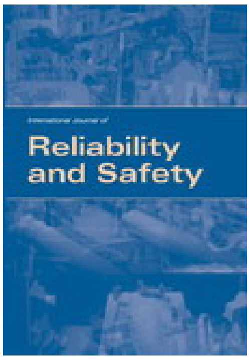

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Recent advances in structural health monitoring: techniques, applications and future directions

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Recent advances in structural health monitoring: techniques, applications and future directions

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Abstract: Structural Health Monitoring (SHM) ensures structure safety, reliability, and durability in many sectors. SHM methods have improved structural evaluation and maintenance efficiency to meet sustainable infrastructure and lower maintenance expenses. This article discusses current SHM achievements, their benefits, and future research in this rapidly growing field. Basic SHM procedures start with manual monitoring and visual inspections. Advanced sensors, data analytics and machine learning algorithms have transformed SHM. Industrial, aerospace, energy and civil infrastructure use SHM. SHM optimises processes and quality control, improving product reliability and waste reduction. It covers smart materials, low-cost, lightweight, energy-efficient sensor technologies and advanced data analytics for better decision-making. Advanced sensors, data analytics and machine learning algorithms enable real-time monitoring, anomaly detection and preventative maintenance using SHM. Advanced sensor technologies and SHM integration with cutting-edge technology will shape this industry and improve SHM and maintenance**.**

Keywords: SHM; structural health monitoring; sensor; data analytics; machine learning; durability; safety; maintenance; reliability.

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1 Introduction

Structural Health Monitoring (SHM) is a critical aspect of guaranteeing the safety and reliability of infrastructure and other structures (Karbhari and Ansari, 2009). In order to continually monitor a structure's condition and give real-time data on its health, the SHM procedure makes use of sensors (Kaya and Safak, 2015; Khan et al., 2016). In order to avoid catastrophic failures, identify possible structural issues and maximise maintenance and repair efforts, data gathered by SHM can be utilised (Liu and Nayak, 2012). In the last several years, the field of SHM has grown significantly due to the quick development of sensor technology, data-gathering methods, and processing approaches (Sony et al., 2019).

For example, SHM makes it possible to monitor bridges, dams, tunnels and other infrastructure assets proactively in civil engineering (Chen, 2018; Wu et al., 2020). It assists in identifying early indicators of degradation, such as corrosion, deformation or cracks, which can jeopardise structural integrity and seriously endanger public safety (Li et al., 2017; Feroz and Abu Dabous, 2021). SHM improves these vital infrastructure systems' operational effectiveness and safety by means of prompt maintenance interventions and real-time monitoring (Feroz and Abu Dabous, 2021). Furthermore, the aerospace sector mainly depends on SHM to guarantee the structural integrity of spacecraft and airplanes (Broer et al., 2022). To identify fatigue, stress and damage accumulation, structural health must be continuously monitored due to the complexity of aerospace structures growing and the need for lightweight designs (Boller, 2000). Advanced sensor networks are used by SHM to provide real-time monitoring of vital components, reducing the possibility of catastrophic failures and enhancing aviation safety in general aircraft (Farrar and Worden, 2007; Chandrasekaran, 2019). SHM has an effect on other industries as well. For instance, in the field of renewable energy, where solar panels and wind turbines are exposed to severe weather (Le et al., 2022), SHM helps to maximise energy production efficiency (Olabi et al., 2021), optimise maintenance schedules and identify flaws or performance degradation. In order to reduce the danger of leaks, spills or catastrophic breakdowns in the oil and gas sector, SHM is used to monitor the structural integrity of offshore platforms, pipelines and storage tanks (Ho et al., 2020).

All things considered, the study of structural health monitoring has become an important topic that offers a proactive maintenance strategy, enhances safety and maximises the life cycle management of structures in a variety of sectors (Chen, 2018). As sensing technologies, data analytics and artificial intelligence continue to progress, SHM will also make monitoring, evaluation and decision-making procedures more precise and effective (Ahmed et al., 2021). Keeping up with the lightning-fast speed at which technology is developing, SHM has made significant strides recently. Smart materials, wireless sensor networks and fibre optic sensors are examples of advanced sensor technologies that have made data collection more thorough and accurate (Li et al., 2004; Guo et al., 2011; Noel et al., 2017). Furthermore, advances in machine learning algorithms, predictive modelling, and signal processing techniques have improved data interpretation and analysis, making structural health evaluation more accurate and efficient (Farrar and Worden, 2012; Flah et al., 2021).

