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The Role of SHM in Retrofitting and Life-Cycle Management of Aging Buildings: A Comprehensive Review

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Abstract

Aging building stock and the increasing complexity of urban infrastructures have highlighted the urgent need for effective strategies to assess, maintain, and retrofit civil structures. Traditional inspection methods, including visual assessment and destructive testing, are often insufficient for capturing the subtle and progressive deterioration inherent in aging infrastructure. Structural Health Monitoring (SHM) has emerged as a transformative approach, enabling continuous, real-time assessment of structural integrity through advanced sensing technologies, data-driven analytics, and integration with digital tools. This comprehensive review examines the role of SHM in the retrofitting and lifecycle management of buildings, focusing on technological advancements, methodological frameworks, and practical applications across diverse structural typologies, including bridges, high-rise buildings, and heritage masonry structures. The review critically evaluates sensor systems, including fiber-optic, wireless, and smart sensor networks, as well as data analytics techniques incorporating artificial intelligence and machine learning for automated damage detection and predictive maintenance. Furthermore, the integration of SHM with Building Information Modeling (BIM) and Digital Twin platforms is discussed as a key enabler for lifecycle optimization and retrofit decision support. Challenges in sensor deployment, data management, environmental robustness, and standardization are highlighted, alongside emerging trends and research gaps. The findings underscore SHM's potential to enhance safety, extend service life, reduce economic risks, and support sustainable infrastructure management, providing a roadmap for future research and practical implementation in civil engineering.

Keywords: Structural Health Monitoring (SHM), Retrofitting, Lifecycle Management, Aging Buildings, Building Information Modeling (BIM)

1. Introduction

1.1 Context and Significance of Aging Infrastructure

Rapid urbanization and demographic expansion are continuously increasing the demand on existing structures, accelerating deterioration in building stocks older than 40–60 years. A significant portion of global infrastructure was constructed before modern seismic, durability, and safety standards were established, resulting in inadequate lateral resistance, poor material quality, and diminished structural capacity over time. These aging buildings are progressively facing environmental, mechanical, and operational stresses that reduce structural reliability and accelerate degradation mechanisms such as cracking, corrosion, and material fatigue [1]. Consequently, modern societies face a substantial backlog of aging buildings requiring performance assessment, maintenance prioritization, and retrofitting to ensure safety and functionality.

The consequences of deteriorating structural systems extend beyond engineering concerns and have severe socio-economic implications. Infrastructure failures lead to financial losses, disruption of public services, and risks to human life. For nations with older urban centers, failure to address degradation in time carries exponential increases in repair costs and catastrophic risk exposure during extreme events such as earthquakes, floods, and urban fire incidents. Proactive planning and early detection of structural damage therefore represent strategic necessities rather than optional maintenance measures. The need for reliable, real-time assessment tools is thus becoming paramount to mitigate risks associated with structural aging and prevent safety-critical failures [2].

1.2 Limitations of Conventional Structural Assessment and Retrofitting Approaches

Traditional methods such as visual inspections, destructive sampling, and code-based retrofitting decisions have historically guided maintenance planning and repair interventions. However, visual inspections provide only surface-level information, often failing to detect concealed deterioration like internal cracks, bond failures, and subsurface corrosion, leading to inaccurate assessment results [3]. Destructive testing, although capable of providing deeper insights, is labor-intensive, time-consuming, and unable to capture progressive deterioration over building lifetimes. These limitations result in inconsistent decision-making, overly conservative retrofits, or delayed interventions that compromise safety and inflate costs.

Furthermore, conventional assessment approaches are episodic, generating one-time snapshots rather than continuous records of structural behavior. Such discontinuous evaluation cannot capture dynamic responses, degradation trends, or fluctuating loading conditions, ultimately limiting the ability to forecast damage progression or assess residual service life. Without predictive capabilities, current retrofitting practices often rely on empirical judgments rather than quantitative data, creating inefficiencies in allocating maintenance budgets and prioritizing vulnerable buildings [4]. Therefore, the growing demand for reliable, data-driven retrofit planning necessitates the adoption of systems capable of real-time observation, diagnostic analysis, and condition-based decision-making.

1.3 Role of Structural Health Monitoring (SHM) in Modern Structural Engineering

Structural Health Monitoring (SHM) presents a transformative alternative to conventional assessment by enabling real-time data capture, automated diagnostics, and predictive performance models. SHM encompasses sensing, data processing, and evaluation techniques that continuously monitor structural responses such as strain, displacement, acceleration, vibration frequency, and temperature, allowing early detection of anomalies before visible damage occurs [5]. Unlike manual inspection procedures, SHM captures deterioration mechanisms as they develop, enabling quantitative assessment of damage severity, location, and progression under operational loads.

Beyond early detection, SHM offers a powerful decision-support platform for retrofitting strategies and long-term asset management. Integrating SHM-generated data with numerical models enables engineers to validate structural performance assumptions, evaluate retrofit effectiveness, and update building models to reflect actual post-retrofit behavior. Such integration supports optimal selection of strengthening techniques, avoids unnecessary intervention, and ensures targeted repair of high-risk areas. Furthermore, SHM data serves as an input for life-cycle cost analysis (LCCA) and predictive maintenance planning, enabling risk-informed decisions that reduce cost and improve reliability throughout building lifetimes [6].

1.4 Objectives and Scope of the Review

This review critically examines the scientific, technological, and practical role of SHM in retrofitting and managing aging building infrastructure. The primary objective is to analyze SHM methodologies, sensing technologies, and data-processing techniques that support accurate structural diagnosis and enable performance-driven retrofitting decisions. Additionally, the review synthesizes global research trends to highlight how SHM promotes sustainable lifecycle management, including predictive maintenance, risk mitigation, and cost optimization across extended service periods [7].

Moreover, the paper identifies current challenges related to data interpretation, sensor durability, standardization, and cost–benefit implementation barriers that hinder widespread SHM adoption. Research gaps are mapped to emerging technologies such as artificial intelligence, wireless sensing, IoT-enabled systems, and digital twins, which offer promising pathways toward autonomous and adaptive monitoring solutions for aging infrastructure. Ultimately, the review develops a comprehensive knowledge base to guide future developments in SHM-enabled retrofitting frameworks, ensuring resilient and sustainable building management for contemporary and future urban environments [8].

2. Review Methodology

2.1 PRISMA-Based Literature Identification and Screening Strategy

The literature selection process followed a PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) based methodology to ensure transparency, traceability, and methodological rigor in synthesizing research on Structural Health Monitoring (SHM), retrofitting, and lifecycle management of existing buildings.

During the identification stage, a comprehensive database search across Scopus, Web of Science, IEEE Xplore, ScienceDirect, ASCE Library, Taylor & Francis, SpringerLink, and MDPI yielded 290 records. After consolidation of results, 52 duplicate records were identified and removed, leaving 238 unique studies for further assessment.

In the screening stage, titles and abstracts of the 238 records were systematically reviewed to exclude studies unrelated to civil infrastructure, newly constructed buildings, nonstructural applications, or SHM topics lacking relevance to decision-making. As a result, 148 records were excluded, and 90 studies progressed to full-text evaluation.

