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Metamaterials as transducers for structural health monitoring: a critical review and perspective

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Abstract

Structural health monitoring (SHM) has traditionally relied on distributed sensors, data acquisition systems, signal transmission, and external data processing to assess the condition of engineering structures. Although this sensor-centric paradigm enables reliable damage detection, it remains limited by system complexity, wiring, power consumption, maintenance, and scalability. Recent advances in metamaterials offer an alternative approach in which the material itself participates in sensing by transducing structural responses into measurable information through its engineered architecture. This review examines how architected metamaterials encode, transform, and communicate structural information for next-generation SHM. Recent developments are organized according to the physical domain of the generated information: visual information, including shape transformation, structural color, mechanochromism, and mechanoluminescence; electromagnetic information, including electrical, capacitive, piezoelectric, triboelectric, radio-frequency, metasurface, and passive wireless responses; and wave information, including elastic-wave propagation, bandgaps, resonance shifts, mode conversion, localization, and mechanical filtering. Enabling technologies, including inverse design, topology optimization, additive manufacturing, machine learning, and digital twins, are highlighted for developing multifunctional metamaterials capable of sensing, filtering, amplifying, and communicating structural information. Finally, future opportunities and challenges are outlined for material-centric SHM, in which architected materials evolve from passive structural components into intrinsically intelligent systems that physically process and communicate information before they reach conventional electronic systems.

1. Introduction

Damage detection and classification remain central challenges in structural health monitoring (SHM) for civil, aerospace, and mechanical engineering structures, where timely identification of structural degradation is essential for ensuring safety, reliability, and economic efficiency [1–3]. Recent advances in data-driven SHM [4] have enabled increasingly accurate assessment of structural condition using various sensing modalities, including strain [5], vibration [6], and temperature [7], to estimate intrinsic physical attributes such as material fatigue [8], modal properties [9], and remaining service life [10]. Conventional SHM systems generally comprise three interconnected components: sensor devices, data acquisition and transmission networks, and data interpretation modules. Sensors capture structural

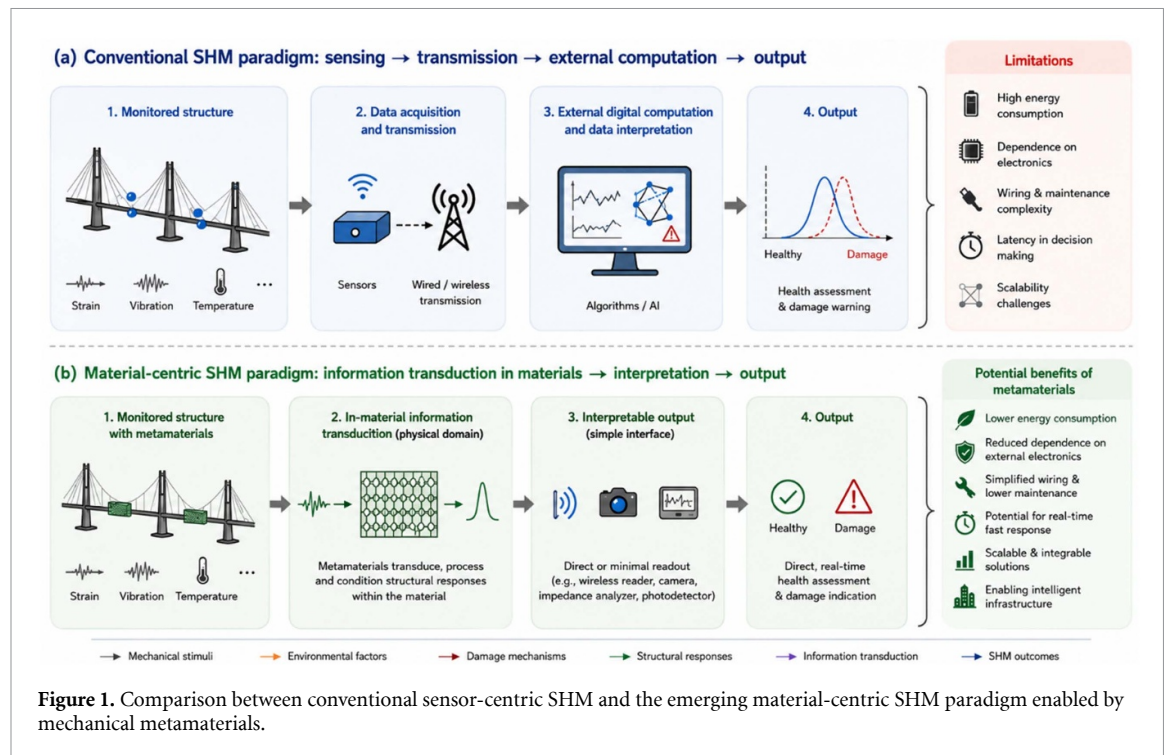


Figure 1. Comparison between conventional sensor-centric SHM and the emerging material-centric SHM paradigm enabled by mechanical metamaterials.

responses, communication systems transmit the acquired data, and computational algorithms process the information to assess structural integrity and detect damage. As illustrated in figure 1(a), despite its widespread success, the conventional sensor-centric SHM framework is constrained by communication overhead associated with large-scale data transmission [11], the high computational cost and energy consumption of conventional digital computing architectures [12], and the limited robustness of electronic components in harsh operating environments [13]. These limitations are driving a paradigm shift toward material-centric SHM, where sensing and information processing are embedded directly within the structure rather than relying on distributed sensor networks and external computing. As illustrated in figure 1(b), metamaterials provide a promising platform for this transition by enabling a fundamentally new paradigm for SHM by transforming structural materials from passive load-bearing components into active information transducers.

