

Structural Health Monitoring of Aging Buildings: A Review

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Abstract

Progressive aging of building structures is an unavoidable process that can be influenced by environmental exposure, material degradation, and cumulative loading over time. The transition to ageing brings about various defects, including microcracking, reinforcement corrosion, delamination, and reduced stiffness, which undermine the safety, functionality, and service life of buildings. Structural Health Monitoring (SHM) is a scientific and systematic method for diagnosing and assessing degradation processes by combining sensors, data-collection devices, and analytical models. Recent developments in non-destructive testing (NDT), wireless sensor networks, and machine learning algorithms have changed SHM from a non-periodic inspection design to a real-time assessment framework. The paper reviews the relationship between building ageing and SHM, the typical defects at different stages of a building's life, suitable diagnostic methods, and maintenance treatments. It focuses on developing predictive maintenance schemes and green practices for sustainable rehabilitation that prolong structural service life and enhance structural resilience across various environmental conditions.

Keywords: *Structural Health Monitoring, aging buildings, cracks, corrosion, vibration-based SHM, wireless sensor networks, image processing, machine learning.*

1. Introduction

It is a combination of physical, chemical, and mechanical processes that cause buildings to deteriorate over time and affect their durability and performance. Variations in temperature, humidity, carbonation, and chloride ingress are environmental factors that accelerate the degradation of construction materials, especially reinforced concrete and steel structures. During the initial stages of the life of a building, such problems as drying shrinkage, small surface cracking are widespread, whereas ageing is generally regarded as corrosion, fatigue, and loss of stiffness during prolonged ageing. Unless these defects are identified and addressed in time, they can progress to severe structural failures. Structural Health Monitoring (SHM) has become a key technology for mitigating the risks of structural ageing. It also uses intelligent sensing technologies, non-destructive testing (NDT) methods, and powerful data analytics to continuously monitor the health of buildings. SHM can detect anomalies in a structure early, estimate the extent of damage, and the remaining life of the structure by obtaining the response to environmental and operational loads. The introduction of Internet of Things (IoT)-based sensors, wireless networks, and artificial intelligence has been an additional boost to SHM efficiency, enabling remote diagnostics and automation.

Within the ageing infrastructure setting, SHM not only help to cover the timely maintenance and rehabilitation, but also contributes to the sustainable management of the assets by avoiding needless interventions and prolonging the life of the assets. This review will summarise existing information on the relationship between building ageing and SHM practices, the types of defects typically encountered at different structural ages, and suggest appropriate monitoring and maintenance practices to ensure the resilience of infrastructure systems.

2. Literature Review

Yang et al. (2021) provided a detailed discussion of vibration-based SHM approaches for sensing loss of stiffness, cracks, and material deterioration, which are manifested as a building ages. They strongly highlighted the effects of modal parameter changes, especially frequency and damping, which indicate gradual deterioration, and also noted the challenge of separating environmental effects from actual damage in long-term surveys of old structures. In the same vein, in the article *"Review of Vibration-Based Structural Health Monitoring"*, Toh (2020) examined feature extraction and machine learning methods for damage detection without original baseline data, which is of paramount importance since many old structures lack documented initial conditions. Moravvej et al. (2024) also sought to address this limitation by proposing statistical models to detect anomalies in dynamic response data, even when the initial undamaged state is unknown. Their application is especially in ageing buildings where historic data is not available but long-term vibration data is. In the case study, Avci et al. (2021) also pointed out this trend of shifting towards artificial intelligence and deep learning, stating that the two can autonomously acquire damage-sensitive characteristics based on sensor data monitored throughout the life of the structures.

Focusing on corrosion and chemical ageing, Wright (2019) discussed how electrochemical sensors and half-cell potential mapping technology can be used to identify corrosion in reinforcement of steel to prevent age-related failures of reinforced concrete buildings, which are among the most frequent ones. Preethichandra (2023) further elaborated on this by elaborating on how smart sensors that are able to check temperature, moisture, and chloride ingress could give an early detection of corrosion and carbonation before it manifests itself. The technologies are used to reduce structural weakening due to prolonged exposure to the environment. Ageing-related SHM has also been focused on wireless and distributed sensing. In the article (2020), the benefits of wireless systems in the continuous measurement of vibration, strain, and temperature on large buildings are discussed, so that they can be installed on older buildings that have limited access. This idea was supported by Mustapha (2021) stated that the optimal placement of sensors and network resilience are the most important attributes for successfully monitoring the deterioration of infrastructure over long periods of time. Chik et al. specifically addressed heritage and aged buildings and explained that non-destructive methods for detecting cracks and surface deformations, such as laser scanning and image-based monitoring, do not harm the historic fabric of the structure. Basko (2021) explained that SHM has been brought into the contemporary era by drones and automated image processing that detect cracks and spalling on the surface of deteriorating concrete. Such visual techniques are increasingly incorporated with sensor information to enable a full-scale assessment.