This essay will explore several innovative methods used in SHM. The capabilities of SHM systems are anticipated to be improved as technology develops through the integration of cloud computing, big data analytics and the Internet of Things (IoT)

(Tokognon et al., 2017; Yu and Lin, 2017; Sun et al., 2020). Other instances are non-destructive testing techniques that provide non-intrusive means of evaluating structural integrity, such as acoustic emission, infrared thermography and ultrasonic testing (Strantza et al., 2015; Ciampa et al., 2018; Ramesh et al., 2020; Hassani and Dackermann, 2023). Moreover, the application of data-driven methodologies, like anomaly detection and data fusion, offers insightful methods for locating damage or irregularities in structures (Tang et al., 2019b; Choi et al., 2021). Furthermore, the application of cutting-edge materials, including nanocomposites and self-healing materials, has the potential to revolutionise the area of SHM by enabling self-monitoring and self-repairing structures (Idumah et al., 2020; Nowacka and Kowalewska, 2022). Through an analysis of recent developments, methodologies, uses, and prospects in the field of structural health monitoring, this article seeks to offer a thorough grasp of the state-of-the-art as well as the possibility of future developments in this vital field and illustrate its influence on various industries.

2 Techniques in structural health monitoring

2.1 Traditional techniques used in structural health monitoring

Structural Health Monitoring (SHM) evaluates the performance and state of structures using a variety of conventional methods. These methods are the cornerstone of SHM practices and have been used extensively for many years. Here, we give a summary of a few widely used conventional methods.

2.1.1 Visual inspection

Visual inspection is the process through which qualified experts examine constructions up close. It is an easy-to-use, reasonably priced method for identifying obvious flaws like corrosion, deformation, or fissures. Visual inspection is a useful technique for routine inspections and maintenance planning and is frequently employed in the early phases of SHM (Drury et al., 1997; Campbell et al., 2020; Wang et al., 2021b; Ierimonti et al., 2023).

2.1.2 Ultrasonic testing (UT)

High-frequency sound waves are used in ultrasonic testing to find flaws or modifications in the material properties of a construction. It is possible to identify and define faults like cracks, voids, or delamination by examining the reflected or transmitted ultrasonic waves. UT is very useful for determining how well-welded and concrete constructions are constructed (Rose, 2004; 2010; Kot et al., 2021; Hassani and Dackermann, 2023).

2.1.3 Acoustic emission (AE)

A passive monitoring method called acoustic emission finds and examines the elastic waves released when a structure deforms or fails. By monitoring the acoustic signals generated by cracking, friction, or other stress-related phenomena, AE can identify the presence of defects or structural damage. Monitoring composite materials and structures under dynamic stress conditions is a popular use for it (Holford, 2009; Wevers and Lambrighs, 2009; Strantza et al., 2015).

2.1.4 Strain gauges

Electrical sensors called strain gauges are used to quantify variations in a structure's strain or deformation. Usually, these sensors are embedded in or adhered to the surface of a structure. When it comes to the load distribution, fatigue behaviour, and structural reaction of the component under observation, strain gauges can offer invaluable insights (Kang et al., 2006; Rao et al., 2006; Choi et al., 2008; Dos Reis et al., 2018).

2.1.5 Destructive testing

Destructive testing involves the physical removal and examination of structural samples or components to assess their properties and behaviour. This method is frequently applied to check material properties, assess structural integrity, and calibrate numerical models during the design and construction phases. Destructive testing is mostly used in particular situations and is not appropriate for ongoing monitoring (Miller et al., 1994; Yang et al., 2008; Brown et al., 2018; Belouadah et al., 2021; Chakrawarthi et al., 2022).

In SHM, these conventional methods have been widely used to identify and evaluate structural flaws, track material behaviour and guarantee the dependability and safety of diverse structure kinds.

2.2 Recent technological advancements in structural health monitoring

2.2.1 Wireless sensor networks (WSNs)

Wireless sensor networks have transformed SHM by empowering real-time data acquisition from distributed sensors (Bhuiyan et al., 2015; Sofi et al., 2022). WSNs are made up of self-contained, tiny sensor nodes that interact wirelessly to gather and send information on a range of structural characteristics, including temperature, humidity, vibration, strain and vibration (Harms et al., 2010; Meyer et al., 2010; Hodge et al., 2014; Ahmad et al., 2021). Scalability, flexibility and lower installation and maintenance costs are among the benefits of these networks (Qing et al., 2019). WSNs improve the monitoring systems' spatial coverage and make it easier to integrate a lot of data for a thorough structural health assessment (Abdulkarem et al., 2020).

2.2.2 Non-destructive testing (NDT) methods

Recent progressions in non-destructive testing techniques have expanded the competencies of SHM (Kot et al., 2021). Non-Destructive Testing (NDT) techniques, such as infrared thermography, ultrasonic testing and ground-penetrating radar, allow structural faults to be identified and documented without endangering the structures being observed (Ciampa et al., 2018; Kumar et al., 2021; Montaggioli et al., 2021; Samaitis et al., 2021). By detecting problems including cracks, corrosion, delamination and voids, these methods offer insightful information about the interior state of materials (Kamsu-Foguem, 2012; Dwivedi et al., 2018). Improved sensitivity, resolution and efficiency provided by NDT technology advancements help to provide a more accurate and trustworthy condition evaluation of structures (Ciampa et al., 2018; Bandara et al., 2023).

