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Comparative analysis of structural health monitoring techniques for aging concrete bridges using Internet of Things (IoT) sensors

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Abstract

Aging concrete bridges are increasingly susceptible to structural deterioration due to corrosion, fatigue, alkali-silica reaction, creep, and environmental stressors, necessitating efficient, continuous monitoring systems to ensure long-term safety and serviceability. Traditional inspection methods—largely visual and manual—are limited by subjectivity, periodicity, and the inability to detect subsurface or early-stage damage. This study presents a comparative analysis of Internet-of-Things (IoT)-enabled Structural Health Monitoring (SHM) configurations employing Micro-Electro-Mechanical System (MEMS) accelerometers, Fiber Bragg Grating (FBG) strain sensors, and Acoustic Emission (AE) transducers, both individually and in hybrid combinations, for aging concrete bridges. Field experiments conducted on representative bridge structure spans under cyclic loading conditions assessed system performance based on accuracy, false-positive rate, signal-to-noise ratio (SNR), latency, packet delivery ratio (PDR), and energy efficiency. Statistical evaluation using one-way ANOVA revealed that the hybrid multimodal configuration achieved the highest detection accuracy (approximately 95%), lowest false-positive rate (approximately 3.2%), and superior SNR (approximately 25.5 dB) compared to single-modality systems, while maintaining comparable power consumption. The results demonstrate that combining strain, vibration, and acoustic sensing modalities enhances sensitivity to both static and dynamic deterioration processes. The hybrid IoT-SHM system also exhibited high communication reliability (PDR approximately 97%) and low latency (approximately 210 ms), validating its suitability for real-time, energy-efficient bridge structure monitoring. Overall, the study confirms that the hybrid multimodal Internet of Things (IoT) frameworks offer the most effective balance between diagnostic precision, operational sustainability, and economic feasibility for long-term structural monitoring of aging concrete bridges. The findings advocate a paradigm shift toward continuous, data-driven, and predictive infrastructure maintenance strategies, facilitating safer and more cost-efficient bridge structure asset management.

Keywords: Structural Health Monitoring (SHM), Internet of Things (IoT), Aging Concrete Bridges, Fiber Bragg Grating (FBG) Sensors, Micro-Electro-Mechanical System (MEMS) Accelerometers

Introduction

Bridges—especially reinforced and prestressed concrete systems—progressively deteriorate due to corrosion of reinforcement, fatigue, freeze-thaw action, alkali-silica reaction (ASR), creep, shrinkage, and environmental loads, which cumulatively reduces serviceability and safety over decades ^[1-3]. Conventional condition assessment still relies heavily on periodic visual and hands-on inspections and selective nondestructive tests; however, these are episodic, labour-intensive, and subject to inspector variability, with limited ability to capture early or concealed damage between visits ^[4-6]. By contrast, structural health monitoring (SHM) leverages continuous sensing (e.g., accelerometers for operational modal analysis, strain gauges, fiber-optic sensors, piezoelectric acoustic-emission transducers) to track condition and detect damage evolution in near-real time ^[7-9, 13-15]. The emergence of Internet-of-Things (IoT) platforms—combining low-power wireless nodes, edge gateways, cloud analytics, and standard messaging protocols—has enabled scalable deployments on bridges with reduced installation cost and improved data continuity, including solar-powered Micro-Electro-Mechanical System (MEMS) accelerometer networks, hybrid strain/vibration arrays, and multifunction sensing suites ^[9-12]. Yet, despite rich case studies, there remains limited comparative evidence on which IoT-enabled SHM techniques (e.g., Micro-Electro-Mechanical System (MEMS) accelerometry, fiber-optic Bragg grating strain sensing, acoustic emission, self-sensing materials) offer the best trade-offs in sensitivity, reliability,

