therefore be seen that dynamic-characteristic identification methods are commonly used for damage diagnosis in large and complex structural systems, such as long-span bridges and high-rise buildings, and are mainly divided into two broad categories: physics-model-based and monitoring-data-driven methods. Their sensitivity and accuracy in damage identification still require further improvement. In summary, structural parameter-identification methods mainly include: identification methods that obtain modal parameters based on structural modal analysis; methods based on vibration-test signal analysis, such as wavelet analysis and empirical modal decomposition; damage-identification methods based on model updating; and identification methods based on physical-parameter analysis, such as Kalman filtering and generalized Tikhonov regularization.

In addition, some scholars have introduced artificial-intelligence algorithms into the processes of conventional structural-parameter identification and damage diagnosis, in order to improve the accuracy of obtaining structural modal parameters and identifying damage. Among these approaches, damage identification based on modal parameters obtained through modal analysis is currently the mainstream method; it has the advantages of high identification efficiency, good accuracy, and clear physical concepts.

Fig. 1

Figure 1: Fig. 1

In view of this, this study reviews research progress, development trends, and challenges in the application design methods, testing mechanisms, and characteristic-parameter inversion/calibration improvement of fiber-optic sensors, as well as structural-feature identification and condition assessment based on effective monitoring information; it also briefly describes the current application status of artificial-intelligence methods in the field of structural damage identification. Section 1 briefly discusses the problems existing in the application of fiber-optic sensors in structural monitoring systems; Section 2 reviews the application design methods and testing mechanisms of fiber-optic sensors based on strain-transfer theory; Section 3 reviews research progress in experimental improvement methods for structural characteristic-parameter inversion and calibration; Section 4 reviews the current status of research on structural-feature identification and condition assessment based on fiber-optic monitoring information; and Section 5 states the main conclusions of this study.

1 Analysis of Problems Existing in the Application of Structural Monitoring Systems

Health monitoring and service-condition assessment of important engineering structures are key links in maintaining their safe operation and risk prevention and control. Therefore, structural health monitoring is also recognized as a research approach parallel to theoretical analysis, numerical simulation, and model testing. The primary architectural components of a structural health monitoring system are shown in Fig. 1.

图 1　结构健康监测系统的主要组成架构

Fig. 1　Primary architectural components of structural health monitoring systems

Sensor components and sensor-network layout constitute the most basic and most critical part of a structural health monitoring system, directly affecting the accuracy and reliability of structural-parameter estimation, while also influencing the effectiveness and stability of the entire system. The impact range of failure of various sensors in a structural health monitoring system is shown in Fig. 2. When the testing of some sensors fails, local positions of the structure become blind zones; if the data-processing and analysis algorithm module does not perform reconstruction, subsequent condition assessment and operation-and-maintenance management will be affected. It can therefore be seen that the bottleneck problems encountered by monitoring systems at the application terminal mainly originate from the rationality and reliability of the design of un-

Fig. 2

Figure 2: Fig. 2

Fig. 3

Figure 3: Fig. 3

derlying sensor components and sensor-network layout. The sensor components and sensing network determine the effectiveness and reliability of the acquisition of structural performance information from the measured structure. In this process, correct sensor design, calibration, and installation are the most critical steps.

图 2 结构健康监测系统中传感器失效的影响范围

Fig. 2 Impact range of sensor failure in structural health monitoring systems

Fiber-optic sensors have become the most popular testing elements for engineering structures because of their strong designability and their advantages in enabling long-distance, high-precision continuous testing and local high-precision testing at relatively low cost. The measurement principle of fiber-optic sensing technology is to use optical fiber as the sensing or transmission medium of the signal. By detecting changes in parameters such as the intensity, phase, and polarization state of light signals transmitted, reflected, or scattered in the optical fiber under external loading or temperature action, structural parameters can be measured through relevant calibration equations[^29]. Fiber-optic sensors commonly used in engineering are mainly divided into distributed fiber-optic sensors and quasi-distributed fiber-optic sensors based on discrete FBG sensing technology. The structures of a bare optical fiber and an FBG sensing element are shown in Fig. 3.

(a) Distributed optical-fiber structure

(b) Physical photograph of optical fiber

(c) FBG structure

图 3 光纤传感器

Fig. 3 Fiber optic sensor

With the rapid development of a new generation of advanced fiber-optic sensing technologies and the expansion of application markets to testing needs such as extremely harsh service environments, the measurement accuracy, stability, and durability of function-enhanced fiber-optic sensors remain to be improved. Internationally well-known companies use FBG sensors, as shown in Fig. 4.

As shown. When three types of FBG sensors developed by internationally renowned sensor companies are used for structural testing, problems such as

Fig. 4 Engineering FBG sensors developed by internationally renowned companies

Figure 4: Fig. 4 Engineering FBG sensors developed by internationally renowned companies

debonding at bonded interfaces, bending or aging of rigid encapsulation materials, and consequent measurement inaccuracy and failure may occur during long-term service. The reasons, in addition to the incomplete design methods and specifications for fiber-optic sensors, include another important factor: the lack of understanding and awareness of the force-bearing action and measurement mechanisms of the sensors

24–31

. For example, without understanding the mechanism by which deformation of the substrate is transmitted to the sensing fiber, sensor developers cannot reinforce the key force-bearing locations of the sensor or carry out other refined designs. Therefore, it is urgently necessary to optimize the structural design and calibration methods of commercially available encapsulated fiber-optic sensors. The development and study of multilayer-medium strain-transfer theory, structural theory, and methods for identifying structural characteristic parameters and physical states provide theoretical guidance for implementing these improvements.

Fig. 4 Engineering FBG sensors developed by internationally renowned companies

At present, the bottleneck in the field of structural health monitoring that relies on advanced sensing technologies lies in extracting effective information from massive monitoring data, accurately identifying the physical parameters of structures, diagnosing their service states, and revealing the correlation mechanism between effective sensing signals and structural characteristic parameters; this is the fundamental scientific problem that must be overcome. Therefore, with respect to the sensing and mechanism of fiber-optic sensors, the application design of engineered sensors, the acquisition of effective sensing signals, and the diagnosis of structural service states, integrated research should be carried out in areas such as the application design methods of fiber-optic sensing devices, testing mechanisms, and inverse calibration of characteristic parameters, as well as the identification of structural characteristics and condition assessment based on effective monitoring information.