2.2.3 Data analytics

Data analytics plays a vital role in extracting expressive information from the vast amount of data collected by SHM systems (Ciampa et al., 2018; Bacco et al., 2020). Automated data processing, pattern identification and anomaly detection are made possible by sophisticated data analysis approaches, such as machine learning and artificial intelligence algorithms (Bao et al., 2019; Woldaregay et al., 2019). By identifying crucial events or structural aberrations from normal behaviour, these approaches enable the development of tailored maintenance interventions and early warning systems interventions (Afridi et al., 2022). In order to optimise maintenance plans and resource allocation for better structural performance, data analytics also supports predictive modelling and decision-making processes (Frangopol, 2011; Frangopol et al., 2017).

3 Applications of structural health monitoring

3.1 Importance of structural health monitoring in various sectors

3.1.1 Civil infrastructure

In order to guarantee the security and dependability of civil infrastructure, such as bridges (Ko and Ni, 2005), dams (Kang et al., 2019), buildings (Wu et al., 2020), tunnels (Tan et al., 2023) and highways (Brownjohn, 2007), structural health monitoring is essential (Brownjohn, 2007; Glisic and Inaudi, 2007; Moreu et al., 2018; Wu et al., 2020), because numerous operational and environmental factors might cause deterioration and eventual breakdowns in these structures. Continuous monitoring of structural integrity is made possible by SHM, which can identify early indicators of degradation including corrosion, deformation or cracks (López-Higuera et al., 2011; Mishra et al., 2022). The lifetime and optimal performance of civil infrastructure assets are ensured by proactive maintenance and decision-making made possible by SHM, which offers real-time data on structural behaviour and conditions (Chen, 2018; Futai et al., 2022).

3.1.2 Aerospace

The structural health of aircraft, spacecraft and associated components is monitored by the aerospace industry primarily using SHM (Giurgiutiu, 2015; Zelenika et al., 2020; Broer et al., 2022). Extreme operating conditions for spacecraft and airplanes include vibration, temperature swings and heavy loads (Thornton, 1996; Balaban et al., 2009; Glaessgen and Stargel, 2012; Stanciulescu et al., 2012). It is essential to continuously monitor structural integrity in order to identify and evaluate the accumulation of fatigue, stress and damage (Boller, 2000; Pollock et al., 2021). Fibre optic sensors, strain gauges and non-destructive testing procedures are examples of SHM approaches that enable real-time monitoring of essential components, maintenance schedule optimisation and flight (Stolz and Neumair, 2010; Guo et al., 2011; López-Higuera et al., 2011; Karbhari, 2013; Braga et al., 2014; Yoon et al., 2022).

3.1.3 Renewable energy

Monitoring and enhancing the efficiency of energy-producing systems is a major responsibility of SHM in the renewable energy industry (Yang and Sun, 2013; Hamdan et al., 2014; He et al., 2021). Harsh environmental factors, such as temperature swings, vibrations and wind gusts, can affect solar panels and wind turbines (Hyers et al., 2006; Sahu et al., 2016). With the help of SHM, these structures may be continuously observed to identify problems such as solar panel deterioration, fatigue cracks and damage to the blades (Ciang et al., 2008; López-Higuera et al., 2011; Fremmelev et al., 2022; Mishra et al., 2022). Through the identification and resolution of these problems, SHM increases the efficiency of energy production, lowers maintenance expenses and increases the longevity of renewable energy resources (Bhuiyan et al., 2014; Akhtar and Rehmani, 2015; Shafiee and Sørensen, 2019; Ren et al., 2021; Tan et al., 2021).

3.1.4 Oil and gas

For offshore platforms, pipelines, storage tanks and other vital infrastructure in the oil and gas sector, structural health monitoring is essential (Cawley, 2018; Chandrasekaran, 2019; Chen et al., 2023). These structures are subjected to operational stresses, corrosion and hostile maritime environments (Adedipe et al., 2016; Abbas and Shafiee, 2020). Early identification of structural deterioration, including metal loss, stress corrosion cracking and leakage, is made possible by SHM (Adedipe et al., 2016; Arun Sundaram et al., 2018). By keeping an eye on structural integrity, SHM reduces the possibility of spills, leaks or catastrophic failures, protecting people and the environment (El-Bendary et al., 2013; Arun Sundaram et al., 2018).