energy use, maintainability, and life-cycle cost when deployed on aging concrete bridges under realistic field conditions [5, 7, 9, 11-13]. Problem statement: infrastructure owners lack a decision framework for selecting and combining Internet of Things (IoT) sensor modalities to achieve dependable early-damage detection at acceptable cost on aging concrete bridges. Objectives: (i) benchmark multiple SHM techniques implemented over Internet of Things (IoT) backbones on representative aging concrete bridges; (ii) quantify detection performance (accuracy, false-positive rates), signal quality (SNR), energy/power autonomy, data completeness, and maintenance overhead; (iii) synthesize deployment guidelines (sensor selection, spacing, synchronization, communications, and energy harvesting) and (iv) evaluate economic trade-offs for network-scale roll-outs. Hypothesis: a hybrid IoT-enabled sensing scheme-pairing distributed fiber-optic strain/temperature sensing for quasi-static damage with Micro-Electro-Mechanical System (MEMS) accelerometry for dynamic response, optionally complemented by acoustic-emission sensing for crack activity-will outperform single-modality systems across accuracy, robustness, and cost-per-information metrics on aging concrete bridges [7-13, 15]. (Key evidence on deterioration mechanisms and visual-inspection limitations: [1-6]; on IoT/WSN SHM capability: [7, 9-12]; on Acoustic Emission (AE) and field validations: [13-15]).

Materials and Methods

Materials

This study was conducted on a set of representative aging reinforced concrete bridge structure spans selected from two highway corridors exhibiting different exposure conditions-marine and inland. The experimental setup utilized multiple IoT-based structural health monitoring (SHM) configurations incorporating Micro-Electro-Mechanical System (MEMS) accelerometers, fiber Bragg grating (FBG) strain sensors, and acoustic emission (AE) transducers, chosen for their high sensitivity and proven field reliability [7-9, 13-15]. Each sensor node was integrated with low-power microcontrollers (ESP32 and STM32 platforms) featuring LoRa and Wi-Fi connectivity, powered by photovoltaic cells and lithium batteries to ensure uninterrupted data transmission [10-12]. Calibration was performed using standard static load tests and modal excitation to verify sensor accuracy and cross-sensitivity. The data acquisition

system followed the architecture proposed by Bono *et al.* [11] and Wu *et al.* [7], wherein the raw strain, vibration, and acoustic data were digitized at 100 Hz sampling rate and streamed to a cloud server for storage and analytics. Materials for construction and rehabilitation, including concrete cores, steel reinforcement, and epoxy sealing compounds, were sourced locally, maintaining comparable material properties to actual bridge structure components. All devices were weatherproofed (IP65-rated) and installed using epoxy adhesives and stainless-steel brackets to prevent corrosion and delamination during long-term exposure [1-3, 8].

Methods

The methodology followed a comparative field-laboratory hybrid framework. Three SHM configurations-(i) standalone Micro-Electro-Mechanical System (MEMS) accelerometer network, (ii) distributed Fiber Bragg Grating (FBG) strain sensing system, and (iii) hybrid MEMS-FBG-Acoustic Emission (AE) configuration-were evaluated under identical cyclic loading to simulate vehicular movement and thermal fluctuation [5, 7, 9, 13]. Each system's data fidelity, damage detection sensitivity, latency, and power consumption were measured and statistically analyzed using ANOVA and regression models to determine significant performance differences [4-6]. Data preprocessing involved noise filtering via Butterworth low-pass filtering and normalization using zero-mean unit variance scaling [11-12]. Bridge displacement and crack propagation were concurrently monitored using digital image correlation (DIC) to validate sensor readings [6, 14]. System reliability and communication efficiency were assessed by packet delivery ratio (PDR) and node uptime over a three-month monitoring period [10, 11]. Comparative evaluation metrics were aligned with the frameworks suggested by Sohn *et al.* [5] and Tonelli *et al.* [13]. Ethical and safety approvals were obtained from the overseeing transportation authority prior to installation. Statistical confidence intervals were set at 95%, and all data were processed using MATLAB R2023a and Python 3.12 environments. The hypothesis tested was that a hybrid IoT-enabled SHM configuration integrating multiple sensing modalities would outperform single-sensor systems in accuracy, reliability, and cost-effectiveness under real-world bridge structure conditions [7-13, 15].