Unlike conventional engineering materials, whose behavior is governed primarily by constituent composition, metamaterials derive their unique functionalities from architected geometries spanning multiple length scales [14]. Metamaterials encompass a broad family of architected materials that can be classified according to their governing physical domain, architectural design, or engineered functionality (figure 2). By tailoring structural architecture rather than material composition alone, they enable precise control over interactions with mechanical, electromagnetic, acoustic, optical, and thermal fields, creating new opportunities for structural sensing and information transduction [15]. Over the past decade, their application in SHM has evolved significantly. Early studies primarily exploited metamaterials to enhance sensing performance through strain amplification [16–19], wave manipulation, and resonance tuning [20, 21]. More recently, research has expanded toward architected metamaterials capable of transducing, filtering, and physically processing structural information, thereby reducing reliance on distributed sensor networks and conventional electronic computation [22]. This progression reflects a broader shift from metamaterials that merely enhance sensing performance to materials that intrinsically integrate sensing, information transduction, and physical information processing within their engineered architecture.

Despite the rapid growth of metamaterials, numerous review articles have examined their design principles, architectures, physical mechanisms, and applications across diverse fields, including sensing [15, 23], wave manipulation [24], and programmable matter [14, 25]. Within SHM, however, existing reviews have primarily focused on specific classes of metamaterials or individual sensing mechanisms, such as wave-based SHM using mechanical metamaterials [26], providing valuable yet application-specific perspectives. A comprehensive review that systematically examines the broader role of metamaterials as information transducers for SHM is still lacking. From an SHM perspective, the defining characteristic of a metamaterial is its ability to generate, transform, and communicate structural information for condition assessment and decision-making. Motivated by this perspective, as shown in figure 3, this

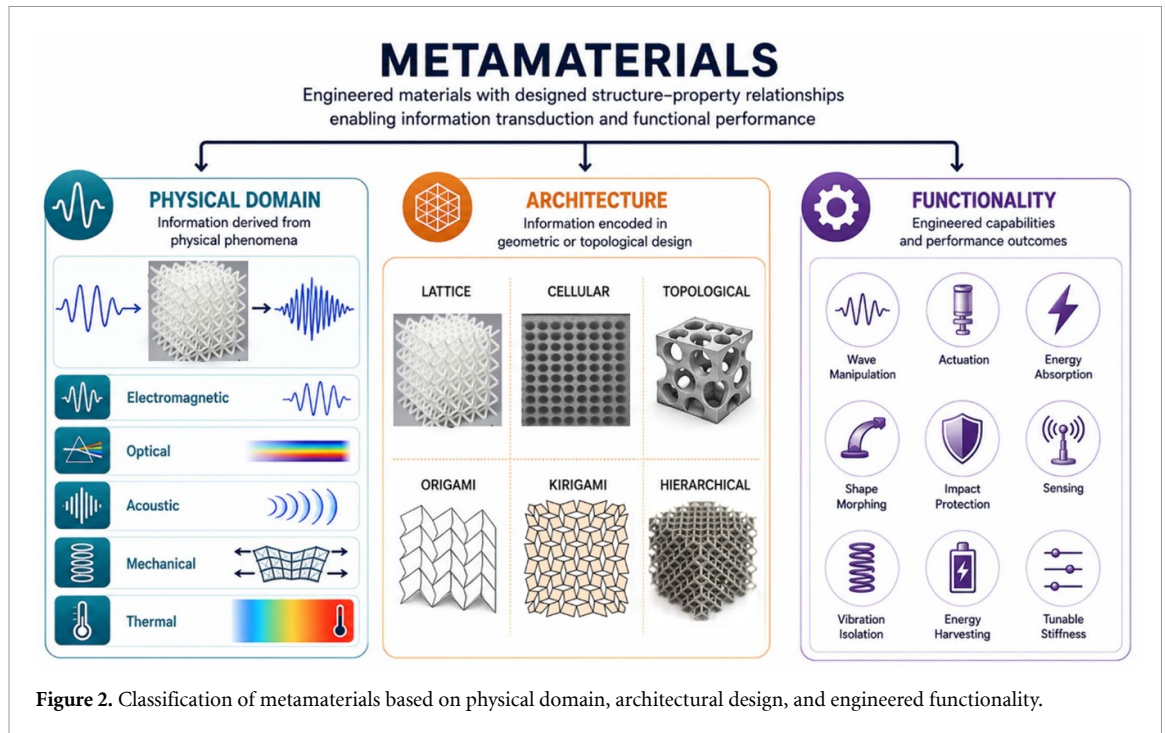


Figure 2. Classification of metamaterials based on physical domain, architectural design, and engineered functionality.