3.2 Present case studies that demonstrate the effectiveness of SHM in detecting and preventing failures

3.2.1 Case study: Forth Road Bridge, Scotland

The Forth Road Bridge in Scotland is an iconic suspension bridge that underwent extensive structural health monitoring after the discovery of a crack in one of its steel truss end links (Wang et al., 2016). SHM systems were installed to continuously monitor the bridge's behaviour and detect any changes. This monitoring allowed engineers to identify additional cracks and structural abnormalities, leading to timely repairs and preventing a potential catastrophic failure (Dervilis et al., 2016).

3.2.2 Case study: NASA's Space Shuttle Program

Structural health monitoring played a critical role in the safety and reliability of NASA's Space Shuttle program (Ocasio, 2005). The Space Shuttle's thermal protection system was continuously monitored using temperature sensors and strain gauges to detect any signs of damage or degradation (Uyanna and Najafi, 2020). This monitoring helped identify issues such as foam shedding from the external fuel tank, enabling necessary repairs and ensuring the integrity of the shuttle's heat shield during re-entry (Yang, 2005).

3.2.3 Case study: wind turbine blades

SHM is crucial in the wind energy industry to monitor the structural health of wind turbine blades (Yang et al., 2017). In one case study, strain gauges and accelerometers were used to continuously monitor the dynamic behaviour and fatigue damage accumulation of wind turbine blades (Kaewniam et al., 2022). By detecting strain variations and monitoring vibration patterns, SHM enabled the early detection of blade damage, allowing for timely repairs or replacement and avoiding catastrophic failures (Ciang et al., 2008).

3.2.4 Golden Gate Bridge, San Francisco

The Golden Gate Bridge in San Francisco has a comprehensive SHM system in place to monitor its structural health (Matarazzo and Pakzad, 2014; Nagarajaiah and Erazo, 2016; Noel et al., 2017). The system includes various sensors such as strain gauges, accelerometers, and corrosion sensors, which provide real-time data on the bridge's behaviour, load distribution, and corrosion levels (Ye et al., 2014; He et al., 2022). This monitoring allows engineers to detect structural abnormalities, track corrosion rates and implement targeted maintenance strategies, ensuring the long-term safety and reliability of the bridge (Brownjohn, 2007).

4 Recent advances in structural health monitoring

4.1 Cutting-edge techniques and technologies in structural health monitoring

4.1.1 Internet of things (IoT) and edge computing

The Internet of Things (IoT) has meaningfully converted SHM by empowering the integration of sensors, data communication and cloud computing (Alavi et al., 2018; Jo et al., 2018). IoT-based SHM systems make use of a network of networked sensors to gather data on structural activity in real-time and send it to cloud-based platforms for analysis (Tokognon et al., 2017; Alavi et al., 2018). Real-time data processing and analysis at the network's edge is made possible by edge computing, an IoT paradigm that lowers latency and speeds up response times (Zyrianoff et al., 2022). These technologies improve SHM systems' intelligence, connection and scalability (Jo et al., 2018; Wang et al., 2023).

4.1.2 Structural health monitoring using unmanned aerial vehicles (UAVs)

Unmanned Aerial Vehicles, normally known as drones, offer a promising approach for SHM (Reagan et al., 2018; Akbar et al., 2019; Sreenath et al., 2020). Even in difficult-to-reach places, UAVs equipped with high-resolution cameras, LiDAR sensors and other imaging technologies may take detailed pictures and gather data from a variety of angles (Gopalakrishnan et al., 2018; Mandirola et al., 2022). They offer useful visual information and aid in the detection of structural flaws, making it possible to efficiently check and monitor big structures like buildings and bridges (Boddupalli et al., 2019; Spencer et al., 2019; Gharehbaghi et al., 2021). The safety, effectiveness and financial viability of SHM inspections are all improved by the employment of UAVs (Herkenhoff et al., 2023; Vijayan et al., 2023).

4.1.3 Wireless sensor networks with energy harvesting

Wireless Sensor Networks (WSNs) have progressed with the integration of energy harvesting technologies (Tang et al., 2018; Sundriyal and Bhattacharya, 2019; Vijayan et al., 2023). Energy-harvesting WSNs do not require cable connections or battery replacements since they use energy sources like sun, wind or vibration to power the sensor nodes (Akhtar and Rehmani, 2015; Lee et al., 2016; Adu-Manu et al., 2018). Long-term, self-sustaining monitoring systems in isolated or difficult-to-reach places are now possible thanks to this development (Grigg et al., 2022; Yahya-Alkhalaf et al., 2022). Cost savings, environmental sustainability and increased monitoring capabilities are all aided by energy-harvesting WSNs (Srbinovski et al., 2015, 2016).