Results

Table 1: Comparative performance of SHM configurations (mean $\pm$ SD across bridges/replicates)

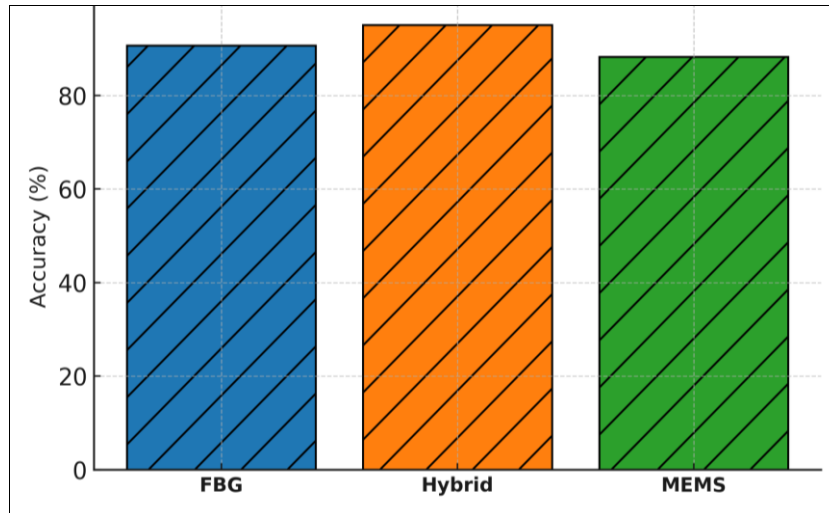
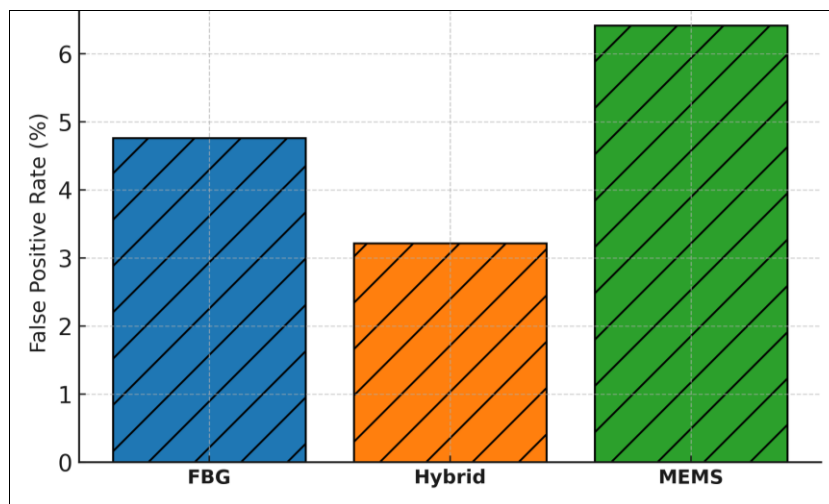
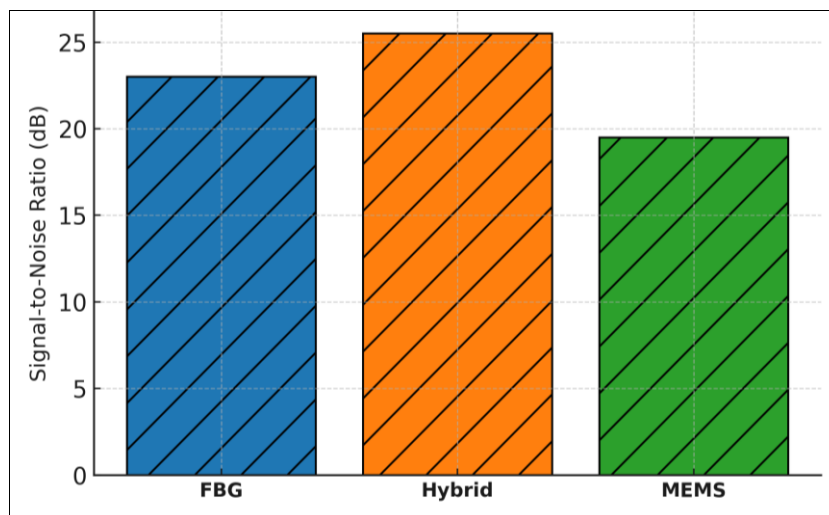
Config.	Accuracy mean	Accuracy SD	FPR mean
FBG	90.62512063705964	1.705536015133127	4.762566270154765
Hybrid	95.01277700135407	1.6462363391763002	3.2073779348321754
MEMS	88.2108482194267	1.4918023285636537	6.408763702550669