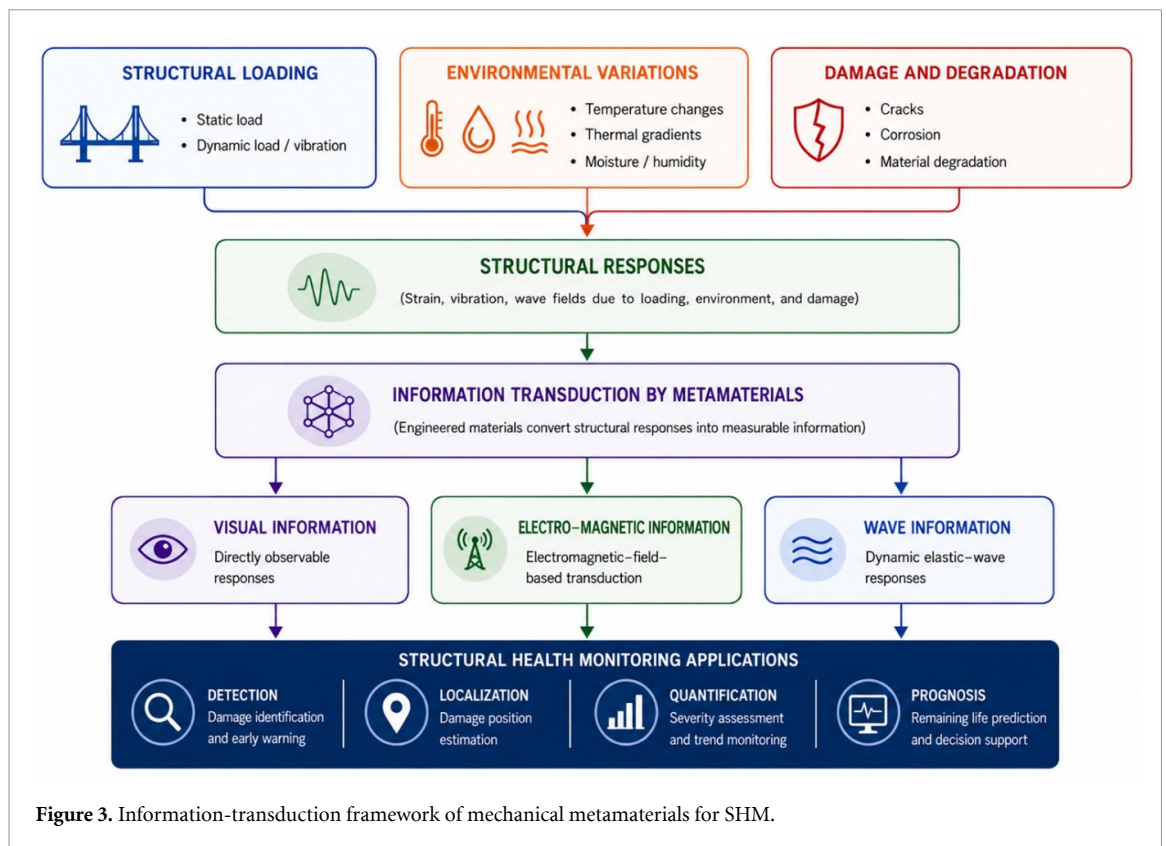


Figure 3. Information-transduction framework of mechanical metamaterials for SHM.

review organizes recent advances according to the physical domain of the structural information generated by metamaterials, namely wave, visual, and electromagnetic information. Rather than classifying metamaterials by their architectures or transduction mechanisms, this information-centric framework establishes a direct connection between architected material design and SHM objectives, highlighting the ongoing transition from conventional sensor-centric monitoring toward material-centric, intrinsically intelligent structural systems.

2. Metamaterials for visual information

Visual information is one of the most intuitive forms of transduction in metamaterials, in which structural responses are converted directly into observable optical signatures. Here, information transduction refers to the process by which mechanical stimuli, such as strain, stress, or damage, are converted into a detectable signal (optical, electrical, or mechanical) through the geometry-driven response of the metamaterial architecture, without requiring conventional electronic transducers. This concept is closely related to mechanical computing, which is defined as the ability of architected materials to perform logical operations, store memory states, or process information through deformation-induced mechanical reconfiguration rather than electronic circuitry. More broadly, this capability falls under the emerging concept of physical intelligence, where materials and structures inherently sense, process, and respond to environmental or mechanical stimuli through their architecture alone, without external controllers or power sources [27]. Instead of relying on electrical transducers, data acquisition systems, and signal processing algorithms, architected metamaterials encode strain, stress, damage, or environmental stimuli into changes in geometry, color, light emission, or surface morphology that can be interpreted directly by the human eye or simple optical imaging systems. This direct conversion of mechanical stimuli into visual information enables passive, low-power SHM while eliminating many of the complexities associated with conventional electronic sensing systems.

