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Review of State-of-the-art of structural health monitoring in hydrogen composite pressure vessels

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ABSTRACT

Ensuring the safety and durability of composite pressure vessels is critical due to their extensive use in aerospace, automotive, and energy sectors. This review examines recent advances in Structural Health Monitoring (SHM) technologies tailored for Composite Overwrapped Pressure Vessels (COPVs). Special focus is given to flexible strain sensors based on nanofillers such as carbon nanotubes, graphene, MXene, and polymer nanocomposites, which provide high sensitivity, stretchability, and tunable sensing behavior. Key sensing mechanisms including tunneling, piezo-resistivity, and crack propagation and fabrication methods influencing sensor performance and integration are discussed. Shape memory alloy (SMA) filament sensors are also analyzed for their exceptional fatigue resistance, elastic stretchability, and high gauge factors. Case studies demonstrate their practical effectiveness under cyclic pressure loading and burst tests. The review further highlights multifunctional composites integrating self-sensing features for next-generation smart pressure vessels. Challenges related to sensor embedding, environmental impacts, data processing, and scalability are addressed. Future research directions emphasize multi-scale modeling, machine learning for damage detection and prognosis, and fully autonomous SHM systems enabling real-time safety management. These advances are poised to enhance reliability, reduce maintenance costs, and extend the operational life of composite pressure vessels in demanding industrial applications.

1. Introduction

Composite Overwrapped Pressure Vessels (COPVs) are integral to hydrogen energy systems due to their high strength-to-weight ratio and mechanical resilience [1,2]. As hydrogen storage requirements intensify, COPVs have gained prominence over metallic tanks for their enhanced safety and energy density [3–6]. Structural Health Monitoring (SHM) is increasingly essential in this context, enabling damage detection and lifecycle assessment under cyclic and harsh service conditions [7–9]. Smart COPVs, embedding real-time diagnostics, represent a step toward autonomous SHM systems. Smart pressure vessels are advanced storage systems equipped with embedded sensors and diagnostic capabilities, while fully autonomous structural health monitoring (SHM) refers to the self-contained, real-time detection and assessment of damage or degradation without human intervention.

Traditional SHM approaches based on fiber Bragg gratings and piezoelectric ceramics face integration challenges in composites [10–13]. In contrast, flexible nanocomposite piezoresistive sensors using CNTs, graphene, or MXenes offer improved durability, sensitivity, and adaptability to curved surfaces [14–16]. Conductivity in such materials is governed by tunneling, hopping, and percolation mechanisms, all sensitive to mechanical strain ideal for SHM integration.

Advanced modeling supports both vessel design and SHM data interpretation. Analytical and numerical frameworks, including Classical Laminate Theory and progressive failure models, have been applied to simulate failure initiation and propagation [17–24]. FEM-based studies confirm the role of winding angle, fiber clustering, and polar boss stresses in failure evolution [25–30].

Manufacturing-process optimization has further emphasized how nozzle diameter, pre-tension, and filament winding parameters affect impregnation quality and mechanical properties [31–34]. Fig. 1 underscores the rising global interest in COPVs and SHM over the last decade, with steady increases in research output and patent activity.

This document provides a comprehensive review of the state-of-the-art in composite hydrogen pressure vessels, focusing on their structural

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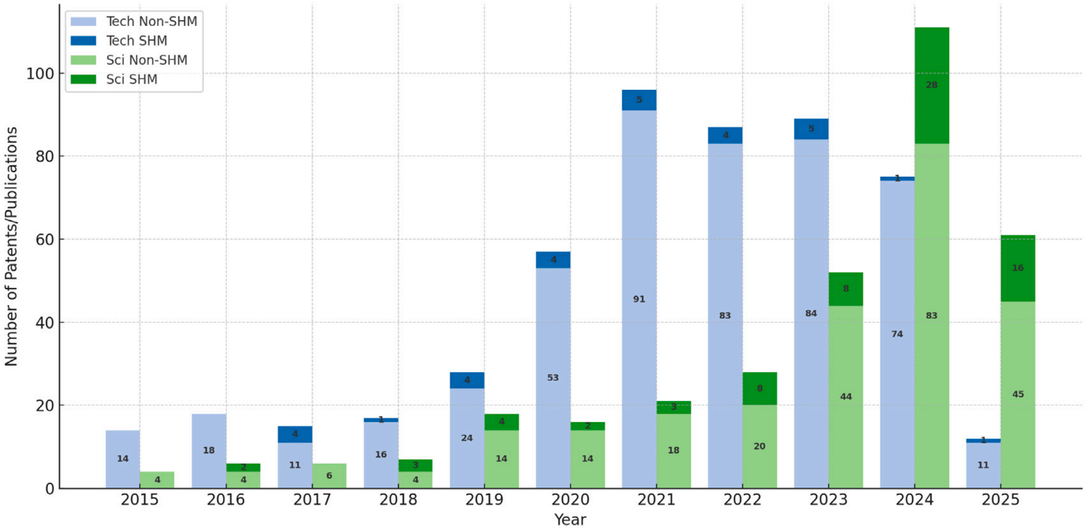


Fig. 1. Analysis of the evolution in patent filings and scientific publications concerning COPVs broadly, and SHM for COPVs in particular, over the last ten years.

design, failure mechanisms, and advances in SHM integration. Particular attention is given to the role of nano-material-based self-sensing systems and embedded piezoelectric sensors, highlighting their potential to enable smart, responsive composite structures. The document presents a selection of representative studies acknowledging that the coverage is not exhaustive but intended to illustrate key contributions in the field. The document is organized as follows: Section 2: **Architecture and Failure Behavior of Composite Hydrogen Vessels** explores the layered architecture of COPVs, analyzing how factors such as fiber orientation, matrix composition, and manufacturing processes influence failure modes including matrix cracking, delamination, and fiber rupture. Followed by Section 3: **Techniques and Advances in SHM for Composite Pressure Vessels** that gives an overview of current SHM technologies, covering acoustic emission, strain sensing, fiber optic methods, and their integration challenges in harsh operational environments. Section 4: **Self-Sensing Based on Nano-Fillers** examines how nano-materials such as carbon nanotubes, graphene, and MXenes can be embedded into the composite matrix to enable intrinsic sensing capabilities for strain, damage, and environmental conditions. In Section 5: **Integration of Piezoelectric Sensors in Composite Pressure Vessels**, we discuss the embedding of piezoelectric elements within composite layers for active and passive SHM, including methods for detecting damage and characterizing mechanical loading. Section 6: **Applications and Case Studies** focuses on real-world implementations of smart composite vessels, showcasing aerospace and automotive case studies that demonstrate the feasibility and advantages of integrated SHM systems. The final Section 7 summarizes key insights, technological gaps, and future directions for the development of intelligent, high-performance composite pressure vessels for hydrogen storage.

2. Architecture and failure behavior of composite hydrogen vessels

The structural performance of composite hydrogen pressure vessels depends on design choices such as geometry, layup, and material selection, which influence stress distribution, burst strength, and buckling resistance [35–37]. Finite element studies show that toroidal and hemispherical geometries with optimized layups (e.g., basalt/epoxy $[-45/45]_s$) offer enhanced burst pressure and stability, supporting their potential in ISO-compliant hydrogen storage and high-pressure transport applications [38–40].