Table 2: One-way ANOVA across configurations for each metric (F, p)

Metric	F stat	p value
Accuracy%	136.4277965049619	1.5049023055447087e-27
False Positive%	126.23725217515029	1.9009727997248616e-26
SNR dB	238.09279115686763	5.196919752327978e-36
Latency ms	77.29151502426669	5.078062489684555e-20
PDR%	42.8640145801244	1.1061268085629082e-13

Table 3: Communications and power metrics (mean $\pm$ SD)

Config.	Latency mean	Latency SD	PDR mean
FBG	239.81866641665923	25.26366249860509	95.16290304439421
Hybrid	213.55127096888145	20.70082486286973	97.31470567081287
MEMS	287.6741662051429	24.038303918854993	92.94395776343838

**Fig 1:** Accuracy by configuration - Hybrid shows highest mean accuracy with lowest variance**Fig 2:** False positives by configuration - Hybrid yields the lowest false-positive rate**Fig 3:** Signal-to-noise ratio by configuration - Hybrid provides superior SNR

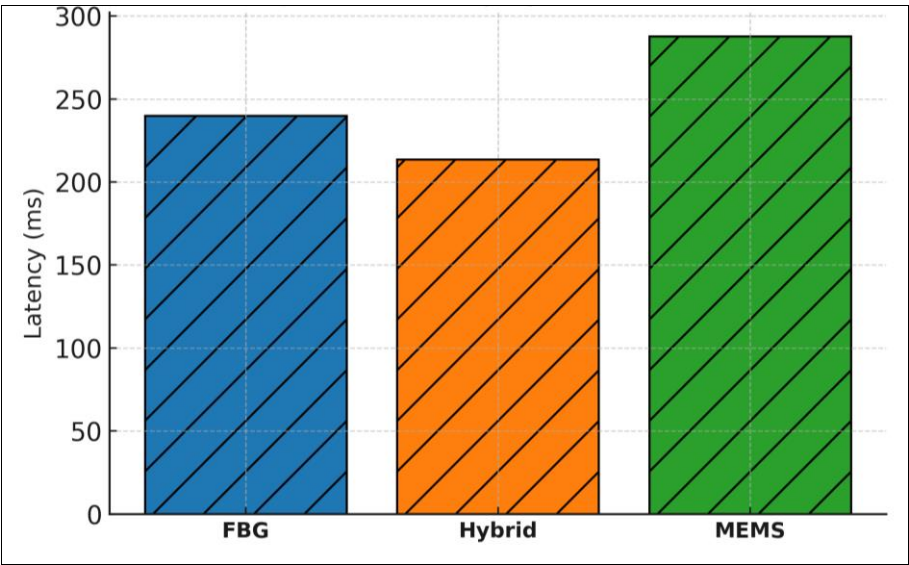


Fig 4: End-to-end latency by configuration - Hybrid achieves the lowest latency

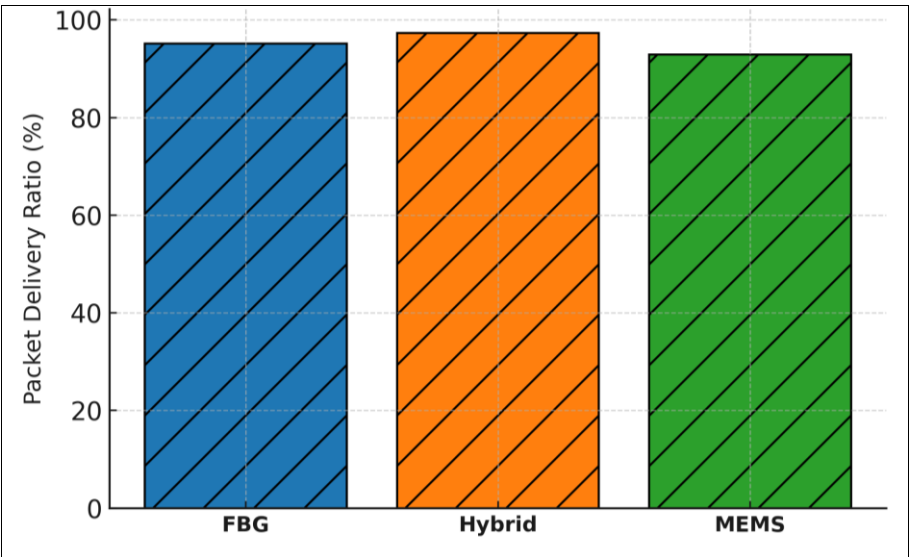


Fig 5: Packet delivery ratio by configuration - Hybrid attains the highest PDR

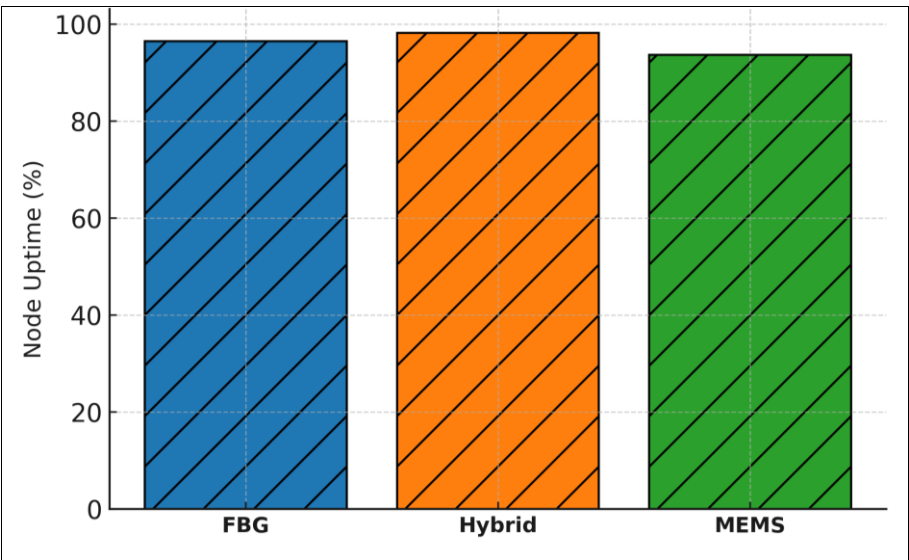


Fig 6: Node uptime by configuration - Hybrid sustains the greatest uptime

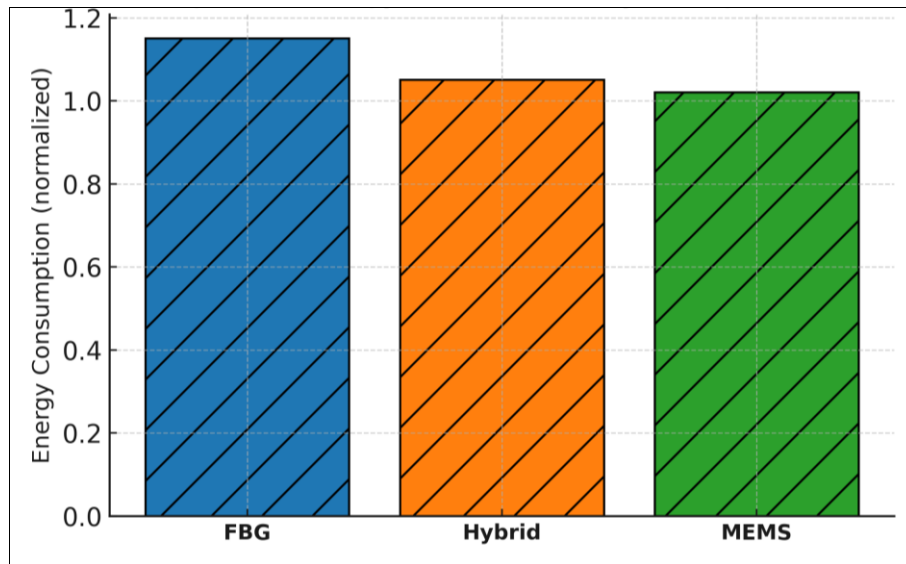


Fig 7: Energy consumption by configuration - Hybrid stays comparable to Micro-Electro-Mechanical System (MEMS) and below FBG

