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Structural Health Monitoring in India: Progress and Prospects (2000–2025)

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ABSTRACT

Because it provides real-time insights into structural integrity through advanced sensing and data analytics, structural health monitoring, or SHM, has emerged as a crucial element of contemporary infrastructure management. The need for strong monitoring systems has been highlighted by India's infrastructure's exponential growth since 2000, which includes bridges, dams, high-rise buildings, and rail. However, early practices relied on reactive "run-to-failure" maintenance and periodic visual inspections, and SHM has only recently gained institutional traction. With an emphasis on the revolutionary effects of technologies like the Internet of Things (IoT) and Wireless Sensor Networks (WSNs), this review plots the development of SHM in India from 2000 to 2025. Predictive maintenance, lower inspection costs, and better risk mitigation have all been made possible by the use of embedded sensors and fiber-optic systems analytics.

Urban transit systems like the Mumbai Metro, dam safety improvements through digital monitoring proposals, and SHM implementations in large-scale bridges like Bogibeel and Chiraiyatand are some of the important applications examined. Key policy landmarks include the introduction of the Indian Bridge Management System (IBMS) in 2014 and publication of national Structural Health Monitoring (SHM) guidelines in 2024. However, issues like insufficient regulation, a shortage of qualified workers, data silos, and financial limitations still exist. The report outlines strategic recommendations for public-private partnerships, training initiatives, centralized data infrastructure, low-cost sensor innovation, and policy enforcement. It is both timely and viable to institutionalize SHM on all public properties since the Indian SHM market is predicted to grow at a rate of over 21% by 2030. In addition to improving performance and safety, India's shift to a data-driven infrastructure paradigm will pave the way for resilient, sustainable urban growth.

Keyword: - Internet of Things (IoT), Wireless Sensor Networks (WSNs), Bridges, Dams, Buildings, Railways, Structural Health Monitoring (SHM).

1. INTRODUCTION

Introduction Structural Health Monitoring (SHM) is the continuous or intermittent sensing of infrastructure to determine its condition and identify damage prior to failure. Structural Health Monitoring (SHM) has gained worldwide relevance in the management of tunnels, dams, buildings, and bridges. [1]. Through real-time monitoring of strain, vibration, and deflection, SHM systems allow preventive maintenance and prolong the lifespan of critical infrastructure. In India, rapid infrastructure growth since 2000 including highways, rail networks, bridges, dams, and high-rise construction has created a pressing need for SHM. But until very recently, SHM has been a very new idea in India. As Rather et al. note, “no guidelines or regulations” existed to enforce monitoring, and the infrastructure industry typically followed a “run-to-failure” maintenance model [2], [3]. Landmark structures such as long-span bridges and dams often rely on traditional visual inspection and periodic surveys. Only in the last few years has India begun introducing formal SHM programs: for example, the Ministry of Road Transport launched the Indian Bridge Management System (IBMS) in 2014 to inventory 170,000 bridges [4], and the Indian Structural Health Monitoring Society published national SHM guidelines in 2024 [4]. This review scans the development of SHM in India (2000–2025), including technology advancements (IoT, WSN, AI), bridge, building, dam, and railway applications, and flagship Indian projects. In addition, we evaluate challenges facing current practice and provide advice for the speeding up of SHM adoption in India.

2. EVOLUTION OF SHM TECHNOLOGIES

Modern SHM relies on advanced sensing and data-processing technologies. Over the past two decades, innovations like wireless sensors, the Internet of Things (IoT), and artificial intelligence (AI) have transformed monitoring practice. Wireless Sensor Networks (WSNs) and IoT platforms enable distributed, real-time data collection. Indian guidelines now explicitly recommend IoT-based automated monitoring: “agencies may adopt either manual or internet-of-things (IoT) based automatic mode (preferred) for data acquisition" with real-time online data access and automated alerts [5]. Wireless accelerometers, strain gauges, and tiltmeters (with cellular or satellite links) reduce wiring complexity and allow remote sites to be monitored. For example, fiber-optic strain sensors and long-gauge fiber optic (SOFO) sensors offer high sensitivity for large structures, while WSNs dramatically cut installation cost and complexity [1]. The deployment of embedded microcontroller-based sensor nodes (with power harvesting or low-energy radios) has proven effective for civil structures like bridges and overpasses.

