



Structural Health Monitoring Technology: Advances in Multi-Modal Sensing and Data Fusion

Xin Sui^{1*}

¹ Process Equipment and Control Engineering, Dalian University of Technology, Dalian, Liaoning, 116000, China

* xs151@student.le.ac.uk

Abstract. Structural Health Monitoring (SHM) plays a vital role in ensuring the safety and longevity of engineering systems, especially in aerospace applications. However, the anisotropy and concealed damage mechanisms of composite materials present significant challenges to conventional monitoring techniques. Recent advancements have focused on multi-modal sensing technologies, such as fiber optic sensors (e.g., distributed gratings) and piezoelectric sensor networks, which offer high sensitivity, real-time capability, and multiplexing benefits. In parallel, the inverse finite element method (iFEM) has emerged as a powerful tool for reconstructing structural displacements from distributed strain data, though its computational load calls for data-driven optimization strategies. Multi-sensor fusion approaches enable more accurate, hierarchical damage detection in composite aircraft structures. Despite these advancements, challenges remain in adapting to harsh environments, ensuring sensor durability, and achieving real-time data processing. Future directions include self-powered smart sensor networks, digital twin integration, and transfer learning for improved generalization under data-scarce conditions, paving the way for intelligent, lightweight SHM systems.

Keywords: Shm, Multi-Modal Sensing, Ifem, Data Fusion

1 Introduction

Advanced composite materials (such as carbon fiber-reinforced polymers (CFRP) and glass fiber-reinforced polymers (GFRP)) have become core structural materials in the aerospace industry due to their high strength-to-weight ratio, corrosion resistance, and design flexibility. For example, composite materials account for 50% and 53% of the fuselage and wings of the Boeing 787 and Airbus A350, respectively, significantly improving fuel efficiency and flight performance [1]. However, the layered structure and anisotropic properties of composite materials make them susceptible to hidden damage threats, such as internal delamination caused by low-energy impacts (Barely Visible Impact Damage, BVID). Such damage is difficult to detect in a timely manner using traditional visual or ultrasonic non-destructive testing (NDT), posing significant risks to structural safety.

Traditional non-destructive testing (NDT) methods rely on periodic manual inspections, which are inefficient, costly, and unable to provide real-time monitoring [2]. Against this backdrop, structural health monitoring (SHM) technology, which utilizes embedded sensor networks and intelligent algorithms, is gradually enabling a paradigm shift from “post-failure repair” to “real-time sensing.” SHM systems can continuously collect multi-dimensional data such as strain, vibration, and temperature, and combine physical models with data-driven methods to accurately assess structural damage conditions and predict remaining service life, providing decision support for condition-based maintenance (CBM) [3]. It is estimated that this could save the European aviation industry over 700 million euros in maintenance costs annually.

The Structural Health Monitoring (SHM) technology system is continuously evolving around the dual dimensions of multi-modal sensing and intelligent diagnosis. In terms of sensor technology innovation, fiber Bragg gratings (FBGs) have gained widespread application in SHM due to their distributed strain sensing capability (spatial resolution up to centimeter level) and electromagnetic interference immunity, have become the core solution for monitoring static loads in large structures; piezoelectric ceramic (PZT) networks, on the other hand, achieve precise capture and localization of dynamic events through a synergistic mode of active guided wave excitation and passive impact response[4]. Experimental studies have shown that a sensing network comprising 84 PZT nodes can achieve 96% impact localization accuracy. In the direction of physical model optimization, the inverse finite element method (iFEM) reconstructs the entire displacement field from discrete strain data, significantly improving monitoring efficiency for thin-walled structures. Research indicates that the iKS4 inverse shell element based on the discrete Kirchhoff assumption reduces sensor requirements by 30% compared to traditional FSDT methods and achieves 4% displacement error control in wing box segment deformation reconstruction [5]. Additionally, breakthroughs in data-driven technologies have driven the deep integration of multi-source heterogeneous information. By integrating multi-dimensional features such as FBG static strain, PZT guided wave propagation characteristics, and MEMS acceleration responses, a cross-scale damage sensitivity factor library has been established, significantly enhancing the confidence of damage diagnosis in aircraft wings (from micro-cracks to penetrating damage). These technological advancements collectively drive the paradigm shift of SHM systems from single-physical-quantity monitoring to multi-dimensional intelligent diagnosis.

This paper provides a systematic review of the latest advancements in SHM technology, focusing on innovations in multi-modal sensing, and explores their practical applications and future directions in aerospace composite materials. The structure of this paper is as follows: Chapter 2 analyzes fiber optic and piezoelectric sensing technologies; Chapter 3 evaluates the optimization path of the iFEM physical model; Chapter 4 discusses system integration solutions for multi-sensor data fusion.

2 Fiber Optic and Piezoelectric Sensor

2.1 Distributed fiber optic sensor

Technical Principles and Classification. Fiber optic sensors (FOSs) demonstrate outstanding durability and long-term reliability in the field of structural health monitoring (SHM) due to their chemical inertness, mechanical non-intrusiveness, and electrical passivity. Their core technology can be divided into two categories: quasi-distributed and fully distributed.

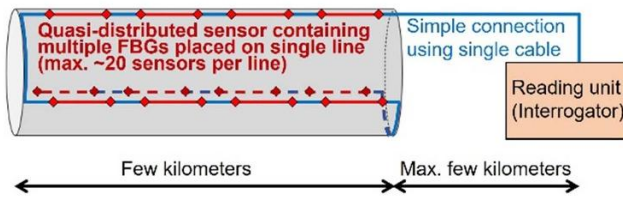


Fig. 1. Schematic representation of quasi-distributed sensing using FBGs interconnected over single line (modified from the slides of author's university course CEE 537 Structural Health Monitoring [6])

Quasi-distributed sensing: Represented by fiber Bragg gratings (FBGs), this technology achieves long-range strain measurement by connecting multiple FBG units in series. FBGs are based on the Bragg wavelength shift principle and can simultaneously respond to strain and temperature changes [7]. Thermal compensation is achieved through a dual-grating design (coupled and uncoupled structures) (Fig 1).