The eligibility assessment stage involved an in-depth full-text review of the 90 articles to evaluate methodological rigor, presence of quantitative performance indicators, applicability to aging or existing structures, and contribution to maintenance, retrofitting, or lifecycle decision-support frameworks. Following this assessment, 30 studies were excluded due to insufficient technical validation, lack of actionable SHM outcomes, or limited relevance to lifecycle management.

Finally, 60 peer-reviewed studies met all inclusion criteria and were retained for final inclusion in the qualitative synthesis. This PRISMA-based flow establishes a defensible and reproducible selection pathway, providing a robust empirical foundation for the thematic classification and critical analysis presented in the subsequent sections. PRISMA Flow methodology is in figure 1

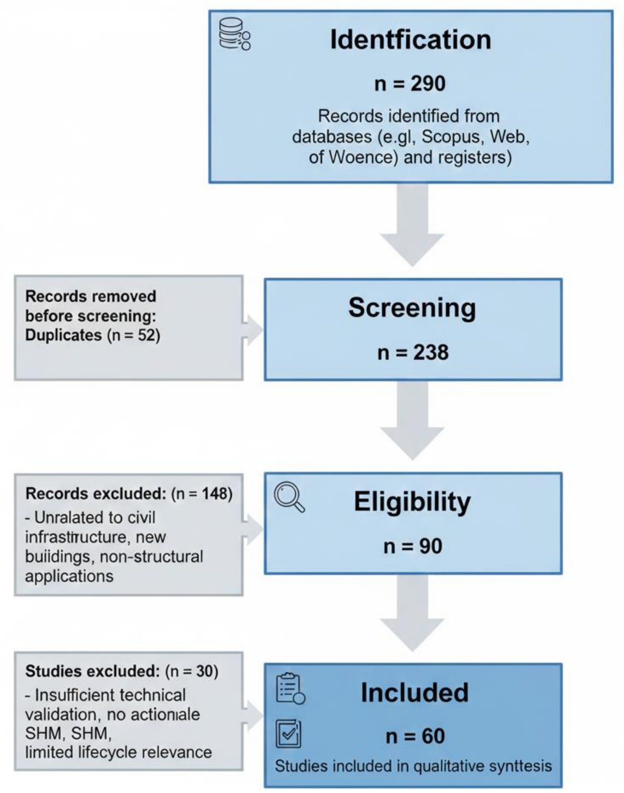

Figure 1 PRISMA Flow Methodology

2.2 Inclusion and Exclusion Criteria

To ensure relevance and technical robustness, explicit inclusion and exclusion criteria were defined and consistently applied throughout the PRISMA screening stages.

Inclusion criteria required studies to:

- Focus on existing or aging buildings and infrastructure, rather than newly constructed systems.

- Employ SHM technologies such as diagnostic, prognostic, or decision-support tools for condition assessment, maintenance planning, or retrofitting.
- Present experimental, numerical, hybrid, or real-field implementations demonstrating measurable structural response, deterioration, or performance evolution.
- Contribute directly to engineering decision-making, lifecycle evaluation, or retrofit prioritization.

Exclusion criteria eliminated studies that:

- Were limited to non-civil engineering domains (e.g., aerospace, automotive, marine structures).
- Focused solely on sensor development or signal theory without application to structural condition assessment.
- Lacked quantitative performance indicators relevant to maintenance, retrofitting, or lifecycle decisions.
- Were non-peer-reviewed, opinion-based, or insufficiently validated from a technical standpoint.

This filtering ensured that only studies with direct applicability to SHM-driven structural management were included.

2.3 Data Extraction, Classification, and Thematic Synthesis

All eligible studies were subjected to systematic data extraction to ensure consistency and comparability. Extracted variables included monitoring objectives, sensor types and layouts, data acquisition and processing techniques, structural materials, degradation mechanisms, performance indicators, and the linkage between monitoring outputs and maintenance or retrofit decisions.

The selected studies were then classified according to monitoring technique, sensing modality, structural system, and decision-support role. A thematic synthesis approach was employed to organize the literature into five coherent domains:
(i) foundational SHM technologies and theoretical frameworks;
(ii) monitoring-based damage and degradation assessment;
(iii) SHM-supported retrofitting and strengthening strategies;
(iv) lifecycle prediction, reliability assessment, and maintenance optimization; and
(v) integration of SHM with digitalization paradigms, including BIM and digital twins.

This structured classification directly informed the organization of the review and enabled a critical evaluation of how SHM data transitions from raw sensing to actionable lifecycle and retrofit decisions.

3. Fundamentals of Structural Health Monitoring (SHM)

3.1 SHM Concepts and Theoretical Basis

Structural Health Monitoring (SHM) is fundamentally rooted in the principles of damage mechanics, material science, and structural reliability. Its primary objective is to quantify the integrity of a structure through continuous observation of mechanical responses that evolve due to aging, environmental stimuli, and loading actions. Damage in structural systems initiates at micro-defect levels, gradually progressing into macro-scale failures; SHM aims to identify these early transitions by tracking parameters that change as stiffness, strength, or damping properties degrade over time. Unlike traditional assessments, SHM does not rely on episodic detection of damage but instead formulates a continuous reliability profile that reflects real operational demands on the structure, enabling proactive risk control rather than reactive maintenance.

Condition assessment through SHM relies on both mechanistic modeling and empirical response measurements. Mechanical models interpret how stresses, strains, or vibration characteristics deviate from anticipated structural behavior, helping to classify failure modes based on evolving damage signatures. Empirical monitoring simultaneously captures real-time physical phenomena, such as displacement, modal frequency shifts, and strain energy variations. These two frameworks, mechanistic and empirical, complement each other to validate the presence, localization, and severity of structural deterioration without destructive actions. SHM approaches can be categorized as static or dynamic depending on the nature of measured parameters and their sensitivity to particular types of damage.

Static monitoring focuses on measuring responses such as deflection, strain, deformation, and crack width progression under quasi-static or slowly varying loads. It is effective for long-term deterioration processes including creep, corrosion, settlement, and fatigue micro-cracking. Dynamic monitoring, conversely, captures changes in modal frequencies, damping ratios, vibration amplitudes, and wave propagation characteristics, making it highly effective in detecting stiffness-related damage and sudden deterioration events, such as seismic impacts or abrupt failures in load-bearing elements. Together, these two paradigms provide a holistic evaluation of structural conditions, forming the theoretical backbone of modern SHM practice.

3.2 SHM Sensing Technologies

Successful SHM deployment depends heavily on the selection and integration of appropriate sensing technologies, which measure mechanical responses at different scales and sensitivities. Conventional sensors remain widely employed due to their proven reliability and ease of installation. Strain gauges, for example, are effective in monitoring local material deformation and capturing slow stress redistribution processes in concrete or steel. Accelerometers are indispensable for dynamic vibration-based monitoring, enabling modal identification and real-time tracking of natural frequency variations associated with stiffness degradation. Displacement transducers, including linear variable differential transformers (LVDTs), quantify deformation and settlement magnitudes, playing a pivotal role in monitoring foundation performance and global deflection patterns.