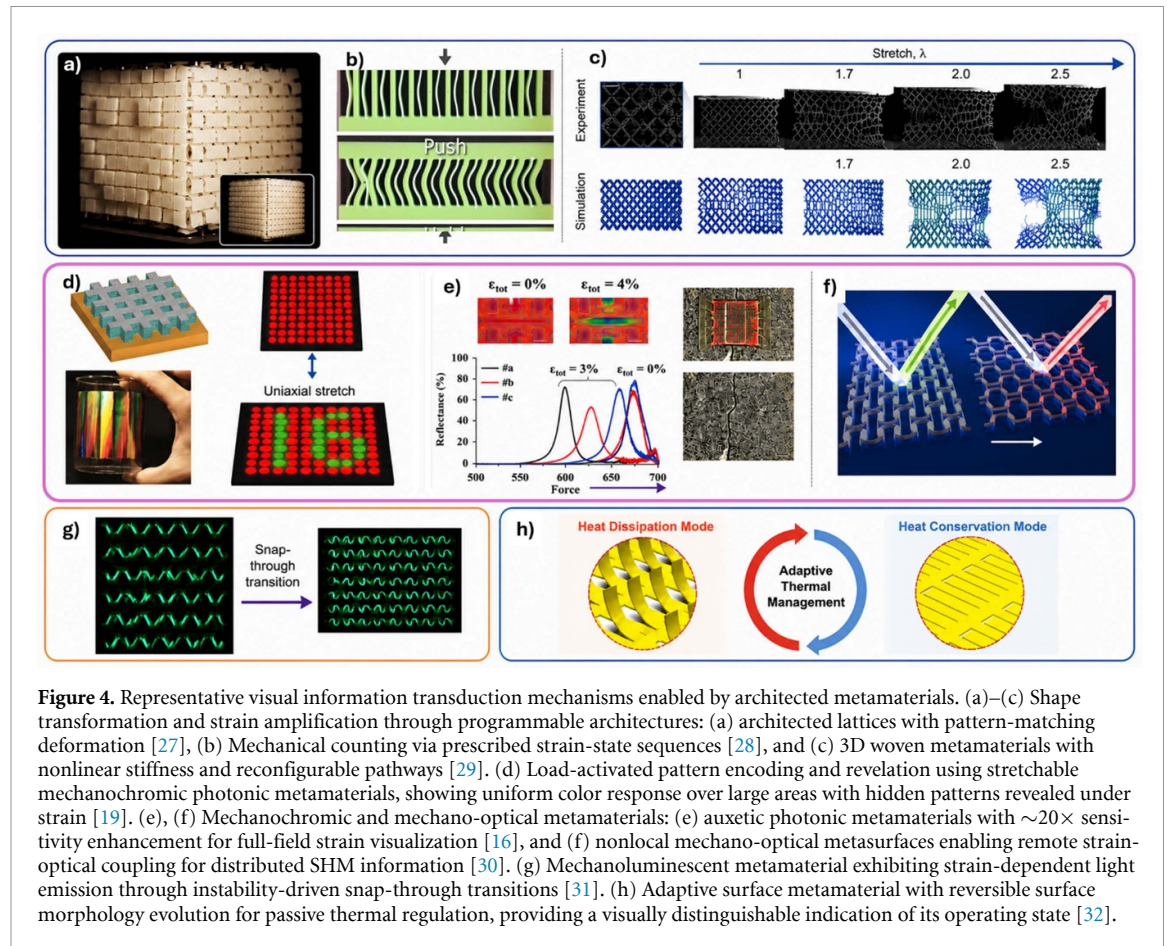
Although visual metamaterials have attracted increasing attention in recent years, much of the existing research has focused on applications in programmable materials, soft robotics, photonics, adaptive optics, thermal management, and multifunctional structures rather than SHM. Nevertheless, the underlying design principles developed in these fields are directly applicable to structural monitoring because they fundamentally address the same challenge: converting structural responses into measurable and interpretable information. Figure 4 summarizes representative visual information transduction mechanisms discussed in this section with high relevance to SHM applications.

2.1. Shape transformation

Visual information transduction can arise from shape transformation when metamaterials are exposed to external stimuli such as strain, where carefully designed architectures amplify relatively small structural strains into large, easily observable geometric changes [33]. Beyond strain amplification, shape transformations can be deliberately programmed to encode, reveal, and process structural information. Representative examples of these mechanochromic and mechano-optical mechanisms are shown in figures 4(a)–(c). Coulais *et al* [27] introduced a combinatorial design strategy for textured mechanical metamaterials based on compatible voxel building blocks, demonstrating that the internal architecture uniquely determines the surface morphology that emerges during strain through the concept of holographic order. Initially, featureless structures reveal predefined surface textures only after compression, enabling structural strain to be directly converted into visually interpretable information without electronic sensing or external processing.

The same study further demonstrated that architected metamaterials can perform elementary mechanical information processing by encoding hidden surface patterns within the material. In a representative example, a metamaterial programmed with a concealed ‘smiley-face’ texture mechanically compared its internally stored pattern with externally applied patterned boundaries (figure 4(a)). Matching patterns resulted in cooperative deformation and low stiffness, whereas mismatched patterns generated geometric frustration and increased mechanical resistance. Consequently, the mechanical response quantified the similarity between the external input and the internally encoded pattern, demonstrating that architected metamaterials can simultaneously store, reveal, and mechanically process information through their geometry alone. Although originally proposed as a demonstration of mechanical computation, this concept provides an intriguing paradigm for material-centric SHM. By engineering architectures with multiple strain thresholds or pattern-specific responses, structural states such as strain, overload, or damage could be physically encoded into distinct mechanical or visual outputs, enabling the material itself to perform both information transduction and elementary decision-making before any external measurement is required.

In another study, metamaterials were engineered to offer programmable sequential information processing. Kwakernaak and van Hecke [28] demonstrated that mechanical metamaterials can perform counting operations by progressing through prescribed sequences of strain states (figure 4(b)), where each loading event triggers a deterministic geometric transition that represents a discrete computational state. Rather than relying on electronic memory or digital logic, the material stores and processes



information through its evolving mechanical configuration, illustrating that architected geometry can implement elementary logical operations directly within the material itself. By associating successive strain states with repeated loading events, cumulative strain, or damage progression, similar architectures could function as passive mechanical memories capable of recording load history, fatigue cycles, or time-dependent structural evolution without continuous electronic sensing.