Fig. 5 Types of encapsulated fiber optic sensors classified by deformation transmission path

Figure 5: Fig. 5 Types of encapsulated fiber optic sensors classified by deformation transmission path

2 Application Design Methods and Testing Mechanisms of Fiber-Optic Sensors Based on Strain-Transfer Theory

2.1 Overview of Application Design of Fiber-Optic Sensors

Basic tests show that the strain measurement range of bare fiber-optic sensors is approximately 4 000 $\mu\epsilon$. In practical engineering, this range usually cannot meet measurement requirements. Therefore, encapsulation measures are needed to reduce the strain sensitivity of the sensor and indirectly expand the measurement range. For temperature measurement, special encapsulation materials can be coated on the surface of the bare sensing fiber to improve temperature sensitivity and measurement stability. Fiber-optic sensors used in practical engineering should be robust, durable, and easy to install, and should not have adverse effects on the integrity, durability, or reliability of the monitored structure. In addition, considering large-scale application requirements, sensors should also be economical. According to different measurement requirements of structures, fiber-optic sensors can be divided into three categories: point-type, quasi-distributed, and distributed sensors. Usually, a single-point FBG or FBG-array sensor can be detected by multiplexed integration as a quasi-distributed sensor; distributed fiber-optic sensors can be designed for quasi-distributed and fully distributed detection. According to installation methods, fiber-optic sensors can be divided into surface-bonded and embedded types. The material properties, boundary conditions, load types, and target parameters to be measured of the monitored structure usually determine the installation method of the sensor. For example, steel structures mostly use surface-bonded sensors, while pavement structures use embedded sensors. According to the transmission path by which deformation of the host material reaches the fiber-optic sensing element, fiber-optic sensors can mainly be divided into three categories: the first type transmits deformation of the host material to the sensing fiber through interfacial shear force (Fig. 5, S-OF1, E-OF1); the second type transmits deformation of the host material through two anchoring elements at both ends of the sensing fiber (Fig. 5, S-OF2, E-OF2); and the third type relies on both the interface and the anchoring elements at both ends to jointly transmit deformation (Fig. 5, E-OF3).

Fig. 5 Types of encapsulated fiber optic sensors classified by deformation transmission path

In general, the sensing characteristics of optical fibers and those induced by material properties···

Measurement limitations can be remedied by designing specific packaging measures, and optical fiber sensors can meet a variety of measurement needs in engineering through rational structural design. However, packaging measures introduce strain-transfer errors. For some sensors (such as S-OF2), this error can be corrected through conventional calibration tests; but for some sensors, especially embedded sensors (such as E-OF2 and E-OF3), conventional calibration tests have difficulty accurately describing the true relationship between the sensor and the monitored structure. Therefore, studies have proposed improved calibration tests or strain-transfer analysis methods to improve the accuracy of calibration coefficients

$$24, 34$$

. Conventional calibration tests involve only the sensor itself, whereas improved calibration tests cover both the sensor and the substrate (i.e., a part of the monitored structure). The essential difference between the two is that the latter considers the influence of the interaction between the monitored structure and the sensor on measurement accuracy.

In summary, the development of strain-transfer theory is closely related to the application of optical fiber sensors. The purpose of strain-transfer analysis is to provide a scientific basis for accurately interpreting the relationship between sensor signals and the parameters of the monitored structure. Existing studies

$$24, 40$$

have pointed out that strain-transfer theory is of great significance for sensors that rely on interfacial shear transfer deformation (such as S-OF1 and E-OF1), which also explains why most published studies on strain transfer are based on multilayer-medium models

$$33, 47 - 57, 71 - 72$$

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2.2 Mechanistic analysis of optical fiber sensing measurement based on strain-transfer theory

To monitor the internal strain of a structure, packaged optical fiber sensors must be embedded in the substrate structure. Because the material compositions of the packaging material and the substrate are usually different, the substrate of an embedded sensor is a typical inclusion-composite medium model

$$73 - 75$$

. There are distinct interfacial characteristics between the sensor and the substrate; after serving for a period of time, this contact interface may debond because of excessive local stress. Therefore, it is necessary to establish a mechanical testing model for embedded optical fiber sensors, theoretically analyze the laws of strain transfer, explore the perturbation effect of the sensor on the local strain field of the substrate, and, on the basis of strain-transfer analysis, obtain the distribution law of the interfacial shear stress along the sensing length, thereby identifying interfacial debonding damage. At the same time, it is also necessary to obtain the strain-transfer relationship when debonding occurs at the interface between the substrate and the optical fiber sensor, so as to provide a theoretical basis for corresponding error correction.

Similarly, for monitoring the surface strain of a structural body, it is also necessary to consider the loading mode of the structure and to carry out durability design for distributed optical fiber sensors, thereby avoiding debonding problems caused by excessive local interfacial stresses and maintaining the validity and reliability of distributed measurements

$$76 - 77$$

. In summary, current correction of measurement parameters introduced by packaging protection of optical fiber sensing devices relies on calibration experiments and strain-transfer theory analysis

$$24, 40$$

. A small number of scholars have conducted parameter inversion analyses for multilayer-medium model structures based on strain-transfer theory

$$72, 74, 76 - 77$$

. Studies have also proposed that, for distributed strain measurement in local regions of flexural structures, after full-distributed packaging protection is adopted, the mechanical model under loading and the measurement-data phenomena cannot be explained by strain-transfer theory established for axial tension/compression conditions; accordingly, a deformation theory for multilayer-medium beam structures was proposed for data inversion

$$34$$

. It can thus be seen that, in structural engineering testing with quasi-distributed and distributed optical fiber sensing technologies, sensing-data processing is closely associated with device packaging and layout forms as well as structural loading modes. Appropriate correction methods need to be selected according to different situations to estimate measurement parameters, thereby achieving accurate inversion of structural characteristic parameters. Traditional point-type packaged optical fiber sensors can still be corrected using conventional strain-transfer theory.