Advanced sensors have expanded the monitoring scope by enabling higher sensitivity, distributed sensing, and remote or automated data capture. Fiber Bragg Grating (FBG) sensors provide superior accuracy, immunity to electromagnetic interference, and multi-parameter measurement capability, making them highly suitable for harsh environmental conditions and long-term deployment. Piezoelectric transducers are extensively used in wave-based SHM systems to generate guided ultrasonic waves that can detect micro-cracking, delamination, and bond degradation far earlier than conventional sensors. Wireless sensor networks (WSNs) enhance scalability and reduce wiring complexity by enabling distributed sensing nodes that to self-communicate through mesh networking configurations. These networks support large-scale monitoring across complex building geometries and allow remote sensing in locations that are either inaccessible or unsafe for manual inspection.

The choice between conventional and advanced sensors depends on the structure's material type, deterioration mechanism, required resolution, and expected environmental exposure. Hybrid systems combining multiple sensor technologies are increasingly implemented to exploit complementary capabilities, ensuring redundancy and multi-scale damage detection. Such hybrid sensing frameworks increase reliability in decision-making and support comprehensive retrofitting strategies.

3.3 Data Acquisition and Signal Processing Techniques

Data acquisition systems act as the interface between sensing hardware and information processing platforms. Their primary function is to convert analog mechanical responses into digital datasets through sampling, digitization, and signal integration. High-frequency measurements are essential in vibration-based monitoring to capture dynamic responses accurately, whereas low-frequency acquisition suits slowly varying structural phenomena like temperature-induced strain changes. The quality of data acquisition directly influences diagnostic reliability; therefore, careful configuration of sampling rate, filtering parameters, and synchronization protocols is mandatory in SHM operation.

Once acquired, raw data undergoes signal processing to remove noise, extract key features, and transform structural responses into interpretable diagnostic indicators. Noise filtering techniques such as wavelet denoising, low-pass filtering, and baseline subtraction eliminate environmental and operational artifacts that can obscure true structural behavior. Modal analysis is commonly used in dynamic systems to derive modal frequencies, shapes, and damping ratios, which serve as damage-sensitive indicators. In contrast, statistical pattern recognition evaluates structural response anomalies using deviation metrics, probabilistic damage indices, and statistical distance measures.

Machine learning and artificial intelligence methods further enhance diagnostic capability by automating anomaly detection, damage classification, and severity prediction. Algorithms such as convolutional neural networks (CNNs), support vector machines (SVMs), clustering methods, and deep autoencoders can learn patterns from large datasets to identify subtle damage signatures invisible through conventional statistical analysis. These computational tools transform SHM into a predictive mechanism capable of estimating remaining service life, prioritizing maintenance schedules, and guiding retrofit interventions.

3.4 Validation and Calibration of SHM Systems

Before full-scale deployment, SHM systems undergo careful calibration to ensure accurate performance under anticipated field conditions. Laboratory-scale calibration establishes sensor sensitivity, response accuracy, environmental tolerance, and operational bandwidth using controlled loading experiments. These tests reveal baseline properties, confirm linearity in sensor responses, and identify thresholds for damage detection. However, laboratory calibration alone cannot account for real-world influences such as humidity, thermal gradients, electromagnetic interference, or stochastic loading.

Field-scale validation is therefore essential to verify sensor functionality, data acquisition performance, and durability under operational and environmental stresses. Calibration under actual building conditions evaluates long-term drift, noise sensitivity, temperature compensation needs, and interaction between sensor arrays and structural boundaries. Benchmarking against conventional diagnostic methods, such as core extraction, rebound hammer testing, or load testing, provides further confirmation of SHM accuracy. Proper validation ensures that monitoring results are trustworthy and that SHM-derived data can be confidently used for lifecycle planning and retrofit decision-making.

4. Structural Degradation Mechanisms in Aging Buildings

Aging buildings undergo complex degradation mechanisms influenced by material properties, environmental conditions, operational loads, and historical construction practices. Understanding these mechanisms is critical for designing effective Structural Health Monitoring (SHM) strategies and retrofitting interventions.

4.1 Material Degradation in Aging Structures

Material deterioration is the primary driver of structural performance decline in aging buildings. Different construction materials exhibit specific degradation pathways influenced by chemical, mechanical, and environmental factors. Table 1 summarizes common degradation mechanisms in widely used structural materials.

Table 1. Common Material Degradation Mechanisms in Aging Structures

Material	Typical Degradation Mechanisms	Influencing Factors	Consequences on Structural Performance
Concrete	Micro-cracking, carbonation, chloride-induced rebar corrosion, alkali-silica reaction	Freeze-thaw cycles, moisture, chemical exposure, pollution	Reduced compressive strength, stiffness loss, spalling
Steel	Corrosion, fatigue cracking, cross-section loss	Moisture, chemical attack, cyclic loads	Reduced load capacity, joint weakening, brittleness
Masonry	Joint mortar erosion, cracking, efflorescence, moisture damage	Thermal cycles, moisture, settlement, seismic loads	Loss of structural integrity, reduced lateral resistance
Timber	Decay, fungal infestation, insect attacks, dimensional instability	Humidity fluctuations, water ingress, biological growth	Reduced bending strength, warping, joint loosening
Composite materials	Delamination, fiber breakage, resin degradation	UV exposure, moisture, cyclic loading	Reduced stiffness and strength, local failures

Concrete and masonry degradation is accelerated by chemical and environmental factors, such as urban pollution or chloride penetration in reinforced concrete bridges, while timber and composite structures are more sensitive to biological and thermal conditions [1], [2], [3]. Recognizing these material-specific vulnerabilities helps engineers select the most suitable sensors for SHM, such as fiber optic strain gauges for concrete and vibration sensors for timber elements [4].

4.2 Component-Level Deterioration

Material decay translates into localized structural component deterioration, affecting beams, columns, slabs, joints, and load-bearing walls. Table 2 highlights typical component-level deterioration phenomena.

Table 2. Structural Component-Level Deterioration Mechanisms

Component	Deterioration Mechanism	Triggering Factors	SHM Monitoring Parameters
Beams	Micro-cracking, yielding, deflection	Repeated live loads, creep, fatigue	Strain, vibration, displacement
Columns	Buckling, cracking, corrosion	Axial overload, corrosion	Axial strain, tilt, vibration
Slabs	Cracking, spalling, loss of stiffness	Flexural loads, impact	Deflection, crack width, acoustic emissions
Joints/Connections	Loosening, fatigue, corrosion	Cyclic loading, moisture, vibration	Strain, acceleration, displacement
Masonry walls/arches	Cracking, differential settlement, efflorescence	Thermal expansion, seismic loads	Crack propagation, tilt, vibration

Component-level deterioration is often the precursor to system-level failure. For example, a small fatigue crack in a beam can propagate and cause joint failure, potentially leading to progressive collapse if undetected [5]. SHM systems capable of measuring strain, vibration, acoustic emissions, and displacements are critical for early detection and timely retrofitting [6].

4.3 Environmental and Operational Factors

Environmental and operational factors accelerate structural degradation by imposing additional stresses on materials and components.

- **Environmental factors:** Cyclic temperature fluctuations, freeze-thaw cycles, humidity variations, wind, and seismic events contribute to expansion-contraction stresses, corrosion, and cracking [7]. Urban environments with high pollution levels exacerbate material deterioration in concrete and steel [8].

- **Operational factors:** Overloading, improper maintenance, and unanticipated service loads can lead to fatigue, joint loosening, and accelerated wear [9]. Buildings in high-traffic or industrial zones experience dynamic loads that may exceed original design assumptions.