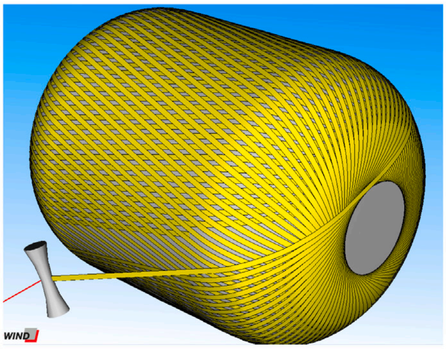
2.1. Materials and manufacturing processes

A wide range of primary materials and fabrication methods have been explored for composite hydrogen pressure vessels, with a particular focus on fiber–matrix selection [41–43] and advanced manufacturing techniques such as filament winding and automated fiber placement (AFP) [44–47]. These factors critically influence the structural performance of the vessels, shaping the current state of the art. Notably, Park et al. [48] modeled filament winding patterns for complex shapes using ABAQUS [49], with experimental validation on standard test bottles. Sharma et al. [50] analyzed six dome geometries, showing that ellipsoidal and isotensoidal profiles significantly enhance burst pressure and internal volume. Similarly, Kumar et al. [51] found that equal thicknesses of metal liners and composite layers optimize burst strength and stiffness in Type-III COPVs. Belardi et al. [52] proposed a bending theory tailored for the transition zones of linerless Type-V vessels, offering a closed-form analytical tool beyond traditional membrane theory.

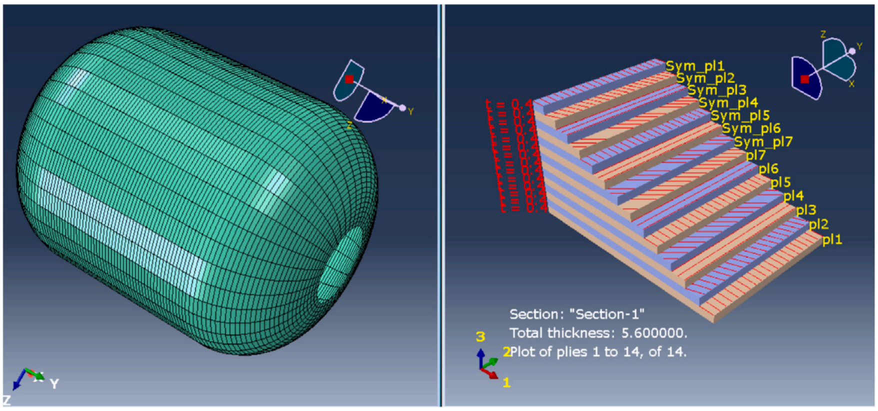
Recent advancements also target material enhancement for linerless cryogenic hydrogen vessels. Studies have introduced strategies to improve resin toughness and hydrogen barrier properties [53–55], including the incorporation of Multi-walled carbon nanotubes (MWCNTs) into epoxy, which boosts cryogenic tensile strength and gas impermeability [56]. Composite systems such as T700/Epoxy and Basalt/Epoxy offer trade-offs between performance and sustainability [57], while PE inter-layers have been shown to improve cryogenic adhesion and reduce hydrogen permeability below international thresholds [58,59]. Complementarily, Bouhala et al. [60] presented a comparative review of finite element modeling approaches for COPVs, and dos Reis et al. [61] proposed a robust Ni/Pt catalyst for hydrogen generation, underlining the broader innovation landscape in hydrogen energy technologies.

2.2. Failure mechanisms

Composite hydrogen vessels experience complex failure mechanisms such as matrix cracking, fiber breakage, interfacial debonding, and delamination often initiated by internal pressure, thermal stresses, or manufacturing flaws [62,63]. These phenomena have been examined using classical laminate theory and various failure criteria (e.g., Tsai–Wu, Hashin) [64], enabling advancements in simulation and optimization for burst pressure prediction, lifetime estimation, and lightweight structural design. Experimental and analytical studies also reveal the influence of size on fiber strength [65] and compare



(a) Stacking design using CADWIND [69]



(b) Tow orientation and stacking sequence displayed in ABAQUS[49].

Fig. 2. Sequential Design of a Composite Overwrapped Pressure Vessel (COPV) using CADWIND [69]and Finite Element Analysis in ABAQUS [49].

the performance of different matrix systems carbon/vinylester composites, for instance, exhibit higher ultimate pressures and delayed damage initiation than epoxy-based ones [66]. Alternative eco-friendly fibers have been evaluated against conventional T700S carbon fiber for sustainable COPV design [67]. Furthermore, multiscale modeling using Representative elementary volume, coupled with Finite Element Analysis (FEA), has effectively predicted vessel failure through progressive damage analysis and stiffness degradation [68]. Fig. 2 illustrates a design workflow combining CADWIND for stacking sequence and ABAQUS for FEA-based failure assessment.

Recent efforts aim to enhance modeling accuracy while streamlining SHM integration [70]. Leh et al. [71] demonstrated that both mixed and solid finite element models can effectively simulate burst behavior in filament-wound hydrogen vessels, enabling significant design time and cost reductions using minimal experimental input. Wang et al. [72] advanced a micromechanics-based failure model embedded in ABAQUS to capture constituent-level damage and post-failure behavior under coupled pressure-thermal loads. Zhang et al. [73] provided a comprehensive overview of failure prediction methods, including failure criteria and progressive FEA strategies. More recently, models tailored for Type V prepreg-based COPVs showed strong agreement with burst tests [74], while broader reviews emphasized the roles of experimental–numerical coupling, hydrogen–thermal interactions, and uncertainty quantification [75]. Machine learning is also gaining traction for burst pressure prediction based on manufacturing parameters, with kPCA-Lasso, GPR, and ensemble regressors offering high accuracy and robust uncertainty handling [76–79].

3. Techniques and advances in SHM for composite pressure vessels

Structural Health Monitoring (SHM) describes the technology-driven continuous assessment of a structure to facilitate early damage detection and prevent structural failures. The key benefits of SHM include increasing the safety of structures while minimizing their dead weight and downtime. Additionally, SHM enables timely maintenance and repair, improving structural integrity, reliability, and availability. This proactive approach not only extends the life of structures but also contributes to long-term cost savings. SHM has been successfully applied across various engineering fields such as infrastructure [80], wind energy [81], aircraft [82], and automotive engineering [83]. Comprehensive reviews on SHM methodologies and applications can be found in [8,80,81,84,85]. Commonly, SHM employs non-destructive testing (NDT) techniques [86] such as acoustic emission and ultrasonic testing to acquire data, which is then processed and analyzed often using machine learning algorithms to evaluate structural condition [87,88]. An overview of SHM techniques with their advantages and disadvantages is provided by Hassani et al. [87], including methods such as acoustic emission, digital image correlation, neutron imaging, and ultrasonic testing. SHM techniques can be classified in several ways:

Local vs Global Techniques: Based on the size of the structure area being monitored [87].

Active vs Passive Techniques: Active methods involve actuating or exciting the structure and measuring its response (e.g., ultrasonic testing), whereas passive methods measure signals generated by operational loads or damage initiation (e.g., acoustic emission) [85,88].