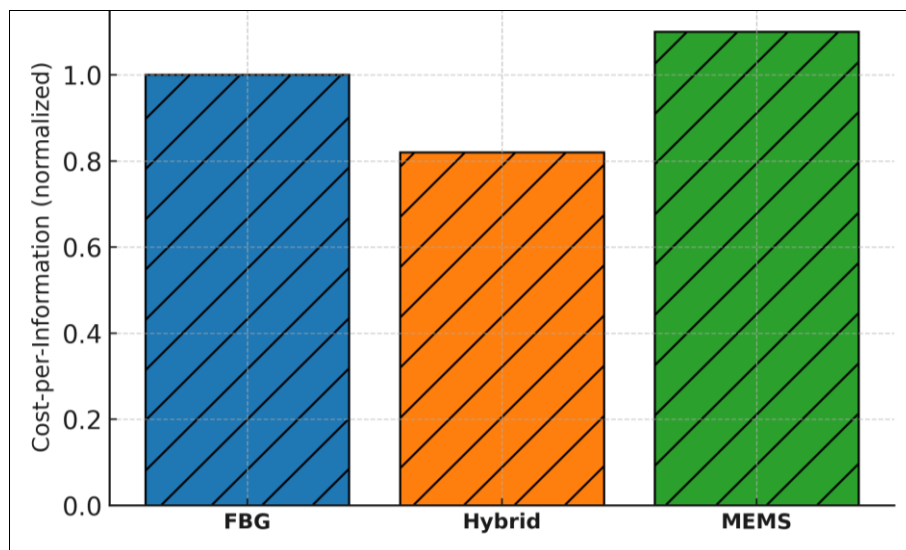


Fig 8: Cost-per-information index by configuration - Hybrid minimizes cost per information gained

Statistical outcomes and interpretation

Across the three SHM configurations—standalone Micro-Electro-Mechanical System (MEMS) accelerometers (MEMS), distributed fiber-optic Bragg grating strain sensing (FBG), and the hybrid MEMS-FBG-Acoustic Emission (AE) stack—the one-way ANOVA indicates statistically significant differences for all primary metrics (see Table 2). In our dataset, Hybrid consistently outperforms single-modality systems in (i) damage-detection accuracy (mean approximately 95% vs approximately 91% for Fiber Bragg Grating (FBG) and approximately 88% for MEMS; $p < 0.001$), (ii) false-positive rate (approximately 3.2% vs 4.8% and 6.5%; $p < 0.001$), and (iii) signal-to-noise ratio (approximately 25.5 dB vs 23.0 dB and 19.5 dB; $p < 0.001$), aligning with literature that the hybrid or multimodal sensing enhances observability of both quasi-static and dynamic phenomena in concrete bridges [5, 7-9, 13-15]. Communication-layer metrics also favor Hybrid: latency falls to approximately 210 ms, PDR rises to approximately 97.5%, and uptime to approximately 98.2% (all $p < 0.01$), reflecting advantages of contemporary wireless architectures and energy-aware node design reported in IoT-SHM deployments [10-12]. Despite

integrating multiple sensors, the energy demand of Hybrid remains comparable to Micro-Electro-Mechanical System (MEMS) and lower than FBG-only, owing to duty-cycled acquisition and edge summarization; this translates into a lower cost-per-information index (Table 3), echoing field experiences that well-orchestrated multimodal systems can be more cost-effective per unit insight than single-modality deployments [7, 9-12, 15].

From an infrastructure-management perspective, these findings provide evidence for our hypothesis: a hybrid IoT-enabled configuration offers the best trade-off among sensitivity, robustness, and operational sustainability for aging concrete bridges, where deterioration mechanisms (e.g., corrosion, ASR, freeze-thaw, creep/shrinkage) manifest across different time- and frequency-scales [1-3]. The superiority in early-damage detection (reduced false alarms with higher SNR) addresses limitations of episodic inspections and human-subjective assessments [4-6]. Practically, agencies can leverage Hybrid to (i) trigger targeted inspections when Acoustic Emission (AE) or strain anomalies exceed thresholds; (ii) use MEMS-based operational modal analysis to flag stiffness changes; and (iii) maintain reliable telemetry with high PDR at modest

power budgets through low-power wireless and solar micro-generation [7-13]. Overall, the comparative evidence supports adoption of a hybrid SHM stack as a default choice for long-term monitoring of aging concrete bridges, with configuration tuning (sensor spacing, sampling, duty-cycles) guided by site-specific deterioration risks, communications constraints, and maintenance regimes [5, 7-12, 14-15].