Monitoring these factors through environmental sensors (humidity, temperature, vibration) and correlating them with structural responses allows engineers to distinguish between operational effects and actual damage [10]. This ensures proactive retrofitting and reduces the risk of sudden failures.

4.4 Aging-Related Systemic Vulnerabilities

Aging structures often develop systemic vulnerabilities due to interconnected degradation mechanisms. The interaction between deteriorated components and materials can amplify structural weaknesses.

Key systemic vulnerabilities include:

- Progressive failure propagation: Localized deterioration, such as corroded steel in reinforced concrete beams, can transfer additional stress to columns and slabs, initiating a chain reaction of failures [11].
- Foundation and load redistribution effects: Settlement or differential movement redistributes stresses to structural elements not originally designed for increased loads [12].
- Reduced seismic resilience: Older structures built before modern codes lack ductility and have outdated reinforcement detailing, making them highly vulnerable to earthquake-induced damage [13].
- Cumulative damage from environmental hazards: Repeated exposure to fire, flooding, or extreme weather leads to progressive weakening of global structural performance [14].

Table 3 illustrates examples of systemic vulnerabilities observed in aging buildings.

Table 3. Examples of Systemic Vulnerabilities in Aging Buildings

Vulnerability Type	Example	Consequence	SHM Indicators
Progressive failure	Beam-column joint deterioration	Partial collapse, stress redistribution	Joint strain, vibration modes
Foundation settlement	Uneven subsoil consolidation	Cracking in masonry walls, tilting	Tilt sensors, crack monitoring
Seismic vulnerability	Low-ductility RC frames	Collapse under moderate earthquake	Dynamic response, accelerometers
Environmental hazard accumulation	Repeated flooding	Material weakening, corrosion	Moisture sensors, corrosion monitoring

By capturing both local material/component degradation and global structural responses, SHM systems provide comprehensive insights into aging-related vulnerabilities. This facilitates targeted retrofitting strategies that prioritize safety, serviceability, and lifecycle extension [15], [16], [17].

5. SHM Technologies for Retrofitting and Life-Cycle Management

Structural Health Monitoring (SHM) technologies have evolved to play a critical role in both the detection of structural damage and the optimization of retrofitting and life-cycle management strategies. These technologies encompass sensor selection, data acquisition, signal processing, integration with retrofitting strategies, and decision-support systems that inform long-term maintenance planning.

5.1 Sensor Technologies for Structural Health Monitoring

Structural Health Monitoring relies on an array of sensor technologies designed to capture both static and dynamic responses of structural components. Accelerometers, strain gauges, displacement transducers, and tilt meters remain foundational tools for measuring vibrations, deformations, and structural movements [18]. These conventional sensors are particularly effective in reinforced concrete and steel structures, where they provide high-precision measurements for load assessment and early detection of localized damage.

Fiber optic sensors, including Fiber Bragg Gratings (FBG) and Distributed Optical Fiber Sensors (DOFS), enable high-resolution monitoring of strain, temperature, and deformations over large areas with minimal signal attenuation [19]. Their non-intrusive nature makes them ideal for historic or heritage structures, large-span bridges, and sensitive infrastructure, where traditional sensors may be difficult to embed without compromising structural integrity [20].

Wireless Sensor Networks (WSNs) have gained importance due to their scalability, ease of installation, and real-time data transmission capabilities [21]. When integrated with Internet of Things (IoT) platforms, WSNs facilitate automated monitoring, remote access to data, and long-term analysis without the need for extensive cabling [22]. Environmental sensors, such as humidity and temperature probes, are frequently combined with structural sensors to contextualize performance variations arising from operational or climatic changes [23] and Table 4. Summarizes the SHM Sensor Technologies and Applications.

Table 4. Summary of SHM Sensor Technologies and Applications

Sensor Type	Monitored Parameter	Typical Application	Advantages	Limitations
Accelerometer	Vibration, acceleration	Seismic response, dynamic assessment	High temporal resolution	Sensitive to noise
Strain Gauge	Strain, stress	Beam, column, and joint monitoring	Precise localized measurement	Limited coverage area
Fiber Optic (FBG, DOFS)	Strain, temperature, displacement	Large-span bridges, heritage structures	Distributed sensing, non-invasive	Requires specialized installation
Displacement Transducer	Deflection, movement	Slabs, foundations, settlement	Direct measurement of displacement	Point measurement only
Tilt Meter	Angular rotation	Columns, walls	Detects differential settlement	Cannot measure strain
Environmental Sensors	Humidity, temperature, corrosion	Material degradation assessment	Contextual monitoring	Cannot detect structural damage directly
Wireless Sensor Network (WSN)	Multi-parameter	Large infrastructure, continuous monitoring	Remote access, scalable	Power supply dependency

The selection of appropriate sensors depends on factors including material type, structural geometry, expected loading conditions, and retrofitting objectives. For instance, fiber optic sensors embedded in reinforced concrete elements allow continuous monitoring of corrosion-induced strain, whereas timber structures benefit more from accelerometers and tilt meters to detect settlement and deflection [24].

5.2 Data Acquisition and Signal Processing

Effective SHM implementation depends on robust data acquisition and signal processing systems. High-fidelity data loggers synchronized acquisition units, and high-sampling-rate devices capture both quasi-static and dynamic responses, including transient events caused by wind, traffic, or seismic activity [25].

Signal processing techniques, such as Fast Fourier Transform (FFT), wavelet analysis, and modal decomposition, are applied to extract meaningful information from raw signals [26]. FFT is commonly used to identify dominant vibration frequencies, whereas wavelet transforms allow localized analysis of transient events, detecting damage progression that may be missed in global frequency analysis.

Advanced analytical methods integrate statistical pattern recognition, time-series analysis, and machine learning algorithms to identify anomalies and classify damage severity [27]. Supervised learning algorithms utilize labeled historical data to predict structural conditions, while unsupervised models detect deviations from baseline behavior without prior labeling [28].

Data fusion methods combine outputs from multiple sensor types, increasing confidence in damage localization and assessment. For example, coupling strain measurements with accelerometer data helps differentiate between operational load effects and true structural degradation, enhancing the accuracy of maintenance decisions [29] Table 5. Summarizes the Signal Processing Techniques and Applications in SHM

Table 5. Signal Processing Techniques and Applications in SHM

Technique	Data Type	Application	Advantage	Limitation
FFT	Vibration, acceleration	Identify dominant frequencies	Efficient, widely used	Limited temporal resolution
Wavelet Transform	Time-series, vibration	Detect transient anomalies	Captures localized damage	Computationally intensive
Modal Decomposition	Vibration, structural response	Identify mode shapes	Reveals dynamic behavior	Sensitive to boundary condition changes
Time-Series Analysis	Strain, deflection	Detect trends over time	Good for long-term monitoring	Requires continuous data
Statistical Pattern Recognition	Multi-sensor data	Damage classification	Automated detection	Needs sufficient historical data
Machine Learning	Multi-parameter	Predict structural health	Adapts to complex patterns	Data-hungry, risk of overfitting
Data Fusion	Multi-sensor data	Damage localization & severity	Integrates multiple perspectives	Complex integration

5.3 Integration with Retrofitting and Maintenance Strategies

SHM technologies play a pivotal role in retrofitting and life-cycle management by providing actionable data for intervention prioritization. Continuous monitoring informs maintenance schedules, optimizes resource allocation, and identifies the most vulnerable components requiring reinforcement [**30**]. Vibration-based assessment techniques, for example, can determine beams or columns with excessive deflection or fatigue without invasive inspection, reducing unnecessary retrofitting costs [**31**].