Static vs Dynamic Methodologies: Static approaches assess the structure in a steady state (e.g., electrical impedance tomography),

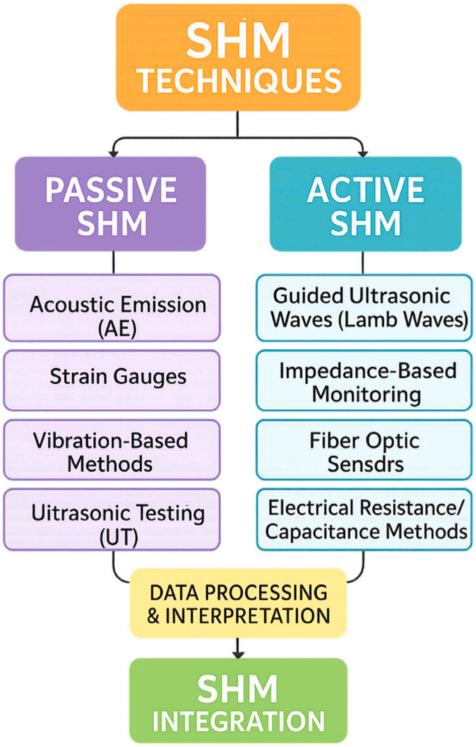


Fig. 3. Overview of existing structural health monitoring (SHM) techniques applied to COPVs.

while dynamic methods focus on responses to transient events (e.g., electromechanical impedance) [85].

Data Homogeneity: Use of multiple sensors of the same type (homogeneous data) or different types (heterogeneous data) to overcome issues such as redundancy and environmental noise [85].

Baseline-Dependent vs Baseline-Independent Methods: Baseline-dependent approaches compare data from damaged and undamaged states, while baseline-independent methods analyze structural responses without prior baseline information [87].

Physics-Based vs Data-Driven Methodologies: Physics-based methods use analytical or numerical models to simulate damage [89,90], whereas data-driven (machine, deep learning, etc.) methods rely solely on processing sensor data to diagnose damage [82,91].

These techniques support various levels of damage diagnosis, including detection (level 1), localization (level 2), classification (level 3), and quantification (level 4). This multi-level assessment may further enable prognosis of the remaining useful life of the structure [84].

3.1. Overview of SHM Techniques and Sensor Technologies

An overview of key Structural Health Monitoring (SHM) techniques and sensor technologies used in composite pressure vessels can be found in [92,93]. Here we discuss both passive and active approaches such as acoustic emission, strain sensing, fiber optic sensors, and guided wave methods highlighting their strengths, limitations, and practical applications [94]. While not exhaustive, the review focuses on significant advancements and strategies for effective damage detection and long-term structural assessment under challenging conditions. Fig. 3 provides an overview of existing structural health monitoring (SHM) techniques applied to Composite Overwrapped Pressure Vessels (COPVs), highlighting the various sensing technologies, signal processing approaches, and diagnostic strategies currently employed to assess structural integrity and predict failure.

A variety of SHM techniques have been explored for composite pressure vessels, including:

- Fiber Optic Sensors: Fiber Bragg Gratings (FBGs) and distributed fiber optic sensors are widely used for strain and temperature monitoring due to their high sensitivity, immunity to electromagnetic interference, and capability for embedding within composite layers [80,88,95–97]. Their use in composite pressure vessels has been demonstrated to allow real-time monitoring of strain and thermal effects without compromising structural integrity [85,98–101].
- Acoustic Emission Sensors: These sensors detect real-time acoustic signals generated by cracking, delamination, or fiber breakage events, providing early-warning damage detection and monitoring [87,102]. Acoustic emission techniques have been shown to be effective in detecting matrix cracking and micro-damage in composite vessels subjected to pressure cycling [84,103]. Hoop tensile properties and damage evolution in filament-wound CFRP composites with varying winding angles can be explored using acoustic emission and deep learning. A Mel spectrogram-based Convolutional Neural Network (CNN) model effectively classifies damage modes, revealing that ±55° winding enhances tensile strength, with dominant failure modes being matrix cracking and fiber/matrix debonding [104].
- Ultrasonic Guided Waves (UGWs): UGWs enable monitoring across large areas with high sensitivity to defects inside multi-layer composites, making them suitable for detecting internal flaws in complex vessel geometries [87,88,105,106]. Their application in composite pressure vessels allows for detection of delamination and impact damage at early stages [89,107,108].
- Piezoelectric Sensors: Often used in active SHM systems, piezoelectric sensors generate and receive ultrasonic waves, monitor structural vibrations, and can detect changes in wave propagation caused by damage [85]. Embedding piezoelectric transducers in composite vessel walls supports wave propagation based damage detection while enabling simultaneous actuation and sensing [88].

3.2. Integration and challenges

Embedding or surface-mounting sensors on composite pressure vessels poses challenges related to sensor durability, signal attenuation, and potential impact on the vessel's mechanical properties. Careful consideration of sensor placement, bonding methods, and environmental protection is crucial to maintain both sensor performance and structural integrity [87,88]. The multilayer heterogeneous nature of composites and operational conditions (temperature, humidity, pressure) also complicate SHM implementation [84].

In summary, the continuous development and integration of advanced sensors and data analysis techniques pave the way for robust SHM systems that enhance the safety and operational reliability of composite pressure vessels in hydrogen storage and other critical applications.

4. Self sensing based on nano-fillers

An emerging and promising approach in structural health monitoring of composite pressure vessels involves the integration of nano-fillers within the composite matrix to enable *self-sensing* capabilities. Unlike traditional SHM systems that rely on externally mounted or embedded sensors, self-sensing composites inherently detect and report damage or deformation via changes in intrinsic properties such as electrical conductivity or impedance. Various nano-fillers such as carbon nanotubes (CNTs), graphene nanoplatelets (GNPs), carbon black, MXene and metallic nanoparticles are dispersed in the matrix to establish conductive networks. Under applied loads or damage scenarios, these networks undergo perturbations, leading to measurable electrical resistance changes [93,109–112]. To guide the selection of nanomaterial-based sensors for hydrogen COPVs, Table 1 presents a comparative

Table 1
Comparative summary of CNTs, Graphene, and MXenes for sensing in hydrogen COPV environments.

Criterion	CNTs	Graphene	MXenes
Strain/Damage Sensitivity	Moderate (GF ∼ 2–10), piezoresistive [113,114]	High (GF up to 1000), sensitive to cracks [115]	Very high (GF > 100), tunable surface response [116]
Hydrogen Detection	Moderate (doping effects), low selectivity [117]	High sensitivity at defects/edges [118]	Excellent (fast, selective, surface termination–driven) [119]
Integration in COPVs	Mature: spray, film, yarns [120]	Challenging: transfer, adhesion [121]	Good: inkjet/sprayable, adherent via -OH/-F groups [116]
Electrical Conductivity	∼ 10^3–10^4 S/m [113]	∼ 10^5 S/m, layer/defect dependent [115]	∼ 10^4–10^5 S/m, high EMI shielding [122]
Environmental Stability	Good, but UV/oxidation sensitive [117]	Fair, needs encapsulation [118]	Limited, degrades with moisture/air [119]
Thermal/H_2 Compatibility	Stable, chemically inert [114]	Stable, but defects susceptible to H_2 [118]	Moderate, reactive surface groups [119]
SHM Suitability in COPVs	Reliable for strain/damage sensing [120]	High-performance with protection [115]	Promising for dual sensing; stability improving [116]
Maturity and Scalability	High: commercial, proven [113]	Moderate: integration/cost limits [121]	Emerging: scalable, stability in progress [122]

summary of the key performance attributes of carbon nanotubes, graphene, and MXenes. The evaluation considers their strain and hydrogen sensing capabilities, integration compatibility with composite structures, environmental durability, and overall maturity for structural health monitoring in harsh hydrogen environments. This comparison highlights both the technological readiness and current limitations of each material in realistic COPV operating conditions.