4.1.4 Data-driven and machine learning approaches

Data analytics, machine learning and artificial intelligence techniques have innovative SHM by aiding more accurate and efficient data processing, analysis and decision-making (Salehi and Burgueño, 2018; Sujith et al., 2022). These methods are able to process massive amounts of sensor data, recognise patterns and instantly spot anomalies or important occurrences (Azimi et al., 2020; Dang et al., 2020). Based on past data and patterns, machine learning algorithms can enhance damage detection and localisation, forecast structural behaviour and maximise maintenance techniques (Dang et al., 2021; Rautela and Gopalakrishnan, 2021). The efficiency and automation of SHM systems are improved by data-driven and machine learning techniques (Niu, 2017; Azimi et al., 2020).

4.2 Advancements in structural health monitoring

This section presents and collects a current literature review of Advancements in Sensor Technology, Data Analysis Algorithms, Machine Learning and Artificial Intelligence in Structural Health Monitoring.

4.2.1 Sensor technology

Recent advancements in sensor technology have led to the development of new types of sensors, improved sensor performance and increased sensor network density (Chong and Kumar, 2003; Gilbert et al., 2012; Zhou and Yi, 2013). Among the most popular kinds of sensors in SHM are wireless, fibre optic and piezoelectric sensors (Li et al., 2004, 2015; He et al., 2022). Because of its excellent stability and sensitivity, piezoelectric sensors are well-suited to monitoring vibration and strain in structures (Hagood and Von Flotow, 1991; Turner et al., 1994; Khoshnoud and De Silva, 2012). The benefits of fibre optic sensors include their immunity to electromagnetic interference and their capacity to offer distributed sensing via a single fibre (Sabri et al., 2013; Sabri et al., 2015; Du et al., 2020). Large-scale structure monitoring is a good fit for wireless sensors because of their ease of deployment and data collecting (Lazarescu, 2013; Ferdoush and Li, 2014). Successful applications of sensor technology in SHM have been shown in a number of case studies, including the monitoring of wind turbines (Antoniadou et al., 2015; Wymore et al., 2015), buildings (Brownjohn et al., 2011; Li et al., 2016) and bridges (Li et al., 2014, 2016), Even though there are still issues with sensor technology, like the necessity for dependable power supplies and signal transmission, it is anticipated that as sensor technology develops further, SHM will get better yet (Chen, 2018; Motwani et al., 2022; Sofi et al., 2022).

4.2.2 Data analysis algorithms

Data analysis algorithms have experienced substantial advancements, enabling more well-organised processing and interpretation of the large amounts of data collected by SHM systems (Karbhari and Ansari, 2009; Cremona and Santos, 2018; Zinno et al., 2022). Among the most popular data analysis techniques in SHM are principal component analysis, wavelet analysis and modal analysis (Gharibnezhad et al., 2013; Tibaduiza et al., 2013; Ulriksen et al., 2016; Singh et al., 2021). While wavelet analysis is used to evaluate non-stationary signals (Sifuzzaman et al., 2009; Bhattacharyya et al., 2018), modal analysis is used to determine the natural frequencies and mode shapes of a structure (Ren et al., 2004). By reducing the dimensionality of SHM data, principal component analysis facilitates easier interpretation and analysis (Li et al., 2020; Nie et al., 2020). Additionally, statistical tools, pattern recognition algorithms and signal-processing methods aid in the extraction of useful information from unprocessed sensor data (Meyer-Bäse, 2004; Jardine et al., 2006; Wen et al., 2021). Based on historical data analysis, advanced algorithms enable the identification of structural anomalies, damage detection, localisation and behaviour prediction (Huang et al., 2019; Sun et al., 2020; Niyirora et al., 2022). Several case studies, including the monitoring of aircraft structures and civil infrastructure, have shown how effective data collecting and analysis approaches can be used in SHM (Brownjohn, 2007; Catbas, 2009; Kahandawa et al., 2012; Gupta et al., 2013; Li et al., 2016). Even though there are still difficulties with data collection and analysis, such as the requirement for trustworthy analysis algorithms and high-quality data, it is anticipated that these methods will continue to advance and result in additional advancements in SHM (Tao et al., 2019; Lynch et al., 2022).

4.2.3 Machine learning

Machine learning techniques have transformed SHM by allowing systems to learn from data, detect patterns and make intelligent decisions (Khan and Yairi, 2018; Baduge et al., 2022; Malekloo et al., 2022). Support vector machines and neural networks are examples of supervised learning algorithms that make it possible to classify structural health issues and identify particular types of faults (Worden and Manson, 2007; Gui et al., 2017; Bull et al., 2020; Flah et al., 2021; Lin, 2021). Algorithms for unsupervised learning, such as clustering and anomaly detection, assist in spotting anomalies and aberrant behaviour that were previously undetected (Himeur et al., 2021a, 2021b; Usmani et al., 2022). The accuracy, efficacy and automation of structural health evaluation are improved by machine learning techniques (Flah et al., 2021; Kot et al., 2021). Machine learning's primary benefit is its capacity to process massive volumes of data reliably and fast (Rajkomar et al., 2018; Djenouri et al., 2021). Notwithstanding, the utilisation of these methodologies presents several obstacles such as the requirement for superior data, dependable and precise models and suitable training methods (Vamathevan et al., 2019;

Abdar et al., 2021). It is anticipated that further developments in the field of SHM will result from ongoing research and development in machine learning and AI.