As shown in figure 4(c), Carton *et al* [29] demonstrated that three-dimensional woven metamaterials extend visual information transduction beyond conventional elastic strain by exploiting the topological arrangement of interlaced fibers to create highly programmable mechanical responses. Unlike traditional lattice metamaterials, whose behavior is primarily governed by elastic bending or stretching of individual struts, woven metamaterials derive their functionality from fiber interlocking, self-contact, frictional interactions, and entanglement within the architecture. Initially, these materials deform elastically under small loads, preserving their overall topology. As strain increases, however, progressive fiber interactions activate additional deformation mechanisms, resulting in nonlinear stiffness, reconfigurable deformation pathways, and multiple mechanically stable configurations that are directly observable. Through a computational design framework based on graph representations of woven unit cells, fiber radius, pitch, connectivity, and weaving topology can be systematically programmed to tailor these deformation modes over a broad design space. The resulting architectures exhibit complex yet deterministic shape transformations that can be visually interpreted as distinct structural states, providing an attractive design concept for strain visualization, mechanically encoded information, and future material-centric sensing applications.

Mohammed *et al* [34] proposed a pufferfish-inspired kirigami metamaterial layer that amplifies local strain while simultaneously generating easily observable deformation patterns through slit opening, ligament rotation, and out-of-plane buckling. The architecture achieved strain amplification factors approaching twofold while providing direct visual indication of localized deformation, demonstrating that kirigami geometries can serve as passive visual indicators for composite SHM. These kirigami geometries, typically fabricated by laser cutting or 3D printing of polymer sheets, exploit geometric features such as slit opening and ligament rotation to achieve strain amplification without requiring complex material synthesis.

2.2. Mechanochromism

A second class of visual transduction mechanisms exploits mechanochromism, where mechanical deformation modifies the interaction between light and the architected structure, producing observable color changes. Representative examples of these mechanochromic and mechano-optical mechanisms are shown in figures 4(d)–(f), where structural loading is converted into measurable optical responses through architected photonic metamaterials. Unlike pigment-based coloration, these responses originate from geometry-dependent optical phenomena, including structural color, photonic crystal effects, diffraction, and optical resonance. Because the optical response is directly linked to structural strain, even small mechanical changes can produce significant shifts in reflected wavelength or color. These systems employ periodic photonic architectures whose lattice spacing or refractive-index distribution changes under mechanical loading, resulting in reversible shifts in structural color through Bragg diffraction and photonic band modulation.

Owing to their passive operation and high sensitivity to geometric perturbations, flexible photonic crystals have been investigated as visual strain sensors capable of directly revealing strain, fracture, and stress concentrations without electrical transducers or external power. Their ability to transform mechanical responses into easily interpretable optical signals demonstrated the feasibility of structural color as an intrinsic carrier of mechanical information and provided the conceptual foundation for subsequent developments in mechano-optical metamaterials [35]. More recently, architected photonic materials have evolved beyond simply producing strain-dependent color changes toward actively controlling how visual information is generated and displayed.

Shin *et al* [19] (figure 4(d)) developed intrinsically stretchable mechanochromic metamaterials based on chiral liquid crystal elastomers, in which kirigami-inspired cuts and strategically positioned rigid strain stoppers redistribute strain to create highly uniform strain fields across large multi-pixel arrays. Rather than simply converting strain into color, the architected geometry physically conditions the strain field before optical transduction, minimizing strain localization and ensuring homogeneous structural-color responses over large areas. Furthermore, by integrating deformable and strain-isolated regions within the same architecture, hidden visual patterns remain indistinguishable in the undeformed state but are selectively revealed under mechanical loading through localized color and polarization changes. This load-activated pattern revelation demonstrates that metamaterial architectures can simultaneously perform mechanical strain control, optical information encoding, and programmable visual information display. Such architecture offers considerable potential for SHM, where predefined patterns, colors, or optical signatures can be calibrated to correspond to specific strain levels, damage states, critical structural conditions, providing intuitive visual indicators without relying on conventional electronic sensing systems.

Complementing this approach, Lee *et al* [36] developed a polydiacetylene-based mechanochromic polymer film that exhibits a visible color transition from blue-purple to red-orange under strain, with a strain-at-break of 204% and stable performance under harsh acidic and basic conditions. The film was successfully evaluated for crack monitoring in cement–concrete composites under flexural loading, where deformation in the polydiacetylene structure triggered a visible color change, demonstrating its potential for self-reporting structural crack monitoring in SHM applications.

Building upon these concepts, Lee *et al* [16] developed auxetic photonic metamaterials in which negative Poisson's ratio (NPR) architectures amplify local strain to produce ultrasensitive mechanochromic responses (figure 4(e)). By coupling auxetic strain with photonic crystal effects, the engineered architecture significantly enhances optical sensitivity by nearly twentyfold, enabling highly visible structural-color changes under relatively small applied strains and providing an effective platform for full-field strain visualization. More recently, van Gorp *et al* [30] introduced a nonlocal mechano-optical metasurface, demonstrating that strain occurring in one region of a structure can be mechanically transmitted to modulate optical responses at a remote location (figure 4(f)). This nonlocal coupling enables spatial separation between mechanical input and optical output, providing new opportunities for distributed information transduction, mechanically programmable optical responses, and spatial encoding of structural health states. The sensitivity and color response of these photonic architectures are determined by the lattice spacing and refractive-index contrast of the constituent materials, which are typically elastomeric polymers or liquid crystal elastomers, with fabrication relying on soft lithography or self-assembly techniques.