The piezoresistive effect allows for real-time monitoring of damage events such as matrix cracking, fiber/matrix debonding, and delamination. For example, Thostenson et al. [109] demonstrated early on that CNT-filled epoxy composites exhibit significant resistance changes under strain, making them suitable for strain sensing. Bauhofer and Kovacs [110] provided a detailed review of the conductive percolation threshold and sensor response for various CNT/polymer systems. More recently, Omrani et al. [111] investigated the influence of dispersion and aspect ratio of nanofillers on sensing capabilities, concluding that uniform dispersion is crucial for consistent performance. Self-sensing composites offer advantages in terms of high spatial resolution, reduced sensor weight, and simplified integration [112,123]. However, challenges remain, such as achieving uniform nano-filler dispersion, optimizing filler content for simultaneous sensing and mechanical reinforcement, and managing signal drift due to environmental variations [124].

Fig. 4 depicts the experimental setup used for self-sensing structural health monitoring during a three-point bending test, featuring various electronic systems dedicated to signal acquisition, conditioning, and processing.

4.1. Preparation of conductive polymer piezoresistive sensors

Piezoresistive conductive polymer sensors are widely studied for structural health monitoring due to their intrinsic flexibility, lightweight nature, and ease of fabrication. These sensors are typically fabricated by incorporating electrically conductive fillers such as carbon black, carbon nanotubes (CNTs) [16], graphene, or metallic nanowires into a polymer matrix to create a percolated conductive network [125,126]. The percolation threshold is a critical concept in such composites, representing the minimum filler concentration required to establish a continuous conductive path within the insulating polymer [127]. Near this threshold, small mechanical deformations can significantly disrupt or enhance conductive pathways, leading to a large change in resistance and thus a high piezoresistive sensitivity [128]. Therefore, by precisely tuning the filler concentration just above the percolation point, one can design highly sensitive strain or pressure sensors using a minimal amount of conductive material, which also preserves the polymer's flexibility and processability [129]. Common matrices include elastomers like polydimethylsiloxane (PDMS) and polyurethane (PU), while fabrication techniques such as melt mixing, solution casting, in-situ polymerization, or 3D printing are used depending on the target properties [130,131]. The piezoresistive response primarily arises from changes in tunneling resistance and conductive network rearrangement under mechanical load [132], making these sensors attractive for embedded monitoring of strain, fatigue, and damage evolution in composite structures such as COPVs.

4.2. Data acquisition and interpretation in self-sensing composites

The efficacy of self-sensing systems in composite pressure vessels hinges on robust data acquisition and interpretation frameworks. Raw signals from nano-sensing networks are typically non-linear, noisy, and sensitive to environmental and operational variabilities.

Signal processing techniques such as Fourier transform, wavelet analysis, and filtering algorithms are widely used to extract relevant information and reduce noise from raw electrical or impedance data [123,133]. These techniques help highlight damage signatures and isolate them from operational vibrations or environmental changes.

The advent of **machine learning and data analytics** has enabled new paradigms in damage diagnosis [103,134,135]. Techniques such as support vector machines (SVM), convolutional neural networks, and autoencoders are increasingly used to perform pattern recognition, damage localization, and prediction of remaining useful life (RUL) [88,124,136]. These methods are especially powerful when dealing with high-dimensional, heterogeneous sensor data.

However, **challenges in data interpretation** persist. The complexity of signal patterns in heterogeneous, anisotropic materials like composites makes it difficult to draw universal conclusions. Baseline

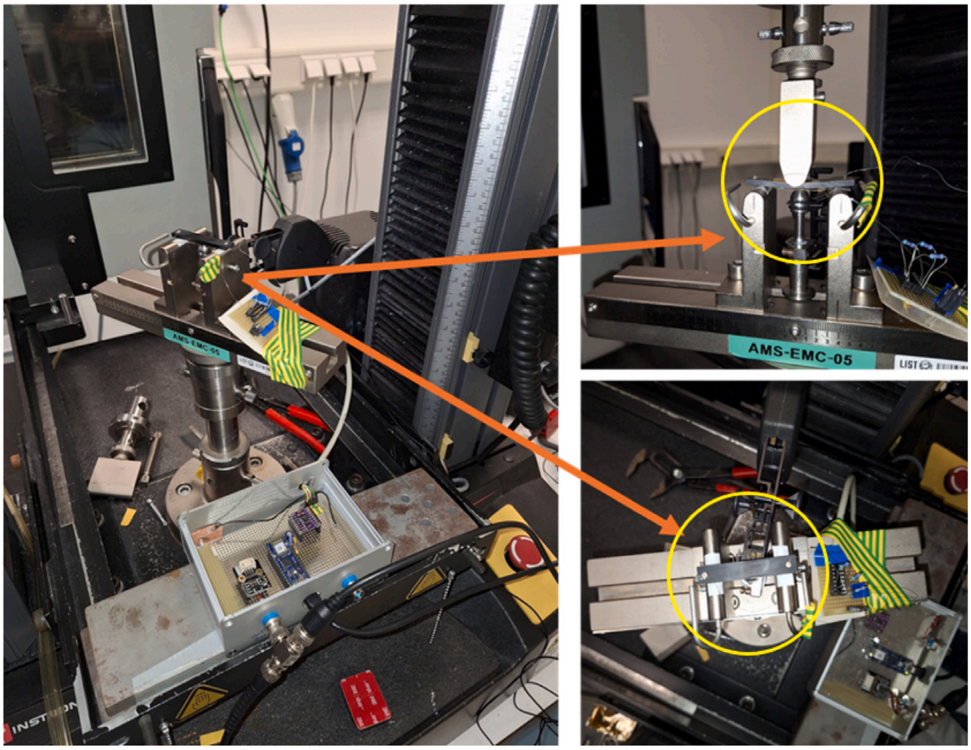


Fig. 4. Experimental setup for self-sensing structural health monitoring under a three-point bending test, incorporating multiple electronic systems for signal acquisition and processing.

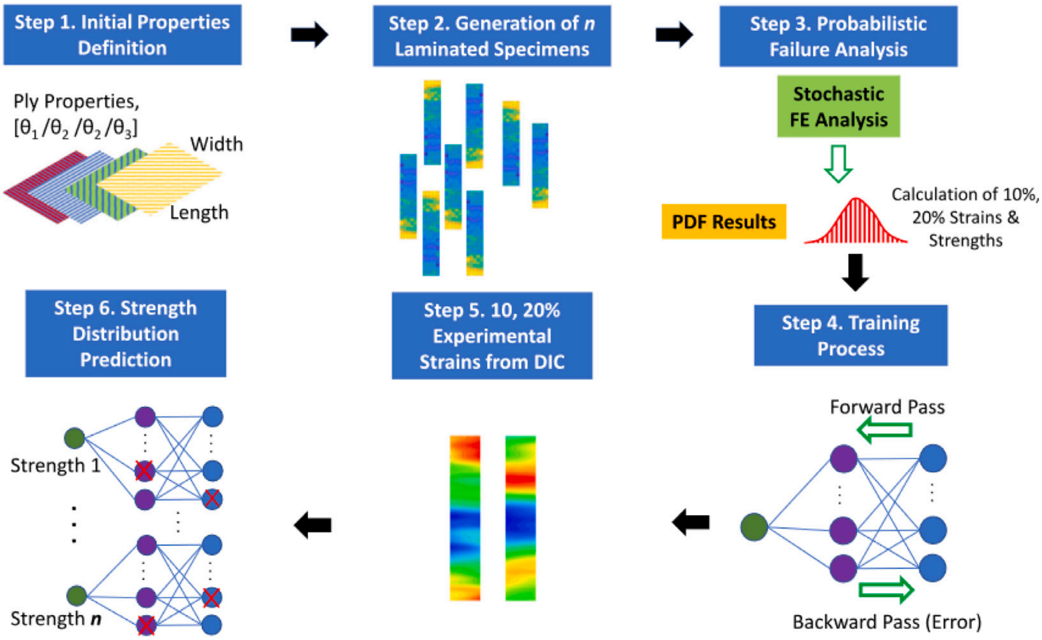


Fig. 5. The concept of non-destructive methodology for prediction of strength in composite laminates using deep learning and the stochastic finite element methods, adapted from [139].

shifts due to temperature, moisture, and long-term aging can mask or mimic damage signatures, leading to false positives or missed detections [84,85]. Thus, there is a growing trend towards hybrid methods that combine physics-based models and data-driven approaches for robust SHM [89,90,137,138].