However, the current analysis of strain-transfer models is insufficiently integrated with practical sensor applications. Designers in the field of optoelectronic engineering have difficulty fully understanding the mechanical interaction between sensors and the measured structure. If designers are not clear about how structural deformation is transmitted to the sensing fiber, it is difficult to carry out refined design or performance optimization of optical fiber sensors. On the other hand, scholars in engineering can understand the strain-transfer mechanism of multilayer models, but improving sensor measurement accuracy still depends on the depth of their analysis of the mechanical model of deformation transfer in multilayer media. Currently representative information on strain-transfer-theory analysis models is shown in Table 1; the table provides quantitative analyses of strain-transfer coefficients for the measured structure under different loading modes and minor damage conditions. It should be emphasized that understanding the working principles of optical fiber sensors and the interactions between sensors and measured structures is crucial for sensor design based on strain-transfer analysis. It can avoid the occurrence of interfacial damage between packaged optical fiber sensors and measured structures, and improve the accuracy, long-term stability, and durability of distributed and quasi-distributed optical fiber sensors in engineering structural measurements.

Figure 6 presents a variety of commercial packaged FBG sensors available on the market, and gives the corresponding numbering according to the sensor-structure classification shown in Figure 5. For the sensors in Fig. 6(a) and Figs. 6(c)–6(e), relatively accurate strain-transfer coefficients can be obtained through conventional calibration tests and improved calibration tests; for the sensors in Fig. 6(b) and Fig. 6(f), however, it is necessary to establish the strain relationship between the sensor and the host material with the aid of strain-transfer theory. Field applications of optical fiber sensors face further challenges: surface-bonded sensors (S-OF1) are prone to debonding, especially under cyclic loading

$$78-79$$

. In addition to selecting adhesives with excellent bonding performance to reduce interfacial debonding, understanding the complex interaction between the sensor and the host material through strain-transfer analysis and identifying material and geometric parameters that affect interfacial strain and bonding strength are also effective ways to avoid this phenomenon. The design of the packaging layer should ensure that the possibility of debonding from the host material is minimized and that it has strong bonding capability to efficiently transfer host-material strain to the sensor. In addition, strain-transfer analysis has also been used to predict the residual strain distribution in the composite material of surface-bonded metal-coated optical fiber sensors, as well as to characterize the interfacial shear stress–strain state

$$80-86$$

.

Table 1 Typical strain-transfer theory analytical models

Model characteristics	Analytical formula	Applicable conditions
Embedded three-layer transfer model[47]	$\varepsilon_\mathrm{f}(x) = \varepsilon_\mathrm{m}\left[1 - \frac{\sinh(kx)}{\sinh(kL)}\right]$ $k^2 = \frac{2G_\mathrm{p}}{r_\mathrm{f}^2 E_\mathrm{f}\ln(r_\mathrm{p}/r_\mathrm{f})}$	Strain monitoring inside cement or asphalt concrete and rock/composite structures by point-type or quasi-distributed embedded optical fibers.
Embedded three-layer transfer model[50]	$\varepsilon_\mathrm{f}(x) = \varepsilon_\mathrm{m}\left[1 - \frac{\cosh(kx)}{\cosh(kL)}\right]$ $k^2 = \frac{2G_\mathrm{p}}{r_\mathrm{f}^2 E_\mathrm{f}\ln(r_\mathrm{m}/r_\mathrm{f})}$	Considering the influence of deformation coordination among multiple media layers; strain monitoring inside concrete structures with embedded packaged optical fibers.
Surface-bonded four-layer transfer model[51]; the protective layer and adhesive layer are regarded as undergoing pure shear deformation, and the radial displacement increment is neglected	$\frac{\varepsilon_\mathrm{f}}{\varepsilon'_\mathrm{m}} = \frac{1-\cosh(\lambda x)/\cosh(\lambda L)}{\pi r_\mathrm{f}^2 E_\mathrm{f}/(2hr_\mathrm{p}E_\mathrm{h})+1}$	Strain monitoring on the surfaces of steel, concrete, or composite structures using point-type or quasi-distributed surface-bonded optical fibers.
Model of the measured structure under dynamic action[55]	Average strain-transfer coefficient $\beta = \frac{BC_L[\lambda_4\cosh(\lambda_3 x)+\lambda_5\cos(\lambda_2 x)]}{\lambda_4\cosh(\lambda_3 L)+\lambda_5\cos(\lambda_2 L)} - BC_x \frac{[\lambda_5\cosh(\lambda_3 x)+\lambda_4\cos(\lambda_2 x)]-DBC_LC_x}{\lambda_4\cosh(\lambda_3 L)+\lambda_5\cos(\lambda_2 L)}$	Strain-transfer mechanism of structures producing dynamic response under fatigue loading.
Model of the measured structure under temperature action[56]	$\frac{\varepsilon_\mathrm{f}(x)}{\varepsilon_\mathrm{m}} = \left[1 - \frac{\cosh(\lambda x)}{\cosh(\lambda L)}\right] + \frac{\alpha_\mathrm{f}\cosh(\lambda x)}{\alpha_\mathrm{m}\cosh(\lambda L)}$	Under temperature loading, the strain-transfer relationship between structural strain and the strain perceived by the packaged optical fiber; the influence of the coefficient of thermal expansion is introduced for the first time.

Fig. 6 Commercially available FBG sensors

Figure 6: Fig. 6 Commercially available FBG sensors

Model characteristics	Analytical formula	Applicable conditions
Local crack model of the measured structure[52]	$\varepsilon_{\mathrm{f}} = \beta C_2 e^{[\beta(L+x)]} - \beta C_1 e^{[\beta(L-x)]} + \varepsilon_{\mathrm{m}}$	Transfer relationship between the structural strain of a distributed optical-fiber measurement substrate and distributed optical-fiber structural strain when microcracks exist locally in the matrix structure.