2.3. Mechanoluminescent and surface engineering

Beyond passive optical modulation, metamaterials can actively generate visual information through mechanoluminescence, whereby mechanical strain directly produces light emission without external illumination. Although mechanoluminescent materials have been investigated for several decades, recent

advances demonstrate that architected metamaterials can substantially enhance their sensitivity by amplifying local strain concentrations through geometric design. Li *et al* [31] developed rate-dependent mechanoluminescent metamaterials that significantly increase luminescent intensity by combining architected strain amplification with mechanoluminescent materials, enabling highly sensitive visualization of strain, impact, and damage. Figure 4(g) illustrates a representative example in which instability-driven strain generates distinct luminescent states during snap-through transitions, providing a direct visual indication of structural state.

Visual information may also be generated through surface and texture evolution, where changes in surface morphology communicate structural or environmental conditions. Unlike mechanochromic systems that rely on optical resonance, these metamaterials modify their surface topology through reversible geometric reconfiguration. Such adaptive surfaces have been investigated for tunable friction, wettability, adhesion, camouflage, and thermal regulation [37], with the evolving surface morphology providing an inherent visual indication of the material state. A recent example is the self-adaptive mechanical metasurface developed by Ge *et al* [32], which reversibly switches between disordered and ordered surface configurations to regulate thermal radiation without external energy input (see figure 4(h)). Although originally developed for passive thermal management, the underlying thermally responsive architecture provides an attractive concept for SHM. By engineering reversible surface morphologies or emissivity states to correspond to predefined structural conditions, architected metasurfaces could generate enhanced thermal contrast or distinct infrared signatures, improving the sensitivity and interpretability of thermal imaging for damage detection and condition assessment. The thermal response of such metasurfaces is governed by the coefficient of thermal expansion mismatch between the constituent materials (e.g. liquid crystal elastomer and copper), while geometric features such as unit cell height and spacing determine the reconfiguration temperature and emissivity contrast.

Beyond morphology-driven thermal regulation, infrared metamaterials demonstrate that structural reconfiguration can directly modulate thermal emission, providing an alternative pathway for visual information transduction. Liu and Padilla [38] developed a thermochromic infrared metamaterial in which thermally induced MEMS reconfiguration dynamically alters surface emissivity, producing a 215-fold enhancement in infrared emission, far exceeding the conventional Stefan–Boltzmann response, and enabling passive, zero-power thermal indication through remote infrared imaging. Building upon this concept, Coppens and Valentine [39] demonstrated a photoactive infrared metamaterial capable of spatially programmable emissivity modulation through optical excitation, allowing localized thermal signatures to be remotely written and reconfigured. More recently, Liu and Padilla [40] introduced an electrostatically actuated MEMS infrared metamaterial capable of high-speed dynamic emissivity modulation, enabling programmable infrared patterns through an 8×8 pixel array. Collectively, these studies demonstrate that architected metamaterials can actively encode and communicate structural information through engineered thermal signatures, offering a promising platform for contactless SHM using infrared imaging. The visual information transduction mechanisms discussed in this section are summarized in table 1, where the corresponding SHM applications are highlighted.

Overall, the visual information-transduction mechanisms reviewed here span a broad range of sensitivities, operating ranges, and implementation complexities. A key advantage of this information domain is that the mechanical stimulus can be transduced into a directly observable material response without requiring electrical power at the sensing location; energy may only be required for remote interrogation and data acquisition. Shape-transformation and kirigami architectures (table 1) provide strong strain amplification and intuitive visual readout, but often operate around discrete thresholds rather than providing continuous quantitative measurements. Mechanochromic and photonic architectures enable continuous strain-to-color mapping with high sensitivity, although they generally require more complex material architectures and controlled optical interrogation. Mechanoluminescent, fluorescent, and thermal/infrared mechanisms further extend this concept by enabling contact-free image-based acquisition of mechanically generated optical or thermal information. Consequently, these mechanisms are particularly attractive for passive, large-area SHM, where cameras, thermal imagers, or other optical systems can remotely collect and quantify material-level information without wired or powered sensors distributed over the structure.

3. Electromagnetic and electric information

In this review, electromagnetic and electric information refers to the transduction of mechanical deformation or other physical stimuli into measurable electromagnetic signals through electromechanical, dielectric, or resonant mechanisms. Unlike visual information, which relies on direct optical observation,

Table 1. Summary of visual information metamaterials for different applications, highlighting the underlying mechanisms, corresponding functionalities, material types and manufacturing/implementation methods.