Fig. 5 presents the conceptual framework of a non-destructive approach for predicting the strength of composite laminates, combining deep learning techniques with stochastic finite element analysis to account for material variability and uncertainty. The data-driven methodologies have proved to be more efficient and robust compared with traditional physics-based methods for damage detection, localization and quantification [140]. There are several reasons for implementing machine learning (ML) algorithms for SHM related problems [141], such as:

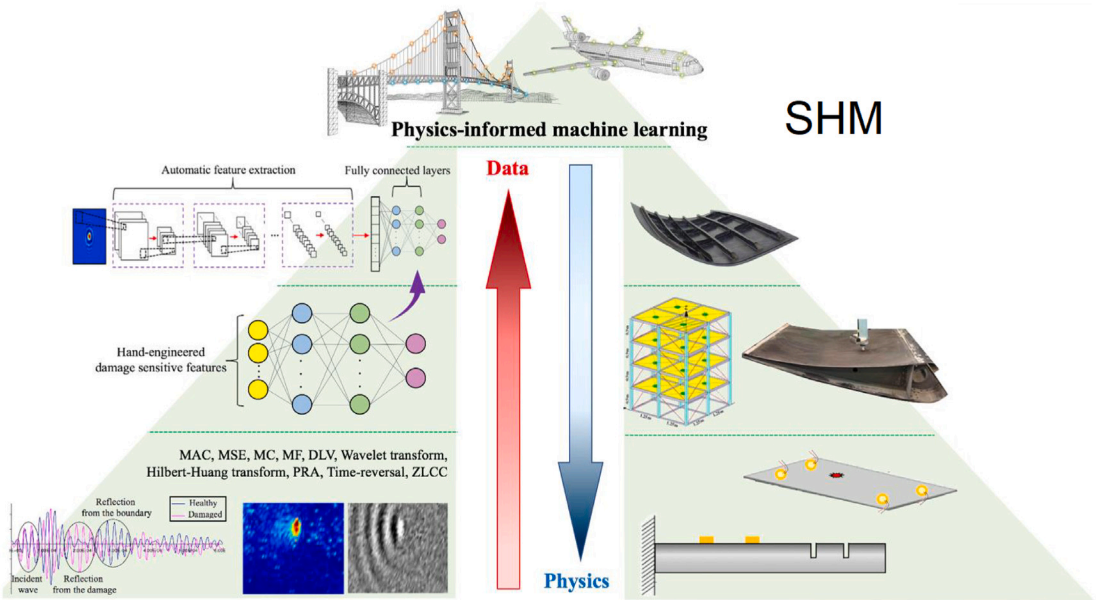


Fig. 6. The concept of non-destructive methodology for prediction of strength in composite laminates using physics informed machine learning, adapted from [149].

- **Automation**: ML automates sensor data analysis, reducing time and resources that would be spent on manual analysis.
- **Handling data**: ML algorithms are built to handle and analyze large volumes of data in high-dimensional spaces.
- **Adaptability**: ML algorithms are designed to learn and adapt over time, identifying patterns and anomalies in data to generate results and improving accuracy with increased data exposure [142,143].
- **Cost effectiveness**: Manual structural monitoring is costly, labor-intensive, and susceptible to bias and errors. ML algorithms address these challenges by offering efficient, cost-effective, and unbiased monitoring solutions.
- **Developing continuously**: ML techniques are rapidly evolving, enabling accurate, reliable analysis of complex real-world data and advancing SHM from lab settings to real-life engineering applications [144,145].

Physics-informed ML enhances traditional ML by integrating physical laws, improving the accuracy and reliability of model predictions [141,146,147]. A Structural Health Monitoring Digital Twin (SHMDT) model framework is proposed to address the growing integration between SHM technology and Digital Twin (DT), aiming to enhance the digitalization, visualization, and intelligent management of SHM systems [148].

In particular, deep learning (DL) has transformed SHM by enhancing model efficiency, safety, and reliability, and enabling its application in complex real-world infrastructures. DL has opened new avenues in vibration-based, data-driven SHM for large-scale structures, enabling efficient acquisition and processing of data from diverse sensors [150–153]. However, DL faces key limitations, including high labeled data demands, inconsistent results, and poor generalization to unseen scenarios. Fig. 6 presents the concept of a non-destructive methodology for strength prediction in composite laminates using physics-informed machine learning, which integrates physical modeling with data-driven approaches to enhance predictive accuracy.

5. Integration of piezoelectric sensors in composite pressure vessels

Piezoelectric materials play a critical role in Structural Health Monitoring (SHM) of composite pressure vessels, enabling both sensing and actuation functions. Common piezoelectric materials include lead zirconate titanate (PZT), polyvinylidene fluoride (PVDF), and quartz. PZT offers high piezoelectric coefficients and is ideal for sensing strain and generating guided waves; PVDF provides flexibility and low weight for embedding within composite laminates; and quartz delivers excellent stability and precision for high-accuracy measurements [154,155].

Fig. 7 presents an overview of various sensor types employed to monitor critical parameters necessary for verifying the operational and structural health status of the tank.

5.1. Current trends and advances

Smart Composites: Development of self-sensing composites integrates piezoelectric phases or coatings directly into the matrix, allowing the material to act as its own sensor. Such smart composites simplify SHM architectures and reduce wiring complexity [157,158].

Energy Harvesting and Wireless Monitoring: Piezoelectric energy harvesting devices convert ambient or operational vibrations into electrical power, enabling self-powered SHM systems. Coupled with wireless data transmission modules, these systems can monitor remote or inaccessible vessels without external power sources [159,160].

Multi-Functional Materials: Emerging designs incorporate both sensing and energy harvesting functionalities within a single material system. Examples include PVDF-based laminates that simultaneously monitor strain and harvest energy under dynamic loading [161,162].

5.2. Sensor integration techniques

Piezoelectric sensors in composite pressure vessels are implemented using three main approaches:

- **Embedded Sensors:** Piezoelectric elements (e.g., thin PZT wafers or PVDF films) are embedded between laminate plies during filament winding or lay-up, enabling real-time, internal monitoring without altering vessel integrity [92,163].
- **Surface-Mounted Sensors:** Piezo patches or strips are bonded onto vessel exteriors using adhesives, allowing retrofitting on existing structures and ease of replacement [164].
- **Smart Coatings:** Piezoelectric inks or coatings are directly applied to composite surfaces, forming conformal sensor networks that minimize added mass and preserve aerodynamic profiles [165].