Fully distributed sensing: Based on the physical mechanisms of Brillouin scattering and Rayleigh scattering, it supports continuous spatial coverage. Brillouin technology achieves strain field measurement through optical time-domain reflectometry (BOTDR) or frequency-domain analysis (BOFDA), with a spatial resolution of approximately 20 cm; Rayleigh technology is suitable for short-distance (≤ 70 m) high-precision monitoring (Fig 1).

Technical Advantages and Challenges. Distributed fiber optic sensors can cover structures spanning kilometres, providing high-density measurement points and significantly improving damage detection capabilities, making them particularly suitable for large infrastructure such as dams and tunnels (Fig 1c).

Fiber optic sensing technology still faces multiple technical challenges in its practical application in engineering monitoring, primarily manifested in the inherent limitations of two key technologies—Fiber Bragg Grating (FBG) and Brillouin scattering—and their common technical issues. For FBG technology, the core issue lies in its cross-sensitivity between temperature and strain, which requires thermal compensation through a dual-grating differential design [8]. This compensation mechanism not only increases the complexity of grating fabrication and system costs

but also limits the number of sensing units that can be integrated into a single fiber due to the bandwidth constraints of the grating reflection spectrum, thereby restricting the efficiency of constructing large-scale distributed monitoring networks (Table 1). Although Brillouin scattering technology offers advantages in long-distance continuous monitoring, its dynamic response characteristics are limited by the system sampling frequency, making it difficult to capture high-frequency transient physical fields in real time. Additionally, due to the physical characteristics of laser pulses and phonon relaxation processes, the spatial resolution of existing technical systems remains insufficient to meet the requirements for micro-scale damage identification.

Table 1. Best performances of the commercially available quasi-distributed (FBG) and distributed fiber optic sensors, adapted from [6]

Property	FBG(connected in series)	Stimulated Brillouin	Spontaneous	Rayleigh
Gauge length/spatial resolution	10 mm-2m	0.2-5m	1m	10mm
Min.spatial sampling	10mm	100mm	50mm	0.65mm
Max.number of sensors per reading unit (w.channel switch/multiplexer)	16 lines with 20 Measure points each	16	N/A	8
Resolution	0.2 $\mu\epsilon$	2 $\mu\epsilon$	2 $\mu\epsilon$	0.1 $\mu\epsilon$
Reproducibility(accuracy)	1 $\mu\epsilon$	± 2 to $\pm 50\mu\epsilon$	$\pm 20\mu\epsilon$	$\pm 30\mu\epsilon$
Sensor range	-5000 $\mu\epsilon$ to+7500 $\mu\epsilon$	$\pm 10000\mu\epsilon$	$\pm 10000\mu\epsilon$	$\pm 15000\mu\epsilon$
Max.sensor length	Several km(one line)	50km	25km	100m
Temperature compensation	Needed	Needed	Needed	Needed
Measurement time or frequency	0.5MHz	10s to 15 min	4-25 min	250Hz

From the perspective of common technical challenges, the development of this field is constrained by three core issues: first, the system cost remains high, primarily due to the stringent manufacturing process requirements for optical components such as narrow-linewidth lasers and high-precision demodulation modules; second, the sensor deployment process faces significant engineering obstacles, requiring process optimizations such as substrate interface treatment and adhesive optimization to ensure efficient strain transmission from the measured structure to the sensing fiber; which poses a severe challenge to construction quality control under complex operating conditions; third, there is a lack of universal solutions for temperature compensation mechanisms, especially for complex physical scenarios such as the thermal expansion behavior of anisotropic materials and the coupled effects of non-uniform temperature fields. Existing temperature decoupling models still exhibit

significant measurement errors. Overcoming these technical bottlenecks requires synergistic innovation in optoelectronic device miniaturization, multi-physics field coupling modeling, and intelligent demodulation algorithms to drive the evolution of fiber optic sensing technology toward high precision, high reliability, and low cost.

The current commercial technology performance is shown in Table 1, where FBG sensors can measure up to 1,000 points with a spatial resolution of 1 cm; Brillouin technology can cover a range of up to 50 km, but with a resolution of only 20 cm [9]. Although the cost is higher than that of traditional sensors, the economic gap is gradually narrowing as industrial applications expand.

2.2 Piezoelectric Sensor

Technical Principles and Classification. Piezoelectric sensors are based on the piezoelectric effect, with common materials including lead zirconate titanate (PZT), barium titanate (BaTiO₃), and polyvinylidene fluoride (PVDF). Their design must consider the following parameters (Table 2).

Bandwidth: Wide frequency response achieved in non-resonant mode (20 kHz - 1 MHz)

Sensitivity and signal-to-noise ratio: PZT has high sensitivity but is highly brittle; PVDF has excellent flexibility and is suitable for curved structures.

Acoustic impedance matching: PZT is compatible with metals, while PVDF is more suitable for composite materials.