Artificial Intelligence and Data Analytics are also becoming integral to SHM. Machine learning algorithms now process vast SHM datasets to recognize damage signatures and predict deterioration. A recent review highlights seven core AI-enabled SHM functions, including enhanced signal processing, anomaly detection, predictive maintenance scheduling, and resilience analysis [1]. In particular, AI-based pattern recognition (using vibration data and imagery) can pinpoint crack growth or corrosion before failure. Integrating AI with IoT data allows automated alarm generation when structural response crosses critical thresholds. Reviews of the literature note that combining IoT sensor networks with AI "significantly enhances the ability to detect structural damage, while reducing costs and reliance on manual inspections" [1]. AI-driven digital twins (real-time virtual replicas of structures) are an emerging capability: these computational models, continuously updated with sensor data, enable scenario simulation and informed decision-making.

Other **emerging technologies** are shaping SHM as well. Unmanned aerial vehicles (drones) equipped with cameras and thermal imagers can access hard-to-reach areas (e.g. tall towers or cable-stays) for visual inspections. The construction of digital twins and use of Building Information Modeling (BIM) are gaining traction, allowing engineers to integrate SHM data with detailed as-built models. Table-top and smartphone-based sensing methods are also under study for quick condition surveys. Overall, these technologies are making SHM more comprehensive and cost-effective worldwide [1], and India is gradually beginning to leverage them.

3. SHM for Bridges

Bridges are among the most safety-critical infrastructure, and India's long bridges (especially in seismic or flood-prone regions) benefit greatly from SHM (Fig. 1). Several Indian projects illustrate this trend. At the national level, the **Indian Bridge Management System (IBMS)** (Ministry of Road Transport & Highways) was launched to catalogue all highway bridges (>170,000) and rate their condition [4]. Although IBMS started with visual surveys, it provides a framework to prioritize monitoring on critical spans. In practice, large-span and cable-stayed bridges are increasingly instrumented. The newly completed Bogibeel Bridge in Assam, running 4.95 kilometers long and carrying rail and road traffic over the Brahmaputra River, has been fitted with an automated Structural Health Monitoring system. Sensors on its concrete-girder deck continuously record temperature, strain, and displacement to assess response to traffic and seismic loads [2]. Similarly, the **Chiraiyatand Bridge** in Patna (a 110 m cable-stayed rail/road bridge) is reported to have strain gauges on each of its 42 stay cables, allowing engineers to monitor cable tension and detect overload [6].

The new 2024 Indian SHM guidelines specifically target bridge types that exceed certain span thresholds. For instance, all *cable-stayed*, *suspension*, and *extradosed* bridges (any span) are advised for SHM, as well as older prestressed girder bridges (I-girders >30–40 m span, box-girders >25–30 m) and steel trusses >75 m [5]. In line with this, projects like the **Allahabad (Prayagraj) Bypass Bridge** (over the Ganges) and the **Patiala Overpass** have employed sensor networks (embed strain gauges and tilt meters) during construction and early operation. The Konkan Railway has taken interim measures by using portable vibration monitoring: it procured an Austrian BRIMOS vibration recorder to collect ambient-frequency "signatures" of multiple bridges [7], aiding visual inspectors.

By contrast, many older Indian bridges remain without formal SHM. Classic examples: Shastri Bridge (Prayagraj) and Mahatma Gandhi Setu (Patna) are beyond design age yet see heavy traffic [2]. These structures would greatly benefit from monitoring of fatigue and scour, but budget constraints have so far limited installations to isolated projects. Overall, India is gradually expanding bridge monitoring: a combination of government programs (IBMS surveys, SHM guidelines) and private firms (e.g. Encardio-Rite's instrumentation contracts) has led to selective SHM deployment on major bridge projects [2], [4].

4. SHM for Buildings

Structural monitoring of buildings in India has lagged behind bridges and dams. Tall and critical buildings (hospitals, stadiums, high-rises) ideally require SHM, especially in seismic zones (Fig. 1). The new SHM guidelines explicitly recommend monitoring for high-rise buildings: for example, structures above 50 m height (roughly 15+ stories) should be instrumented in seismic zones up to IV, and buildings above 20 meters in zone V . In practice, only a handful of Indian buildings have advanced monitoring. Some landmark structures (e.g. towers or heritage buildings) have been fitted with tiltmeters or crack gauges after seismic events, but systematic SHM networks are rare. Recent trends in "smart buildings" integrating IoT sensors for energy and security – could facilitate SHM adoption. However, lack of mandated policy has kept uptake low. As Rather *et al.* observe, India traditionally follows a "run-to-failure" model with minimal monitoring [5]. Thus, except for a few pilot studies (for instance, dynamic monitoring of tall R.C.C. towers by research groups), building SHM remains largely at the proposal stage.

Fig. 1. : Structural Health Monitoring (SHM) of Building and Bridge.

