ACCSCIENCE PUBLISHING

Journal of Chinese Architecture and Urbanism

REVIEW ARTICLE

Comparative review of structural health monitoring and innovative materials in classical and modern vernacular architecture: Insights from China and India

Palve Ankush[1]*, Gogate Nivedita[1], Chandak Narayan[2], and Dod Ramesh[1]

[1]Department of Civil Engineering, Dr. Vishwanath Karad MIT World Peace University, Pune, Maharashtra, India

[2]Department of Civil Engineering, SVKM's Institute of Technology, Dhule, Maharashtra, India

***Corresponding author:** Palve Ankush (ankpal2018@gmail.com)

Citation: Ankush P, Nivedita G, Narayan C, Ramesh D. (2026). Comparative review of structural health monitoring and innovative materials in classical and modern vernacular architecture: Insights from China and India. *Journal of Chinese Architecture and Urbanism*, 8(3):025310061. https://doi.org/10.36922/JCAU025310061

Received: July 28, 2025

Revised: September 15, 2025

Accepted: September 28, 2025

Published online: October 28, 2025

Abstract

Structural health monitoring (SHM) has advanced from traditional load-testing methods to intelligent, sensor-based systems that enable real-time, non-invasive assessment of structures. It plays a crucial role in preserving the structural integrity and cultural heritage of classical and vernacular architecture in China and India. This study reviews SHM systems and load testing methods for pre-stressed concrete and reinforced concrete girder bridges, focusing on their application in Chinese and Indian bridges. Load testing is classified into diagnostic and proof tests, each serving to assess structural behavior under service and ultimate loads. Traditional instrumentation, including strain gauges, linear variable differential transformers, and accelerometers, is compared with advanced non-contact methods such as digital image correlation, acoustic emission, and fiber optic sensors, which are increasingly used in urban and rural bridge maintenance in both countries. These technologies are evaluated for their effectiveness in detecting early signs of deterioration, including stiffness loss, fatigue, corrosion, and scour. The discussion emphasizes the importance of effective sensor deployment, precise data collection, and real-time monitoring in modern engineering practices. Emerging innovations such as video vibration sensing, wireless sensor networks, and artificial intelligence-powered data analysis are examined for their potential to improve diagnostics and facilitate predictive maintenance. The study advocates for hybrid SHM systems that combine global and local monitoring approaches, many of which are now integrated into China's national intelligent infrastructure initiatives and India's heritage preservation and smart highway projects. The article demonstrates how SHM can enhance the resilience, functionality, and sustainability of girder bridges under complex loading and environmental conditions.

Keywords: Reinforced concrete bridges; Pre-stressed concrete; Load testing in China; Diagnostic and proof load evaluation; Structural health monitoring; Sensor technologies; Non-contact measurement; Chinese bridge infrastructure

1. Introduction

Structural health monitoring (SHM) is an important element in the conservation of historical and modern built heritage. It provides critical information for evaluating structural integrity, performance, and service life. In the early 20th century, traditional evaluation methods relied on empirical procedures, such as load-to-failure tests, to track indicators including deflection and deformation (Lantsoght *et al.*, 2017). By comparison, modern SHM systems employ advanced sensors capable of continuously assessing stress, deflection, rotation, and environmental factors in real time, thereby enabling early warnings of structural deterioration and potential collapse (Lantsoght, 2020).

SHM technologies are particularly relevant for classical and modern vernacular architecture in China and India. In China, traditions of harmony, symbolism, and longevity are expressed through timber structures, ancestral halls, temples, and classical gardens (Cai, 2011; Jiang *et al.*, 2019; Shan, 2011). Similarly, in India, centuries-old temples, wooden palace structures in Kerala, Mughal forts, and vernacular homes in Himachal Pradesh reflect diverse material traditions and symbolic spatial arrangements. Both nations possess historical buildings that are vulnerable to constant environmental decay, urban development, and public neglect, highlighting the need for minimally invasive approaches to conservation (Luo *et al.*, 2021; Rossi & Bournas, 2023).

Modern vernacular architecture in China and India blends ancient design sensibilities with modern materials and construction techniques. In China, such buildings aim to preserve cultural continuity while meeting contemporary structural standards (K. Liu *et al.*, 2022; Song & Liao, 2022). A similar focus on vernacular identity and resilience is evident in India, where eco-sensitive rural housing, smart village schemes, and the adaptive reuse of heritage buildings are being developed. Therefore, the development of smart SHM systems—incorporating wireless sensor networks, fiber Bragg grating (FBG) sensors, and non-contact optical methods—represents a crucial step toward the sustainable regeneration of urban areas and rural revitalization in both countries (Abdulkarem *et al.*, 2020; Jiang *et al.*, 2019).

Despite these advancements, implementing SHM in vernacular and heritage buildings in China and India remains challenging. Conventional SHM methods, especially the use of contact sensors (e.g., strain gauges and displacement transducers), are time-consuming with respect to installation, calibration, and data collection (Lantsoght, 2024). Consequently, newer SHM techniques, including digital image correlation (DIC), laser distance measurements, acoustic emission (AE) monitoring, and wireless sensor networks, are increasingly favored because they are more efficient and less physically invasive to fragile heritage buildings (Abdulkarem *et al.*, 2020; Luo *et al.*, 2021). Nonetheless, economic, technological, and training barriers continue to hinder the implementation of large-scale historical conservation programs in both countries (Rossi & Bournas, 2023).

In addition to technical applications, SHM practices are shaped by broader cultural, social, environmental, and political considerations. In China, preservation decisions are heavily influenced by political governance, cultural revival programs, and urban heritage policy frameworks (Bell, 2010; Esherick, 2000; Yeh, 2000). In India, organizations such as the Archaeological Survey of India (ASI), Indian Institute of Technology (IIT) research centers, and the Smart Cities Mission have played central roles in advancing sensor-based conservation of temple complexes, havelis, and colonial-era buildings. Real estate and infrastructure development projects in both countries that incorporate SHM systems while preserving vernacular aesthetics highlight an emerging compromise between modernization and heritage ideals (Wu *et al.*, 2025).

Reflecting the rapid expansion of this multidisciplinary research domain, Figure 1 illustrates the number of articles referenced in this comparative review, categorized by year of publication between 2000 and 2025. The recent surge in academic interest can be attributed to technological advancements, reduced sensor costs, and improvements in data visualization and remote accessibility, all of which have enhanced the viability of SHM tools for heritage and modern infrastructure projects.

This review seeks to bridge a knowledge gap by offering a comparative analysis of SHM practices and innovative material applications in the classical and modern vernacular architecture of China and India. By systematically evaluating monitoring approaches, their benefits and limitations, and their practical implications, the study aims to support architects, engineers, conservationists, and policymakers in optimizing SHM deployment. The ultimate goal is to foster resilience, sustainability, and cultural continuity in the architectural landscapes of both nations.

Figure 1 demonstrates the steady growth of publications on diagnostic and proof load testing, non-contact sensing (DIC, AE, FBG, vision-based techniques [VVS]), and heritage monitoring applications in China and India. This trend underlines the increasing emphasis on integrating advanced monitoring technologies into both infrastructure and heritage management.

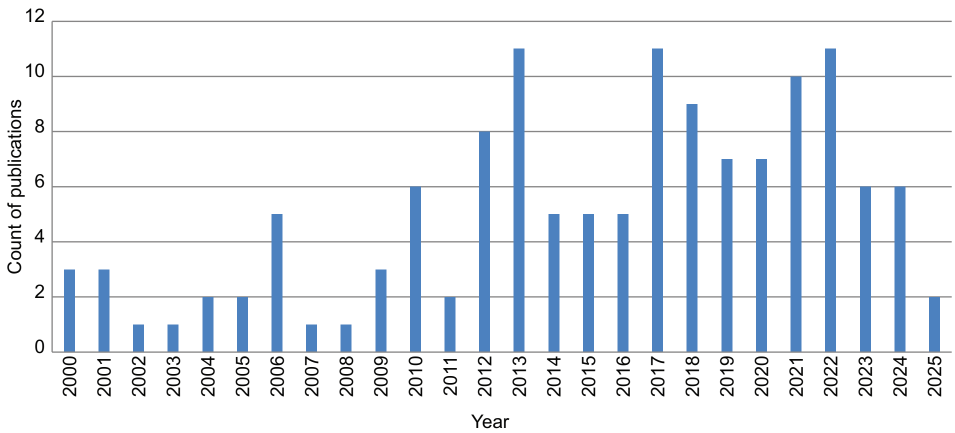

Figure 1. Bibliometric distribution of structural health monitoring and load-testing literature (2000–2025)
Source: Graph by the authors.

1.1. Research aim and contribution

This review examines how SHM and load-testing practices are deployed across China and India in both infrastructure (pre-stressed concrete [PSC]/reinforced concrete [RC] bridges) and heritage contexts. Our aim is to: (i) consolidate the state of practice in diagnostic and proof load tests; (ii) evaluate contact versusNon-contact sensing (DIC, AE, FBG, VVS, wireless sensor network, light detection and ranging [LiDAR], interferometric radar [InSAR]) with respect to accuracy, invasiveness, and cost; and (iii) draw comparative insights on adoption barriers/enablers, governance, and environmental constraints unique to the two countries.

The significance of the current review lies in its originality. In contrast to previous studies that have focused on either single countries or specific technologies, the China–India comparison undertaken here highlights how policy frameworks, heritage-ethics requirements, climate exposures such as monsoon and seismicity, and project-delivery models shape SHM implementation choices. This comparative lens yields actionable contrasts. For example, China has pursued programmatic roll-outs of SHM within intelligent-infrastructure initiatives, whereas India has relied more heavily on heritage-led pilots within Smart Cities and the ASI. Such distinctions clarify when and why hybrid non-contact stacks outperform legacy arrays in each national context.