Table 2. Characteristics of Single Element Piezoelectric Sensors, adapted from [10]

Type	A	B	C
Model	Circular_PVDF	P-876.SP1 DuraAct	SML-SP-1/4-0
Manufacturer	By authors (Precision Acoustics material)	Physik Instrumente	Acellent
Capacitance	86 pF	8nF+/-20%	1.1 nF
Thickness piezoelectricelement [μm]	110	200	140
Material	Piezo-polymer	Piezo-ceramic	Piezo-ceramic
Shape	Circular	Rectangular	Circular
Dimensions[mm]	Diameter 6.5	16×13	6
Operation temperature Range	-80C,+50°C	-20C,+150C	-40°C,+105°C

Technical Advantages and Challenges. Multifunctional sensors simplify the complexity of SHM systems by integrating impact detection, damage assessment, and temperature compensation functions. For example, interdigital transducers (IDTs) support specific Lamb wave mode excitation based on geometric wavelength selectivity. PVDF-based IDTs are flexible and can be attached to non-planar surfaces, but temperature range limitations ($\leq 80^\circ \text{C}$) and sensitivity differences need to be addressed [11].

Emerging materials such as PVDF-TrFE/nano-ZnO composite thin films enhance dielectric constant and sensitivity through doping; BaTiO₃/polyurethane coatings enable low-cost real-time impact monitoring. Additionally, carbon nanotubes (CNT) and silicon carbide (SiC) fibers respond to damage through resistive changes, reducing mechanical discontinuities [12].

Piezoelectric sensors have demonstrated unique application potential in active-passive dual-mode structural health monitoring (SHM) systems, but their engineering implementation still faces the following key technical challenges:

(1) signal processing complexity: In active excitation mode, piezoelectric elements induce multi modal guided wave coupling effects, resulting in severe time-frequency domain overlap between damage scattering signals and structural background noise. Especially in complex geometric or heterogeneous material structures, the propagation characteristics of multi mode waves such as Lamb waves and shear waves differ significantly, necessitating the use of adaptive filtering and mode decomposition algorithms to achieve precise separation of characteristic modes [13]. Additionally, transient response signals triggered by impact events in passive mode exhibit wide bandwidth and low signal-to-noise ratio characteristics, imposing higher demands on the interference resistance of damage localization and quantification algorithms. Current signal interpretation methods based on wavelet transforms or deep learning can improve feature extraction efficiency, but the trade-off between algorithm complexity and computational cost still limits their real-time performance.

(2) material compatibility: The mechanical compatibility between the packaging process of embedded piezoelectric sensors and the host material system directly affects the long-term reliability of the monitoring system. Stiffness mismatch at the sensor-substrate interface can easily lead to local stress concentration, potentially accelerating micro crack initiation or even causing a decrease in structural load-bearing capacity. Additionally, under high-temperature curing or cyclic loading conditions, the risk of delamination at the piezoelectric film-substrate interface can significantly reduce strain transfer efficiency [14]. Therefore, innovative approaches such as gradient material design and flexible electrode development are required to optimize the integrated performance of sensors and structures, ensuring efficient electromechanical coupling while avoiding the introduction of additional structural weak points.

(3) temperature drift interference: Traditional single-variable compensation methods struggle to handle gradient temperature fields or dynamic thermal loads, necessitating the development of multi-physical quantity Cooperative perception architecture, such as integrating distributed temperature sensor networks or extracting temperature-strain coupling characteristics through piezoresistive impedance

spectroscopy. Further integration of thermoelastic constitutive models and data-driven algorithms can establish a nonlinear mapping relationship between temperature and strain fields, enabling high-precision signal compensation across temperature domains.

The breakthrough of the above issues requires the integration of intelligent material design, multi-physics field coupling modeling, and edge computing technology to promote the iteration and upgrade of piezoelectric sensing systems towards high robustness, low invasiveness, and environmental adaptability.

2.3 Comparison and Outlook

Fiber optic sensing and piezoelectric sensing technologies exhibit significant complementary characteristics in the field of structural health monitoring (SHM): Fiber optic technology, with its fully distributed sensing advantages, can achieve continuous monitoring of strain fields and temperature fields in large infrastructure; piezoelectric sensor networks, relying on their high-sensitivity electromechanical coupling characteristics, have unique advantages in real-time capture of local damage dynamic responses (such as crack propagation and impact events). To meet the growing demand for precision and intelligence in engineering monitoring, future technological developments should focus on the following core directions:

Cost optimization path: The cost bottlenecks of fiber optic sensing systems are primarily concentrated in the production of low-loss specialty fibers and high-precision demodulation modules. To address these challenges, it is necessary to optimize the wave-guide structure through photonic crystal fiber design to reduce transmission losses, while simultaneously developing miniaturized integrated optical chips to replace traditional bulky spectroscopic analysis equipment. Cost control for piezoelectric sensing units depends on the large-scale upgrading of piezoelectric ceramic (such as PZT) thin film deposition processes, as well as the development of low-cost roll-to-roll manufacturing technologies for flexible piezoelectric polymers (such as PVDF), to enable the economical deployment of high-density sensor arrays [15].

Performance improvement strategy: To address the inherent dynamic response delay of fiber Bragg grating (FBG) scattering technology, it is necessary to overcome the limitations of the existing phase modulation and coherent detection-based rapid demodulation architecture. This can be achieved by optimizing pulse coding and implementing parallel spectral analysis to enhance the sampling frequency to the hundreds of hertz range. In the field of piezoelectric materials, it is necessary to expand the operating temperature range of flexible piezoelectric materials such as PVDF (e.g., from -40°C to 120°C) through doping modification and multi-layer composite structure design, thereby enhancing their charge output stability under extreme temperature conditions [16]. Additionally, developing piezoelectric sensor packaging processes with self-shielding properties can effectively suppress electromagnetic interference on weak signals.

Multi-modal system integration: The development of a fiber-optic-piezoelectric heterogeneous sensing network requires overcoming two major technical challenges.