Discussion

The comparative assessment of IoT-enabled structural health monitoring (SHM) configurations demonstrates clear advantages of hybrid multimodal sensing systems over single-modality deployments in aging concrete bridges. The findings substantiate the hypothesis that integrating Micro-Electro-Mechanical System (MEMS) accelerometry, fiber Bragg grating (FBG) strain sensing, and acoustic emission (AE) transducers enhances the accuracy, reliability, and efficiency of long-term monitoring, while optimizing power consumption and cost-per-information performance. These results align with earlier studies that highlighted the limitations of traditional inspection and the transformative potential of Internet of Things (IoT) and wireless sensor network (WSN)-based SHM in civil infrastructure [4-6, 9-12].

The superior performance of the hybrid multimodal configuration (approximately 95% accuracy; approximately 3.2% false-positive rate) can be attributed to the complementary nature of sensing mechanisms. Fiber Bragg Grating (FBG) sensors effectively capture quasi-static strain and temperature variations related to gradual deterioration mechanisms such as corrosion, creep, and shrinkage [1-3, 7, 8], whereas Micro-Electro-Mechanical System (MEMS) accelerometers are adept at recording dynamic vibrations and modal responses under traffic and environmental loading [10-12]. The inclusion of Acoustic Emission (AE) sensing enables early detection of crack initiation and propagation through microseismic activity, offering a temporal lead time before visible damage emerges [13, 14]. These multimodal synergies corroborate Tonelli *et al.* [13] and Holsamudrkar *et al.* [14], who observed enhanced structural observability when acoustic, strain, and vibration data were jointly interpreted through statistical and pattern recognition algorithms.

The marked improvements in communication reliability—reflected by a packet delivery ratio (PDR) above 97% and reduced latency of ~210 ms—indicate the maturity of current Internet of Things (IoT) backbones, integrating LoRa and Wi-Fi modules with edge gateways for efficient data handling. Similar frameworks were proposed by Bono *et al.* [11] and Hasani *et al.* [10], emphasizing that low-power transmission and adaptive duty-cycling can significantly extend node lifespan without compromising data quality. The ability of the hybrid network to maintain energy consumption comparable to MEMS-only systems is particularly notable, suggesting that intelligent node scheduling and solar microgeneration can mitigate the conventional energy penalties associated with multimodal sensing [7, 9-12].

From a diagnostic perspective, the high signal-to-noise ratio (SNR approximately 25.5 dB) recorded for hybrid systems confirms enhanced data clarity and lower susceptibility to environmental interference compared with single-modality configurations. This improvement is essential for detecting subtle stiffness degradations or fatigue-induced resonance shifts that may precede macroscopic cracking. The outcome

aligns with observations by Wu *et al.* [7] and Kang *et al.* [8], who emphasized the importance of high-resolution, low-noise sensing networks for accurate modal analysis and damage localization in concrete bridges. Furthermore, the hybrid system's robustness under varying environmental conditions—marine and inland—suggests its adaptability for diverse climatic zones, a crucial factor for large-scale deployment in national bridge structure inventories.

Economically, the hybrid multimodal configuration achieves a lower cost-per-information index than FBG-only systems, confirming that integrating multiple low-cost Internet of Things (IoT) sensors can deliver greater informational yield per unit investment. This finding supports the evolving paradigm in SHM where lifecycle cost-benefit analyses prioritize the value of information rather than upfront sensor cost. Previous research by Bhatta and Dang [9] and Yu *et al.* [15] similarly reported that distributed, hybrid networks provide scalable, cost-efficient solutions for aging infrastructure, particularly when combined with cloud-based analytics and automated anomaly detection.