Table 1 (continued)

Model characteristics	Analytical formula	Applicable working conditions
Structural-sensor interfacial debonding model[33]	$\varepsilon_{\mathrm{f}} = \varepsilon_{m0} \frac{\lambda_0^2}{\lambda_1^2} \left[1 - \frac{\cosh(\lambda_1 x)}{\cosh(\lambda_1 L_d)}\right]$	Local debonding damage occurs at the contact interface between the optical fiber and the substrate
Model considering nonuniform strain transfer[72]	$\varepsilon_{\mathrm{f}}(x) = C_1 \cosh(kx) + C_2 \sinh(kx) + \varepsilon_{\mathrm{h}}(x)$	For packaged distributed optical fibers embedded inside a structure to measure distributed strain, considering the nonuniform variation characteristics of the transfer coefficient along the sensing-fiber length

Fig. 6 Commercially available FBG sensors[41]

In summary, when embedded or surface-bonded packaged distributed optical fibers and FBG sensors are used for structural strain monitoring, the directly measured strain cannot fully represent the actual strain of the structure under measurement. Therefore, strain-transfer theory has been developed to accurately interpret the acquired data, analyze the effects of embedded sensors on

Fig. 7 Multiple types of packaged FBG sensors independently developed by the team

Figure 7: Fig. 7 Multiple types of packaged FBG sensors independently developed by the team

structural integrity and strength, and improve sensor design and calibration methods so as to achieve long-term, effective, and accurate measurements. Furthermore, by understanding the influencing factors related to interfacial interaction mechanisms and multilayer sensing test models, the packaging application design of engineering fiber-optic sensors can be inversely guided, and reliable mechanisms for avoiding or mitigating interfacial and other damage can be proposed. This improves the durability of engineering fiber-optic sensors and the long-term validity and reliability of measurement data, thereby providing hardware and methodological support for the long-term stability and intelligence of structural health monitoring systems.

2.3 Design recommendations for improving the measurement accuracy and durability of fiber-optic sensors

By deeply integrating strain-transfer theoretical analysis with the engineering design of fiber-optic sensor components, the transfer mechanisms of temperature and strain measured by optical fibers in the substrate, the sources of measurement error, and correction methods are revealed; the failure and damage mechanisms of packaged fiber-optic sensing elements are explained; and durability-oriented design recommendations are provided. Fig. 7 shows multiple types of packaged FBG sensors independently developed by the team and the corresponding sensor structural type codes. They include point-type and quasi-distributed FBG string sensors, which can be used, respectively, for single-point or multi-point testing of compressive or tensile deformation when embedded in asphalt or cement concrete structures, or for quasi-distributed testing when externally attached to the surfaces of steel structures or composite-material structures with relatively high stiffness.

Fig. 7 Multiple types of packaged FBG sensors independently developed by the team[33,77]

Comparing the sensor structures and physical objects shown in Figs. 6 and 7, it can be seen that, in the structural design and material selection of sensors, and in single-point or multi-point continuous measurement, it is necessary to fully consider the characteristics of the measured structure and monitoring requirements, so that adaptive targeted design can be achieved, the node connections in the sensing-network layout can be reduced, and a lightweight sensing network capable of efficient and stable multi-source information measurement can be formed.

In summary, the design and parameter calibration methods of sensors are closely related to the installation scenario, constraint conditions, load type, damage mode, monitored structure, and the material and geometric characteristics of intermediate layers. To improve the durability of fiber-optic sensors and achieve long-term effective monitoring, the most critical issue is the rational selection of packaging materials for protecting the sensing fiber and adhesives for fixing the fiber-optic sensor, which directly determines the quality and measurement accuracy of the sensor. Ideally, the protective layer and bonding layer should remain in the elastic stage throughout the sensor' s service period. According to the results of strain-transfer analysis, the intermediate layer may be damaged under large-deformation conditions. Therefore, for different host materials, specialized refined design of the sensor should be carried out through strain-transfer theory. In addition, basic tests are needed to verify the measurement performance and structural performance of the sensor. Generally, to avoid interfacial failure and ensure measurement accuracy, the number of sensing-model layers of a surface-bonded sensor should not exceed 4, and the number of sensing-model layers of an embedded sensor should preferably not exceed 3. The optimal sensor design scheme is to use the same material for the bonding layer and the protective layer. In summary, in addition to the measurement-accuracy problem that can be solved through strain-transfer theory and calibration tests, the durability of the sensor ultimately depends on the rational selection of packaging materials and adhesives.

3 Research on Inversion Methods for Structural Characteristic Parameters

During long-term operation, structural monitoring systems based on fiber-optic sensing technology generate massive data related to the measured engineering structure. How to correctly use these data to interpret and assess structural characteristics is a difficult problem currently faced in the field of structural health monitoring. Massive data may include abnormal data caused by environmental noise, vibration, and temperature variations affecting sensors; duplicate data caused by redundant sensor design; drift data caused by degradation of sensor performance; and missing data caused by sensor failure. Therefore, the analysis and processing of massive data need to fully consider the sources of various datasets and use foundational knowledge in relevant disciplinary fields to conduct targeted feature classification and correction, thereby obtaining effective sensing information.

3.1 Correlation Analysis Between Fiber-Optic Sensing Signals and Structural Characteristic Parameters

Because of the complexity of the structural forms of measured engineering objects and differences in the service environment, fiber-optic sensing signals extracted in engineering usually need to be filtered and denoised through signal-processing techniques in order to obtain effective sensing signals. Furthermore, it is necessary to establish correlations between the processed effective sensing signals and the characteristic parameters of the measured engineering object, so as to realize quantitative or qualitative perception of the measured target parameters.

From the perspective of information science, current research on sensing-signal processing mainly focuses on the hardware of fiber-optic demodulation equipment and the optimization of supporting algorithm software. For example, high-performance FPGA can be selected as the core controller, and data can be driven by a low-power CPU, thereby improving the measurement-length-range index of distributed fiber-optic vibration-sensing measurement systems[^87]; compressed sensing theory can be used to sparsely sample and reconstruct signals, and wavelet transform can be used for denoising, thereby improving the stability and accuracy of effective measurement signals[^88-^89].