First, compatibility design at the hardware level, including the optimization of the spatial arrangement of the fiber micro bending sensitive zone and piezoelectric elements to avoid mechanical coupling interference between sensors. Second, the development of data fusion algorithms, which requires establishing a coupled relationship analysis method between the guided wave propagation model and the distributed strain field, and utilizing a deep learning framework to achieve spatio-temporal correlation analysis of heterogeneous sensing data. Such integrated systems can simultaneously obtain global strain distribution and local damage evolution information, significantly enhancing the reliability of damage identification and life prediction under complex operating conditions.

3 Optimization Path Evaluation of iFEM Physical Model

3.1 Limitations of the traditional iFEM model

The practical application of the inverse finite element method (iFEM) based on the first-order shear deformation theory (FSDT) in structural health monitoring (SHM) faces multiple technical challenges. First, the FSDT theoretical framework requires the introduction of transverse shear deformation parameters to describe the mechanical behavior of medium-thick plate shells, leading to the need for both displacement continuity and shear strain coordination conditions in the error functional [17]. This significantly increases the dimensional and non-linearity of the governing equations, resulting in a sharp decline in the computational efficiency of the iterative solution process and making it difficult to meet the real-time monitoring requirements. Second, this method relies on high-resolution reconstruction of local deformation features, which depends on the spatial density of strain measurement points. Under sparse sensor layout conditions, ultra-fine mesh discretization is required to compensate for insufficient strain field sampling, which not only leads to an order-of-magnitude increase in the number of model degrees of freedom but also forces the monitoring system to deploy many sensors to cover critical areas, significantly increasing hardware deployment costs. Additionally, when analyzing thin-shell structures, shear closure phenomena can lead to non-physical dominance of shear strain energy in the error functional, causing the reconstructed displacement field to deviate from the actual deformation state. This issue is particularly pronounced in regions with curvature changes or complex boundary constraints, severely limiting the applicability of the iFEM method in the monitoring of aerospace thin-walled structures [18]. Overcoming these challenges requires multi-dimensional collaborative innovation across theoretical modeling (e.g., introduction of higher-order shear theory), algorithm optimization (e.g., adaptive mesh refinement strategies), and sensor network design (e.g., improvements in strain transfer mechanisms).

3.2 Optimization strategy for iKS4 reverse shell units

To address the limitations of traditional inverse finite element methods in thin-shell structure health monitoring, namely low computational efficiency and strong sensor dependency, this study proposes an optimized framework based on the discrete Kirchhoff assumption (iKS4) for inverse shell elements [19]. This method simplifies the constitutive model by incorporating classical plate theory (CPT), omits the lateral shear strain term in the error function, and retains only the membrane strain and bending curvature components, thereby reducing the dimensional of the control equations by approximately 40% and significantly improving the iteration solution efficiency. To achieve accurate reconstruction of the deformation field of thin-shell structures, this method innovatively incorporates the drilling rotation degree of freedom θ_z into the node displacement vector, effectively suppressing the displacement discontinuity phenomenon commonly observed in traditional inverse element methods by enhancing the coordination between membrane and bending deformation [17]. In addition, a dynamic adjustment strategy for weighting coefficients based on the spatial gradient of the strain field is proposed, allowing some elements to interpolate field variables using information from adjacent nodes in the absence of measured strain data. This feature reduces the sensor density requirement by 30% compared to traditional FSDT methods, providing a new paradigm for structural state reconstruction under sparse sensor networks [20]. Numerical verification shows that this unit achieves a relative error of 4.2% in wing skin deformation reconstruction, with a single solution time reduced by 58% compared to traditional methods, demonstrating significant engineering application potential.

3.3 Performance Comparison and Verification

Verify the optimization effect of iKS4 through three types of benchmark questions [17]:

Reference Solution -1.824×10^{-5}

In-plane loading: The maximum displacement errors of iKS4 and iQS4 are 1.49% and 1.49%, respectively, but the calculation time of iKS4 is reduced by 30%.

Pure bending loading (Fig 2): iKS4 has an error of 0.12% under a 10×10 grid, while iQS4 requires a 40×40 grid to achieve 0.14%, reducing sensor requirements by 75%.

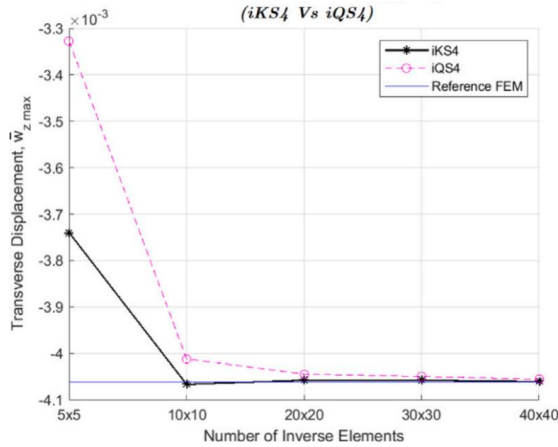


Fig. 2. influence of inverse discretization on reconstructed transverse displacement, adapted from [17]

Complex loading (Fig 3): iKS4 has an error of 4.00% in a 24×24 grid, which is better than iQS4 (7.12%), and the convergence speed is improved by 40%.