1.2. Review methodology

To address the aims, we conducted a narrative, scoping-style review guided by the overarching research question: How are SHM and load-testing practices implemented across China and India in both infrastructure and heritage settings, and what comparative lessons can be drawn for technology choice, ethics, and policy?

Our literature search was performed in Scopus, Web of Science, and Google Scholar, covering publications between 2000 and 2025, with additional backward and forward citation chasing from key papers. Search strings included combinations such as “bridge diagnostic load test China/India,” “proof load pre-stressed concrete,” “non-contact DIC AE FBG bridge/heritage,” “vibration visual sensing VVS mode shapes,” “wireless sensor network SHM,” and “InSAR/GPR/IRT bridge/temple/heritage.”

Articles were eligible for inclusion if they were peer-reviewed journal or major conference papers, field or laboratory studies with clear instrumentation or protocols, or reviews and methods papers synthesizing SHM and load-testing. Applications had to focus specifically on China or India in infrastructure or heritage contexts. Studies were excluded if they were purely numerical with no measurement validation, belonged to non-civil domains, were published in languages other than English, or consisted of theses or white papers lacking methodological transparency.

Screening was conducted in two stages: titles and abstracts were first assessed for relevance, followed by full-text evaluations that emphasized clarity of instrumentation and outcome metrics. The final set of studies constitutes the corpus referenced in the present review. For each included study, we extracted information on structure type, test type (diagnostic or proof), sensor stack, environmental conditions, key findings, and limitations. These data were synthesized thematically and comparatively across China and India, with particular emphasis on cost and logistics, the standards and policy context, and heritage ethics.

It is important to note that this review is a literature synthesis only; no new experiments were conducted.

2. Health monitoring scheme for PSC girder bridges in the context of vernacular and modern Chinese and Indian architecture

SHM plays a critical role in the assessment of performance, durability, and serviceability of engineered structures such as PSC girder bridges and conventional vernacular architecture. It fills the gap between technological development and construction activities, particularly in urban China and India, where infrastructure expansion and cultural heritage preservation proceed in parallel (Jiang *et al*., 2019; Rossi & Bournas, 2023). In India, SHM has been increasingly adopted for evaluating bridge health under dynamic loading, particularly along high-speed corridors such as the Mumbai–Pune Expressway and Delhi–Meerut Regional Rapid Transit System. At the same time, SHM techniques are being applied to the surveillance of colonial-era rail bridges and stone aqueducts under the custodianship of heritage authorities.

In modern PSC girder bridges, clinometer sensors are frequently employed to measure real-time rotation and stress due to traffic loads (Bertagnoli *et al*., 2023). Nevertheless, these systems typically rely on small-scale sensor arrays, which risk missing early indicators of damage, including micro-cracks, strain localization, and stress redistribution caused by fatigue (Park *et al*., 2006). A similar issue exists in Chinese timber structures and Indian wooden palaces (such as Padmanabhapuram Palace in Tamil Nadu and traditional buildings in Gujarat), where intricate joints and decorative elements are difficult to access, making SHM system design more challenging (Jiang *et al*., 2019). Locally developed SHM techniques, such as impedance-based monitoring with resistors, capacitors, and inductors, are gaining popularity due to their high sensitivity to material degradation. These methods can reveal minor variations suggestive of joint loosening or water ingress in wooden structures such as ancestral halls in China or traditional Kerala temples in India, conditions that resemble crack propagation in PSC girders (Luo *et al*., 2021).

Global and local damages in PSC structures are typically distinguished by hybrid SHM systems through variations in impedance, stiffness loss, and vibration anomalies. These systems begin with the collection of frequency-response data and apply the frequency response ratio assurance criterion (FRRAC) to evaluate overall structural modifications (Zhan *et al*., 2021). Although originally designed for modern buildings, such methods have also been adapted for heritage conservation under limited-load conditions. For instance, experiments at UNESCO sites in India, including the Sun Temple at Konark and the Rani ki Vav stepwell, have tested impedance-based systems for mapping material degradation without invasive inspection.

Damage classification progresses from evaluating global structural responses to examining local impedance spectra, facilitating identification of deterioration processes, such as pre-stress loss from tendon relaxation in PSC structures, concrete cracking, and wood degradation in historic timber constructions (Caicedo *et al*., 2021). The technique has particular application in detecting pre-stress loss in tendon systems as well as deterioration in traditional mortise-and-tenon joints in Chinese and Indian contexts. SHM also enables the detection of pre-stress loss or load redistribution by strategically deploying sensors in critical stress zones (i.e., tendons or main columns) (Jia *et al*., 2023). FBG sensors, for example, have shown high sensitivity to micro-vibrations and stress changes in historical Chinese timber buildings, and are currently being tested in Indian stone pavilions and brick vaults to detect minute changes that may indicate foundation weakening (Jiang *et al*., 2019).

These indices capture changes in modal behavior caused by structural damage and have proven effective in evaluating both concrete bridges (Duvnjak *et al*., 2021) and heritage buildings subject to environmental fluctuations (Luo *et al*., 2021). Environmental factors in China and India, including monsoonal moisture cycles, thermal gradients, and atmospheric pollution, accelerate structural degradation through fatigue, underscoring the need for predictive diagnostics based on SHM.

A unified SHM system that incorporates impedance studies, acceleration sensing, and frequency-domain assessment facilitates broad local and global monitoring. This holistic approach is necessary not only for modern long-span bridges but also for traditional architectural systems, where localized damage can precipitate system-level failure (Alipour *et al*., 2019). Agencies in India, including the Indian Railways and Central Public Works Department, have begun implementing hybrid SHM systems in both new infrastructure projects and pilot heritage restoration initiatives to track real-time evolution.

Finally, Figure 2 illustrates a three-phase SHM procedure applicable to both infrastructure and cultural heritage contexts. The framework demonstrates how engineering-based SHM can contribute to cultural preservation in China and India while also supporting sustainable urbanization and historical continuity.

2.1. Health monitoring scheme for RC girder bridges and heritage structures

SHM safeguards the long-term safety and serviceability of RC girders, bridges, and heritage structures. In both China and India, these assets are subjected to accelerated deterioration from environmental exposure, fatigue, and aging, making continuous monitoring essential (Jiang

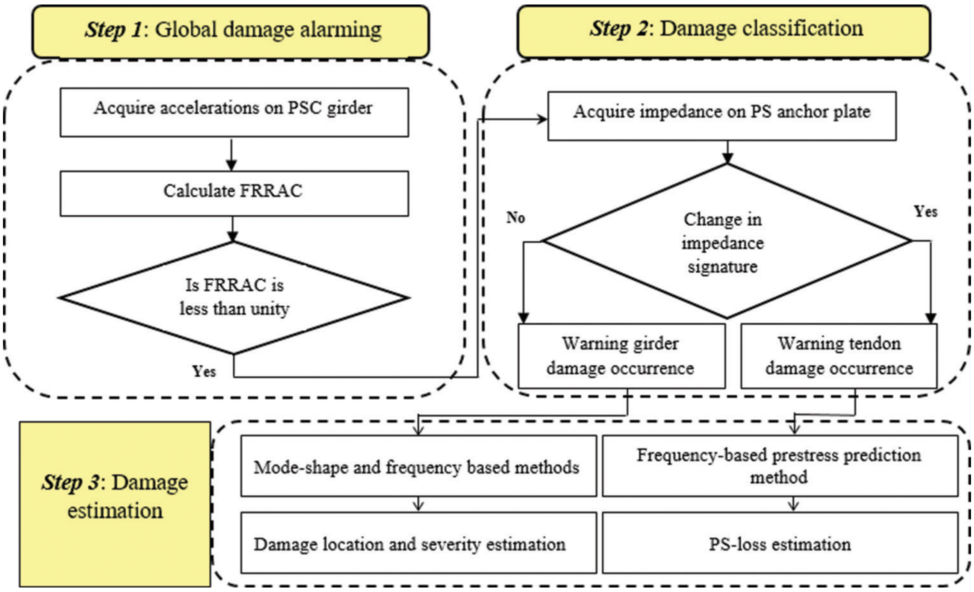

Figure 2. Schematic representation of the three-phase structural health monitoring process: (i) global assessment using low-cost screening tools and vibration surveys, (ii) local assessment with targeted instrumentation such as strain gauges, DIC, and AE sensors, and (iii) decision-making for maintenance, retrofitting, or continued service. This workflow applies to both PSC/RC bridges and heritage structures, ensuring efficient resource allocation and minimizing invasive testing.
Source: Schematic by the authors.
Abbreviations: AE: Acoustic emission; DIC: Digital image correlation; FRRAC: Frequency response ratio assurance criterion; PS: Pre-stress; PSC: Pre-stressed concrete; RC: Reinforced concrete.

et al., 2019; Luo *et al.*, 2021). SHM has also become integral to conservation practice, supporting the adaptive reuse of historic footbridges, temples, and stepwells.

Modern SHM systems combine strain gauges, accelerometers, displacement transducers, and wireless sensor networks to track vibration, deflection, and stress. These tools enable real-time anomaly detection and predictive maintenance in both bridges and culturally significant sites (Abdulkarem *et al.*, 2020). Environmental sensors further monitor humidity and temperature, which are particularly critical for lime plaster, bamboo, and timber elements in Rajasthan havelis, northeastern bamboo houses, and Chinese pagodas (Y. Q. Song & Liao, 2022).

Sensor placement is typically optimized according to structural behavior and project budget, with common locations at mid-span, tension zones, joints, and columns. Urban projects often employ solar- or battery-powered sensors for remote spans, while heritage monitoring relies on minimally invasive wireless nodes. Examples include Chettinad mansions in Tamil Nadu and Dravidian temples, where localized SHM modules support targeted preservation.