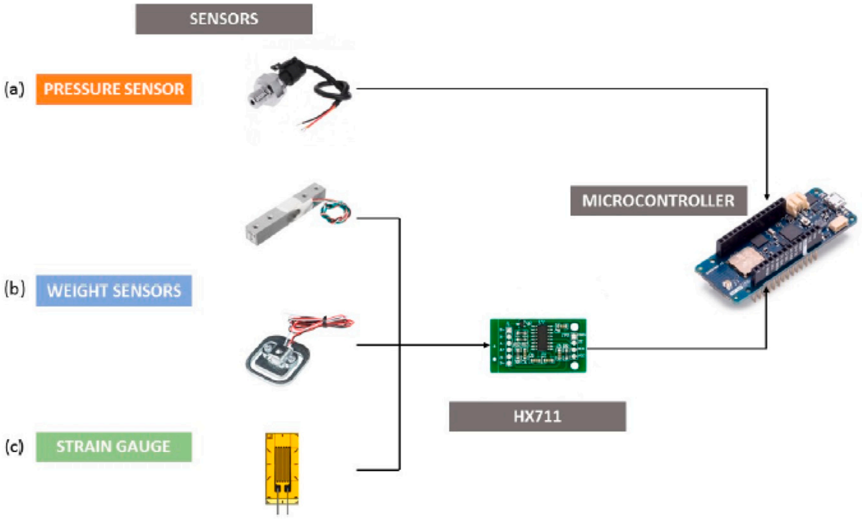


Fig. 7. Different types of sensors used to measure the different parameters necessary to verify the status of the tank [156].

5.3. Mechanisms of sensing and conduction

Piezoelectric sensing in composites relies on direct and converse piezoelectric effects:

- **Direct Effect:** Mechanical strain induces charge separation within the piezoelectric phase, generating a measurable voltage proportional to the applied stress [166].
- **Converse Effect:** Applied electric fields cause dimensional changes in the piezoelectric element, enabling active SHM methods like guided-wave generation for damage interrogation [167].

In contrast, nanofiller-based self-sensing composites utilize piezoresistive and tunneling conduction mechanisms. Conductive networks formed by carbon nanotubes, graphene, or metallic nanoparticles change resistance under strain due to percolation and tunneling effects [109,110,112]. Five key mechanisms govern their response: tunneling effect, geometric effect, intrinsic piezoresistive effect, crack propagation, and particle disconnection [168].

Fig. 8 integrates schematic representations from literature to summarize the combined effects of percolation behavior, tunneling resistance, and contact resistance under mechanical deformation, emphasizing how filler morphology, distribution, and strain influence device response.

5.4. Materials and technologies

PZT and PVDF: PZT wafers provide high sensitivity for ultrasonic and impedance-based SHM, while PVDF films offer flexibility for conformal sensing [173]. Quartz resonators deliver precise frequency-based measurements for critical areas (e.g., dome region).

Nanofiller Networks: Carbon nanotubes (CNTs) and graphene nanoplatelets (GNPs) dispersed in polymer matrices form self-sensing networks with gauge factors up to several hundred [111,174]. MXene sheets and metal nanowires (AgNWs) extend this concept to multifunctional sensing and energy harvesting [168,175].

5.5. Challenges and future directions

Despite significant advances, integrating piezoelectric and nanosensing technologies into composite pressure vessels faces several challenges:

- **Signal Interpretation:** Complex signal patterns due to anisotropy, multilayer construction, and environmental factors complicate damage diagnosis [84].
- **Manufacturing Compatibility:** Embedding sensors must not degrade mechanical performance or introduce defects during high-pressure vessel fabrication [176].
- **Reliability and Longevity:** Sensor durability under cyclic loading, temperature fluctuations, and hydrogen exposure requires extensive validation [80].

Future work should focus on hybrid SHM approaches that combine robust piezoelectric systems with self-sensing composites, advanced signal processing, and machine-learning-driven data interpretation to achieve fully autonomous monitoring solutions.

6. Applications and case studies

This section presents real-world examples of SHM applications in composite pressure vessels, focusing on nanofiller-based sensors and shape memory alloy (SMA) filament sensors. Performance metrics such as sensitivity, durability, and correlation with pressure profiles are discussed.

6.1. Application case for COPV

The integration of nanofiller-based flexible strain sensors in Composite Overwrapped Pressure Vessels (COPVs) has not been extensively studied, despite their promising robustness, sensitivity, and compatibility with COPV applications. Lin et al. [177] and Zhang et al. [178] benchmarked MXene (synthesized from etched Ti_3AlC_2 powder) and buckypaper (BP) nanofiller-based strain sensors for embedding in COPVs to create “smart” tanks capable of monitoring strain and pressurization states. The COPV structure consists of an aluminum-lined, filament-wound carbon fiber epoxy (CFRP) composite with a protective outer layer of glass fiber-reinforced polymer (GFRP). The vessel holds a nominal volume of 6.8 L, with operational and autofrettage pressures of 30 MPa and 50 MPa, respectively. Two sensor placements were explored:

1. MXene and BP sensors placed directly on the aluminum liner, followed by CFRP overwrap and a GFRP hoop-wound layer on top.
2. MXene and BP sensors placed on the outer surface of the first GFRP layer, with an additional GFRP layer wound over it.

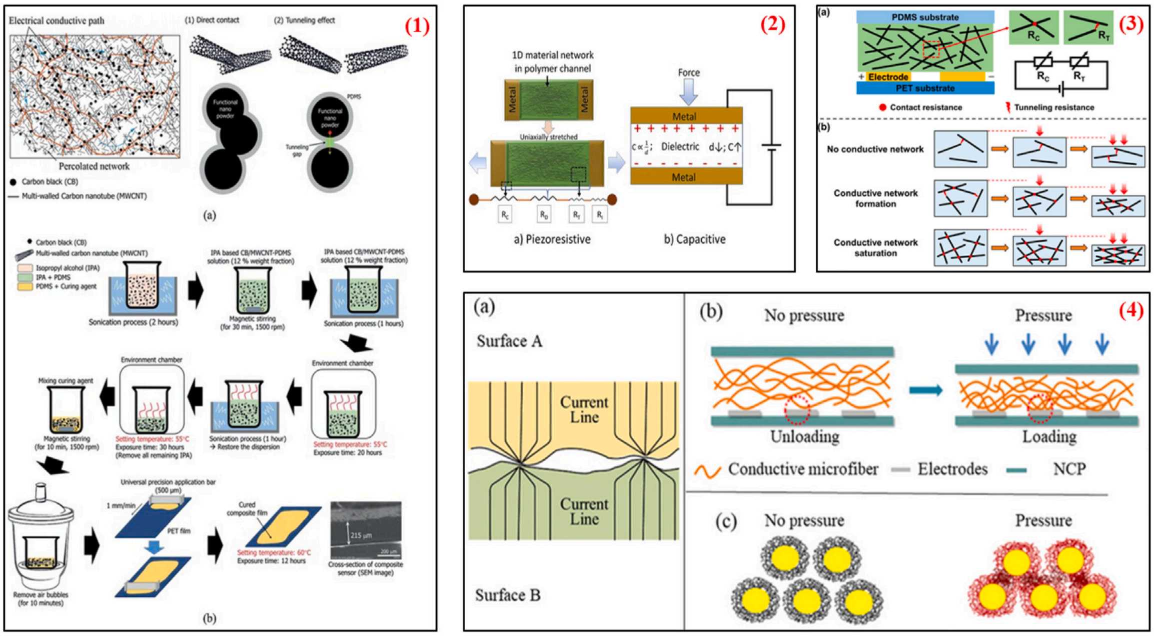


Fig. 8. Composite summary of piezoresistive sensing mechanisms in conductive polymer nanocomposites. (1) network percolation, particle contact and tunneling, adapted from [169]; (2) schematic of contact resistance R_C vs. tunneling resistance R_T under deformation, adapted from [170]; (3) resistance vs. filler content and response under cycling, adapted from [171]; (4) percolation topology for different filler morphologies adapted from [172].