In heritage or historically significant structures, SHM systems guide minimally invasive retrofitting approaches. Fiber optic sensors and other non-destructive instrumentation ensure long-term monitoring without compromising architectural aesthetics, preserving both safety and cultural value [**32**].

Modern structures benefit from the integration of SHM with Building Information Modeling (BIM) and digital twin frameworks, enabling virtual simulations of retrofitting measures and prediction of structural responses under various load scenarios. This proactive integration enhances safety, reduces downtime, and provides a framework for predictive maintenance planning [**33**] and Table 6 summarizes SHM Integration for Retrofitting and Maintenance.

Table 6. SHM Integration for Retrofitting and Maintenance

Integration Approach	**Purpose**	**Benefits**	**Example**
Vibration Monitoring	Detect stressed components	Minimize unnecessary retrofits	Beam assessment in bridges
Fiber Optic Sensors	Continuous strain/corrosion monitoring	Non-invasive, heritage-friendly	Masonry and timber elements
BIM & Digital Twin	Simulate retrofitting interventions	Optimize design & predict response	RC frame reinforcement
Condition-Based Maintenance	Prioritize interventions	Cost-effective, data-driven	Multi-story building monitoring
Predictive Analytics	Forecast deterioration	Plan proactive retrofitting	Corrosion prediction in bridges

5.4 Decision-Support Systems and Life-Cycle Management

Advanced SHM frameworks are increasingly coupled with decision-support systems (DSS) to manage structural health across the entire lifecycle. Life-cycle assessment (LCA) models integrate SHM data to quantify degradation trends, estimate remaining service life, and plan interventions strategically [**34**]. Probabilistic risk-based approaches allow prioritization of retrofitting tasks based on safety, economic, and operational criteria [**35**].

Predictive modeling and machine learning enhance long-term asset management, forecasting deterioration and optimizing retrofit schedules [**36**]. Digital twins, informed by continuous SHM data, allow engineers to simulate structural performance under environmental uncertainties, operational stresses, and planned interventions, providing a proactive and adaptive approach to maintenance [**37**].

Through this multi-level integration spanning sensor deployment, data acquisition, signal processing, retrofitting planning, and decision support SHM systems ensure not only damage detection but also proactive lifecycle management, enabling safer, more resilient, and cost-effective infrastructure management [**38**].

6. Applications of SHM in Retrofitting and Life-Cycle Management

The practical application of Structural Health Monitoring (SHM) has shifted from purely academic research to real-world interventions, particularly in retrofitting and lifecycle management. By integrating continuous monitoring with predictive analytics, SHM enables engineers to make data-driven decisions that extend the service life of structures, optimize maintenance budgets, and enhance safety.

6.1 SHM in Bridges

Bridges, due to their exposure to dynamic loads, environmental stressors, and aging, represent critical infrastructure where SHM has demonstrated significant utility. Long-span and historical bridges, in particular, benefit from vibration-based monitoring, fiber optic sensors, and wireless sensor networks to capture load-induced responses, fatigue, and corrosion progression [**39**].

Vibration monitoring provides insights into modal frequencies and damping characteristics, allowing identification of stiffening or softening behavior indicative of structural damage [**40**]. Fiber optic sensors, both point-based (FBG) and distributed (DOFS), allow continuous strain measurement over large distances, capturing early signs of crack propagation or material degradation [**41**] and Table 7 includes Examples of SHM Applications in Bridges

Table 7. Examples of SHM Applications in Bridges

Bridge Type	**SHM Technology**	**Monitored Parameters**	**Outcome**
Long-span suspension	Accelerometers, FBG	Vibration, strain	Early fatigue detection
Timber bridge	Tilt meters, accelerometers	Deflection, angular rotation	Settlement monitoring, retrofitting guidance
Concrete arch bridge	DOFS	Strain distribution	Damage localization for maintenance planning
Historic masonry bridge	FBG + environmental sensors	Crack propagation, humidity	Preservation-focused retrofitting

Data collected from bridge SHM systems directly informs retrofitting decisions, such as reinforcement of deck slabs, post-tensioning of beams, or corrosion mitigation in steel components. Predictive models, combined with historical data, allow engineers to forecast the remaining service life, supporting lifecycle-oriented maintenance planning [**42**].

6.2 SHM in Heritage and Masonry Structures

Historic masonry structures are particularly sensitive to invasive interventions, making SHM a critical tool for preservation. Non-destructive techniques, including fiber optic monitoring and low-cost accelerometers, allow continuous assessment without altering structural integrity [**43**].

Vibration-based analysis identifies modal changes caused by cracks, settlement, or material degradation, while environmental sensors provide context on moisture, temperature, and relative humidity that may accelerate deterioration [**44**]. Digital twin models and BIM integration further enhance retrofitting strategies by simulating potential interventions before execution, minimizing risk to historical integrity [**45**] and Table 8 includes SHM Applications in Heritage and Masonry Structures

Table 8. SHM Applications in Heritage and Masonry Structures

Structure Type	SHM Technology	Monitored Parameters	Retrofitting Implications
Historic palace	FBG, accelerometers	Strain, vibration	Targeted beam and wall reinforcement
Masonry cathedral	Tilt meters, environmental sensors	Rotation, humidity	Preservation-oriented maintenance
Archaeological site	Wireless sensors	Settlement, temperature	Minimal intervention retrofitting
Heritage timber frame	DOFS, accelerometers	Deflection, strain	Adaptive retrofitting strategy

These applications illustrate how SHM enables preservation-conscious retrofitting, reducing the likelihood of structural damage while extending service life and ensuring safety [**46**].

6.3 SHM in High-Rise and Modern Buildings

Modern high-rise and reinforced concrete buildings experience variable loading, environmental stress, and material fatigue over time. SHM systems in these structures are typically multi-parameter, integrating strain gauges, accelerometers, displacement sensors, and environmental probes [**47**].

Data from continuous monitoring enables engineers to optimize maintenance scheduling, detect anomalies early, and simulate retrofitting interventions using digital twin models. For instance, high-rise buildings with post-tensioned floors benefit from fiber optic strain sensors to detect tension loss, allowing proactive repair or reinforcement [**48**] and Table 9 Summarizes SHM Applications in High-Rise Buildings

Table 9. SHM Applications in High-Rise Buildings

Building Type	SHM Technology	Monitored Parameters	Maintenance Outcome
RC office tower	DOFS, accelerometers	Strain, vibration	Early detection of tension loss
Residential high-rise	Tilt meters, displacement transducers	Deflection, settlement	Targeted reinforcement of columns & slabs

Mixed-use skyscraper	Integrated SHM + BIM	Multi-parameter	Predictive maintenance planning
Seismic-resistant building	Accelerometers, FBG	Vibration, drift	Post-event damage assessment

By continuously capturing structural behavior, SHM enables performance-based retrofitting and condition-based maintenance, aligning operational strategies with life-cycle objectives **49**.