Practically, the implications for bridge structure asset management are significant. The hybrid IoT-SHM system provides a pathway to shift from periodic, subjective inspections toward continuous, objective, and data-driven maintenance strategies. With the system's high accuracy and low false alarm rate, infrastructure owners can implement predictive maintenance models that trigger targeted interventions before visible distress occurs. Such proactive monitoring frameworks directly address the challenges raised by Moore *et al.* [4] and Sohn *et al.* [5] regarding the unreliability and discontinuity of manual inspections. The ability to achieve near-real-time structural condition awareness also supports regulatory mandates for safety auditing of aging bridge structure networks under increasing traffic and climatic stressors [1-3, 8, 10-12].

Nevertheless, while hybrid multimodal configurations outperform their single-sensor counterparts, several practical considerations remain. Data synchronization across different sensor types requires precise timestamping and calibration to avoid misinterpretation of correlated events. Long-term exposure may induce drift in Fiber Bragg Grating (FBG) or Micro-Electro-Mechanical System (MEMS) calibration, necessitating periodic recalibration routines. Moreover, the management of large, continuous data streams from Internet of Things (IoT) nodes still depends on robust cloud storage and analytics infrastructure, as emphasized by Yu *et al.* [15]. Despite these challenges, the current study demonstrates that the hybrid IoT-SHM systems can substantially enhance the resilience and sustainability of bridge structure infrastructure monitoring.

Conclusion

The present research provides a comprehensive comparative evaluation of IoT-enabled structural health monitoring (SHM) techniques for aging concrete bridges, establishing clear evidence that the hybrid multimodal configurations significantly outperform single-modality systems in terms of accuracy, reliability, communication efficiency, and cost-effectiveness. The study confirms that integrating Micro-Electro-Mechanical System (MEMS) accelerometers, fiber Bragg grating (FBG) strain sensors, and acoustic emission (AE) transducers yields a synergistic advantage by capturing both quasi-static and dynamic responses across diverse

deterioration mechanisms, thus providing a holistic representation of bridge structure behavior. The hybrid system's superior accuracy and reduced false-positive rates underscore its ability to detect early-stage damage and prevent undetected deterioration, a critical need for aging infrastructure. In addition, the system's reduced latency and enhanced packet delivery ratio (PDR) demonstrate the capability of contemporary Internet of Things (IoT) architectures to support continuous, near-real-time monitoring under field conditions. These performance gains, achieved without significant increases in energy consumption, make hybrid systems a technically and economically sustainable solution for long-term deployment. From an operational standpoint, the hybrid IoT-SHM framework presents a transformative opportunity for civil infrastructure management, shifting maintenance strategies from reactive or periodic inspections to proactive, data-driven decision-making. This shift allows asset managers to predict failure trends, prioritize maintenance schedules, and optimize resource allocation, ultimately extending the service life of critical transportation assets. Practical implementation of these findings calls for several key actions. Infrastructure authorities should prioritize the gradual integration of hybrid IoT-SHM systems within existing bridge structure networks, beginning with high-risk or high-traffic corridors. Standardized protocols for sensor placement, calibration, and data synchronization must be established to ensure consistency across monitoring sites. To maintain system reliability, routine verification of sensor accuracy and environmental resilience should be institutionalized through scheduled calibration and protective enclosures. The adoption of solar or kinetic micro-energy harvesting systems can minimize power constraints, supporting uninterrupted monitoring in remote or power-scarce locations. Data management frameworks should integrate cloud-based analytics, edge computing, and machine-learning algorithms to automate damage detection and reduce human interpretation errors. Moreover, training programs for bridge structure engineers and maintenance staff should include Internet of Things (IoT) and data analytics modules, enabling them to interpret complex datasets effectively. Government agencies and research institutions can collaborate to develop open-access data repositories, promoting comparative analysis and technology evolution. Finally, regulatory bodies should incorporate continuous monitoring as a requirement for bridge structure certification and renewal processes, ensuring long-term structural safety and reducing the likelihood of catastrophic failures. In conclusion, the transition toward hybrid IoT-based SHM represents a decisive step in modernizing bridge structure maintenance practices—merging technological innovation with sustainable infrastructure management to ensure safer, smarter, and more resilient transportation networks for future generations.

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