4.2.4 Artificial intelligence

More sophisticated and intelligent SHM systems have been made possible by Artificial Intelligence (AI) approaches such as machine learning, expert systems and knowledge-based reasoning (Nuhu et al., 2021; Baduge et al., 2022; Futai et al., 2022). AI gives SHM systems the ability to learn from past data, adjust to new circumstances and make deft decisions instantly (Hamed et al., 2021; Futai et al., 2022). AI-based methods support the diagnosis, prognosis and decision-making processes related to structural damage, enhancing maintenance plans and raising the general dependability of structures (Ran et al., 2019; Wang et al., 2021a; Al-Surmi et al., 2022). Structural engineers can create structures that are more amenable to monitoring, maintenance and repair by combining SHM with structural design and maintenance (Chen, 2018; Mishra et al., 2022). For instance, the application of SHM data can assist in making design choices about the arrangement and kind of sensors, as well as the structural components and materials utilised in a certain structure (Noel et al., 2017; Valinejadshoubi et al., 2017). Engineers can concentrate their efforts on the parts of a structure that require the greatest care by using SHM data to optimise maintenance and repair operations (Glisic et al., 2010; Orcesi and Frangopol, 2011).

5 Challenges and future directions

Current challenges in structural health monitoring and the potential limitations of existing techniques are discussed in this section.

5.1 Current challenges in structural health monitoring

5.1.1 Data management and analysis

The growing amount and intricacy of data gathered by SHM systems present difficulties for data analysis and administration. Robust algorithms, computational resources and data analytics knowledge are necessary for the efficient storage, processing and interpretation of huge data sets. Real-time data handling and analysis can be particularly difficult, especially for distributed or large-scale monitoring systems (Catbas, 2009; Li and Ou, 2016; Gulgec et al., 2017; Sadhu et al., 2023).

5.1.2 Sensor reliability and durability

One major problem is ensuring the longevity and dependability of sensors employed in SHM systems (Abbas et al., 2018). Sensor accuracy and performance can be impacted by age, mechanical stress, and environmental factors (Pham et al., 2020). Accurate and continuous time monitoring depends on preserving sensor reliability and resolving problems such as sensor drift, calibration and failure is essential (Ansari, 2005; Karbhari and Ansari, 2009; Jesus et al., 2017; Maraveas and Bartzanas, 2021; Mustapha et al., 2021).

5.1.3 Data interpretation and false alarms

Interpreting the collected data and distinguishing between normal structural variations and real damage or anomalies can be challenging (Kromanis and Kripakaran, 2016; Sun et al., 2020). False alarms or missed detections may result from noise, uncertainty, and fluctuation in sensor data (Moradi and Sivoththaman, 2014; Sarrafi and Mao, 2016). It is a continuous struggle to develop strong algorithms and models that consider these elements and offer reliable damage assessment (Rainieri and Fabbrocino, 2015; Jang et al., 2019; García-Macías and Ubertini, 2022).

5.1.4 Cost and scalability

The cost of implementing and maintaining SHM systems can be a significant challenge, especially for large-scale infrastructure or complex structures (Malere and Dos Santos, 2013; Ni et al., 2020). Installation costs for sensors, data acquisition systems and analytic tools might be high (Leduc, 2008; Smarsly and Law, 2014). Furthermore, it is still difficult to scale up SHM systems for broad industry and structural adoption while maintaining cost-effectiveness (Cawley, 2018; Ahmed et al., 2021).

5.2 Potential limitations of existing techniques

5.2.1 Limited sensitivity or resolution

Some existing SHM approaches may have limitations in their sensitivity or resolution, making it challenging to perceive and characterise certain types of defects or subtle changes in structural performance (Yao et al., 2014; Wu et al., 2021; Soleymani et al., 2023). The ability to identify and quantify smaller or localised damage accurately remains a challenge. Accurately identifying and measuring smaller or isolated damage is still difficult (Hackmann et al., 2012; Gomes et al., 2019).

5.2.2 Calibration and maintenance requirements

Certain techniques, e.g., strain gauges or accelerometers, necessitate regular calibration and maintenance to confirm accurate and reliable measurements (Guo et al., 2011; Chae et al., 2012; Vazquez-Ontiveros et al., 2021). These calibration and maintenance activities can be time-consuming and labour-intensive, posing limitations for continuous monitoring or remote locations (Niu, 2017; Sarrafi et al., 2018; Feng and Feng, 2021).