Pre-processing routines filter noise and highlight key indicators such as strain, microcracks, and modal shifts. Increasingly, AI and machine learning models support early-warning systems by predicting crack initiation or foundation settlement (Comisu *et al.*, 2017). Initiatives under China's smart infrastructure programs and India's Atal Mission for Rejuvenation and Urban Transformation/Smart Cities Mission are already testing artificial intelligence (AI)-driven SHM in bridges and heritage precincts such as Varanasi and Jaipur.

Sensors can be classified either by measured parameter—corrosion, cracking, displacement, or fatigue—or by mode of operation, namely, contact or non-contact (Elsaid & Seracino, 2012). Non-contact techniques such as laser interferometry and DIC are especially valuable for fragile or inaccessible structures. Recent advances now allow near-real-time monitoring of wooden pagodas and Kath-Kuni buildings using distributed optical and vision-based sensors (Moreno-Gomez *et al.*, 2018; Taheri, 2019).

Table 1 compares the major SHM sensor types used in China and India, summarizing their measurement focus, strengths, and limitations.

2.2. Stiffness loss: Implications for bridges and heritage structures

Stiffness loss is a primary indicator of structural degradation in RC, timber, and masonry systems. It reflects fatigue, joint deterioration, or loss of load-carrying capacity and typically triggers intervention protocols (Catbas *et al.*,

Table 1. Key sensor types and applications

Sensor type	Measured parameter	Typical application	Advantages	Limitations
Strain gauge/Linear variable differential transformer	Strain, displacement	Pre-stressed concrete/reinforced concrete bridges, soffit monitoring	High accuracy, low cost	Requires wiring, susceptible to drift
Fiber Bragg grating/Fiber optic	Distributed strain, temperature	Long-span bridges, buried pipelines	Electromagnetic interference immunity, distributed sensing	Higher cost, installation complexity
Acoustic emission	Crack initiation, energy release	Concrete fatigue, heritage timber beams	Early damage detection	Complex data interpretation
Digital image correlation/ Vibration visual sensing	Full-field displacement, modal shapes	Fragile heritage structures, inaccessible zones	Non-contact, spatially rich	Sensitive to lighting, requires calibration
Environmental sensors	Temperature, relative humidity	Heritage masonry, lime plaster	Detects climate-induced deterioration	Provide only indirect structural data

2007). Non-invasive vibration-based methods are widely applied, especially for large-span bridges where direct access is limited. Modal parameters such as natural frequencies and mode shapes serve as proxies for stiffness change (Sakiyama *et al.*, 2023).

Similar approaches are applied to vernacular timber buildings, where portable sensors and VVS detect weakening in mortise-and-tenon or dovetail joints. Curvature-deviation methods (Limongelli, 2019) quantify stiffness loss through distributed measurements and have been successfully adapted to beams in Chinese palaces and South Indian temples. Where direct curvature measurement is impractical, machine learning models infer stiffness loss from displacement differentials—an approach gaining traction in heritage monitoring projects led by Indian National Institutes of Technology.

Table 2 presents a side-by-side comparison, clarifying how policy frameworks, climatic factors, and heritage-related constraints shape SHM and load-testing practices in China and India.

2.3. Time- and temperature-dependent factors: Bridging infrastructure and heritage concerns in China and India

Both concrete and timber structures exhibit time- and temperature-dependent deformation and durability patterns. In RC bridges, creep and shrinkage lead to long-term deflections that are often underestimated by predictive models. Ghali *et al.* (2000) and Elbadry *et al.* (2001) examined deflection in large-span concrete bridges using the ACI 209 and CEB-FIP MC90 models, emphasizing the need for field-based SHM data to calibrate predictive approaches. In India, long-span RC bridges such as the Munger Ganga Bridge and Howrah Flyover have also shown divergence from model-based predictions, necessitating SHM-supported recalibration.

Robertson (2005) improved deflection prediction in the North Halawa Valley Viaduct by integrating creep, shrinkage, and material degradation into a hybrid model validated with SHM data. Similarly, a study of the Koror–Babeldaob Bridge demonstrated that only the B3 model, when independently calibrated, could accurately predict early-stage deformation (Glisic, 2018). Such hybrid approaches are being piloted in India through the Central Road Research Institute (CRRI) for the monitoring of concrete box-girder viaducts.

Timber buildings in both China and India are equally sensitive to temperature and humidity cycles. In China, traditional structures with passive ventilation and exposed timber joints experience shrinkage and swelling that alter load paths. Indian buildings in tropical and monsoonal climates face similar issues. For example, the Sanchi Stupa wooden railings and the teakwood architecture of Maharashtra exhibit seasonal moisture-related deformation.

Therefore, SHM in heritage conservation requires temperature-compensated sensors and long-term data analytics to distinguish between seasonal movement and structural deterioration (Y. Q. Song & Liao, 2022). The application of these techniques to both RC bridge design and historic structure conservation enhances resilience under conditions of rapid climate change, urbanization, and cultural transformation across China and India.

2.4. Fatigue evaluation in contemporary bridges and vernacular structural systems in China and India

Fatigue behavior is a critical factor in ensuring long-term structural integrity, particularly in aging RC, PSC, and steel infrastructure exposed to repetitive loads and

Table 2. Comparative synthesis of SHM/load-testing practice in China and India

Dimension	China	India
Primary drivers	Intelligent infrastructure programs; seismic resilience; megaproject asset management	Serviceability of aging bridges; monsoon/climate stresses; heritage tourism safety
Typical assets	Expressway pre-stressed concrete/reinforced concrete bridges; urban flyovers; timber pagodas/arch bridges	National/State highways, rail overpasses; stepwells, temples, havelis
Sensor stacks (dominant)	Hybrid: DIC/total station+FBG/AE; WSN at corridor scale	Contact (linear variable differential transformer/strain) + selective optical (DIC/VVS/TS); emerging FBG/AE pilots
Load-testing practice	Programmatic diagnostic campaigns; staged proof tests with real-time stop criteria	Case-by-case diagnostic tests; scaled/simulated proof tests in heritage
Governance and standards	Centralized codes/specs; city/provincial funding streams	Multi-agency (MoRTH, ASI, state PWDs); mixed procurement and budgets
Heritage ethics	Visual/minimal-intrusion requirements; reversible mounting	ASI/INTACH protocols emphasize non-invasiveness & reversibility
Cost/logistics	Higher upfront cost, but corridor-level deployments reduce per-asset overhead	Budget-sensitive; preference for low-cost, low-intrusion tools and shorter closures
Data infrastructure	Integrated platforms; movement toward digital twins	Heterogeneous systems; increasing use of dashboards in Smart Cities
Adoption maturity	Advanced hybrid SHM at scale; strong municipal buy-in	Rapid pilots; growing academia–agency collaborations (IITs/CSIR)
Representative examples	Yangtze corridor bridges; Zhejiang/Fujian heritage	Ganga/Brahmaputra corridors; Gujarat/Rajasthan heritage

Abbreviations: AE: Acoustic emission; ASI: Archaeological Survey of India; CSIR: Council of Scientific and Industrial Research; DIC: Digital image correlation; FBG: Fiber Bragg grating; IIT: Indian Institute of Technology; INTACH: Indian National Trust for Art and Cultural Heritage; MoRTH: Ministry of Road Transport and Highways; PWD: Public Works Department; SHM: Structural health monitoring; TS: Total station; VVS: Vibration visual sensing; WSN: Wireless sensor network.

environmental stresses. Damage frequently initiates at welded joints or connections subjected to cyclic loading, leading to micro-cracks that propagate over time (Kwon & Frangopol, 2010). Modern SHM systems monitor strain and stress accumulation using high-sensitivity sensors, applying continuum damage mechanics models to simulate fatigue progression in critical areas (Sakano *et al*., 2006).

Initially developed for large-scale steel highway bridges in China and Japan (M. Liu *et al*., 2009), fatigue monitoring techniques are now extensively used in complex urban structures, such as Hong Kong's Tsing Ma Bridge. These systems analyze stress variations using rain-flow counting and probabilistic S–N curves to identify fatigue-prone zones (Chen *et al*., 2011; Ye *et al*., 2012). In India, fatigue assessments have been introduced in aging bridges across the Golden Quadrilateral and in metro infrastructure in cities such as Mumbai and Chennai, where high-cycle loading demands continuous health surveillance.

China's traditional architecture also exhibits fatigue-like deterioration. Timber beams and columns degrade gradually due to moisture fluctuations, biological agents, and wind-induced micro-movements accumulated over decades (Jiang *et al*., 2019). SHM systems now deploy low-strain sensors and high-resolution optical devices to monitor minute deformations and joint displacements, especially in pagodas, ancestral halls, and Qing-era (1644–1912) compounds. Comparable Indian structures, such as the gopuram towers of South Indian temples or the timber-framed Kath-Kuni buildings in Himachal Pradesh, exhibit similar long-term fatigue behavior linked to climatic exposure and seismic history.

Recently, probabilistic damage assessment using finite element modeling has been extended to evaluate fatigue in complex bridge geometries such as orthotropic steel decks (Farreras-Alcover *et al*., 2017). These modeling approaches are now also being tested for the adaptive reuse of historic buildings in both China and India, especially where reinforcement retrofits involve steel or composite additions to fragile timber or masonry systems.

2.5. Corrosion evaluation: From RC bridges to traditional architectural elements in China and India

Corrosion-induced deterioration of RC infrastructure remains one of the most critical degradation processes in embedded steel structures (tendons, cables, rebars). Conventional evaluation techniques, such as concrete resistivity testing, offer only early indications of electrochemical activity under different environmental exposures (Morris *et al*., 2002). For example, in coastal buildings or structures exposed to de-icing salts, the accelerated ingress of chlorides significantly increases the likelihood of corrosion, necessitating timely intervention.