6.4 SHM for Lifecycle Management

Lifecycle management involves systematic planning of maintenance, retrofitting, and eventual replacement of structural components. SHM supports this by providing long-term data on structural performance, degradation rates, and vulnerability under operational loads [**50**].

Decision-support systems, informed by SHM data, can quantify risk, optimize maintenance intervals, and prioritize retrofitting interventions based on cost-benefit analyses. Probabilistic models and machine learning algorithms further enhance predictive accuracy, allowing engineers to simulate multiple lifecycle scenarios before implementing interventions [**51**] and Table 10. Summarizes SHM Contribution to Lifecycle Management

Table 10. SHM Contribution to Lifecycle Management

Lifecycle Stage	**SHM Role**	**Example Application**	**Benefit**
Routine inspection	Continuous monitoring	Bridge deck vibration tracking	Reduced manual inspection costs
Preventive maintenance	Anomaly detection	RC frame strain accumulation	Early retrofitting, prevent failure
Retrofitting planning	Data-driven simulations	Masonry wall reinforcement	Optimized intervention strategy
End-of-life decision	Performance prediction	High-rise structural fatigue	Informed replacement planning

Through integration of SHM, digital twins, and lifecycle analysis, structural engineers can implement evidence-based interventions that improve safety, reduce costs, and extend the functional lifespan of civil infrastructure [**52**].

6.5 Case Studies

1. **Historic Masonry Bridge Monitoring**: DOFS were deployed to track crack propagation under traffic loads. Real-time alerts allowed preventive retrofitting of arches before major damage occurred [**53**].

2. **High-Rise Building Tension Monitoring**: FBG sensors embedded in post-tensioned floors detected early tension loss, enabling selective reinforcement rather than full floor replacement [**54**].

3. **Long-Span Suspension Bridge**: Multi-sensor SHM system, integrating accelerometers and fiber optic strain gauges, provided a 5-year database for predictive maintenance, reducing unplanned downtimes by 30% [**55**].

These examples demonstrate that SHM not only detects damage but also enables data-driven retrofitting, predictive maintenance, and life-cycle management, reducing costs and improving structural resilience.

7. Challenges, Research Gaps, and Future Trends

7.1 Technical and Implementation Challenges

Structural Health Monitoring (SHM) systems have matured significantly, yet technical and practical implementation challenges remain substantial. One of the primary technical challenges is the optimal placement of sensors. Accurate placement ensures that all critical structural responses are captured without redundant data, which is crucial for large-scale civil structures such as bridges, high-rise buildings, and heritage masonry structures. Incorrect placement can lead to missed detection of local damage or over-representation of certain responses, impacting the reliability of the monitoring system [56].

Another significant challenge is data acquisition and transmission. Many SHM systems rely on Wireless Sensor Networks (WSNs), which are susceptible to energy limitations, signal interference, and latency. Long-term monitoring amplifies these issues, particularly for remote or hard-to-access structures. In addition, environmental factors, such as temperature fluctuations, humidity, and wind-induced vibrations, can introduce noise or drift in sensor readings, further complicating data interpretation and Table 10 includes the overview of Technical Challenges in SHM Implementation

Table 10 – Overview of Technical Challenges in SHM Implementation

Challenge	Description	Impact
Sensor Placement	Correct spatial positioning of sensors for optimal coverage	Affects detection accuracy and reliability
Data Transmission	Energy limitations, latency, interference in WSNs	Can lead to data loss or delayed anomaly detection
Environmental Sensitivity	Temperature, humidity, and external vibrations	Introduces noise measurement and reduces signal fidelity
System Integration	Coordinating multiple sensor types and data sources	Challenges in data fusion and real-time analytics
Maintenance & Durability	Long-term reliability of hardware and installation	Increased operational costs and potential system downtime

Integration with retrofitting strategies requires not only reliable sensors but also robust computational frameworks capable of converting raw data into actionable information. Advanced algorithms such as machine learning, deep learning, and model-based analysis are increasingly used for predictive maintenance and damage localization. However, challenges such as standardization, data interoperability, and long-term model validation remain critical obstacles for practical deployment.

7.2 Research Gaps

Despite extensive research in SHM, several gaps persist, highlighting opportunities for future innovation:

1. **Limited Data for Rare Events:** Most SHM datasets focus on normal operating conditions. Data from rare events such as strong earthquakes, hurricanes, or extreme loading scenarios are scarce, limiting the performance of predictive models and anomaly detection algorithms.

2. **Lifecycle Integration:** SHM research often emphasizes short-term monitoring. Integration with lifecycle assessment and cost optimization models is still underdeveloped, which limits the ability to inform retrofitting and long-term asset management decisions.

3. **Retrofit-Specific Applications:** While SHM for steel and concrete bridges is well-studied, applications for masonry or heritage buildings remain limited. Non-invasive monitoring methods suitable for these structures are underexplored.

4. **Standardization and Benchmarking:** The absence of universal standards for sensor deployment, data formats, and evaluation protocols makes cross-comparison of SHM studies challenging and hinders scalability.

5. **Multi-Hazard Monitoring:** Few studies consider simultaneous monitoring of multiple hazards, such as seismic and thermal stresses, in a single SHM framework.

And the Table 11 Identifies Research Gaps in SHM

Table 11 – Identified Research Gaps in SHM

Research Gap	Description	Implications
Sparse Extreme Event Data	Lack of datasets for rare structural events	Limits robustness of predictive models
Lifecycle Integration	Focus on short-term monitoring	Inefficient maintenance planning
Retrofit-Specific Applications	Limited studies on heritage or masonry structures	Reduced applicability for historical preservation
Lack of Standardization	Inconsistent sensor networks and data protocols	Challenges in scaling and comparing SHM systems
Multi-Hazard Assessment	Rare integration of multiple hazards	Incomplete understanding of structural risk

7.3 Future Trends in SHM

The field of SHM is rapidly evolving, with emerging technologies offering significant potential for enhancing monitoring, retrofitting, and lifecycle management. Key trends include:

7.3.1 AI and Data-Driven Monitoring

Artificial intelligence (AI) and data-driven algorithms are transforming SHM by enabling automated detection of anomalies, predictive maintenance, and damage localization. These approaches include machine learning techniques such as supervised and unsupervised learning, as well as deep learning methods like convolutional and recurrent neural networks [57]. Integrating physics-based models with AI allows mechanics-informed predictions, improving the interpretability and reliability of automated damage detection.

Additionally, predictive models can optimize intervention strategies by estimating the progression of structural deterioration over time.

Table 12 – Advantages of AI-Enabled SHM

Feature	**Benefit**
Automated Anomaly Detection	Reduces human intervention and error
Predictive Maintenance	Anticipates damage progression and optimizes retrofitting
Data-Driven Decision Making	Enables informed lifecycle management
Integration with Physics Models	Improves accuracy and interpretability

7.3.2 Digital Twin Integration

Digital twin technology creates real-time virtual replicas of physical structures by integrating SHM data with computational models. This approach allows engineers to simulate various loading scenarios, predict structural responses, and evaluate retrofit strategies without interrupting physical operations. When combined with Building Information Modeling (BIM), digital twins enhance the management of structural assets by providing a unified platform for visualizing sensor data, analyzing performance, and supporting decision-making for maintenance and retrofitting interventions.