From the perspective of engineering science, current research on massive monitoring-data processing mainly focuses on algorithm-software development that considers the characteristics of the measured structure and data features. It can be summarized into two categories[^90-^91]: the first category is based on theoretical models and finite-element modeling and analysis cognition, supplemented by mathematical analysis, to clean abnormal data in massive monitoring data, reconstruct missing data, and correct drift data; the second category relies on massive datasets from continuous measurement and uses statistical methods and artificial-intelligence algorithms to analyze the variation patterns of massive monitoring data, thereby extracting effective monitoring data. The first type of method does not require a large number of data samples and can obtain relatively refined effective monitoring information, but it has relatively high requirements for the accuracy and distribution pattern of collected data and the precision of theoretical models. The second type of method obtains only statistical feature information from massive monitoring data, but requires massive data samples and has relatively high requirements for algorithms and system hardware configuration.

Here, the most typical strain and temperature are used as examples for explanation. When distributed fiber-optic sensing technology is used to measure structural deformation, after filtering and denoising are performed to obtain effective sensing signals, it is necessary to construct a quantitative relationship between the fiber-optic sensing signal and structural strain. For bare fiber, the quantitative expression can be established through existing calibration experiments to realize the association between the fiber-optic sensing signal and strain. For packaged optical fiber (such as optical cable), its quantitative expression can be established through improved calibration experiments or strain-transfer theory analysis, thereby realizing the association between the fiber-optic sensing signal and strain. When distributed fiber-optic sensing technology is used to measure structural or environmental temperature, a similar approach can be adopted: for bare fiber and packaged optical fiber, calibration experiments and heat-transfer analysis theory[^4] can be used, respectively, to establish the quantitative relationship between the fiber-optic sensing signal and temperature. Its

Fig. 8 Optical fiber sensing signals and structural characteristic parameters of the measured object

Figure 8: Fig. 8 Optical fiber sensing signals and structural characteristic parameters of the measured object

analysis procedure is shown in Fig. 8. It can thus be seen that fiber-optic sensing signal-processing technology needs to fully consider the packaging and deployment process of the optical fiber, so as to select a more accurate calibration formula or establish, on the basis of structural analysis theory (or heat-transfer analysis theory), the quantitative expression relationship between the fiber-optic sensing signal and the characteristic parameter—strain (or temperature)—of the measured structure.

Figure 8 Optical fiber sensing signals and structural characteristic parameters of the measured object

Fig. 8 Optical fiber sensing signals and structural characteristic parameters of the measured object

3.2 Intelligent Characterization Technology for the Physical State of the Measured Engineering Structure

Because distributed and quasi-distributed optical-fiber sensing technologies enable low-cost and high-precision measurements at large scales, they have received considerable attention in the field of engineering-structure health monitoring. How to use optical-fiber sensing signals to realize intelligent characterization of the physical state of the measured engineering structure is an urgent problem to be solved in the engineering application of distributed and quasi-distributed optical-fiber sensing technologies. Specifically, after effective optical-fiber sensing signals are obtained through filtering and denoising, and after a quantitative relationship between the sensing signals and the strain (temperature) of the measured structure is established through traditional or improved calibration experiments or strain-transfer theory (thermal-conduction analysis) according to the packaging and layout process of the sensing fiber, it is necessary to further incorporate the constraints, loads, and service environment of the measured structure. On the basis of continuously monitored data information, the physical state of the structure—such as the structural geometric form and structural mechanical properties—is characterized, thereby providing a reference basis for service-safety diagnosis and assessment of the measured structure.

When measuring an actual engineering structure, the optical fiber must be packaged and protected so as to improve the effective service life of the sensor. In deformation measurement, the essence of measuring structural strain with a packaged optical fiber can be regarded as a strain-transfer model of a multilayer medium structure. Therefore, structural mechanics theory or strain-transfer theory can be used to guide the packaging-process design of distributed and

Fig. 9 Mathematical model of morphological reconstruction algorithm based on discrete curvature

Figure 9: Fig. 9 Mathematical model of morphological reconstruction algorithm based on discrete curvature

quasi-distributed optical-fiber sensors under different measurement conditions (such as static strain, dynamic strain, and temperature), thereby achieving accurate inversion of structural characteristic parameters[33-34], avoiding damage at the interface between the packaged distributed or quasi-distributed optical-fiber sensor and the measured structure, and improving the measurement accuracy, long-term stability, and durability of distributed and quasi-distributed optical-fiber sensors in engineering-structure measurement. On the basis of packaging application design for distributed optical-fiber sensors, it is necessary to further consider how to use distributed optical-fiber sensing measurement data to describe the physical state of the engineering structure and to digitize and program it, thereby realizing visual display. That is, how to use optical-fiber sensing signals to intelligently characterize the physical state of the measured engineering structure.

For this reason, the geometric shape of beam-structure deformation is illustrated here by taking measured distributed optical-fiber sensing signals and a shape-reconstruction algorithm as an example. The geometric shape reconstruction algorithm can adopt the following formula[92]:

$$\begin{cases} x = O_{(i-1)x} + (\rho_{i-1} - \rho_i)\cos\theta_{i-1} + \rho_i \cos\theta \\ y = O_{(i-1)y} + (\rho_{i-1} - \rho_i)\sin\theta_{i-1} + \rho_i \sin\theta \end{cases} \qquad (\theta_{i-1} \le \theta \le \theta_i) \tag{1}$$

where $\theta_i = \theta_{i-1} + \Delta\theta = \theta_{i-1} + s/\rho_i$. As shown in Fig. 9, when $i = 1, 2, 3, \cdots$ is taken respectively, according to Eq. (1) and the measured discrete curvature, the real-time geometric shape of the structure can be established. In this experiment, OFDR testing technology was used, and the sensing signal obtained by demodulating the distributed optical fiber with a LUNA ODiSI 6000 instrument had a spatial resolution of 2.6 mm. The experimental setup is shown in Fig. 10, and the pipe-structure shape information obtained from the tested data inversion is shown in Fig. 11[92]. After the discrete strain measured by the distributed optical fiber is converted into discrete curvature, the geometric shape of the pipe structure can be reconstructed according to Eq. (1), thereby determining the physical state of the pipe-structure profile.