Contemporary SHM systems deploy integrated sensor networks to monitor temperature, humidity, and electrical resistivity in real time, thereby improving early warning in inaccessible areas such as bridge towers, cable anchorages, and foundation piles (Betti *et al*., 2016). These systems are increasingly used in megaprojects, including the Sutong Yangtze River Bridge in China and the Signature Bridge in Delhi, India.

A major advancement is the implementation of hybrid sensor arrays that incorporate electrochemical impedance spectroscopy and linear polarization resistance with optical sensors enhanced by AI-driven pattern recognition algorithms (Frankowski *et al*., 2024). These enable accurate diagnosis of corrosion initiation and geometrical progression in both new and retrofitted structures.

Corrosion monitoring is also a growing concern in heritage preservation, especially where structural strengthening has been introduced to resist seismic or wind loading. Medieval Indian temples, colonial bungalows, and Mughal-era (1526–1857) monuments have sometimes incorporated hidden steel reinforcement to stabilize masonry domes or buttresses. As these elements age, non-intrusive corrosion monitoring has become a priority for conservation agencies such as the Indian National Trust for Art and Cultural Heritage (INTACH) and ASI.

In China, Jiang *et al*. (2019) demonstrated the use of FBG sensors to monitor corrosion and moisture in historic Chinese wooden structures. On the same note, in India, embedded sensors have been installed at sites such as the Konark Sun Temple and the Neemrana Fort to measure water ingress and steel oxidation during monsoonal cycles. Hidden SHM arrays are now integrated into conservation projects for Qing-era compounds in China and Rajput palaces in Rajasthan, where they monitor the corrosion of anchor plates, stainless steel pins, or tie rods embedded in retrofits (Rossi & Bournas, 2023).

Modern architecture inspired by vernacular architecture also incorporates new materials such as weathering steel, reinforced adobe, or fly ash concrete. These material systems, increasingly used in heritage-themed public buildings and resorts in both countries, require SHM-enabled corrosion protection to balance aesthetics, sustainability, and performance. In this evolving context, SHM emerges not only as a safeguard for structural safety but also as a means of ensuring cultural continuity and material authenticity.

2.6. Scour monitoring and its relevance to infrastructure and cultural sites in China and India

Scour refers to the erosion or removal of sediment and soil around bridge foundations and structural supports by flowing water and is a leading contributor to sudden infrastructure failure. Globally, scour accounts for over 60 percent of bridge collapses in flood-prone regions, including the United States. In China, it poses a critical risk in densely connected transport corridors intersecting major rivers such as the Yangtze and Yellow Rivers. In India, scour is a persistent hazard in monsoon-sensitive regions along rivers, including the Ganga, Brahmaputra, and Godavari, where high sediment loads and variable discharge patterns threaten both modern and historic infrastructure.

Contemporary SHM technologies address scour using a suite of instrumentation, including tilt sensors, sounding rods, magnetic sliding collars, sonar-based reflectometry, and fiber-optic probes. These tools enable real-time monitoring of riverbed depth, soil displacement, and foundation exposure at bridge piers and abutments (Walker & Hughes, 2005). Both China and India have integrated these sensors into automated SHM systems, providing early detection and supporting hazard mitigation strategies.

Automated scour monitoring using global positioning system (GPS)-based data transmission is now employed along tributaries of the Yangtze and Yellow Rivers in China. In India, agencies such as the Central Water and Power Research Station in Pune and IIT Madras are testing GPS- and global system for mobile communication-enabled scour detection in flood-prone areas such as Bihar and Assam. These initiatives are increasingly supported by numerical modeling and hydrodynamic simulations to design effective countermeasures.

Halding *et al*. (2017) proved that scour-related damage can be reliably interpreted through shifts in horizontal mode shapes identified by distributed sensors and validated by finite element models. This confirms the applicability of SHM in proactive maintenance planning, particularly in contexts characterized by complex and dynamic soil–fluid–structure interactions.

Scour also threatens historic structures near rivers, including arch bridges, retaining walls, embankments, and waterfront pavilions. In China, numerous Ming (1368–1644)- and Qing-dynasty arch bridges with shallow foundations and porous stone construction have suffered flood-induced undermining. In India, cultural assets such as the 16th-century Shahi Bridge in Jaunpur and the Kallanai Dam in Tamil Nadu—the latter among the world's oldest water-regulation structures—face similar threats from changing hydrology and sediment transport.

Pilot SHM projects are underway at riverside heritage sites in both countries. In China, manual tilt sensors and automated water-level gauges have been discreetly installed in heritage bridges of Anhui and Zhejiang provinces to track stability without altering architectural integrity (Wu *et al*., 2025). In India, comparable techniques are being applied along the Yamuna and Sabarmati rivers in collaboration with the ASI to monitor substructure movements during high-flow seasons.

Integrating scour detection into broader SHM frameworks ensures dual protection for large-scale transportation infrastructure and riverine cultural heritage. In the face of climate change, rapid urbanization, and upstream land-use pressures, such monitoring is indispensable for structural resilience, public safety, and the conservation of architectural history. Comparative evidence further shows that choices of sensor stacks and load-testing protocols are not solely technical; they reflect heritage-conservation ethics, budgetary and traffic constraints, and policy frameworks. Integrating SHM within conservation principles (such as reversibility and minimal intervention) and the maintenance frameworks of transport agencies results in distinct yet mutually supportive approaches in both China and India. Recognizing these interactions is essential for developing hybrid, non-contact monitoring solutions in culturally sensitive or logistically constrained environments.

3. Evolution and analysis: Bridging diagnostic approaches in modern and vernacular architectural systems in China and India

Structural evaluation methods, especially load testing and sensor-based health monitoring, have significantly enhanced the knowledge of both PSC and RC girder bridges' behavior. Research has always demonstrated the importance of proper load assessment for validating design assumptions, predicting performance under fatigue, and enabling timely preventive action (Hemalatha *et al*., 2021). Such methods form the foundation of management strategies for long-span bridges and high-traffic expressways in both China and India.

Instrumentation strategies have also evolved considerably. Earlier applications relied on relatively simple tools, such as fixed linear variable differential transformers (LVDTs) and strain gauges, to measure stress concentration and deflection. Recent advances, such as wireless sensor networks, fiber-optic sensors, and non-contact DIC, now enable real-time visualization of deformation under different loading scenarios. These developments have not only improved infrastructure surveillance but also contributed to the retrofitting and preservation of vernacular heritage buildings such as temple gateways, wooden beam halls, and historic stone bridges in both countries (Jiang *et al*., 2019; Rossi & Bournas, 2023).

In China, sensor systems have been adapted for use in rural villages and urban renewal projects, particularly in structures dating from the Qing dynasty and earlier (Y. Q. Song & Liao, 2022). In India, similar adaptations are evident in the conservation of medieval stone temples, Indo-Islamic mausoleums, and colonial-era public buildings, particularly in seismic-prone states such as Gujarat and Himachal Pradesh. Wireless vibration sensors, thermal cameras, and AI-enhanced deformation models are increasingly integrated into conservation programs supported by the ASI and state-level heritage agencies.

This convergence of civil engineering practice and cultural preservation highlights SHM systems as vital tools not only for functional monitoring but also for safeguarding intangible architectural heritage in China and India.

3.1. Diagnostic load tests: Infrastructure and heritage applications

Diagnostic load testing is a non-destructive method for evaluating structural performance under controlled conditions. Static tests apply gradual loads, pseudo-static tests simulate quasi-seismic actions, and dynamic tests replicate operational stresses. These techniques reveal stiffness, joint behavior, and load distribution, supporting both design validation and maintenance planning.

In China, diagnostic load tests are widely used to assess the seismic resilience of bridges in earthquake-prone regions and to monitor fatigue in urban flyovers (Olaszek *et al*., 2014). In India, diagnostic campaigns focus on Himalayan bridges, coastal viaducts, and aging urban flyovers, where controlled truck or jack loading has guided reinforcement strategies under increasing traffic and temperature extremes.

Heritage applications require minimally invasive approaches. Portable DIC systems, lightweight load rigs, and wireless nodes allow the monitoring of fragile stone arch bridges, stepwells, temples, and mosques without damaging original surfaces. These tests establish benchmarks for safe tourist access and adaptive reuse within cultural corridors.

Historically, strain gauges and LVDTs have been the primary diagnostic tools for tracking neutral-axis shift and crack initiation (Al-Mahaidi *et al*., 2000; S. Taylor *et al*., 2007). Today, hybrid systems integrate optical crack-width measurement, AE, and VVS to improve spatial coverage and reduce blind spots. Table 3 summarizes the principal diagnostic testing methods, instruments, and typical applications across China and India.

A critical perspective is warranted: while diagnostic testing is invaluable, its high implementation cost and traffic-disruption constraints often limit its frequency. Data interpretation also remains highly sensitive to temperature effects, requiring improved environmental compensation and automated analytics. Broader adoption will depend on reducing setup time and integrating AI-based real-time anomaly detection. Table 4 contrasts diagnostic and proof load testing, providing guidance for practitioners in choosing the appropriate methodology.

3.2. Proof load tests: Structural capacity verification

Proof load testing verifies that a structure can sustain factored live loads without permanent damage (Table 5). Unlike diagnostic tests, proof tests intentionally approach the service limit, making them crucial for undocumented or modified structures (Hernandez & Myers, 2018). Typical protocols employ loaded trucks or hydraulic jacks, with strain, displacement, and vibration recorded throughout. Dynamic proof loading further characterizes damping and resonance behavior (de Vries *et al.*, 2025).