Metamaterial Design/Mechanism	SHM application	Constituent material(s)	Manufacturing/implementation
Voxel-based textured metamaterial [27]	Mechanical information processing	Polyvinylsiloxane silicone rubber (Elite Double 32, Zhermack); sintered polyurethane for the larger specimen	Polyvinylsiloxane specimens cast in 3D-printed water-soluble molds; larger specimen directly 3D printed in sintered polyurethane
Mechanical counting via prescribed strain-state sequences [28]	Mechanical information processing/load-history encoding	Vinyl polysiloxane (VPS; Zhermack Double Elite 32)	VPS cast in 3D-printed open-face molds; after curing and demolding, selected beams cut to introduce the required slits
3D woven metamaterials [29]	Strain visualization and information processing	IP-Dip2 acrylate-based photoresist; 10 nm Au coating used for visualization during testing	Two-photon lithography on Si substrates; solvent development, IPA rinsing, and critical-point drying
Pufferfish-inspired kirigami [34]	Visual strain indication	Elastomeric material	Elastomer-based additive manufacturing
Stretchable chiral crystal elastomer [19]	Strain and damage monitoring	RM257/LC756-based CLCE; VHB elastomer; OHP-film rigid strain stoppers	CLCE bar-coating and UV polymerization; laser-cut VHB 5925 kirigami substrate; patterned OHP-film rigid plates; VHB 4905 encapsulation
Auxetic metamaterials [16]	Visual strain indication	Urethane acrylate/isobornyl acrylate framework; silica particles dispersed in PEGPEA with carbon black nanoparticles	3D-printed master and PDMS mold replication; UV photopolymerization of the auxetic framework; silica-PEGPEA filling and photocuring
Nonlocal mechano-optical metasurface [30]	Visual strain indication/distributed monitoring	Silicon resonant nanoparticles; silicon membrane in the second proposed design	Numerical design; no experimental fabrication reported
Rate-dependent mechanoluminescent metamaterial [31]	Damage visualization	ZnS:Cu ²⁺ /PDMS mechanoluminescent composite	ZnS: Cu ²⁺ dispersed in PDMS and mold-cast into bistable mechanoluminescent elements integrated within rigid frames
Self-adaptive metasurface [32]	Thermal/infrared monitoring	Liquid-crystal elastomer (LCE) and copper	Two-step cross-linking and uniaxial alignment of LCE; Cu-LCE bimaterial integration into periodically arranged metasurface units
Thermochromic MEMS infrared metamaterial [38]	Thermal monitoring	Metamaterial infrared emitter with Au/SiN bimaterial MEMS elements	Suspended metamaterial emitter integrated with thermally deformable Au/SiN bimaterial MEMS arms
Photoactive infrared metamaterial [39]	Thermal monitoring	Au/photosensitive ZnO/ITO infrared metasurface stack	Multilayer MIM metasurface; spatially addressed by patterned UV illumination

electromagnetic/electric information enables quantitative, highly sensitive, and often wireless monitoring through changes in electrical impedance (resistance, capacitance, or inductance), dielectric permittivity, piezoelectric (PZT) or triboelectric outputs, or electromagnetic-wave characteristics such as reflection, transmission, absorption, and resonance frequency.

Depending on the sensing architecture, structural deformation may be encoded as changes in electrical impedance, dielectric permittivity, PZT or triboelectric outputs, or electromagnetic-wave characteristics. These transduction mechanisms enable quantitative, highly sensitive, and, in many cases, wireless monitoring of structural deformation and damage, making them particularly suitable for intelligent SHM systems [14]. Representative examples of electromagnetic and electric information transduction mechanisms are discussed in this section.

3.1. Impedance changes

Building on the geometric strain-amplification philosophy, researchers have increasingly integrated architected metamaterials with conductive sensing networks to amplify local deformation before electrical transduction. Representative examples include the work of Lee *et al* [41], who developed a hypersensitive meta-crack strain sensor in which an auxetic substrate promotes multidirectional crack opening, achieving gauge factors exceeding 1000 at strains as low as 10^{-4} , and Jiang *et al* [42], who incorporated an auxetic mechanical metamaterial into a stretchable strain sensor to achieve a 24-fold sensitivity

enhancement through localized strain concentration and microcrack propagation. These studies demonstrate how geometry-driven deformation amplification can substantially improve the electrical response of impedance-based sensing systems.

Building on these concepts, researchers have integrated auxetic architectures with NPR, which expand laterally under tensile loading, into strain-sensor designs to enhance both sensitivity and conformability. Kim *et al* [43] developed an auxetic crack-based strain sensor where a bilayer silicone rubber/platinum film architecture exploits crack formation and propagation for strain sensing, while the auxetic geometry ensures stable, continuous surface adherence under tension (see figure 5(a)). The integration of auxetic substrates with crack-sensitive conductive layers has proven particularly effective for achieving high sensitivity in strain sensing. Wang *et al* [44] advanced this approach by developing an auxetic bilayer conductive mesh strain sensor consisting of a crack-sensitive single-walled carbon nanotube (SWCNT) layer deposited on a stretchable carbon-black elastomer network. The auxetic architecture induced strain concentration and promoted crack formation within the conductive layer, resulting in a gauge factor substantially higher than that of conventional sensors, demonstrating the potential for detecting subtle structural deformations.

To overcome the directional limitations of conventional auxetic designs, Hu *et al* [49] incorporated a chiral auxetic metamaterial (CAM) into the sensor substrate to achieve omnidirectional strain amplification. The tunable NPR generated enhanced crack propagation within the sensing layer, leading to a significant improvement in sensitivity while maintaining consistent performance under different loading directions. Such omnidirectional sensing capability is particularly attractive for systems where structural loads and damage may develop in arbitrary directions. Extending chiral auxetic designs to fiber-reinforced composites, Han *et al* [50] developed a 3D-printed tetra-chiral metamaterial with embedded carbon fibers for piezoresistive self-sensing, achieving 323.3% greater compressive strength than pure PLA while enabling two-stage damage evolution monitoring via electrical resistance changes.

The strain-amplification concept has also been extended to ultrahigh-resolution sensing through meta-crack architectures. In contrast to omnidirectional designs, Yong *et al* [45] demonstrated kirigami-inspired graphene architectures that achieve strain-insensitive electrical properties up to 240% tensile strain and 360° torsion by redistributing stress concentrations away from active sensing elements via out-of-plane buckling at kirigami notches (figure 5(b)). This complementary strategy, maintaining stable electrical resistance under extreme deformation, offers potential for applications requiring consistent signal output on highly deformable structures where strain-amplifying sensors may saturate or fail. The strain-insensitive behavior of these kirigami architectures is enabled by the geometry of the notches, which redistribute stress through out-of-plane buckling, rather than by the intrinsic properties of the graphene layer.