5.2.3 Intrusiveness or disruption

Some SHM techniques, particularly those involving invasive or destructive testing methods, can be intrusive or disruptive to the structure or its operation (Doshvarpassand et al., 2019; Aminzadeh et al., 2023). Access to the monitored region may be necessary for intrusive procedures, which can be difficult for operational structures or in some situations (Boller, 2013; Cawley, 2018).

5.2.4 Complexity and expertise requirements

It may be necessary to have certain training, knowledge and experience in order to use and comprehend the outcomes of several SHM procedures (Brandt et al., 2017; Azimi et al., 2020). The complexity of analysis algorithms or models can limit their widespread adoption and applicability (Gupta et al., 2013; Khan and Yairi, 2018; Mendez et al., 2019; Zhang et al., 2022).

5.3 Promising research areas and future directions for improving SHM systems

5.3.1 Multimodal sensing and fusion

The integration of multiple sensing modalities holds promise for additional comprehensive and accurate SHM (Garai et al., 2019). A combination of different sensors such as strain gauges, accelerometers, acoustic emission sensors and imaging technologies can provide a more holistic view of structural behaviour (Niezrecki et al., 2018; Kot et al., 2021; Sivasuriyan et al., 2021). Research in multimodal sensing and data fusion techniques aims to leverage the complementary strengths of different sensors to improve the detection and characterisation of structural damage (Ahmed et al., 2020; Freddi et al., 2021; Torbali et al., 2023).

5.3.2 Wireless power and communication

Advancements in wireless power transfer and communication technologies can enhance the scalability and ease of deployment for SHM systems (Ayyildiz et al., 2019; Śliwa et al., 2022). Wireless power solutions, such as energy harvesting and wireless charging, can eliminate the need for batteries and enable long-term autonomous operation of sensor nodes (Mathuna et al., 2008; Miller et al., 2010; Shaikh and Zeadally, 2016). Additionally, research in wireless communication protocols and networking schemes can improve the data transmission reliability and energy efficiency of SHM systems (Aygün and Cagri Gungor, 2011; Wang et al., 2012).

5.3.3 Structural health monitoring in extreme environments

A significant area of research is extending the capabilities of SHM to severe environments, such as deep-sea structures, high-temperature environments and space-based systems (Giurgiutiu et al., 2010; Dutta et al., 2021). Developing sensors and monitoring techniques that can withstand harsh conditions, adapt to extreme temperatures and operate in remote or inaccessible locations will enable effective monitoring and maintenance of critical infrastructure (Vaghefi et al., 2012; Giurgiutiu, 2014).

5.3.4 Artificial intelligence and machine learning

The advancement of SHM can be greatly facilitated by the integration of ML and AI approaches. Research in AI and ML algorithms aims to enhance damage detection and classification, improve anomaly detection and enable predictive maintenance strategies (Malekloo et al., 2022; Figueiredo et al., 2023). The development of intelligent algorithms that can learn from large-scale sensor data and historical information will enable a more accurate and efficient assessment of structural health (Ni et al., 2009; Yu et al., 2015).

5.3.5 Structural health monitoring for resilience and sustainability

Enhancing the sustainability and resilience of structures should be the main emphasis of future SHM research (Frangopol and Soliman, 2016). This includes developing monitoring strategies that consider the dynamic behaviour of structures under extreme loading events, such as earthquakes and hurricanes (Nagayama and Spencer, 2007; Chen, 2018). Furthermore, optimal maintenance planning and resource allocation will be made possible by integrating SHM with life-cycle assessment and decision-making frameworks, which will support sustainable practices (Caspeele et al., 2018; Bergez et al., 2022).

5.4 Integration of emerging technologies like IoT and cloud computing in structural health monitoring

The field of SHM has undergone a revolution with the incorporation of developing technologies such as cloud computing and the Internet of Things (IoT). These technologies improve the capabilities and effectiveness of SHM systems by providing new avenues for real-time data collecting, analysis and decision-making.

5.4.1 Internet of things (IoT) in SHM

The IoT plays a vital role in SHM by empowering the interconnectedness of sensors, devices and data communication (Tokognon et al., 2017; Malik et al., 2020). A network of sensors installed on structures that gather and communicate real-time data on a variety of structural characteristics, including strain, vibration, temperature and humidity, makes up IoT-based SHM systems (Bacco et al., 2020; Wiqar et al., 2023). After that, this data is transferred to cloud-based systems for processing, analysis and storage (Mishra et al., 2022). The IoT facilitates continuous monitoring, remote access and centralised data management, improving the scalability and accessibility of SHM systems (Motwani et al., 2022).