In India, proof loading has been employed for major bridges such as the Mahatma Gandhi Setu and the Pamban Bridge, where multi-sensor SHM frameworks measured displacement, strain, and resonance during staged loading. China applies similar staged testing to Yangtze

Table 3. Overview of diagnostic load tests

Studies	Testing campaign	Application	Loading method	Instruments used and measurements
P. Taylor *et al.*, 2016	Reinforced concrete (RC) slab bridges in poor condition	Enhance rating criteria	Dump truck	(A) deck deflection profiles; (B) strains at the top and bottom of the bridge surface
Al-Mahaidi *et al.*, 2000	RC T-beam bridge	Transverse flexural distribution	Hydraulic jacks	Beam deflections (A); applied load (J); strains (E); and superstructure, abutment, and pier rotations (G)
P. Taylor *et al.*, 2016	Composite concrete block on steel girder bridge	Transverse load distribution of a lightweight concrete bridge	Truck	Strain (E) on deck and girders
Abedin *et al.*, 2022	Precast concrete bridge	Finite element model calibration for damage detection	Dump truck	Deflections (A, I)
Abedin *et al.*, 2022; Aguilar *et al.*, 2015; Colombani & Andrawes, 2022	Crooked RC slab bridge	Load evaluation	Dump truck	Strain (E) on the slab
Lienhart *et al.*, 2017	RC T-beam bridge	Verification of the fiber-reinforced polymer strengthening system	Dump trucks	Deflections (A, I)
Gou *et al.*, 2022	Cast-in-place concrete deck bridge with varied concrete mixes	Transverse distribution in a self-consolidating concrete bridge	Dump truck	Vertical girder deflections (I); embedded strain sensors with thermistors (F); dynamic reactions (D)
Aguilar *et al.*, 2015	Skewed RC slab bridge	Evaluation of stiffness	Hydraulic jacks	Applied load (J); abutment and pier deflections and slab rotations (A); concrete strains (A); steel strains (E)
Kaspar *et al.*, 2020	Pre-stressed concrete skew bridge	Flexural distribution in the transverse direction	Trucks	Strains (A, C); shrinkage and temperature effects; girder and bearing displacement (I)
Aguilar *et al.*, 2015	Composite Concrete slab on steel girder bridge	Distribution of transverse flexion	Dump truck	Strain (E) during construction; rotations at piers and abutments (G); temperature (H); dynamic reactions (D)
Jeon *et al.*, 2024; Lantsoght *et al.*, 2017	RC slab bridge	Distribution of transverse flexion	Truck	Strain (E) at the underside of the slab

Note: Column codes are defined as follows: A: Vertical deflection; B: Deflection; C: Crack formation; D: Applied load level; E: Strain; F: Deformation; G: Pier rotation; H: Support fixation; I: Crack monitoring/width; J: Applied load level. These parameters follow standard structural health monitoring notation and are reported consistently across the reviewed studies.

River Expressway bridges, halting loading when unsafe deformations appear.

Heritage structures require scaled or distributed proof loads to avoid damage. Lightweight rigs with real-time DIC monitoring are now deployed in Chinese temple halls and Indian stepwells to confirm safe visitor capacity. Adaptive reuse projects (e.g., Meenakshi Temple precinct retrofits) increasingly employ non-contact proof simulations to validate load-bearing capacity before public reopening.

Table 4. Diagnostic versus proof load testing

Aspect	Diagnostic load test	Proof load test
Purpose	Identify stiffness loss, anomalies under service loads	Verify capacity under factored overload
Load level	≤service load state	Close to ultimate limit (below failure)
Risk	Very low	Moderate (requires stop criteria)
Typical sensors	Strain gauge, LVDT, AE, DIC	LVDT, strain gauge, DIC, AE, LiDAR
Heritage application	Minimal invasive monitoring	Scaled/simulated proof loads only
Cost & logistics	Lower, repeatable	Higher; traffic disruption possible

Abbreviations: AE: Acoustic emission; DIC: Digital image correlation; LiDAR: Light detection and ranging; LVDT: Linear variable differential transformer.

Case highlights include a 68-year-old RC T-beam bridge tested with dual-axle trucks that retained residual strength despite fatigue (Mirdad & Andrawes, 2023). IIT Roorkee and IIT Madras have replicated European proof-load protocols with sub-millimeter DIC accuracy for smart bridge retrofitting. CSIR-CRRI laboratories in Delhi combine AE and LiDAR for metro viaduct tests, providing forensic insight into crack progression.

A critical perspective reveals that proof load tests remain expensive and logistically complex, especially in traffic-heavy corridors. Their application in heritage settings is limited by reversibility concerns, as even controlled overloading can accelerate fatigue in brittle materials. Emerging solutions include hybrid digital twins and simulation-validated virtual proof loading, which may eventually reduce reliance on full-scale field campaigns.

4. Conventional measuring techniques in SHM: Applications in infrastructure and vernacular architecture

4.1. Linear variable differential transformers: High-precision monitoring in infrastructure and timber structures

Linear variable differential transformers are precision electromechanical sensors that convert linear displacement into proportional electrical signals. Operating through the interaction between a ferromagnetic core and surrounding

Table 5. Overview of proof load tests

Studies	Testing campaign	Application	Loading method	Instruments used and measurements
Lantsoght *et al.*, 2017	Four RC bridges	Uncertainties due to inadequate grading and alkali–silica reaction damage	BELFA vehicle with load spreaders, counterweights, and hydraulic jacks	(A) strain, crack width, and deflections; (B) deflection; (C) crack formation; (D) applied load
Lantsoght, 2024	Two pre-stressed concrete (PSC) bridges	Insufficiently rated	Cars with concrete loads	(A) deflection and strain; (K) dynamic responses
de Vries *et al.*, 2025	RC T-beam bridge (68 years old)	Significant uncertainty	Vehicle with dual axles	(A, G) deflections; (I) crack monitoring
Anay *et al.*, 2016	Single-span PSC bridge with double T beams	Lack of structural plans	Dump trucks	(C) crack detection; (M) strains at beam soffits
Fayed *et al.*, 2022	Four collapsed PSC T-beam bridges	Development of a testing method	Test rig with weights and hydraulic jacks	(A, H, B) deflections and support fixation; (D) applied load, (F) deformation and crack initiation; (E) strains; (L) virtual reality-based environment reproduction and point cloud measurement
Anay *et al.*, 2016	Skewed RC slab bridge	Updated load rating	Dump truck	(M) strains; (A, O) deflections

Note: Column codes are defined as follows: A: Vertical deflection; B: Deflection; C: Crack formation; D: Applied load level; E: Strain; F: Deformation; G: Pier rotation; H: Support fixation; I: Crack monitoring/width; K: Natural frequency shift; L: Virtual reality/point cloud measurement; M: Modal damping; O: Additional displacement response. These parameters follow standard structural health monitoring notation and are reported consistently across the reviewed studies.

 https://doi.org/10.36922/JCAU025310061

coils, they provide high-resolution feedback on structural movement with remarkable stability and repeatability. The induced differential voltage corresponds linearly to core displacement, making LVDTs ideal for long-term monitoring where sub-millimeter precision (typically within ±0.5% of the full-scale range) is required.

Linear variable differential transformers are widely used in proof load and diagnostic testing in modern infrastructure, especially in PSC and RC bridges, where they measure vertical deflection, foundation settlement, and crack propagation. Their effectiveness has been demonstrated in field deployments on the Yangtze River Bridge System in China and the Golden Quadrilateral Expressway in India. LVDTs are typically mounted on a deck slab or a girder utilizing bolted or glued brackets and can be oriented either axially or transversely to expected strain directions.

Linear variable differential transformers have also been used in heritage timber architecture, including Ming-era temples in Fujian, China, and Kakatiya temples in Telangana, India, to measure roof truss deflection, beam sagging, and column tilting in conservation applications. They are especially useful for tracking degradation from seasonal humidity changes, biological factors, or differential settlement, due to their precision in detecting minor displacements over extended periods. This non-destructive diagnostic approach aligns closely with cultural preservation standards.

In low-stakes scenarios or where cost constraints exist, cable-extension potentiometric transducers (also known as string pots) offer an alternative. These devices measure displacement by translating the movement of a tensioned cable into voltage. Although less accurate and more vulnerable to environmental interference, they remain useful in non-critical heritage monitoring, such as façade tilt, courtyard lintel settlement, and parapet tracking. They are especially relevant in adaptive reuse projects in historical towns such as Pushkar (India) and villages in Anhui (China), where low-tech, low-cost, and portable monitoring options are preferred (Pan *et al*., 2007).

4.2. Laser distance sensors: Non-contact versatility for heritage and urban systems

Laser distance sensors operate on the principle of triangulation: a laser beam is directed at a surface, and the reflected signal is captured by a position-sensitive device, a CMOS sensor, or a CCD array. The angle and time delay of the returning beam are then processed by the system to calculate displacement with millimeter accuracy over distances ranging from a few millimeters to several meters. These sensors are typically calibrated against reference targets and must be stably mounted and shielded from environmental effects to ensure precise measurements.

The non-contact nature of laser displacement sensors has made them increasingly popular in contemporary civil engineering as well as in the preservation of historic sites, where accurate monitoring is possible without direct contact with sensitive or inaccessible surfaces. In modern bridge engineering, they have been applied in projects such as the Beipanjiang bridge (China) and Atal Setu bridge (India) to monitor mid-span deflection, expansion joint movement, live load testing, and seismic simulation.