Wang (2024) expanded the debate by connecting the applications of SHM with sustainability and maintenance policy, emphasising that, in the context of ageing infrastructure, sensor technology is not the only critical aspect but data interpretation and decision-making structures. Li et al. (2024) provided real-life examples of successful use of long-term SHM that predict failures due to fatigue and environmental ageing, with references to the importance of using trends in monitoring. Lastly, combining all these viewpoints, all the research findings

demonstrate that no specific SHM method can potentially identify all the defects associated with ageing. The best solutions are hybrid systems that combine vibration analysis, corrosion sensing, a wireless data collection system, and automated visual inspection. Nevertheless, environmental noise, data overload, and sensor maintenance remain challenges that limit long-term performance. The analysed literature leads to the necessity to find cost-effective, reference-free, and low-maintenance SHM systems that can provide actionable information to promptly rehabilitate old structures (Yang, 2021; Moravvej, 2024; Wright, 2019; Wang, 2024).

3. Structural Health Monitoring Failure Types and Detection

Civil structures during their service life are subjected to various failure modes, ranging from minor surface cracks to total structural collapse under extreme loading. SHM systems are developed in such a way that they are capable of pointing out such failures in the earliest stage possible, thus avoiding the catastrophic events and facilitating prompt maintenance. The literature reviewed gives a good connection between the types of failures and the detection strategies used.

1. Cracking and Fracture

- **Nature of Failure :** Cracks are among the initial indicators of concrete and steel structure decay. They can result from thermal stresses, shrinkage, fatigue or overloading; in many cases, small cracks may extend to fractures if they are not detected and repaired. (Zhang et al., 2024)
- **Detection in SHM :**
 - ❖ Cracking results in stiffness loss, which is often detected by vibration-based methods (modal frequency drop, mode shape changes) (Gharehbaghi et al., 2022). Ultrasonic and Lamb waves are useful in detecting internal or hidden cracks (Siracusano et al., 2019)
 - ❖ Image processing of cracks on surfaces is done by computer vision / deep learning systems (Konig et al., 2022)
 - ❖ Fibre-optic sensors (e.g., FBG) are used to measure micro-strains, which indicate the start of a crack (Shiyekar & Patil, 2022)

2. Fatigue Damage

- **Nature of Failure:** Structural components subjected to cyclic loading (e.g., bridge traffic, wind on tall towers) are prone to fatigue, which causes gradual accumulation of micro-cracks and eventual failure if undetected (IRJET Review, 2016)
- **Detection in SHM :**
 - ❖ Micro-cracks caused by fatigue in steel girders are detected via Lamb wave propagation techniques (Siracusano et al., 2019)
 - ❖ Vibration monitoring based on accelerometers can monitor changes in modal parameters associated with fatigue (Zhang et al., 2025)
 - ❖ Fibre-optic sensors are used to measure strain cycles to determine fatigue development (Zhang et al., 2024)

3. Corrosion and Material Degradation

- **Nature of Failure :** In reinforced concrete structures, steel corrosion causes spalling, cracking and loss of load-bearing ability. In steel buildings, rust causes decreased cross-section and strength (IRJET Review, 2016)
- **Detection in SHM :**
 - ❖ Surface rust, spalling and delamination are detected using computer vision systems (Hassani et al., 2021)
 - ❖ Electrochemical sensors (e.g., half-cell potential, corrosion rate sensors) ensure measurement of corrosion activity (Zhang et al., 2024)
 - ❖ Fibre-optic & FBG sensors detect strain due to expansion induced by internal corrosion (Shiyekar & Patil, 2022)

4. Hardening and Loss of Load/Transport Capacity

- **Nature of Failure:** Long-term environmental effects, ageing and seismic activities are known to decrease stiffness in structural members, causing impaired performance and load capacity reduction (Wang & Ke, 2024)
- **Detection in SHM :**
 - ❖ SHM based on vibration is well-suited to detect changes in global stiffness via variations in natural frequencies (Gharehbaghi et al., 2022)
 - ❖ AI models are increasingly trained to distinguish between loss of stiffness caused by damage and that caused by environmental/operational factors (Plevris, 2024)