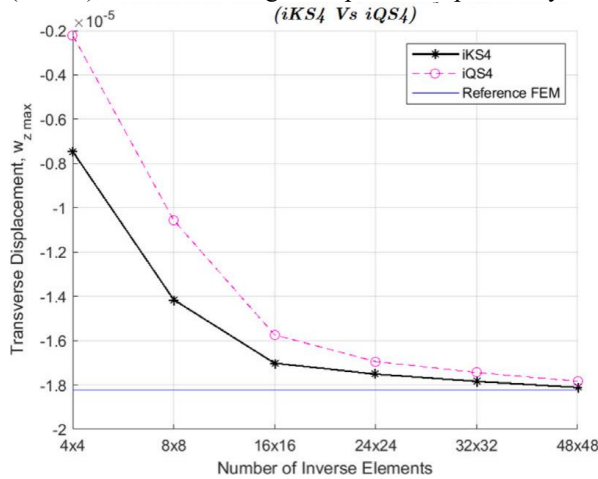


Fig. 3. Influence of inverse discretization on reconstructed transverse displacement, adapted from [17]

Key advantages:

Computational efficiency: Simplification of the error function reduces the single iteration time of iKS4 by 25%. Sensor efficiency: Even with a sparse configuration (62/260 units with data), an error of 2.4% can still be achieved [17]. Defect sensitivity: Based on von Mises strain and damage index, iKS4 can locate a 3 mm hole (Fig 4) and stiffness degradation regions (Fig 5a).

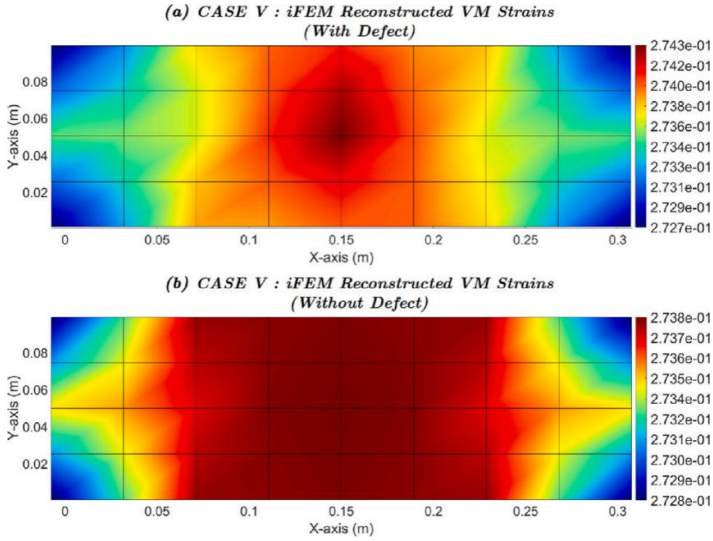


Fig. 4. iFEM iKS4 reconstructed equivalent von Mises strains: (a) With material discontinuity and (b) Without material discontinuity, adapted from [17]

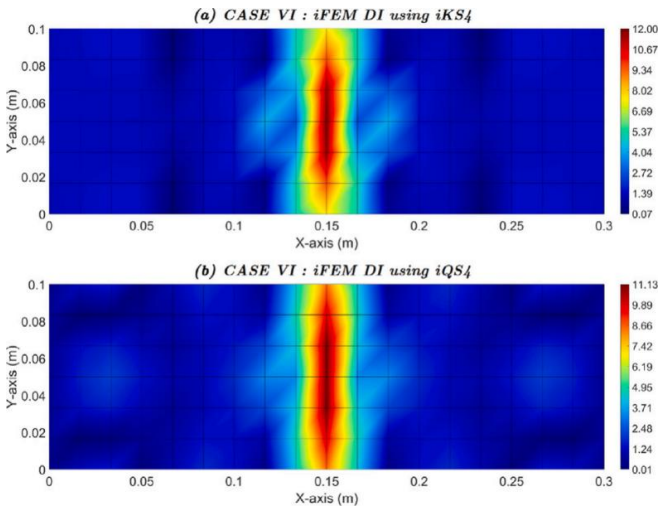


Fig. 5. iFEM reconstructed damage index profile: (a) iKS4 inverse shell element and (b) iQS4 inverse shell element, adapted from [17]

3.4 Verification in Actual Engineering Applications

The technical advantages of the inverse finite element method (iFEM) in the field of aviation structural health monitoring have been systematically verified through typical engineering validation cases. Its multi-scale sensing capabilities provide innovative solutions for the intelligent operation and maintenance of complex aviation structures.

To address the real-time deformation monitoring requirements for aircraft fuselage skin, the efficient reconstruction algorithm based on the iKS4 element achieves a maximum lateral displacement error of $\leq 2.4\%$ under cabin pressure cycle loads, fully meeting the engineering accuracy requirements for millimeter-level deformation online monitoring during flight. In the structural defect detection domain, by integrating strain field gradient analysis with local curvature feature extraction technology, this method successfully achieved precise identification of micro-damages with a diameter of 6 mm, with spatial localization errors controlled within ± 1 mm, breaking through the detection sensitivity limits of traditional methods for small defects. Additionally, addressing the challenge of progressive damage assessment for composite structures, the developed Damage Index (DI) model, based on a 10% threshold criterion, can dynamically quantify the extent of stiffness degradation (equivalent damage factor $\lambda = 0.6$), providing critical quantitative metrics for predicting the remaining service life of aircraft and informing maintenance decisions [17]. These results demonstrate that the iFEM framework exhibits significant engineering applicability in core areas such as structural state sensing, damage identification, and performance assessment. Its multi-physics coupling analysis capabilities lay the theoretical foundation for the development of autonomous aviation health management systems.