The use of laser sensors in vernacular heritage systems is equally transformative. They have been incorporated in conservation strategies for stone pagodas, cantilevered timber roofs, and mural-bearing load-sensitive walls in cities such as Suzhou (China), Xi'an (China), and Mysuru (India). Restoration teams in Nanjing, China, and Lucknow, India, have employed laser triangulation to measure eave curvature, plinth subsidence, and timber column tilting, thereby maintaining both structural stability and cultural authenticity.

Despite their advantages, laser sensors also present certain drawbacks. They are sensitive to dust, surface irregularities, and moisture, which can distort reflected signals and reduce accuracy. To address this issue, sensors should be shielded with protective enclosures, properly sealed, and routinely recalibrated, especially for outdoor settings such as riverfront ghats, elevated viaducts, and exposed temple platforms. Real-time digital interfaces now enable continuous monitoring, remote operation, and integration with building information models, making laser sensors a fundamental technology for AI-enhanced smart infrastructure systems.

In both India and China, these tools are being adopted through state-sponsored initiatives such as the Smart Heritage Cities Program (India) and Intelligent Bridge Maintenance Plans (China), reflecting a policy-level convergence of technological modernization and cultural preservation. Their role in enabling precision SHM, while respecting the constraints of historical materiality, makes them indispensable in a future where infrastructure and cultural identity must co-exist sustainably.

Among the most important benefits of laser distance sensors is their non-contact nature, which allows convenient deployment in both civil infrastructure and cultural heritage contexts where direct surface contact is not feasible or permitted. In bridge engineering, for example, laser sensors are commonly mounted on deck soffits, girders, or parapets with rigid brackets (as shown in Figure 3), allowing real-time surveillance of mid-span deflections during proof or diagnostic load tests.

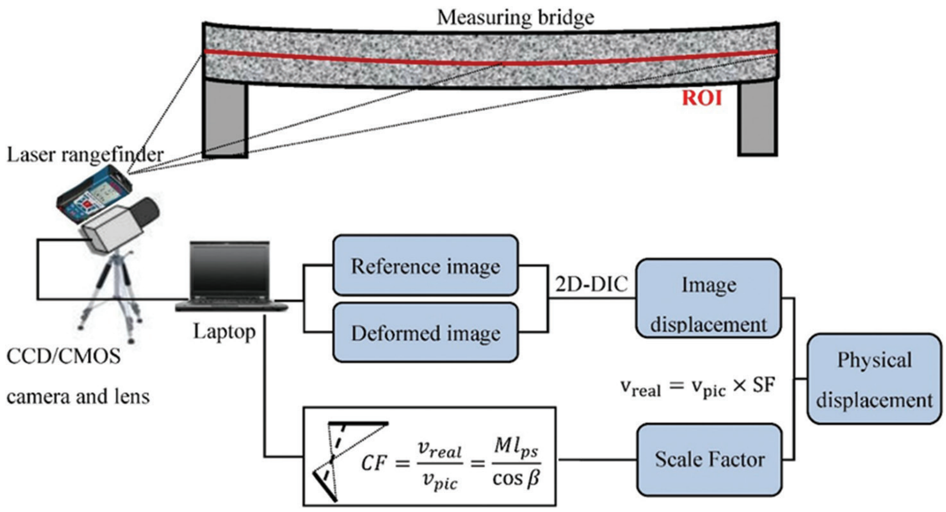

Figure 3. Typical field configuration for proof and diagnostic load testing
Source: Schematic by the authors.
Abbreviations: 2D-DIC: Two-dimensional digital image correlation; CF: Calibration factor; Mlps: Magnification of the lens/pixel system; ROI: Region of interest; SF: Scale factor; V: Velocity.

As shown in Figure 3, trucks or hydraulic jacks are positioned for loading, mid-span LVDTs and strain gauges are used for deflection and strain measurement, and auxiliary optical sensors (DIC/laser) are employed for non-contact displacement capture. Real-time monitoring allows the test to be halted when unsafe deformation thresholds are approached, ensuring structural safety during evaluation.

5. Recent developments in non-contact monitoring technologies

5.1. Digital image correlation: High-resolution field monitoring

Digital image correlation is a non-contact optical method that tracks pixel movement across images to generate full-field displacement and strain maps. Using a random speckle pattern with either stereo or single-camera setups, DIC achieves high spatial resolution without physical sensors. Initially confined to laboratory settings, it is now field-deployable for PSC bridge decks, urban flyovers, and heritage sites, enabling early crack detection and fatigue assessment (Campana *et al*., 2013; Cavagnis *et al*., 2018). On-site challenges, including calibration, illumination control, and environmental effects, can be minimized through the use of high-definition imaging, consistent lighting conditions, and durable weather-resistant enclosures. Pilot projects in Chettinad mansions (India) and Zhejiang pagodas (China) demonstrate their effectiveness for non-invasive heritage monitoring.

5.2. Virtual visual sensors: Low-cost vibration analytics

Virtual visual sensors apply computer vision to extract mode shapes and resonance frequencies from standard video footage, eliminating the need for physical sensors. Validated in metro viaducts (China) and colonial bridges (India), VVS is particularly suited for inaccessible façades and long-span structures (Y. Z. Song *et al*., 2014; Zarate *et al*., 2022).

Its affordability and scalability make it attractive for heritage applications, although success depends on proper camera setup and environmental compensation (Nonis *et al*., 2013). VVS is increasingly used to complement SHM models for damage localization and fatigue threshold estimation.

5.3. Integrated smart monitoring and remote sensing

Modern SHM systems increasingly integrate traditional sensors, AI, and remote sensing for real-time, predictive diagnostics. Machine learning models enhance vibration-based monitoring by interpreting frequency shifts and damping changes, thereby enabling precise damage localization (Fritzen, 2005). Wireless sensor networks now span entire bridges and heritage clusters, streaming strain, tilt, and climate data for immediate alerts. Remote sensing techniques add macro-scale insight: ground-penetrating radar detects deck voids, infrared thermography identifies hidden moisture, and InSAR tracks ground settlement.

These hybrid systems form a core component of China's intelligent bridge programs and India's SMART Cities initiatives, ensuring minimally intrusive monitoring for both infrastructure and culturally significant structures.

6. Critical insights, controversies, and research gaps

The literature review confirms that traditional load testing methodologies, which predominantly rely on contact-based sensors, are increasingly inadequate for modern needs. While functional, these legacy methods are often labor-intensive, time-consuming, and spatially constrained. With the rising complexity of urban infrastructure systems and growing interest in the adaptive reuse of culturally significant structures, particularly in flood-prone and seismic-sensitive regions of China and India, there is a compelling need to embrace advanced, distributed, and non-contact sensing technologies. These innovations enable not only faster deployment and higher accuracy but also enhanced spatial resolution and reduced risk of material intrusion. An effective sensor deployment plan should be simple, physically non-intrusive, and provide the highest diagnostic payoff. Modern methods emphasize spatially distributed and full-field techniques that deliver more comprehensive data with fewer instruments, as opposed to dense sensor arrays. DIC, AE, and fiber optic sensors (FOS) have become the leading technologies in both proof load and diagnostic testing.

Digital image correlation is a non-contact optical technique that enables full-field measurement of surface strain and displacement. It is especially useful in detecting stress concentrations and early signs of failure. DIC has been successfully applied in the tension testing of advanced composites and RC, as well as in full-scale bridge testing, such as on the Eastern Railways Network of India and coastal highway bridges in China. Challenges with specimen edges are mitigated through high-resolution imaging, careful calibration, and well-controlled lighting systems.

Acoustic emission monitoring captures transient elastic waves generated by internal energy releases, such as crack initiation and propagation. In both Indian arch bridges from the colonial period and Ming-era stone bridges, AE has been effectively applied for real-time damage localization. AE systems are highly sensitive to internal material degradation and can provide early warnings, especially in proof load scenarios where surface-based monitoring may fail to reveal hidden defects.

Fiber optic sensors, including FBGs and distributed systems, enable high-resolution measurement of strain, temperature, and acoustics over extended structural spans. Their robustness under electromagnetic interference, long-term durability in harsh environments, and measurement precision make them particular suitable for India's coastal heritage structures in Goa and Pondicherry, as well as for China's historic timber buildings. FOS often outperforms traditional strain gauges in both signal quality and durability, and is increasingly used in infrastructure projects under the Smart Cities Mission (India) and Belt and Road Initiative (China). The integration of AE and FOS within a combined framework offers real-time insight into both external strain behavior and internal fracture development. This dual-mode monitoring, tested in projects such as the Chenab bridge (India) and Jiaxing Grand bridge (China), allows for improved crack width quantification, stress evolution analysis, and displacement mapping under live loading. Such hybrid systems are particularly valuable for bridges and heritage sites where access is limited or invasive instrumentation is prohibited.

Although high-end systems such as FOS may initially appear more costly, they deliver substantial returns through reduced installation time, improved data fidelity, and long-term stability. When the full scope of a load testing program—including planning, instrumentation, monitoring, and analysis—is considered, hardware cost becomes a relatively minor component. Across both urban infrastructure upgrades and heritage retrofitting in India, these modern SHM systems have demonstrated significant cost-effectiveness and long-term performance benefits.

Despite growing adoption, the cost-effectiveness and scalability of SHM and load-testing technologies remain contested. Several studies indicate that hybrid SHM systems (e.g., combining DIC, AE, and fiber optics) improve damage detection but significantly increase capital and maintenance costs, limiting their uptake in smaller municipalities. In India, budget-constrained agencies often rely on periodic visual inspections, despite their lower reliability, highlighting the need for cost-sharing models or government subsidies.

Controversy also surrounds proof load testing in heritage settings. Conservationists argue that even lightweight proof loading can accelerate deterioration in brittle stone or timber elements, while engineers emphasize its importance for ensuring visitor safety. This tension underscores the need for consensus guidelines that balance non-invasiveness with safety assurance.