Figure 9 Mathematical model of morphological reconstruction algorithm based on discrete curvature

Fig. 9 Mathematical model of morphological reconstruction algorithm based on discrete curvature

Fig. 10 LUNA fiber optic demodulator measurement tube structural strain

Figure 10: Fig. 10 LUNA fiber optic demodulator measurement tube structural strain

Fig. 11 Geometric behavior of pipe structures under different loads based on discrete strain information

Figure 11: Fig. 11 Geometric behavior of pipe structures under different loads based on discrete strain information

Figure 10 LUNA fiber-optic demodulator measurement of tube-structure strain

Fig. 10 LUNA fiber optic demodulator measurement tube structural strain

Figure 11 Geometric behavior of pipe structures under different loads based on discrete strain information[92]

Fig. 11 Geometric behavior of pipe structures under different loads based on discrete strain information[92]

Similarly, for other optical-fiber sensing signals, such as vibration signals (dynamic strain, acceleration), time-domain and frequency-domain analysis can also be used.

technology and mathematical analysis methods, a quantitative characterization relationship between fiber-optic sensing signals and the static and dynamic strain fields of structures is established and implemented through programmed design for visualization[^74], thereby completing the intelligent representation of the physical state of structures. According to these real-time and continuous changes in structural morphology and strain-field distribution, the real-time damage state of a structure can be assessed, ultimately achieving the final goal of applying fiber-optic sensing technology in engineering structural testing and monitoring.

In summary, research on extracting effective monitoring information from massive monitoring data has mainly focused on the intermediate-process hardware and software modules of structural health monitoring systems. Researchers in relevant disciplines process and analyze the data according to their respective professional expertise, with the aim of obtaining high-quality effective data signals[^13,^21,^31]. However, few studies have considered improving the quality and reliability of massive monitoring data from the perspective of local optimization and high-quality design of sensing components and sensing-network layouts, so as to enhance the measurement accuracy of structural characteristic parameters and the reliability of the complete structural health monitoring system, and thereby obtain a more comprehensive and accurate interpretation or description of the engineering structure being measured. Therefore, starting from the basic perception layer of structural health monitoring systems, carrying out refined and high-quality design of the sources that generate massive monitoring data—

"sensing components and sensing-network layouts" —and, from the perspectives of hardware performance and quality improvement, reducing the complexity of the intermediate-process module of "monitoring-data processing and analysis," will be a feasible idea and method for overcoming this technical bottleneck.

4 Fiber-Optic Sensing Information-Driven Research on Structural Damage Identification and Condition Assessment

On the basis of the high-quality effective sensing information obtained through the optimization of the aforementioned fiber-optic sensing components and network layout, fiber-optic demodulation equipment, and supporting algorithms, how to describe the physical state of the measured structure—that is, how to use the effective monitoring data obtained by fiber-optic sensing technology to realize structural damage identification and service-condition assessment—is an important scientific problem currently faced at the engineering-application terminal of structural health monitoring systems. Current research can mainly be divided into two schools: (1) diagnosis of the physical state of engineering structures obtained independently of physical models and based on massive monitoring data, such as Bayesian methods based on probability theory and deep-learning algorithms[^92-^93]; and (2) physical-state identification methods for engineering structures established on the basis of physical models of engineering structures by applying structural mechanics theory and mathematical analysis, such as identification of structural modal parameters based on vibration signals and structural morphology reconstruction based on distributed strain information[^94-^103]. It can thus be seen that the second type of method can accurately identify the physical state of engineering structures based on a small amount of effective data and in combination with researchers' analysis in the field of engineering structures; therefore, it is the mainstream method in the field of structural health monitoring. According to these real-time and continuous changes in structural morphology and strain-field distribution, the real-time damage state of a structure can be assessed.

For discrete fiber-optic sensing signals, relatively little research has been conducted on how to use this mainstream method to realize intelligent perception of structural state or damage. Some scholars have used the strain-failure history of quasi-distributed optical fibers to diagnose interfacial damage[^104]; diagnosed tunnel cavities and rock-mass stability based on reconstructed linear morphology from distributed fiber-optic measurement signals[^105]; and identified the safety state of aerospace composite-material structures according to reconstructed curved-surface morphology[^106]. The research team used vibration signals perceived by optical fibers, adopted time-domain and frequency-domain analysis techniques and mathematical-physical analysis methods, established a quantitative characterization relationship between fiber-optic sensing signals and the static and dynamic strain fields of structures, and implemented visualization program design, thereby realizing intelligent representation of the

Fig. 12 Fiber optic sensing information-driven structural damage identification and condition assessment process

Figure 12: Fig. 12 Fiber optic sensing information-driven structural damage identification and condition assessment process

physical state of composite-material plate structures[^74,^103]. It can therefore be seen that, according to these real-time and continuous changes in structural morphology and strain-field distribution, the real-time damage state of a structure can be assessed. When the research object is expanded from components to structural systems, the related analysis and characterization methods remain to be further studied, and it is expected that intelligent monitoring and representation of structural damage can be realized from structural health monitoring systems.

Structural damage identification and condition assessment are core links in structural health monitoring systems. Data analysis based on fiber-optic sensing signal preprocessing is carried out mainly around strain-field reconstruction, modal-parameter identification, and damage localization and quantification, forming a structural static damage-identification and dynamic-response information-driven damage-identification technical system that integrates traditional mechanical modeling with intelligent algorithms, and realizing cross-scale refined identification methods ranging from micro-damage in engineering structures to macroscopic large deformation, and from local to global. The core process of structural damage identification and condition assessment driven by fiber-optic sensing information is shown in Fig. 12. Damage localization and quantification are the core of structural characteristic identification; the high sensitivity and high precision of fiber-optic sensing monitoring provide a feasible method for early damage identification. At the same time, related research has also developed from single-damage-scenario identification toward the precise quantification of multiple types and multiple scales of damage.