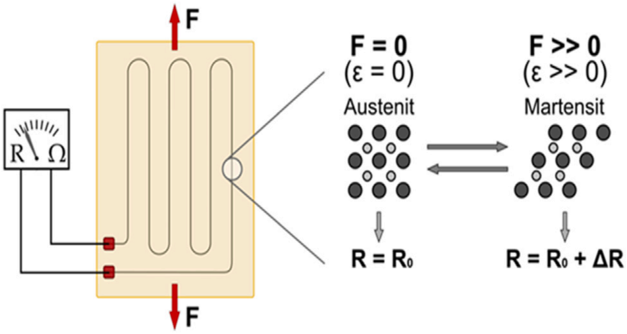


Fig. 9. Operating principle of SMA strain sensors.

Embedding these flexible sensors did not impact the structural strength or fatigue resistance of the COPV. Hydraulic pressure tests revealed distinct piezoresistive responses. For sensors embedded within the overwrap, MXene and BP exhibited similar resistance increases during pressurization, but BP sensors showed irreversible changes upon depressurization due to micro-crack propagation in the BP network. At the liner–overwrap interface, MXene displayed higher sensitivity to plastic deformation and residual compressive strain than BP, attributed to its lamellar network structure enhancing conductive pathways under compression. Filament sensors based on shape memory alloys (SMA) offer high cyclic fatigue resistance, elastic stretchability (up to 6%), and gauge factors above 5, enabled by reversible phase transformations that also modulate electrical resistance [179]. Fig. 9 illustrates the SMA sensing principle.

Under axial load, changes in geometry and Poisson's ratio ($0.3 < \nu < 0.45$ [180]) lead to resistance variations described by:

$$\frac{\Delta R}{R} = \left[(1+2\nu)_1 + \left(\frac{\Delta\rho}{\rho}\right)_2\right]\frac{\Delta L}{L} \tag{1}$$

and the gauge factor relation:

$$\frac{\Delta R}{R} = k\frac{\Delta L}{L} \tag{2}$$

In collaboration with Hexagon Purus, two natural gas pressure tanks were instrumented with SMA half-bridge sensors. Fig. 10 shows a tank equipped with transverse and longitudinal SMA sensors for circumferential and axial strain measurements.

Cyclic pressure loading (100 cycles) and burst tests were conducted. Fig. 11 compares hydraulic pressure (orange) and SMA strain signal (blue), showing stable maxima correlation and residual strain evolution due to composite settling and temperature rise from 22 °C to 35 °C, compensated by the half-bridge.

Fig. 12 presents burst-test profiles. Up to 125 bar, stiffness remains high; between 150–175 bar, slight stiffness decrease indicates further settling. At burst, the SMA half-bridge fails, and the strain signal diverges.

6.2. Performance evaluation

The case studies demonstrate that:

- MXene-based sensors offer superior sensitivity and reversible response suitable for liner health monitoring [177].
- BP sensors are prone to irreversible network damage under cyclic loading limiting re-usability [178].
- SMA filament sensors provide durable, high-fidelity strain measurements with effective temperature compensation in half-bridge configurations [179].

These findings underscore the feasibility and challenges of integrating nano-enabled and piezoresistive sensors in COPVs, highlighting the trade-offs between sensitivity, durability, and integration complexity.

7. Conclusion

7.1. Summary of findings

This review has explored the state-of-the-art in structural health monitoring (SHM) for composite overwrapped pressure vessels (COPVs), emphasizing the role of embedded strain sensing technologies. SHM plays a crucial role in ensuring the operational safety, performance optimization, and lifecycle cost reduction of high-pressure composite

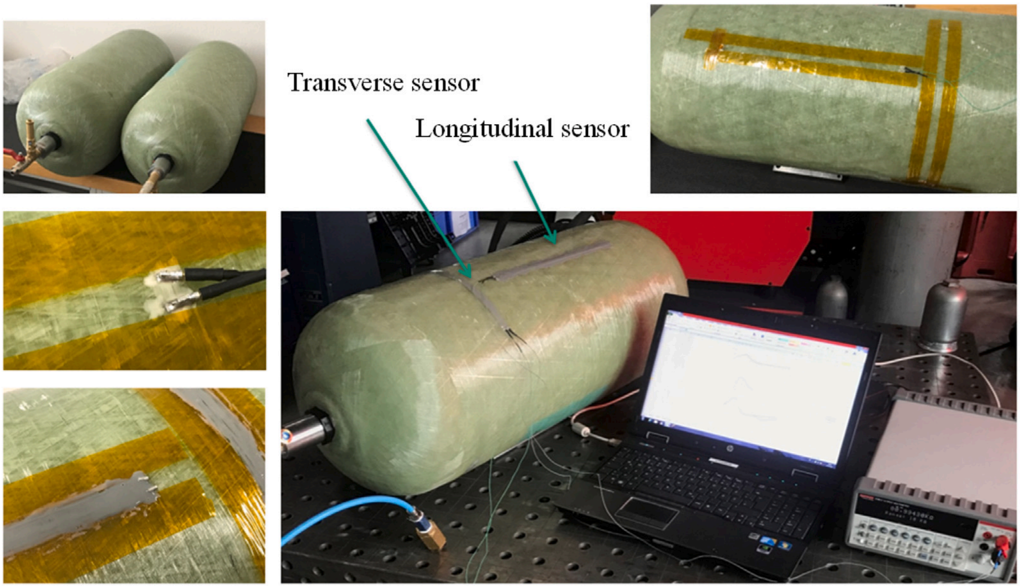


Fig. 10. Pressure tank with applied SMA sensors as a half-bridge for strain measurement under pressure loading.

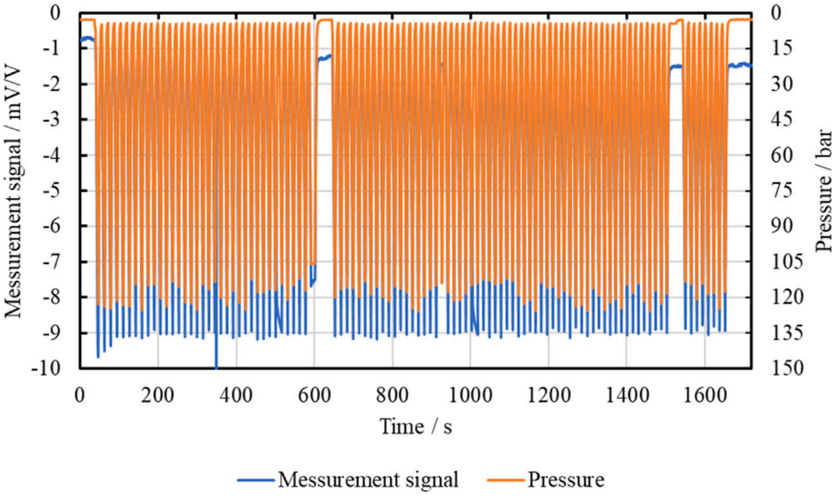


Fig. 11. Cyclic loading tests on high-pressure tank: hydraulic pressure vs. SMA strain signal.