5. SHM for Dams

India's major dams (Tehri, Bhakra, Hirakud, etc.) have long incorporated safety instrumentation such as piezometers, tiltmeters, and movement sensors. These data have been used for operational safety, but were not designed as integrated SHM systems with modern analytics. Recent years have seen proposals to modernize dam monitoring using digital technologies. Global reviews note that IoT-enabled SHM (wireless strain and seismic sensors) is a "critical innovation" for dam safety, providing real-time alerts of seepage or structural changes (Khan et al., 2025).In India, a few pilot efforts (often by academia or local water authorities) are exploring SCADA-based sensor networks for dam parameters. However, published information is limited. One 2025 review specifically highlights the potential of IoT for dam monitoring (e.g. remote sensors, wireless data links) and notes that these methods can enable continuous health assessment in a resource-efficient way [1]. There is growing recognition that digitizing dam data (for example via cloud platforms and AI analytics) would improve risk management especially as extreme hydrological events become more frequent.

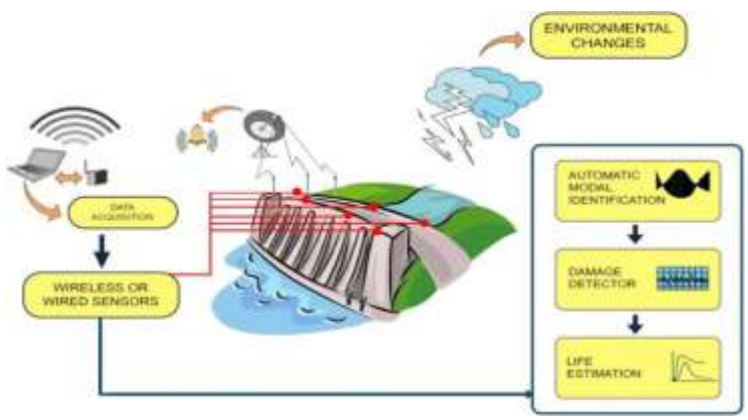

Fig. 2. : Structural Health Monitoring (SHM) of a Dam.

6. SHM for Railways

The Indian rail network, carrying both heavy freight and passengers, has adopted SHM selectively. Bridge structures on rail routes (like the Bogibeel Bridge mentioned above) often share sensors with road deck. For tracks and rolling stock, condition monitoring is evolving: modern coaches include axle-counters and ultrasonic wheel sensors, and some research projects have placed accelerometers on tracks to detect deformations. A concrete example of infrastructure SHM in railways is the Konkan Railway's initiative: as noted, it uses a BRIMOS recorder to establish vibration baselines for bridges [7]. Additionally, the Indian Railways' Research Design & Standards Organization (RDSO) has trialed track-monitoring trains equipped with LiDAR and ground-penetrating radar to flag ballast issues.

In urban transit, SHM is more advanced. Metro rail systems in Delhi, Bengaluru, and Mumbai routinely monitor tunnel deformation and elevated guideway deflection using fiber-optic sensors and laser scanners (partly for maintenance and seismic safety). For example, the **Mumbai Metro's Western Express Highway elevated corridor** has inclination and crack monitors on its cable-stayed sections [9]. As new corridors (e.g. bullet train tracks between Mumbai and Ahmedabad) are built, SHM considerations are being integrated at design stage, including provision for accelerometers and strain sensors along viaducts. In summary, while Indian rail networks have yet to deploy a fully comprehensive SHM regime, key projects are embedding modern monitoring (vibration recorders on bridges, permanent gauges on tunnels and elevated tracks) as part of safety management [7], [9].

Fig. 3. : Structural Health Monitoring (SHM) of a Railway.

7. INDIA'S SHM INITIATIVES AND KEY PROJECTS

Significant milestones have recently emerged in India's SHM journey. The **Indian Structural Health Monitoring Society (ISHMS)** formed in the early 2020s to coordinate industry, academia, and government. In 2024 ISHMS published national guidelines (discussed above) India's first formal SHM standards [5]. At the governmental level, **IBMS** (2014) represents a major inventory effort, and work is underway to extend it by including sensor data for high-priority bridges. Major public projects now routinely include SHM tender clauses; for example, newly awarded long-span bridge and high-speed rail contracts call for real-time monitoring during testing and initial operation.

On the research side, several **Indian laboratories and companies** have developed SHM systems. IIT Bombay and IISc have SHM test beds (vibration tables and lab structures), and startups (e.g. SHM India LLP) commercialize sensor networks for civil sites. The private firm Encardio-Rite has carried out numerous Indian SHM installations: its case studies include geotechnical monitoring on the Jaipur–Kishangarh Expressway and sensor deployment on the Patna and Assam bridges [10]. These projects often integrate new IoT or data-center solutions. Additionally, pilot projects under Indian Railways and National Highways involve MEMS-based accelerometer arrays to detect vehicle-induced bridge vibrations.