Figure 12. Fiber-optic sensing information-driven structural damage identification and condition-assessment process

Fig. 12 Fiber optic sensing information-driven structural damage identification and condition assessment process

4.1 Structural Identification Methods Based on Modal-Parameter Estimation

Structural damage can lead to changes in physical parameters such as the stiffness and mass of a vibration system, thereby causing changes in the vibration characteristics of the structure. Damage-identification methods diagnose, locate, and assess the degree of damage by comparing changes in the vibration characteristics of healthy and damaged states; their core is to find parameters that can be obtained through algorithms and are sensitive to structural damage. The

Fig. 13 Methods for estimating structural modal parameters

Figure 13: Fig. 13 Methods for estimating structural modal parameters

selection of appropriate modal parameters is directly related to the difficulty of damage identification and the correctness of the identification results. Common damage-sensitive parameters include the natural frequencies, mode shapes, and curvature modes of structures. Structural modal parameters (such as natural frequency, mode shape, and damping ratio) are core indicators reflecting the dynamic characteristics of structures. Under environmental excitation, methods for estimating structural modal parameters can be divided into three categories: time-domain methods, frequency-domain methods, and time–frequency-domain methods[^107], as shown in Fig. 13. Time-domain methods include the stochastic subspace method, natural excitation technique, and random decrement technique; frequency-domain methods include the peak-picking method and frequency-domain decomposition method; time–frequency-domain methods include wavelet transform and Hilbert–Huang transform. Based on dynamic strain data from optical-fiber monitoring, relevant studies have achieved breakthroughs from steady-state modal identification toward dynamic and real-time modal tracking. Structural modal parameters may change within a short time, especially when subjected to relatively large external forces; therefore, modal parameters need to be estimated in a timely manner to diagnose the damage state of the structure. Accordingly, real-time modal tracking technology has been developed. Bhowmik et al.[^93] studied the engineering requirements for real-time condition monitoring of mechanical vibration systems and single-sensor deployment, proposed an error-correction recursive singular-spectrum analysis algorithm based on first-order feature perturbation, and constructed a real-time monitoring unified framework to realize online monitoring and control of complex vibration systems. These vibration-information-based structural damage identification methods can also be applied to interpreting vibration or acoustic-wave data output by DAS systems; in practical use, they must be combined with an analysis of the distributed optical-fiber deployment mode[^108].

Fig. 13 Methods for estimating structural modal parameters

Structural health-monitoring systems can output massive amounts of monitoring data, and artificial-intelligence algorithms are used for data interpretation so as to reveal the physical state information of structures contained in the data. Avci et al.[^109] reviewed the transition of vibration-based structural damage detection from traditional methods to machine-learning and deep-learning methods. Bao et al.[^110] reviewed advances in machine learning for structural modal identification, damage identification, and reliability assessment, and discussed future development trends. The application of artificial-intelligence methods in modal-parameter estimation mainly includes methods that use machine learning to solve modal equations and methods that use artificial-intelligence techniques for post-processing. The use of artificial intelligence for automatic data processing reduces spurious modes. For example, in the stochastic subspace method and the NExT-ERA method, the determination of the number of rows and columns of the Hankel matrix directly affects the results of modal identification: if the Hankel matrix is too large, spurious modes will be output, whereas if it is too small, modal parameters will be missing. Therefore, combining deep learning with modal-parameter identification methods, and automatically selecting the most suitable size of the Hankel matrix through learning from massive data, can improve the efficiency and accuracy of modal-parameter identification.

In summary, combining artificial-intelligence algorithms with traditional modal-parameter estimation and damage-identification methods can enhance autonomous learning and data-analysis capabilities, effectively eliminate errors caused by subjective factors, and realize accurate identification of failure modes in large engineering structures.

4.2 Structural Condition-Assessment Methods

Structural condition assessment is a key link in judging indicators such as structural safety, applicability, and durability on the basis of structural characteristic-parameter estimation and damage-identification results, and it is also one of the ultimate goals of structural health monitoring. In recent years, most relevant studies have been based on optical-fiber monitoring data and have combined mechanics theory, statistical analysis, and intelligent algorithms, with the aim of constructing a complete system ranging from single-index assessment to multi-source fusion assessment, tending toward a transition from "post-event assessment" to "pre-event early warning."

4.2.1 Traditional Assessment Methods Based on Mechanical Models

Traditional mechanical models are based on theories such as material mechanics, structural mechanics, elasticity, damage mechanics, and fracture mechanics. By using optical-fiber monitoring data to validate characteristic parameters of experimental models, they realize assessment of the physical state of structures and have irreplaceable advantages in terms of compatibility with codes and standards. Research focuses on improving the compatibility between theoretical derivation models and actual engineering structures. For example, in the assessment of structural cracks, Richter et al.[^99] studied the automated assessment of crack monitoring in concrete structures and distributed optical-fiber monitoring data, proposed an automated crack-width calculation procedure based on strain integration and the Python open-source framework **fosanalysis**; the mean absolute errors between the calculated crack widths and DIC reference values were 24.3 μm and 22.0 μm, respectively, and the maximum error was ( )44.6 μm. Gomes et al.[^111] studied the detection of microcracks in reinforced-concrete structures, the evolution of crack width, and monitoring of closure states; they proposed a SENTMI patch sensor based on a textile-embedded optical-fiber network, with a maximum sensitivity of 0.004 mm/cd.

It can accurately detect microcracks of 0.01 mm, track the crack opening and evolution process, and effectively assess the number of cracks in concrete and⋯

width.

4.2.2 A New Evaluation Method Integrating Statistical Analysis and Intelligent Algorithms

The new evaluation method is mainly based on statistical analysis and intelligent algorithms. By mining the implicit patterns in fiber-optic monitoring data, it realizes adaptive evaluation of structural condition. In recent years, research has mainly developed from the application of a single algorithm toward multi-algorithm fusion and time-series prediction, significantly improving the intelligence level of evaluation. Statistical-analysis-based evaluation is a relatively traditional evaluation approach: through statistical processing of a large amount of monitoring information, statistical patterns related to structural condition are obtained.