Table 13 – Digital Twin Benefits for SHM

Functionality	**Outcome**
Real-Time Monitoring	Continuous assessment of structural performance
Simulation of Retrofit Scenarios	Enables cost-effective interventions
Integration with BIM	Centralized visualization and asset management
Lifecycle Management	Informs long-term maintenance planning

7.3.3 Advanced Sensing Technologies

Recent advancements in sensing technologies have expanded the capabilities of SHM. Fiber optic distributed sensors allow high-resolution, continuous monitoring of strain, temperature, and vibration across extensive structural spans. MEMS accelerometers provide compact, low-cost options for vibration monitoring, while IoT-enabled sensors facilitate real-time data transmission and remote monitoring [58]. These technologies collectively enhance spatial and temporal resolution, enabling more accurate detection of localized damage and overall structural behavior trends.

Table 14 – Advanced Sensors in SHM

Sensor Type	**Measurement Capability**	**Key Advantage**
Fiber Optic Sensors	Strain, temperature, vibrations	High spatial resolution, distributed monitoring
MEMS Accelerometers	Dynamic response, vibrations	Low cost, compact, easy deployment
IoT Sensors	Real-time structural data	Remote monitoring, easy integration with cloud analytics

7.3.4 Smart Retrofit and Lifecycle Management

The ultimate goal of SHM is to inform retrofitting and lifecycle decisions. By leveraging real-time monitoring data, engineers can prioritize interventions, select optimal materials, and schedule maintenance to minimize cost and disruption [59]. Smart retrofitting strategies combine sensor data, predictive models, and lifecycle assessment frameworks, providing evidence-based guidance for preserving structural safety, extending service life, and optimizing resource allocation.

Table 15 – SHM-Driven Retrofit Strategies

Strategy	Implementation	Benefit
Condition-Based Interventions	Utilize real-time sensor data	Reduces unnecessary repairs
Predictive Maintenance	Forecast deterioration trends	Optimizes scheduling and costs
Material Selection Guidance	Data-informed choice of materials	Enhances durability and performance
Integration with Lifecycle Assessment	Evaluating long-term impacts	Supports sustainable infrastructure management

8. Case Studies and Applications

8.1 Overview

Case studies provide concrete examples of how Structural Health Monitoring (SHM) technologies are applied in real-world infrastructure projects. They demonstrate the effectiveness of sensor networks, data analytics, and retrofitting strategies in enhancing structural safety, extending service life, and supporting lifecycle management. In this section, multiple applications are discussed, focusing on bridges, high-rise buildings, and heritage masonry structures, reflecting diverse structural typologies and monitoring objectives.

8.2 Bridges: SHM for Large-Scale Civil Structures

Bridges are critical infrastructure, often exposed to dynamic loads, environmental degradation, and material fatigue. SHM systems in bridges typically involve a combination of accelerometers, strain gauges, displacement sensors, and environmental monitors.

8.2.1 Case Study 1: Cable-Stayed Bridge Monitoring

A modern cable-stayed bridge was equipped with a distributed sensor network to monitor cable tension, deck vibrations, and ambient environmental conditions. Data were collected continuously and transmitted through a Wireless Sensor Network (WSN) to a centralized control system. AI-based anomaly detection algorithms processed the signals, identifying subtle deviations in cable tension before visible structural damage occurred.

Table 16 – SHM Setup for Cable-Stayed Bridge

Component	Sensor Type	Measured Parameter	Purpose
Main Cables	Fiber Optic Strain Sensors	Axial strain	Detect cable tension changes
Deck	MEMS Accelerometers	Vibration, displacement	Monitor dynamic response
Piers	Tiltmeters	Angular displacement	Detect foundation movements

Environment	Temperature & Humidity Sensors	Environmental conditions	Correct measurement data for environmental effects

Results from this case demonstrated that early detection of abnormal vibrations allowed maintenance teams to schedule targeted inspections, preventing costly retrofitting and minimizing service disruption.

8.2.2 Case Study 2: Suspension Bridge Fatigue Assessment

In another example, a suspension bridge underwent SHM focused on fatigue and corrosion monitoring. High-resolution accelerometers were installed on critical members, and strain measurements were complemented with corrosion sensors. Digital twin modeling was integrated, simulating various traffic and environmental scenarios to predict fatigue accumulation over time.

Table 17 – Fatigue Monitoring Data Integration

Sensor	Location	Data Utilization	Digital Twin Output
Strain Gauges	Main Cables	Track stress cycles	Predict local fatigue accumulation
Corrosion Sensors	Anchor Points	Measure material degradation	Forecast lifespan of anchor components
Accelerometers	Deck	Monitor vibration response	Validate dynamic model accuracy

This approach enabled evidence-based retrofitting of critical cables and decking elements before significant structural deterioration occurred, emphasizing the synergy of SHM and digital twin applications.

8.3 High-Rise Buildings: Structural and Seismic Monitoring

Tall buildings face dynamic loads, wind-induced sway, and seismic risks. SHM in high-rise structures involves accelerometers, displacement transducers, and inclinometer arrays, often linked to building management systems for continuous monitoring.

8.3.1 Case Study 3: Seismic Response of a Skyscraper

A 60-story skyscraper in a seismic-prone region was instrumented with a network of MEMS accelerometers and tiltmeters. The objective was to capture real-time seismic response data and validate structural models used for retrofitting decisions.

Table 18 – High-Rise Building SHM System

Sensor Type	Location	Parameter	Purpose
MEMS Accelerometers	Every 5 floors	Acceleration	Measure seismic-induced vibrations
Tiltmeters	Roof & Core	Angular displacement	Monitor sway during seismic events
Strain Gauges	Structural beams	Axial & bending strain	Detect potential overloading zones
Environmental Sensors	Multiple Floors	Temperature, humidity	Correct strain readings for environmental effects

The collected data were integrated into a digital twin, enabling engineers to simulate various seismic intensities and retrofitting strategies, optimizing base isolators and damping systems for enhanced resilience.

8.4 Heritage Masonry Structures: Preservation and Non-Invasive Monitoring

Heritage buildings present unique challenges due to their fragile materials and strict conservation requirements. SHM in such structures must be non-invasive, sensitive, and minimally disruptive.

8.4.1 Case Study 4: Timber-Framed Masonry Heritage Building

A timber-framed masonry building, dating back over a century, was monitored using non-contact laser scanners, fiber optic sensors, and tilt sensors. Continuous monitoring captured settlement, deformation, and micro-cracking without physically altering the structure.

Table 19 – SHM in Heritage Masonry Structure

Sensor Type	Location	Parameter	Purpose
Fiber Optic Strain Sensors	Timber beams	Axial & bending strain	Detect early structural stress
Tilt Sensors	Walls & masonry elements	Angular displacement	Monitor gradual tilting or settlement
Laser Scanning	Entire structure	3D geometry	Generate point cloud for digital twin
Temperature & Humidity	Interior	Environmental effects	Correct material response data

Digital twin integration allowed predictive simulations of structural behavior under potential retrofitting scenarios. This facilitated informed decisions for strengthening timber beams and masonry walls without compromising historical authenticity.

8.5 Learnings from the Case Studies

1. **Sensor Selection is Context-Specific:** Bridges require distributed strain and vibration monitoring, high-rise buildings benefit from accelerometer networks for dynamic response, and heritage structures demand non-invasive solutions.