Another research gap lies in data fusion and interoperability. SHM data are frequently siloed across agencies and vendors, hindering integrated lifecycle analytics. Open-data frameworks and AI-assisted decision tools could help address this challenge, though they raise additional concerns about cybersecurity and intellectual property.

Future research priorities include: (i) the development of low-cost, low-power sensors for rural and heritage sites; (ii) standardized environmental compensation algorithms to minimize false alarms; (iii) digital twins enabling virtual proof loading before field campaigns; (iv) lifecycle cost–benefit models to justify SHM investments relative to traditional inspection cycles. Advancing these areas will help move SHM from pilot-scale projects to mainstream asset management practice while respecting cultural heritage values.

7. Conclusion

Load testing remains a cornerstone of SHM and the extension of service life for both bridges and heritage assets. Diagnostic and proof load tests validate structural integrity, confirm safety margins, and guide targeted rehabilitation. Monitoring critical parameters, such as strain, deflection, vibration, and crack width, under controlled loading enables accurate assessment of both elastic and non-linear behavior. This article synthesizes published evidence; claims about performance gains are based on literature-reported results rather than new experimental validation by the authors. The shift from dense contact sensor arrays to hybrid, distributed, and non-contact approaches has transformed the field. DIC, LiDAR, and InSAR provide full-field, high-resolution data even in inaccessible zones, while FOS, AE, and Smart Aggregates deliver real-time insight into internal damage mechanisms. These tools are particularly important in contexts where invasive methods are prohibited, such as UNESCO heritage sites, and are increasingly integrated into intelligent infrastructure programs in China and India.

Future work should prioritize the development of scalable and cost-effective SHM systems that minimize disruption while maximizing diagnostic value. Key directions include low-power, low-cost sensor networks for rural and heritage applications; integration of AI-driven digital twins for virtual proof loading; and robust environmental compensation algorithms to reduce false alarms. As climate variability and urban growth intensify structural demands, the adoption of adaptive, predictive SHM strategies will be central to maintaining safety, functionality, and cultural continuity across diverse structural typologies.

Acknowledgments

The authors gratefully acknowledge Dr. Rajesh Kumar and Dr. V. Kumar from the Indian Institute of Technology (IIT) BHU, Varanasi, India, for their valuable guidance and technical insights.

Funding

None.

Conflict of interest

The authors declare that they have no competing interests.

Author contributions

Conceptualization: Palve Ankush, Gogate Nivedita, Chandak Narayan, Dod Ramesh
Visualization: Palve Ankush, Gogate Nivedita, Dod Ramesh
Writing–original draft: Palve Ankush
Writing–review & editing: Chandak Narayan

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Availability of data

Not applicable.

References

Abdulkarem, M., Samsudin, K., Rokhani, F. Z., & A Rasid, M. F. (2020). Wireless sensor network for structural health monitoring: A contemporary review of technologies, challenges, and future direction. *Structural Health Monitoring*, *19*(3):693-735.

https://doi.org/10.1177/1475921719854528

Abedin, M., y Basalo, F. J. D. C., Kiani, N., Mehrabi, A. B., & Nanni, A. (2022). Bridge load testing and damage evaluation using model updating method. *Engineering Structures*, *252*:113648.

https://doi.org/10.1016/j.engstruct.2021.113648

Aguilar, C. V., Jáuregui, D. V., Newtson, C. M., Weldon, B. D., & Cortez, T. M. (2015). Load rating a prestressed concrete double T-beam bridge without plans by field testing. *Transportation Research Record*, *2522*(1):90-99.

https://doi.org/10.3141/2522-09

Alipour, M., Washlesky, S. J., & Harris, D. K. (2019). Field deployment and laboratory evaluation of 2D digital image correlation for deflection sensing in complex environments. *Journal of Bridge Engineering*, *24*(4):04019010.

https://doi.org/10.1061/(ASCE)BE.1943-5592.0001363

Al-Mahaidi, R., Taplin, G., & Giuffre, A. (2000). Load distribution and shear strength evaluation of an old concrete T-beam bridge. *Transportation Research Record*, *1696*(1):52-62.

Anay, R., Cortez, T. M., Jáuregui, D. V., ElBatanouny, M. K., &

Ziehl, P. (2016). On-site acoustic-emission monitoring for assessment of a prestressed concrete double-tee-beam bridge without plans. *Journal of Performance of Constructed Facilities*, *30*(4):04015062.

https://doi.org/10.1061/(ASCE)CF.1943-5509.0000810

Bell, D. A. (2010). China's new Confucianism: Politics and Everyday life in a Changing Society. Princeton: Princeton University Press.

Bertagnoli, G., Antognelli, C., Ciccone, E., & Ferrara, M. (2023). Structural health monitoring of a prestressed concrete girder bridge deck using clinometers. In: *AIP Conference Proceedings*. Vol. 2928, No. 1. Melville, NY: AIP Publishing.

Betti, R., Sloane, M. J. D., Khazem, D., & Gatti, C. (2016). Monitoring the structural health of the main cables of suspension bridges. *Journal of Civil Structural Health Monitoring*, *6*:355-363.

https://doi.org/10.1007/s13349-016-0165-8

Cai, Y. (2011). *Chinese Architecture*. Vol. 30. Cambridge: Cambridge University Press.

Caicedo, D., Lara-Valencia, L. A., & Brito, J. (2021). Frequency-based methods for the detection of damage in structures: A chronological review. *Dyna*, *88*(218):203-211.

https://doi.org/10.7440/res64.2018.03

Campana, S., Fernández Ruiz, M., Anastasi, A., & Muttoni, A. (2013). Analysis of shear-transfer actions on one-way RC members based on measured cracking pattern and failure kinematics. *Magazine of Concrete Research*, *65*(6):386-404.

https://doi.org/10.1680/macr.12.00142

Catbas, F. N., Gul, M., & Burkett, J. L. (2007). Damage assessment using flexibility and flexibility-based curvature for structural healthmonitoring. *Smart Materials and Structures*, *17*(1):015024.

https://doi.org/10.1088/0964-1726/17/01/015024

Cavagnis, F., Fernández Ruiz, M., & Muttoni, A. (2018). An analysis of the shear-transfer actions in reinforced concrete members without transverse reinforcement based on refined experimental measurements. *Structural Concrete*, *19*(1):49-64.

https://doi.org/10.1002/suco.201700145

Chen, Z. W., Xu, Y. L., Xia, Y., Li, Q., & Wong, K. Y. (2011). Fatigue analysis of long-span suspension bridges under multiple loading: Case study. *Engineering Structures*, *33*(12): 3246-3256.

https://doi.org/10.1016/j.engstruct.2011.08.027

Colombani, I. A., & Andrawes, B. (2022). Comparison of load rating of reinforced concrete slab bridge using analytical and field-testing approaches. *Innovative Infrastructure Solutions*, *7*(1):79.

https://doi.org/10.1007/s41062-021-00677-9

Comisu, C. C., Taranu, N., Boaca, G., & Scutaru, M. C. (2017). Structural health monitoring system of bridges. *Procedia Engineering*, *199*:2054-2059.

https://doi.org/10.1016/j.proeng.2017.09.472

De Vries, R., Lantsoght, E. O. L., Steenbergen, R. D. J. M., Hendriks, M. A., & Naaktgeboren, M. (2025). Structural reliability updating on the basis of proof load testing and monitoring data. *Engineering Structures*, *330*:119863.

https://doi.org/10.1016/j.engstruct.2025.119863

Duvnjak, I., Damjanović, D., Bartolac, M., & Skender, A. (2021). Mode shape-based damage detection method (MSDI): Experimental validation. *Applied Sciences*, *11*(10):4589.

https://doi.org/10.3390/app11104589

Elbadry, M., Ghali, A., & Megally, S. (2001). Deflection prediction for concrete bridges: Analysis and field measurements on a long-span bridge. *Structural Concrete*, *2*(1):1-14.

https://doi.org/10.1680/stco.2.1.1.40860

Elsaid, A. H. & Seracino, R. (2012). Vibration-based damage detection of scour in coastal bridges. *Journal of Homeland Security Affairs*, 4(2):1-7.

Esherick, J. W. (ed.). (2000). *Remaking the Chinese City: Modernity and National Identity, 1900-1950*. Honolulu: University of Hawaii Press.

Farreras-Alcover, I., Chryssanthopoulos, M. K., & Andersen, J. E. (2017). Data-based models for fatigue reliability of orthotropic steel bridge decks based on temperature, traffic, and strain monitoring. *International Journal of Fatigue*, *95*:104-119.

https://doi.org/10.1016/j.ijfatigue.2016.09.019

Fayed, S., Mansour, W., & Farhan, M. H. (2022). Using surveying instruments in monitoring 3D deformations of an RC structure subjected to differential settlement of its footings. *Arabian Journal for Science and Engineering*, *47*(4), 5315-5336.

https://doi.org/10.1007/s13369-021-06316-w

Frankowski, P. K., Majzner, P., Mąka, M., Stawicki, T., & Chady, T. (2024). Magnetic non-destructive evaluation of reinforced concrete structures: Methodology, system, and identification results. *Applied Sciences*, *14*(24):11695.

https://doi.org/10.3390/app142411695

Fritzen, C. P. (2005). Vibration-based structural health monitoring-concepts and applications. *Key Engineering Materials*, *293*:3-20.

Ghali, A., Elbadry, M., & Megally, S. (2000). Two-year deflections of the confederation bridge. *Canadian Journal of Civil Engineering*, *27*(6):1139-1149.

https://doi.org/10.1139/l00-050

Glisic B., Inaudi D., Vurpillot S., Kronenberg P., Loret S. (1999).