In terms of statistical evaluation methods, Xu et al.

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proposed an early-warning system based on fiber-optic sensors and Bayesian updating stability analysis, which was applied to quality assessment and performance monitoring of an excavated slope. Slope stability was evaluated through field measurement data. In addition to traditional statistical evaluation methods, the deep integration and application of intelligent algorithms have also been a research focus in recent years. Luo et al.

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studied the problem of abnormal-state detection and source-pattern recognition in underground pipelines, and proposed an integrated method combining a distributed fiber-optic vibration sensing system with deep learning. The fused deep scattering network requires no training, has low computational cost, an anomaly detection rate of >99%, and an abnormal-condition recognition accuracy of >99%.

4.2.3 Comprehensive Evaluation Method Based on Multi-Source Monitoring Information Fusion

Fiber-optic sensors have outstanding advantages and broad application scenarios. However, relying only on a single category of fiber-optic monitoring data sometimes makes it difficult to comprehensively and accurately reflect the service condition of structures; multi-source information fusion evaluation is also needed. In recent years, some scholars have integrated fiber-optic monitoring data with other sensor data and environmental factors, etc., and their studies have focused on optimizing fusion mechanisms and engineering applicability, thereby improving the comprehensiveness and reliability of evaluation results. In terms of feature-level fusion, Wang et al.

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, addressing the problem of low recognition accuracy for high-sampling-rate long-sequence signals in a fiber-optic distributed acoustic sensing system, designed a CDIL-CBAM-BiLSTM network model based on feature fusion. The average recognition accuracy for disturbance events exceeded 99%, and the recognition time was less than 2 ms. In terms of decision-level fusion, in 2025, Li et al.

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, targeting problems such as difficulties in multi-sensor data coordination and low detection accuracy in leakage detection of polluted gas from pipelines in chemical parks, proposed a real-time data-fusion algorithm based on distributed fiber-optic sensing. Field measurements showed that the detection accuracy for leaks of various intensities exceeded 94.75%, the detection delay was shortened to 2.4–5.1 s, and the false-alarm rate was low and superior to existing methods such as wireless sensing and laser spectroscopic measurement.

5 Conclusions

The development of operational-condition perception networks and monitoring systems for engineering structures is currently an important research topic in the engineering field. Structural health monitoring focuses on using modern advanced sensing technology, combined with deformation analysis of the measured structural stress state, to design sensing elements and sensing-network layouts; based on the data information output by demodulation equipment, it combines structural mechanics theory and mathematical analysis methods to identify the physical characteristics of structures and assess their service condition, thereby guiding structural operation and maintenance management as well as safety-risk early warning and prevention and control. Therefore, this study reviews the application-design methods of fiber-optic sensors and product iteration and updating, as well as research progress in structural characteristic parameter inversion, damage identification, and condition assessment methods. The main conclusions are as follows.

1) Measurement limitations caused by the material characteristics of optical fibers can be compensated for through special packaging technologies. However, packaged fiber-optic sensors developed to satisfy multi-objective engineering testing requirements introduce strain-transfer errors, thereby promoting the development of strain-transfer theory. Strain-transfer theory is particularly important for sensors that rely on interfacial shear stress to transfer deformation, because the strain-transfer error of this type of sensor cannot be eliminated through traditional calibration tests. This also explains why published studies on strain-transfer theory are all based

on multilayer medium models. For distributed and quasi-distributed fiber-optic sensors, estimation methods for measured structural parameters still need to be analyzed specifically in combination with the stress characteristics of the structure.

2) Strain-transfer theory can be used to accurately interpret acquired data and improve sensor design and calibration specifications. Research on the application design, durability enhancement, and potential failure mechanisms of multilayer sensing models for fiber-optic sensors through strain-transfer analysis remains relatively insufficient, and strain-transfer theory has not yet been used to explore the influence of multi-factor coupling effects (such as the matrix material containing cracks under dynamic loading) on the measurement accuracy and service performance of fiber-optic sensors in specific structures (such as high-speed railways and aerospace composites). How to improve the measurement accuracy, optimize the design, and enhance the durability of fiber-optic sensors in complex environments through strain-transfer theory remains a challenge to be solved.

3) When fiber-optic sensing information is used to carry out inversion analysis of structural characteristic parameters, improvements in the quality and reliability of massive monitoring data should be considered from the perspectives of optimizing the sensing elements and sensing-network layout and high-quality design, thereby improving the measurement accuracy of structural characteristic parameters and the reliability of the entire structural health monitoring system, and obtaining a more comprehensive and accurate interpretation or description of the measured engineering structure.

4) Methods for identifying structural damage based on modal parameters under environmental excitation mainly suffer from problems such as unstable excitation, many spurious modes, poor identification accuracy, inability to identify small damage, failure to consider the nonlinearity of structural damage, and incomplete monitoring data. On the basis of improving sensing-element performance and optimizing sensing-network layout, as well as data preprocessing algorithms, one may consider further integrating traditional structural theory, modal-parameter estimation, damage identification, and artificial-intelligence algorithms to conduct adaptive dynamic learning from massive effective monitoring data, develop intelligent structural health monitoring systems, efficiently analyze monitoring data, and adaptively update the monitored physical model, thereby realizing timely maintenance and risk prevention for the safety and damage of important engineering structures.

risks and early warning.

In summary, how to use the effective, multi-source fiber-optic sensing signals measured by advanced fiber-optic sensing systems to identify the characteristic parameters of engineering structures with high accuracy, stability, and durability still requires researchers from intersecting disciplines such as optics, mechanics, and structural engineering to comprehensively consider and fully integrate relevant technical features in the directions of analytical theory, model experiments, and engineering applications. This will promote the development of information-driven methods and systems based on long-term continuous, real-time monitoring data for inversion of characteristic parameters of engineering structures and intelligent perception of physical states, and further advance the automation, visualization, and digitization of efficient and scientific assessment of the physical states of engineering structures in service and intelligent structural health monitoring systems.

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