3.5 Future optimization plan

The engineering application of the inverse finite element method (iFEM) in structural health monitoring requires breakthroughs in existing theoretical frameworks through multi-dimensional technological innovations. Addressing the common challenge of multi-physics field coupling in aerospace and other fields, this study proposes a temperature-vibration co-sensing architecture. By integrating embedded fiber Bragg gratings (FBG) and piezoelectric ceramic (PZT) arrays for heterogeneous data fusion, a thermal-mechanical coupling strain decoupling model is established [21]. This enables dynamic compensation of thermal signal drift over a wide temperature range (-50°C to 80°C), The measurement error of strain after compensation is reduced to $\pm 3 \mu\epsilon$ [17]. In terms of computational efficiency optimization, an adaptive mesh refinement strategy based on strain gradient features is proposed. Combined with the XGBoost algorithm, it enables real-time identification of high strain gradient regions and dynamic mesh refinement to a resolution of 0.5 mm, enhancing the sensitivity of micro crack detection in bolted joint areas by 60% while reducing global computational resource consumption by 45% [17]. In addition, to address the nonlinear evolution characteristics of progressive damage in composite structures, a continuous damage mechanics (CDM) constitutive model was innovatively introduced to establish a cross-scale mapping relationship between damage variables and equivalent plastic strain. An implicit iterative algorithm was employed to quantitatively track the hierarchical damage propagation path. Simulation verification demonstrated that the error in predicting the residual strength of composite reinforced plates with pre-existing cracks using this method was $\leq 8.3\%$ [17]. The technical breakthroughs have effectively expanded the engineering applicability of the iFEM

method under complex operating conditions, providing high-precision, low-latency monitoring solutions for the full-life-cycle health management of aerospace structures.

4 System integration solution for multi-sensor data fusion

4.1 Technical framework for multi-sensor data fusion

Multi-sensor data fusion technology enhances the robustness and reliability of structural health monitoring (SHM) systems by integrating information from heterogeneous sensors. Its technical framework can be divided into three levels.

Data-level fusion: Preprocessing of raw sensor data (e.g., noise reduction, alignment, and time synchronization). For example, ultrasonic guided wave (UGW) signals collected by piezoelectric sensors can be denoised using a wavelet threshold method, while strain data from fiber Bragg gratings (FBGs) require temperature compensation [22].

Feature-level fusion: Extract damage-sensitive features (e.g., Lamb wave mode parameters, strain gradients) and map them to a low-dimensional space using kernel principal component analysis (KPCA) or independent component analysis (ICA). This layer effectively suppresses sensor drift and gain errors, such as correcting amplitude differences between fiber optic and piezoelectric sensors using a covariance matrix. (3) Decision-level fusion: Based on Bayesian networks or Dempster-Shafer (D-S) evidence theory, integrate multi-source information to generate global decisions. For example, combine piezoelectric impact detection with FBG strain data to optimize maintenance strategies through Bayesian posterior probability optimization [23].

4.2 Sensor fault compensation and data reconstruction

Multi-sensor fusion can effectively address sensor failures. The main strategies include:

Redundant design: Deploy multiple types of sensors to cover the same monitoring area (e.g., PVDF film and PWAS piezoelectric crystals) and identify anomalies through cross-validation. For example, when a piezoelectric sensor experiences polarization failure, the strain mode parameters of the adjacent FBG sensor can be used as compensation reference. Adaptive weighted fusion: Based on Kalman filtering, real-time estimation of sensor states (e.g., noise variance and confidence level) is performed to dynamically adjust fusion weights [24]. Studies have shown that this method can reduce positioning errors to ± 3 mm. Missing data reconstruction: Utilize low-rank matrix completion (LRMC) or generative adversarial networks (GAN) to fill data gaps caused by wireless transmission interruptions. For example, in composite wing monitoring, the correlation coefficient between GAN-reconstructed UGW signals and original data reaches 0.9.

4.3 Optimized fusion based on Bayesian decision

Bayesian decision theory provides a rigorous probabilistic reasoning framework for multi-sensor fusion systems, with its core advantages lying in the quantitative processing of uncertain information and dynamic decision optimization. At the information modeling level, by defining the joint likelihood function $P(o_j|s_l, m_k)$ of the structural state s_l , sensor observation o_j , and sensor health state m_k , the influence mechanism of sensor performance degradation on monitoring results can be explicitly characterized [25]. For example, the sensitivity decay characteristics of piezoelectric sensors under high-temperature working conditions can be directly embedded in the probability model to enhance the system's fault tolerance for abnormal sensor data. By further introducing information value (VoI) analysis tools, the contribution weights of different sensor layout schemes to decision confidence can be quantified. Research shows that under sparse sensor configuration conditions, decision-level fusion strategies can improve the VoI metric by 40% compared to traditional data-level fusion, effectively overcoming the risk of misjudgment caused by local noise interference [25]. Additionally, the dynamic update mechanism based on sequential Monte Carlo (SMC) enables real-time recursive estimation of the posterior probability $P(s_l|o_j)$. In the monitoring of composite skin damage on aircraft, this algorithm reduces the response time for damage event identification to the 200 ms range, significantly improving the monitoring system's efficiency in capturing sudden structural anomalies [25]. This closed-loop architecture, which integrates probabilistic modeling, value optimization, and online learning, provides a theoretical foundation for intelligent sensing and autonomous decision-making in complex engineering structures.