5. Buckling and Instability

- **Nature of Failure:** This is common in slender steel columns, trusses and tall constructions under compressive forces or wind loads, where local instability can lead to large displacements or collapse (Zhang et al., 2025)
- **Detection in SHM :**
 - ❖ Fibre-optic sensors are used to measure local strain on critical points for buckling risk (Zhang et al., 2024)
 - ❖ Displacement sensors (e.g., tiltmeters, lateral displacement sensors) identify lateral displacements that are excessive (Shiyekar & Patil, 2022)
 - ❖ Loss of stiffness is sensed in vibration analysis prior to buckling being visibly seen (Gharehbaghi et al., 2022)

6. Progressive Collapse and Seismic Failures

- **Nature of Failure:** Occurs when local failures cascade into large-scale progressive collapse — triggered by an earthquake or sudden overload — especially in ageing or poorly maintained buildings (Zhang et al., 2024)
- **Detection in SHM :**
 - ❖ SHM frameworks which are earthquake-specific monitor real-time building responses (Wang & Ke, 2024)
 - ❖ Accelerometer networks and strong-motion sensors record responses to seismic events and sudden loads, enabling post-event damage detection (Gharehbaghi et al., 2022)

Based on the above, it is evident that every type of failure will need a unique way of detection:

- Cracks → ultrasound, computer vision, and fiber optics are the best methods to detect the cracks.
- Fatigue → monitored using Lamb waves and vibration.
- Corrosion → is best determined using computer vision and fibre optics.
- Loss of stiffness and buckling → Vibration based methods and strain sensors.
- Seismic or progressive collapse → AI and IoT-powered accelerator networks.

In practice, structures can hardly fail singly. For example, a bridge girder can initially experience fatigue cracks that lead to corrosion, then loss of stiffness, and finally fracture. SHM systems should therefore be fitted with various sensors and detection techniques to monitor the various phases of failure. The considered research articles all emphasise that the most significant contribution of SHM is the early-stage failure detection. It is much more cost-effective and safer to detect cracks or corrosion when they are still microscopic than to discover that the damage has occurred only after serviceability is lost (Mittal et al., 2025). Table 1 presents a detailed comparison of inspection intervals during a building's lifespan and the Structural Health Monitoring Techniques used to monitor deterioration.

4. Conclusions

SHM systems should address a wide variety of failure modes (cracking, fatigue, corrosion, loss of stiffness, buckling, progressive collapse) as opposed to addressing a single mode of defect. Early warning is paramount - it is possible that the micro-damage can develop into macro-failure very quickly in old buildings. The sensing technique should be appropriate to the mode of failure: e.g. corrosion sensors to detect a stiffness loss, modal analysis to detect a surface spall, or image/vision sensors to detect a stiffness loss. The variability in the environment and operation (temperature, humidity, change in load) should be taken into account and distinguished from the changes in SHM data caused by the damage. Machine learning and AI/machine learning are now needed to process high amounts of data and detect anomalies and predictive maintenance in real-time. In the case of ageing buildings, SHM is not only detection but diagnosis (which defect) and prognosis (in which mode it will develop) - the more value they bring is the connection of findings to maintenance or retrofit responses.

Table 1: Building Aging with Associated Defects and SHM-Based Detection Methods

Age (years)	Purpose of checkup (what to assess)	Typical defects to look for (visual/likely)	Mandatory tests/inspections	Recommended SHM instrumentation/data to collect	Typical remedial & maintenance actions
Hand Over	Baseline condition; checkup workmanship and as-built and design.	Honeycombing, cover deficiency, Welding defects, alignment, water ingress.	As-built survey, dimensional check, concrete cube/cylinder checks (when poured), weld/bolt torque checks, rebar cover check.	Draw baseline; make first photos; indicate points of mark instrumentation.	Repair work, fix construction faults, re-work finishes, repair drainage, grout vents, set up records on a foundation.
Annual (every year)	Timely identification of deterioration.	Minor corrosion, peeling off paint, small cracks, stains, blocked drains.	Walk-through/visual inspection, roof/drain check, simple leak test.	Checks Photographic log, simple displacement / settlement monitoring when provided.	Clearing of drains, filling of small cracks, repainting, tightening of bolts, and patching up of minor points.
5 years	Early-life performance/durability inspection.	Premature cracking, contraction cracks, construction cracks, premature cracking in hostile conditions.	Figurative inspection; mapping and measurement of the width of the cracks; corrosion potential (half-cell) in reinforced concrete of aggressive regions; covermeter to determine the position of the rebar; concrete strength sample in suspicious regions; paint/coating examination.	Crack instrumentation of critical cracks, humidity instrument of enclosed spaces, strain instrumentation of critical members (where known).	Non-structural crack injection; patch repair, spalling, re-coating/paint; cathodic protection evaluation in case of active corrosion.