Long-term monitoring of a concrete bridge with 100+ fiber optic long-gauge sensors, Non-destructive Evaluation of Bridges and Highways III, *SPIE*, 3587:50-59.

https://doi.org/10.1117/12.339934

Gou, H., Zhao, T., Qin, S., Zheng, X., Pipinato, A., & Bao, Y. (2022). *In-situ* testing and model updating of a long-span cable-stayed railway bridge with hybrid girders subjected to a running train. *Engineering Structures*, *253*(113823):113823.

https://doi.org/10.1016/j.engstruct.2021.113823

Halding, P. S., Schmidt, J. W., Jensen, T. W., & Henriksen, A. (2017). Structural response of full-scale concrete bridges subjected to high load magnitudes. In: *The 4th Conference on Smart Monitoring, Assessment and Rehabilitation of Civil Structures*.

Hemalatha, K., James, C., Natrayan, L., & Swamynadh, V. (2021). Analysis of RCC T-beam and prestressed concrete box girder bridges superstructure under different span conditions. *Materials Today: Proceedings*, *37*:1507-1516.

Hernandez, E. S., & Myers, J. J. (2018). Strength evaluation of prestressed concrete bridges by dynamic load testing. In: *The Ninth International Conference on Bridge Maintenance, Safety and Management (IABMAS 2018)*. Melbourne, Australia: CRC Press.

Jeon, C. H., Kwon, T. H., Kim, J., Jung, K. S., & Park, K. T. (2024). Quantitative evaluation of reinforced concrete slab bridges using a novel health index and LSTM-based deterioration models. *Applied Sciences*, *14*(22):10530.

https://doi.org/10.3390/app142210530

Jia, J., Zhang, L., Ou, J., & Chen, X. (2023). Nondestructive testing and health monitoring techniques for structural effective prestress. *Structural Control and Health Monitoring*, *2023*(1):8940008.

https://doi.org/10.1155/2023/8940008

Jiang, S. F., Qiao, Z. H., Li, N. L., Luo, J. B., Shen, S., Wu, M. H., *et al*. (2019). Structural health monitoring system based on FBG sensing technique for Chinese ancient timber buildings. *Sensors*, *20*(1):110.

https://doi.org/10.3390/s20010110

Kaspar, K., Santini-Bell, E., Petrik, M., & Sanayei, M. (2020). Comparison between a linear regression and an artificial neural network model to detect and localize damage in the powder mill bridge. *Transportation Research Record*, *2674*(8):394-404.

https://doi.org/10.1177/0361198120920631

Kwon, K., & Frangopol, D. M. (2010). Bridge fatigue reliability assessment using probability density functions of equivalent stress range based on field monitoring data. *International Journal of Fatigue*, *32*(8):1221-1232.

Lantsoght, E. O. (2020). Diagnostic and proof load tests on bridges. *Frontiers in Built Environment*, *6*:586704.

https://doi.org/10.3389/fbuil.2020.586704

Lantsoght, E. O. (2024). Assessment of existing concrete bridges by load testing: Barriers to code implementation and proposed solutions. *Structure and Infrastructure Engineering*, *20*(7-8):1002-1014.

https://doi.org/10.1080/15732479.2023.2264825

Lantsoght, E. O., Van der Veen, C., De Boer, A., & Hordijk, D. A. (2017). State-of-the-art on load testing of concrete bridges. *Engineering Structures*, *150*:231-241.

https://doi.org/10.1016/j.engstruct.2017.07.050

Lienhart, W., Ehrhart, M., & Grick, M. (2017). High-frequency total station measurements for the monitoring of bridge vibrations. *Journal of Applied Geodesy*, *11*(1):1-8.

https://doi.org/10.1515/jag-2016-0028

Limongelli, M. P. (2019). Damage localization through vibration based S 2 HM: A survey. In: *Seismic Structural Health Monitoring: From Theory to Successful Applications*. Germany: Springer, p. 217-235.

Liu, K. W., Xu, Q. F., Wang, G., Chen, F. M., Leng, Y. B., Yang, J., *et al*. (2022). *Contemporary Bamboo Architecture in China*. Singapore: Springer Singapore Pvt Limited.

Liu, M., Frangopol, D. M., & Kim, S. (2009). Bridge system performance assessment from structural health monitoring: A case study. *Journal of Structural Engineering*, *135*(6):733-742.

https://doi.org/10.1061/(asce)st.1943-541x.0000014

Luo, D., Wang, S., Du, X., Zhao, P., Lu, T., Yang, H., *et al*. (2021). Health detection techniques for historic structures. *Materials Testing*, *63*(9), 855-864.

Mirdad, M. A. H., & Andrawes, B. (2023). Experimental and analytical approaches for load rating reinforced concrete slab bridge. *Advances in Structural Engineering*, *26*(13): 2447-2464.

https://doi.org/10.1177/13694332231188417

Moreno-Gomez, A., Perez-Ramirez, C. A., Dominguez-Gonzalez, A., Valtierra-Rodriguez, M., Chavez-Alegria, O., & Amezquita-Sanchez, J. P. (2018). Sensors used in structural health monitoring. *Archives of Computational Methods in Engineering*, *25*:901-918.

Morris, W., Vico, A., Vazquez, M., & De Sanchez, S. R. (2002). Corrosion of reinforcing steel evaluated by means of concrete resistivity measurements. *Corrosion Science*, *44*(1):81-99.

https://doi.org/10.1016/S0010-938X(01)00033-6

Nonis, C., Niezrecki, C., Yu, T. Y., Ahmed, S., Su, C. F., & Schmidt, T. (2013). Structural health monitoring of bridges using digital image correlation. In: *Health Monitoring of Structural and Biological Systems*. Vol. 8695, SPIE, p. 51-63.

Olaszek, P., Łagoda, M., & Casas, J. R. (2014). Diagnostic load testing and assessment of existing bridges: Examples of application. *Structure and Infrastructure Engineering*, *10*(6):834-842.

https://doi.org/10.1080/15732479.2013.772212

Pan, B., Xie, H., Guo, Z., & Hua, T. (2007). Full-field strain measurement using a two-dimensional Savitzky-Golay digital differentiator in digital image correlation. *Optical Engineering*, *46*(3):033601-033601.

https://doi.org/10.1117/1.2714926

Park, G., Farrar, C. R., Di Scalea, F. L., & Coccia, S. (2006). Performance assessment and validation of piezoelectric active-sensors in structural health monitoring. *Smart Materials and Structures*, *15*(6):1673.

https://doi.org/10.1088/0964-1726/15/6/020

Robertson, I. N. (2005). Prediction of vertical deflections for a long-span prestressed concrete bridge structure. *Engineering Structures*, *27*(12):1820-1827.

https://doi.org/10.1016/j.engstruct.2005.05.013

Rossi, M., & Bournas, D. (2023). Structural health monitoring and management of cultural heritage structures: A state-of-the-art review. *Applied Sciences*, *13*(11):6450.

https://doi.org/10.3390/app13116450

Sakano, M., Namiki, H., Yajima, S., Koide, Y., Furuta, H., & Frangopol, D. M. (2006). Monitoring of steel railway floor beams prestressed by steel plates. *Journal of Bridge Engineering*, *11*(6):681-687.

Sakiyama, F. I., Veríssimo, G. S., Lehmann, F., & Garrecht, H. (2023). Quantifying the extent of local damage of a 60-year-old prestressed concrete bridge: A hybrid SHM approach. *Structural Health Monitoring*, *22*(1):496-517.

Shan, D. (2011). *Chinese Vernacular Dwellings*. Cambridge: Cambridge University Press.

Song, Y. Z., Bowen, C. R., Kim, A. H., Nassehi, A., Padget, J., & Gathercole, N. (2014). Virtual visual sensors and their application in structural health monitoring. *Structural Health Monitoring*, *13*(3):251-264.

https://doi.org/10.1177/1475921714522841

Song, Y., & Liao, C. (2022). Structural materials, ventilation design and architectural art of traditional buildings in Guangdong, China. *Buildings*, *12*(7):900.

https://doi.org/10.3390/buildings12070900

Taheri, S. (2019). A review on five key sensors for monitoring of concrete structures. *Construction and Building Materials*, *204*:492-509.

https://doi.org/10.1016/j.conbuildmat.2019.01.172

Taylor, P., Hosteng, T., Wang, X., & Phares, B. (2016). *Evaluation and Testing of a Lightweight Fine Aggregate Concrete Bridge Deck in Buchanan County, Iowa*. Iowa: National Concrete Pavement Technology Center.

Taylor, S. E., Rankin, B., Cleland, D. J., & Kirkpatrick, J. (2007). Serviceability of bridge deck slabs with arching action. *ACI Structural Journal*, *104*(1):39-48.

Walker, J. F., & Hughes, P. E. (2005). *Bridge Scour Monitoring Methods at Three Sites in Wisconsin*. Virginia: US Geological Survey.

Wu, Y., Chen, Z., Lin, X., & Tu, X. (2025). A visual analysis and review of chinese qilou architectural heritage based on citespace. *Buildings*, *15*(10):1638.

https://doi.org/10.3390/buildings15101638

Ye, X. W., Ni, Y. Q., Wong, K. Y., & Ko, J. M. (2012). Statistical analysis of stress spectra for fatigue life assessment of steel bridges with structural health monitoring data. *Engineering Structures*, *45*:166-176.

https://doi.org/10.1016/j.engstruct.2012.06.016

Yeh, W. H. (ed.). (2000). *Becoming Chinese: Passages to Modernity and Beyond*. Vol. 23. United States: University of California Press.

Zhan, J., Zhang, F., & Siahkouhi, M. (2021). A step-by-step damage identification method based on frequency response function and cross signature assurance criterion. *Sensors*, *21*(4):1029.

https://doi.org/10.3390/s21041029