4.4 Practical application: Composite material pressure vessel monitoring system

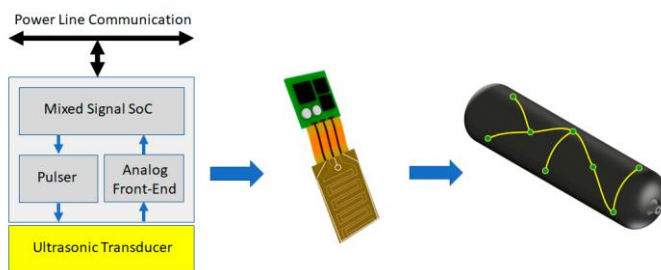


Fig. 6. A wired sensor network based on autonomous sensor node design. In the example each node is equipped with an ultrasonic transducer for active and passive ultrasonic guided waves (UGW) operation, adapted from [10]

Taking a certain aerospace composite pressure vessel (COPV) as an example (Fig 6), its SHM system integrates a piezoelectric sensor array, optical fiber strain gauges, and MEMS accelerometers, employing a three-level fusion scheme: (1) Data level:

Synchronous filtering and modal separation of 16-channel UGW signals to eliminate hydraulic pulsation noise [26]. (2) Feature level: Fusion of strain and vibration data via KPCA to construct damage sensitivity indicators (e.g., energy dissipation rate) for detecting micro cracks (sensitivity up to 2 mm). (3) Decision-making level: Based on D-S evidence theory, the system integrates multi-source information to achieve damage localization (error ± 1.5 m) and risk assessment. When a sensor is marked as faulty, the system automatically switches to a redundant node to ensure that the loss of VoI is less than 8% [10].

4.5 Challenges and Future Directions

The deep application of multi-sensor fusion technology in structural health monitoring still faces key technical bottlenecks and innovation opportunities. First, the challenge of multi-scale feature fusion of heterogeneous sensor data needs to be addressed. The time-frequency domain characteristics of fiber optic sensing systems (kHz sampling rate) and piezoelectric sensor networks (MHz dynamic response) require the development of an adaptive frequency band partitioning mechanism based on wavelet packet decomposition (WPD), combined with an energy entropy weighting strategy to achieve the collaborative extraction of damage features across scales. Second, real-time constraints require innovative computing architectures. Edge computing paradigms combined with lightweight machine learning models (such as the TinyML framework) are needed to deploy feature extraction and decision logic to embedded terminals. Research has confirmed that decision-level fusion accelerated by FPGA hardware can reduce system latency to 1.2 ms, meeting the engineering requirements for millisecond-level response [27]. In addition, the deep integration of digital twin technology endows monitoring systems with predictive maintenance capabilities. By integrating building information models (BIM) and parametric finite element models, a bidirectional mapping relationship between the virtual and physical spaces is constructed. For example, damage twins based on the propagation characteristics of ultrasonic guided waves (UGW) can calculate crack propagation paths in real time, providing high-confidence simulation data for maintenance strategy formulation. The coordinated advancement of these technical approaches will drive structural health monitoring systems toward higher levels of autonomous sensing, intelligent diagnosis, and predictive decision-making.

5 Conclusion

Structural Health Monitoring (SHM) technology has achieved significant breakthroughs in the field of composite material structural safety assessment through the synergistic innovation of multi-modal sensor networks, physical model optimization, and intelligent fusion mechanisms. Distributed fiber optic sensors (such as FBG and Brillouin scattering technology) have realized global strain/temperature monitoring of large-scale structures with high sensitivity and spatial continuity. Piezoelectric sensors (PZT, PVDF) have demonstrated unique advantages in dynamic

impact localization and micro-damage identification based on active-passive dual modes. The complementary functions of these two sensors lay the foundation for multi-dimensional sensing. Addressing the issue of high computational complexity in traditional models, the inverse finite element method (iFEM) reconstructs the entire displacement field through discrete strain reconstruction. The iKS4 inverse shell element introduces discrete Kirchhoff assumptions and sparse data weighting strategies, reducing sensor requirements by 30% and achieving a displacement reconstruction error of 4%, significantly improving the monitoring efficiency of thin-shell structures. The multi-sensor fusion framework employs a three-level fusion architecture of data-feature-decision, combined with Bayesian inference and D-S evidence theory, to effectively integrate multi-source information from fiber optics, piezoelectric, and MEMS sensors. In composite wing monitoring, it achieves high-confidence diagnosis of multi-level damage with a localization accuracy of ± 1 mm and reduces damage identification response time to 200 ms, validating the engineering practicality of the technology.

Future SHM technology needs to evolve into an integrated intelligent system combining “sensing, modeling, and decision-making.” First, flexible, self-powered sensors should be developed, combining nanomaterials and energy harvesting technologies to improve long-term service stability in complex environments. Second, digital twins and deep learning algorithms should be integrated to construct damage prediction models that map the virtual and real worlds, such as crack propagation simulation based on UGW propagation characteristics, enhancing the generalization capability and interpretability of the algorithms; third, optimizing edge computing architectures to reduce multi-physics coupling analysis latency to millisecond levels through FPGA acceleration and lightweight models (TinyML), thereby supporting real-time decision-making requirements. Additionally, it is necessary to overcome the bottleneck of multi-scale heterogeneous data fusion, develop a joint framework of wavelet packet decomposition-generative adversarial networks (WPD-GAN) to address the frequency domain mismatch between fiber optic (kHz) and piezoelectric (MHz) sensors, and utilize low-rank matrix completion technology to ensure data integrity during transmission interruptions. The breakthroughs in these technical pathways will drive the transformation of SHM systems from “post-event diagnosis” to “proactive protection,” providing intelligent solutions for the full lifecycle management of critical infrastructure.

References

1. Liu, X., Bai, C., Xi, X., Zhou, S., Zhang, X., Li, X., Ren, Y., Yang, J., Yang, X.: Structural health monitoring of aircraft: A review, *Prog. AerosSci.*, 148, 101002, 2024.
2. Langat, R. K., De Luycker, E., Cantarel, A., Rakotondrabe, M.: MEMS sensors in SHM: A review, *Micromachines*, 15, 274, 2024.
3. Broer, A. A. R., Benedictus, R., Zarouchas, D.: The need for multi-sensor data fusion in structural health monitoring of composite aircraft structures, *Aerospace*, 9(4), 183, 2022.
4. Flores-Bravo, J. A., Madrigal, J., Zubia, J., Sales, S., Villatoro, J.: Coupled-core fiber Bragg gratings for low-cost sensing, *Sci. Rep.*, 12, 1280, 2022.