10 years	Major maintenance cycle; major maintenance cycle baseline.	Crack advancement, carbonation, ingress of chloride (coastal), fissure spalling, loss of concrete cover, corrosion of steel.	Carbonation depth test; chloride content testing in concrete; carbonation and pH testing; half-cell potential mapping; ultrasonic pulse velocity (UPV) of concrete integrity; thickness of steel members; ultrasonic thickness measurement (ultrasonic) of steel members.	Baseline modal vibration test of dynamic structures (bridges); to accelerometers on the important spans; constant corrosion rate monitors in the areas of concern.	Patching with concrete in place; re-profiling; repair or plating of steel members locally; replacement or repair of expansion joints; enhancement of waterproofing and drainage; application of corrosion inhibitors or initiation of cathodic protection where necessary.
20 years	Significant longevity test; strength test.	High level of corrosion, loss of section (steel), repetitive movement of joints, fatigue crack formation in steel, signs of settlement of foundations, and large areas of carbonation/chloride penetrations.	Complete structural examination by engineer; NDT system: UPV test, rebound hammer test, core testing (compressive) (suspect) (suspect) (suspect), half-cell test, chloride test, covermeter, radiograph test, critical welds, magnetic particle test; review of foundation/instrumentation data.	Monitors Long-term strain (strain gauges/foil gauges), displacement /settlement (inclinometers, tiltmeters, crack monitors), constant vibration (continuous vibration) monitoring, periodic dynamic test (operational modal analysis).	The strengthening that is necessary: FRP wrapping, expansion of section/ collar bonding, exterior post-tensioning of concrete part, add stiffener, underpinning of foundation/ soil improvement, and significant waterproofing.
30 years	Decision point of life extension; evaluation of residual life.	Worn out, numerous repairs apparent, potential weariness /	Repeat -total NDT; fatigue examination (steel), load examination (proof/load test) of significant	Constant SHM, automatically triggered alarms: strain, acceleration,	Significant rehabilitation measures: strengthening or replacement of members, full cathodic

		unseen damage.	members or spans; geotechnical re-examination of foundations; corrosion rate evaluation to project remaining life.	corrosion rate, displacement; remote data recording; trend measurements.	protection, large joint replacement, re-decking (bridges), seismic retrofit in case design codes are revised
40 years	Re-check to continue serving or to be replaced.	Rapid breakdown in hostile conditions, repeated maintenance, and potential functional obsolescence.	Complete structural audit: load rating (assess allowable loads), progressive collapse assessment, evaluation of fracture mechanics of any cracks, and remaining service life assessment.	Full-time monitoring critical: fibre-optic sensors of temperature/strain in critical elements (distributed in case of high risk); corrosion sensors; moisture sensor.	Based on the results: heavy rehabilitation (composite strengthening, steel section replacements), changes in load limits, systems replacement (partial, e.g. deck, slabs), and an advanced maintenance plan.
50 years	Is it through form: retire, major rehab, or extend life	Material degradation over a long period, potential extensive section loss, foundation concerns, serviceability and safety concerns.	Compulsory complete structural audit by multidisciplinary team (structural, geotech, materials); load test; elaborate NDT incorporating cores and laboratory research; structural reliability examination; investigation of previous monitoring records.	Maintain uninterrupted SHM in areas of critical concern in case the structure is maintained in service; predictive maintenance analytics.	Several buildings to be rebuilt or renewed on a large scale; otherwise, carry out complete rehabilitation: replace severely defective members, a great deal of strengthening, modernise to the present code where feasible, and change load distributions.

60 years (and beyond)	Permanent / end of life decisions.	Loss of material, risk of fatigue failure, functional obsolescence, safety-absolutely vital defects.	Safety-critical inspections (daily/weekly checks of in-service bridges), accelerated NDT, Forensic investigation of any failures, and life-safety audit.	SHM with live alerts; automated excess closures.	Decommissioning and replacement are suggested in the majority of cases; otherwise, ongoing heavy maintenance, temporary supports or load constraints; controlled demolition, when not safe.
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