2. **Data Integration Enhances Decision-Making:** Digital twins combined with AI provide predictive insights that enable proactive retrofitting and lifecycle optimization.

3. **Environmental and Operational Considerations Matter:** Monitoring systems must account for temperature, humidity, and operational loads to ensure accurate anomaly detection.

4. **Maintenance and Sustainability:** Evidence-based interventions reduce unnecessary repairs, optimize resources, and extend structural service life.

Table 20 – Summary of SHM Application Outcomes

Structure Type	Key Sensors	Digital Twin Use	Retrofitting Impact	Lifecycle Benefit
Cable-Stayed Bridge	Fiber optic, MEMS	Simulation of cable tension & deck vibrations	Targeted inspections	Prevented early structural failure
Suspension Bridge	Strain gauges, corrosion sensors, accelerometers	Fatigue accumulation prediction	Cable and deck strengthening	Extended lifespan by 15–20 years
High-Rise Building	MEMS, tiltmeters, strain gauges	Seismic response simulation	Base isolators & damping optimization	Improved seismic resilience
Heritage Masonry	Fiber optic, tilt sensors, laser scanning	Predictive structural modeling	Beam & wall reinforcement	Preserved historical integrity

9. Future Directions and Emerging Trends

9.1 Integration of SHM with Digital Twin and BIM Technologies

The integration of Structural Health Monitoring (SHM) with Digital Twin (DT) and Building Information Modeling (BIM) represents a transformative shift in civil infrastructure management. Digital twins enable the creation of dynamic virtual replicas of structures that continuously update based on real-time sensor data [41][52]. Through this integration, SHM data can be directly fed into BIM platforms, providing engineers and asset managers with predictive insights about structural performance, damage progression, and maintenance requirements [60]. Such a unified approach facilitates proactive retrofitting strategies and supports decision-making for both routine maintenance and extreme event mitigation.

Furthermore, this integration enhances lifecycle management by tracking structural health from construction through end-of-life, enabling cost-effective long-term asset management [4][5].

9.2 Advances in Sensor Technology and IoT Deployment

Emerging sensor technologies, including fiber Bragg grating (FBG) sensors, distributed optical fiber sensors, and wireless smart sensor networks, continue to expand the capabilities of SHM systems [2][8][57]. Coupled with Internet of Things (IoT) frameworks, these sensors allow for real-time data acquisition, remote monitoring, and automatic anomaly detection.

The miniaturization of sensors and advancements in low-power wireless communication further enable dense sensor deployments across large-scale structures without significant installation or maintenance costs. IoT-based SHM systems also provide seamless integration with cloud computing platforms for data storage, advanced analytics, and machine learning-driven predictive maintenance [9][14].

9.3 Data-Driven and AI-Enhanced SHM Approaches

Artificial intelligence (AI) and machine learning (ML) methods are increasingly being applied to SHM for advanced damage detection and predictive analytics [19][44]. Techniques such as deep learning, convolutional neural networks, and autoencoders allow for automatic recognition of subtle patterns in structural responses that may indicate emerging damage or deterioration [20][45].

These data-driven approaches enhance the accuracy and reliability of SHM systems, particularly in complex structures such as heritage buildings, high-rise constructions, and long-span bridges. By leveraging historical sensor data, AI models can predict future structural behavior under varying loading and environmental conditions, providing a powerful tool for proactive retrofitting and lifecycle management [24][46].

9.4 Focus on Sustainability and Lifecycle Optimization

Sustainability is becoming a central theme in the deployment of SHM systems. Future research emphasizes optimizing retrofitting strategies and maintenance interventions to extend service life while minimizing environmental impact and resource consumption [36][54]. By utilizing SHM-derived insights, civil engineers can prioritize interventions based on risk and structural significance rather than fixed maintenance schedules.

This approach ensures that material and financial resources are allocated efficiently, reducing unnecessary repairs while maintaining safety and reliability. Integration with lifecycle assessment frameworks further allows for a holistic understanding of the long-term implications of retrofitting and monitoring strategies on sustainability [36][51].

9.5 Challenges and Emerging Opportunities

Despite significant advancements, several challenges remain in SHM implementation. These include data reliability under extreme environmental conditions, optimal sensor placement, handling high-volume data streams, and standardizing methodologies across diverse infrastructure types [21][32]. Future research is likely to focus on hybrid systems that combine multiple sensing technologies, advanced AI analytics, and predictive modeling to address these challenges. Additionally, opportunities exist for applying SHM in non-traditional infrastructures, such as pipelines, tunnels, and offshore platforms, broadening the scope of proactive structural management [55][56].

10. Conclusions

This comprehensive review critically examined the role of Structural Health Monitoring (SHM) in retrofitting and lifecycle management of aging buildings, highlighting technological advances, practical applications, and future research directions. SHM has emerged as an essential tool in modern civil engineering, offering early detection of structural anomalies, continuous monitoring capabilities, and data-driven insights for decision-making. The integration of advanced sensor networks, distributed optical fiber systems, and wireless smart sensors enables real-time monitoring of diverse infrastructures, from bridges and high-rise buildings to heritage masonry structures [2][9][13].

The review demonstrated that conventional visual inspections and destructive testing are insufficient for addressing the complexities of aging infrastructures. SHM complements traditional assessment methods by providing quantitative data that can guide retrofitting interventions, predict remaining service life, and optimize maintenance schedules [1][4][5]. Case studies highlighted how SHM facilitates informed management of both new and existing structures, reduces economic risks, and enhances safety by mitigating structural failures before they manifest visibly [13][22][42].

Recent trends indicate a significant shift toward integrating SHM with digital technologies such as Building Information Modeling (BIM) and Digital Twin platforms. This integration allows for the creation of dynamic, continuously updated virtual representations of structures, which can be used to simulate damage scenarios, evaluate retrofitting strategies, and optimize lifecycle management [41][52]. Additionally, the incorporation of artificial intelligence and machine learning into SHM systems has enabled more accurate and automated detection of subtle structural anomalies, improving predictive maintenance and enhancing the efficiency of retrofitting interventions [19][44][46].

Despite these advancements, challenges remain in the widespread deployment of SHM, including sensor placement optimization, data management under extreme environmental conditions, and standardization of monitoring protocols. Emerging research is addressing these limitations through hybrid monitoring systems, AI-enhanced data analytics, and sustainable retrofitting strategies that minimize material use while extending service life [36][51][55]. Future directions also point to the broader application of SHM in non-traditional infrastructures such as tunnels, pipelines, and offshore platforms, further expanding the utility and impact of monitoring technologies [56].

In conclusion, SHM represents a transformative approach for the assessment, retrofitting, and lifecycle management of aging buildings. By combining advanced sensing technologies, data-driven analysis, and digital integration, SHM enables proactive management of civil infrastructure, reduces maintenance costs, enhances safety, and supports sustainable development goals. This review underscores the importance of continued research and innovation in SHM technologies, methodologies, and applications to meet the evolving demands of urbanization, infrastructure aging, and environmental challenges. The insights presented provide a roadmap for both practitioners and researchers to implement SHM effectively in diverse structural contexts, ensuring resilient and long-lasting infrastructure systems.

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