The market outlook is encouraging: a recent industry report projects the Indian SHM market (hardware+software+services) to grow from about **USD 146 million in 2024 to USD 478 million by 2030** (CAGR ~21.8%) [11]. This indicates rapid adoption potential if barriers are addressed.

8. CHALLENGES AND LIMITATIONS IN INDIA'S SHM PRACTICES

Despite progress, India faces several challenges in SHM implementation. **Regulatory gaps** remain: until 2024 there were no mandatory codes for monitoring, and awareness in the construction industry has been low [5], [9]. Many agencies are hesitant to commit budgets for sensors and data platforms, especially when maintenance funds are constrained. **Technical issues** also arise: deployment in harsh environments (monsoon, seismic regions) raises sensor durability and power-supply concerns. Wireless connectivity in remote areas can be unreliable, and data quality may suffer from noise. There is a shortage of skilled SHM professionals (engineers and data analysts), so interpreting SHM outputs is difficult for many agencies. **Data integration** is another hurdle: various agencies (roads, railways, water resources) use different systems and proprietary software, leading to siloed information. Cybersecurity of IoT devices is an emerging concern as more devices go online. Finally, **funding and maintenance** pose limitations: installing an SHM system is one cost, but maintaining it (calibrating sensors, replacing batteries, validating algorithms) is another that agencies often overlook, leading some pilots to lapse.

9. RECOMMENDATIONS FOR FUTURE PROGRESS

To overcome these challenges, coordinated action is needed across technology, policy, and investment. Key recommendations include:

- **Policy and Standards:** Finalize and enforce SHM provisions in national codes (e.g. make certain monitoring mandatory for large bridges/dams). Public infrastructure projects should require SHM plans in their technical specs. The recent ISHMS guidelines provide a template, but adoption by government bodies is essential.
- **Technology Adoption:** Encourage pilot deployments of IoT and AI in SHM. For example, smart-city and smart-highway programs can include monitoring sensors. Incentivize use of open-source and interoperable sensor platforms to avoid vendor lock-in. Promote development of low-cost, robust sensor nodes (leveraging local industry) suitable for Indian conditions (e.g. solar-powered accelerometers).
- **Data and Analysis:** Build centralized platforms for SHM data (analogous to IBMS) where critical data from bridges, dams, and tunnels are aggregated. Use cloud analytics and AI to process data streams for anomaly detection. Encourage collaboration between infrastructure agencies and research labs to interpret SHM data.
- **Infrastructure Investment:** Allocate dedicated funding for monitoring systems in maintenance budgets. Since the domestic SHM market is growing rapidly, public-private partnerships can help deploy large-scale systems (for instance, leveraging telecom networks for data links).
- **Research Focus:** Support R&D in Indian SHM needs: earthquake-specific damage modeling, monsoon-related scour effects, and heavy-traffic fatigue. Develop AI algorithms trained on local bridge/dam failure modes. Study sensor performance in tropical climates. Also, explore emerging tech like UAV inspection and satellite InSAR monitoring for inaccessible sites.
- **Capacity Building:** Train civil engineers and infrastructure managers in SHM practices. Incorporate SHM modules into engineering curricula and continuing education. Host national workshops and conferences to share case studies (for example, review the Mumbai Metro cable-stay monitoring.
- **Maintenance and Lifecycle:** Plan for long-term operation: set automatic alert thresholds (as suggested in the guidelines) and ensure human oversight. Establish service contracts for sensor maintenance. By prioritizing data-driven decision-making, agencies can optimize maintenance schedules and extend asset life.

By addressing these areas, India can accelerate its SHM adoption. The potential benefits are substantial: more efficient maintenance, reduced infrastructure downtime, and ultimately greater safety of public assets.[5], [9], [11]

10. CONCLUSION

Structural Health Monitoring is an indispensable component of 21st-century infrastructure management. Over the past two decades, India has moved from minimal monitoring towards an era of data-driven asset care. Modern technologies – IoT sensor networks, wireless communications, AI analytics – are steadily being integrated into Indian projects. Milestones like the IBMS inventory and the new national SHM guidelines signal growing institutional support. Yet, to fully realize SHM's promise, India must overcome regulatory inertia, funding shortfalls, and technical challenges. Embracing SHM at scale will require sustained investment in technology and human capital. The recent market data (projected ~21.8% annual growth) suggests that the economic case is strong. Ultimately, widespread SHM will enhance infrastructure resilience and safety across India's bridges, buildings, dams, and railways.

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