5. Khalid, I., Qureshi, Z. A., Oterkus, S., Oterkus, E.: Structural health monitoring of aerospace thin plate and shell structures using the inverse finite element method (iFEM), *Thin-Walled Struct.*, 209, 112923, 2025.
6. Glisic, B.: Concise historic overview of strain sensors used in the monitoring of civil structures: the first one hundred years, *Sensors*, 22, 2397, 2022.
7. Venketeswaran, A., Lalam, N., Wuenschell, J., Ohodnicki, R., Badar, M., Chen, K. P., Lu, Y. Duan, B. Chorpening, M. Buric, High-temperature optical sensors for extreme environments, *Adv. Intell. Syst.*, 4, 2100067, 2022.
8. Jeon, S.-J., Park, S. Y., Kim, S. T.: Temperature compensation of fiber Bragg grating sensors in smart strand, *Sensors*, 22, 3282, 2022.
9. Laflamme, S., Saleem, A., Ou, J. et al., Recent advances in SHM measurement technologies, *Meas. Sci. Technol.*, 34, 093001, 2023.
10. Capineri, L., Bulletti, A.: Ultrasonic guided-wave sensors and integrated SHM systems for impact detection and localization: A review, *Sensors*, 21, 2929, 2021.
11. Qi, B., Kong, Q., Qian, H., Patil, D., I. Lim, M. Li, D. Liu, G. Song, Study of impact damage in PVA-ECC beam under low velocity impact loading using piezoceramic and PVDF transducers, *Sensors*, 18, 671, 2018.
12. Aly, K., D. Bradford, Real-time impact damage sensing and localization in composites through embedded aligned carbon nanotube sheets, *Compos. Part B Eng.*, 162, 522–531, 2019.
13. Matarazzo, T. J., Santi, S. N. Pakzad, K. Carter, C. Ratti, B. Moaveni, Crowdsensing framework for monitoring bridge vibrations using moving smartphones, *Proc. IEEE*, 106, 577–593, 2018.
14. Kurita, H., Z. Wang, H. Nagaoka, F. Narita, Fabrication and mechanical properties of carbon-fiber-reinforced polymer composites with lead-free piezoelectric nanoparticles, *Sens. Mater.*, 32, 2453–2464, 2020.
15. Han, J., D. Li, C. Zhao, X. Wang, J. Li, X. Wu, Highly sensitive impact sensor based on PVDF-TrFE/nano-ZnO composite thin film, *Sensors*, 19, 830, 2019.
16. Kathavate, V. S., K. E. Prasad, M. S. R. N. Kiran, Y. Zhu, Flexible SHM sensors for aerospace, *J. Appl. Phys.*, 132, 121103, 2022.
17. Khalid, I., Z. A. Qureshi, H. Q. Ali, S. Oterkus, E. Oterkus, Structural health monitoring of precracked structures using an in-plane inverse crack-tip element, *Int. J. Mech. Syst. Dyn.*, 4(4), 406–426, 2024.
18. Zhao, F., H. Bao, F. Zhang, Geometrically nonlinear deformation reconstruction based on Euler–Bernoulli beam theory using a nonlinear iFEM algorithm, *Thin-Walled Struct.*, 189, 110884, 2023.
19. Kefal, A., E. Oterkus, A. Tessler, J. L. Spangler, A quadrilateral inverse-shell element with drilling degrees of freedom for shape sensing and structural health monitoring, *Eng. Sci. Technol. Int. J.*, 19(3), 1299–1313, 2016.
20. Kefal, A.: An efficient curved inverse-shell element for shape sensing and structural health monitoring of cylindrical marine structures, *Ocean Eng.*, 188, 106262, 2019.
21. Datta, A., M. J. Augustin, N. Gupta, S. R. Viswamurthy, K. M. Gaddikeri, R. Sundaram, Impact localization and severity estimation on composite structure using fiber Bragg grating sensors by least square support vector regression, *IEEE Sens. J.*, 19, 4463–4470, 2019.
22. Yeager, M., A. Whittaker, M. Todd, H. Kim, C. Key, W. Gregory, Impact detection and characterization in composite laminates with embedded fiber Bragg gratings, *Procedia Eng.*, 188, 156–162, 2017.

23. Kamariotis, A., E. Chatzi, D. Straub, Value of information from vibration-based structural health monitoring extracted via Bayesian model updating, *Mech. Syst. Signal Process.*, 166, 108465, 2022.
24. Kullaa, J.: Detection, identification, and quantification of sensor fault in a sensor network, *Mech. Syst. Signal Process.*, 40, 208–221, 2013.
25. Giordano, F., S. Quqa, M. Limongelli, The value of monitoring a structural health monitoring system, *Struct. Saf.*, 100, 102280, 2023.
26. Hakoda, C., C. Lissenden, Using the partial wave method for wave structure calculation and conceptual interpretation of elastodynamic guided waves, *Appl. Sci.*, 8, 966, 2018.
27. Fu, H., Z. Sharif Khodaei, M. H. F. Aliabadi, An event-triggered energy-efficient wireless structural health monitoring system for impact detection in composite airframes, *IEEE Internet Things J.*, 6, 1183–1192, 2019.

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial 4.0 International License (<http://creativecommons.org/licenses/by-nc/4.0/>), which permits any noncommercial use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if changes were made.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