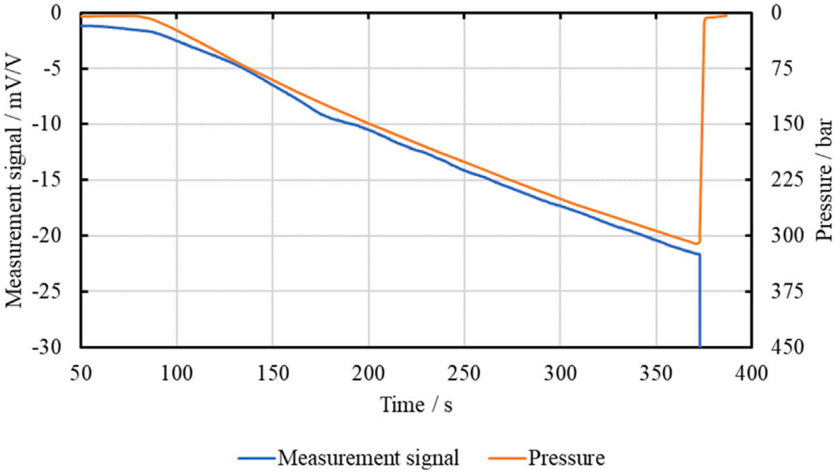


Fig. 12. Burst test on high-pressure tank: hydraulic pressure vs. SMA strain signal.

Table 2
Summary of SHM methods by contact type, real-time capability, and applications.

SHM method	Contact type	Real-time	Typical applications
Acoustic Emission (AE)	Contact	Yes	Crack initiation and propagation in composites, pressure vessels
Ultrasonic Testing (UT)	Contact/Coupled	No	Internal delamination, defect detection in laminates
Guided Wave Testing	Contact/Coupled	Yes	Pipe, tank, and large surface inspection over long ranges
Strain Gauges	Contact	Yes	Local strain monitoring in aerospace, civil, and mechanical structures
Fiber Bragg Grating (FBG) Sensors	Contact	Yes	Strain and temperature monitoring in composites and smart structures
Piezoresistive Sensors (e.g., CNT/polymer)	Contact	Yes	Distributed strain or pressure mapping, wearable SHM
Thermography (IR)	Non-contact	No	Surface/subsurface damage detection in composites and CFRP panels
Digital Image Correlation (DIC)	Non-contact	Yes (in some setups)	Full-field strain and displacement tracking in lab-scale and structural testing
Laser Doppler Vibrometry	Non-contact	Yes (for fast scanning speed)	Vibration-based SHM, modal analysis of structures
Electrical Impedance Tomography (EIT)	Contact	Yes	Monitoring internal changes in electrical properties of smart materials

vessels used in industries such as aerospace, automotive, and hydrogen storage. Among the various sensing approaches reviewed, piezoresistive nanocomposite-based strain sensors and shape memory alloy (SMA) filament sensors have emerged as leading candidates due to their flexibility, high sensitivity, and durability under complex loading conditions. Flexible piezoresistive sensors, particularly those employing nanofillers like carbon nanotubes (CNTs), graphene, and MXenes, demonstrate promising sensitivity, tunability, and compatibility with composite structures. These sensors operate via mechanisms such as tunneling effects, crack propagation, and conductive network disconnection, offering real-time insights into strain and damage states. SMA-based filament sensors, on the other hand, provide excellent fatigue resistance and a clear strain–resistance relationship, proven effective in both cyclic and burst test scenarios. Case studies, including the integration of MXene and buckypaper sensors in COPVs and SMA sensor deployment on high-pressure gas tanks, validate the feasibility and robustness of these SHM strategies under realistic service conditions. These implementations highlight the potential of embedded sensor systems to capture critical structural responses with high fidelity, even under high-pressure cyclic loading.

To provide a comparative perspective on the diverse SHM techniques, Table 2 classifies commonly used methods according to their contact type, real-time monitoring capability, and typical fields of application. This overview highlights the versatility of SHM approaches, ranging from traditional contact-based techniques like strain gauges to advanced non-contact optical methods such as digital image correlation and thermography. The classification serves as a valuable guide for selecting suitable monitoring strategies tailored to specific structural and operational requirements.

7.2. Implications for industry

The advancements in SHM technologies reviewed here have significant implications for industry. The ability to monitor in situ strain and damage accumulation in real time allows for predictive maintenance, minimizing unexpected failures and costly downtime. Improved data on vessel integrity supports more efficient inspection schedules and longer service intervals, ultimately reducing total ownership cost. The integration of flexible sensors during the manufacturing process also promotes the development of “smart tanks” enabling autonomous safety diagnostics, particularly relevant in next-generation hydrogen storage and space applications.

Table 3 summarizes the current state of autonomous SHM systems in the context of COPVs, distinguishing between those that are presently feasible and those that remain largely theoretical or at the early research stage.

7.3. Final thoughts and future outlook

The future of SHM in composite pressure vessels lies at the intersection of material science, sensor miniaturization, and intelligent data analytics. Several emerging directions merit focused attention:

- **AI-Driven Diagnostics:** Leveraging machine learning and digital twins to interpret multi-modal SHM signals will improve fault detection and damage classification.
- **Multi-Functional Materials:** New composite matrices and nanofillers with self-healing, self-reporting, or energy-harvesting capabilities can extend SHM beyond sensing into active structural response.
- **Scalable Manufacturing:** Research into scalable fabrication and integration of embedded sensors will facilitate mass adoption in industrial-scale pressure vessel production.
- **Environmental Durability:** Long-term performance under thermal cycling, moisture, and chemical exposure remains a critical area for future testing and improvement.

In conclusion, SHM in composite pressure vessels is transitioning from experimental validation to industrial deployment, propelled by innovations in smart materials and embedded sensing. With continued research into sensor durability, data integration, and AI-enhanced analytics, SHM systems will become a cornerstone of future safe, efficient, and intelligent infrastructure.

Table 3

Feasibility of autonomous SHM systems applied to COPVs.

SHM technology	Feasible for COPVs (Current State)	Theoretical/Emerging for COPVs
Fiber Optic Sensors (e.g., FBG, Distributed)	– Embedded or surface-mounted FBGs used for strain and temperature monitoring – Proven compatibility with composite layers	– Distributed fiber networks with full shape reconstruction and internal damage localization remain complex and expensive
Piezoelectric Transducers (PZT)	– Effective for active guided wave-based damage detection (delamination, impact) – Can be integrated on liner or overwrap surface	– Fully embedded PZTs with real-time data fusion and decision-making remain a challenge
Wireless Sensor Nodes	– Pressure, temperature, and strain nodes exist – Battery-powered or partially energy-harvested systems feasible in lab settings	– Fully self-powered wireless mesh networks embedded into the COPV wall for long-term SHM are still experimental
Machine Learning Integration	– ML algorithms used for anomaly detection and residual life prediction based on SHM data	– Edge AI fully embedded into the COPV structure for real-time damage inference and adaptive control is not yet realized
Self-sensing Composites	– Carbon fiber-based materials show piezoresistive behavior usable for basic self-sensing	– Multi-functional composites with built-in conductivity, damage awareness, and self-healing remain at the research stage

CRediT authorship contribution statement

Lyazid Bouhala: Writing – review & editing, Writing – original draft, Software, Project administration, Methodology, Investigation, Funding acquisition, Conceptualization. **Jérome Polesel:** Writing – original draft, Investigation. **Argyrios Karatrantos:** Writing – review & editing. **Séverine Perbal:** Writing – review & editing. **Björn Senf:** Writing – original draft. **Alexander Hiekel:** Writing – original draft. **Heiner Reinhardt:** Writing – review & editing, Writing – original draft. **Alexander Rauscher:** Writing – original draft. **Thomas Mäder:** Writing – original draft.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

The data that has been used is confidential.

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