5.4.2 Cloud computing in SHM

The provision of scalable computational resources, storage capacities and data analysis tools via cloud computing has revolutionised SHM (Martín et al., 2022). Cloud-based platforms make it possible to centrally manage and securely store the enormous amounts of data produced by SHM systems (Martín et al., 2022). They facilitate numerous activities like anomaly identification, trend analysis and predictive modelling by enabling real-time data processing, analysis and visualisation (Lu et al., 2014; Palanisamy and Thirunavukarasu, 2019). The infrastructure and processing capacity needed for sophisticated data analytics, machine learning and artificial intelligence algorithms in SHM are made possible by cloud computing (Dang et al., 2021; Sony et al., 2021).

5.4.3 Benefits of integration

There are various advantages of integrating cloud computing and IoT in SHM (Jo et al., 2018; Kumar and Agrawal, 2023). First of all, it makes structural behaviour monitorable in real-time and continuously, allowing for the prompt identification of anomalies or possible breakdowns (Omrany et al., 2023). Second, cloud-based data analysis and storage make it possible to manage massive data sets effectively, which makes it possible to analyse structural health issues in greater detail and with greater accuracy (Tang et al., 2019a). Thirdly, SHM systems are more adaptable and economical due to the scalability and accessibility offered by IoT and cloud computing, which enables the monitoring of many structures in various places (Azimi et al., 2020; Rossi and Bournas, 2023).

6 Conclusions

6.1 The key points discussed in the article

- Structural Health Monitoring (SHM) is critical to maintaining the durability, dependability and safety of a variety of structures in industries like renewable energy, aircraft and civil infrastructure.
- SHM makes proactive maintenance, early damage detection and continuous monitoring possible, which improves performance and lowers risks.
- The functionality and effectiveness of monitoring systems have been greatly increased by recent developments in SHM approaches, including data analytics, non-destructive testing procedures and wireless sensor networks. Real-time monitoring, precise damage detection and effective data processing and analysis are made possible by these developments.
- SHM plays a crucial role in the assessment, maintenance and management of bridges, buildings, wind turbines, aircraft and offshore platforms.
- Case studies and examples have demonstrated the effectiveness of SHM in detecting and preventing failures, thereby enhancing the safety and reliability of structures.
- Data management, sensor reliability, data interpretation, cost scalability and technique restrictions are among the obstacles and limits in SHM that still exist despite progress.
- Research is concentrated on topics including artificial intelligence, resilience and sustainability, multimodal sensing, wireless power and communication and monitoring of extreme environments. Ongoing research helps to solve new problems and needs, adopt sustainable practices, optimise maintenance plans, increase safety and integrate emerging technologies.
- To sum up, SHM is essential for guaranteeing the dependability and safety of structures in a variety of industries. While case studies have shown their efficacy in averting failures, recent developments in SHM approaches have improved monitoring capacities. Nonetheless, obstacles and constraints continue to exist, highlighting the necessity of continued investigation and creativity. ongoing research endeavours will lead to further advancements in SHM, improving safety, optimising maintenance strategies and addressing emerging challenges.

6.2 Importance of ongoing research and innovation in advancing SHM

6.2.1 Enhancing safety and reliability

Sustaining the safety and dependability of structures requires ongoing SHM research and innovation. Researchers are able to identify and evaluate structural deterioration or anomalies in real-time, facilitating prompt interventions and maintenance procedures, by creating more precise, sensitive and dependable monitoring tools. By taking a proactive stance, the likelihood of structural breakdowns is greatly decreased, safeguarding infrastructure and saving lives.

6.2.2 Optimising maintenance strategies

In SHM, ongoing innovation and research allow for the creation of sophisticated models, algorithms and decision-support tools for maintenance strategy optimisation. Through the amalgamation of data-driven methodologies, machine learning and predictive analytics, scholars may discern patterns, forecast structural performance and enhance the scheduling of inspections and maintenance. This results in less downtime, more efficient operations and cost-effective maintenance planning.

6.2.3 Enabling sustainable practices

The adoption of sustainable practices in structural management is facilitated by ongoing research in SHM. Researchers can reduce environmental consequences, increase the lifespan of structures and improve resource allocation by integrating life-cycle assessment approaches, data analytics and decision-making frameworks. Reducing material waste, preserving resources and encouraging a greener and more sustainable built environment are all made possible through sustainable SHM practices.

6.2.4 Embracing emerging technologies

The incorporation of cutting-edge technologies like cloud computing, artificial intelligence and the Internet of Things into SHM systems is fuelled by ongoing research and innovation. These technologies provide new avenues for data analysis, remote access to structural information and real-time monitoring. By means of continuous investigation, scholars can refine the amalgamation of these technologies, augment their capabilities and tackle any constraints or difficulties linked to their execution.

6.2.5 Addressing new challenges and demands

Research in SHM must continue since structures are dynamic and new problems are always emerging. In order to create new monitoring approaches, modify current procedures and meet new needs, it is necessary to continuously innovate due to factors including the age of assets, the complexity of infrastructure, extreme weather occurrences and shifting design paradigms.

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