3.2. Dielectric permittivity variation

Dielectric permittivity variation offers a promising sensing mechanism where changes in a material's dielectric properties, induced by strain, damage, temperature, or moisture, are detected through shifts in resonant frequency or capacitance of metamaterial structures [51]. Sim *et al* [52] comprehensively reviewed advancements in metamaterial-inspired microwave sensors for dielectric material characterization, proposing a classification based on measurement systems: planar transmission lines, cavity waveguides, and free-space measurements. They systematically examine sensing principles including frequency shift, frequency splitting, and amplitude or phase variation, while addressing design strategies for resonator optimization and fabrication techniques, capabilities directly transferable to applications where changes in dielectric properties indicate structural degradation or damage.

Elaborating on this principle, Schossmann and Bergmann [46] developed a fully telemetric millimeter-wave metamaterial strain sensor driven by strain-induced permittivity changes (inverse electrostriction). A key differentiator is the design preventing deformation of metallic sensor elements, effectively addressing delamination and degradation, a critical challenge. Furthermore, reflection-mode read-out enables measurement on metal components, a crucial capability for infrastructure and industrial applications (see figure 5(c)). Further advancing microwave-based strain sensing, Praveen *et al* [53] developed a Double Arrowhead auxetic antenna sensor that leverages NPR behavior to amplify strain response in low-strain regimes, achieving a sensitivity of $-138.74 \pm 0.17 \text{ kHz } \mu\epsilon^{-1}$ while reducing device size by 42% and enhancing gain by 23.5%. Further extending microwave-based sensing to multi-parameter detection, Shen *et al* [54] developed a metamaterial sensor consisting of a double resonant ring (DRR) and a microstrip line, capable of detecting rotational angle, vertical displacement, and horizontal displacement of a metal wire through frequency shifts caused by coupling between the DRR and the metal wire. The sensor achieved high sensitivity for each parameter: $4.06 \text{ MHz degree}^{-1}$ for rotational angle (0° – 180°), 18.9 MHz mm^{-1} for vertical displacement (0 – 21 mm), and up to

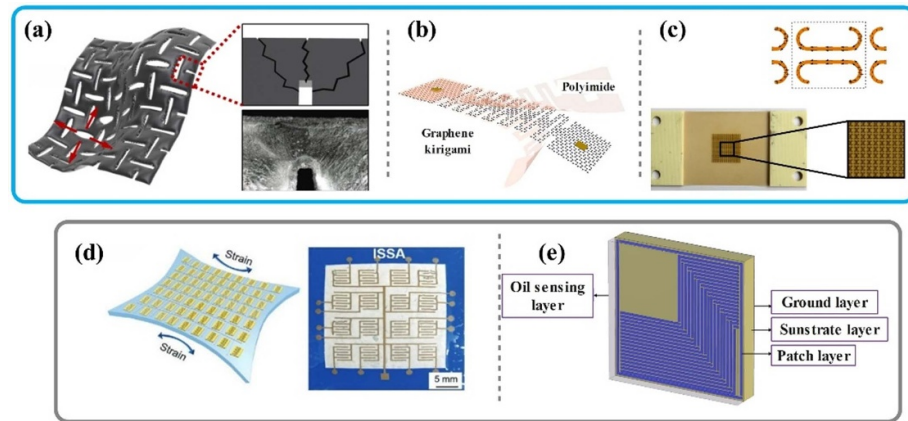


Figure 5. Metamaterials for enhanced impedance and dielectric sensing. (a) Crack formation in auxetic-structured film enabling resistance-based strain sensing [43]. (b) Kirigami-inspired graphene architecture achieving strain-insensitive electrical properties up to 240% strain [45]. (c) Millimeter-wave metamaterial strain sensor with strain-induced permittivity change for telemetric strain sensing [46]. (d) Integrated strain sensor array (ISSA) with 4×4 pixels on an expanded balloon for spatially resolved SHM on curvilinear surfaces [47]. (e) Staircase-shaped microwave metamaterial absorber setup for oil sensing via permittivity variation detection [48].

29.6 MHz mm⁻¹ for horizontal displacement. These multi-parameter detection capabilities demonstrate the sensor's potential for comprehensive SHM, where simultaneous monitoring of multiple deformation modes is required.

Complementing this approach, Fan *et al* [47] advanced this concept with a flexible capacitive strain sensor based on topological-structure modulated dielectric elastic nanocomposites, achieving an ultra-high dielectric permittivity and a positive capacitance-strain response over a wide linear range. A 4×4 pixel integrated strain sensor array was demonstrated for mapping strain distribution on curvilinear surfaces, highlighting potential for spatially resolved SHM on complex structural surfaces (see figure 5(d)). The dielectric response of these flexible sensors is governed by the topological arrangement of nanofillers within the elastomeric matrix, with fabrication typically requiring solution processing or printing techniques to achieve the desired spatial distribution of filler materials.

Beyond direct strain measurement, Yu *et al* [55] developed an all-dielectric metamaterial sensor for simultaneous temperature and humidity measurement, where temperature changes the refractive index of polydimethylsiloxane (PDMS), and humidity alters the dielectric constant of a polyvinyl alcohol (PVA) coating. This approach enables environmental compensation for sensors where temperature and humidity affect measurement accuracy. Similarly, Hossen *et al* [48] developed a staircase-shaped microwave metamaterial sensor for oil detection, where oils with distinct dielectric constants induce measurable resonance shifts, demonstrating the fundamental principle of detecting permittivity variations via resonance frequency shifts (see figure 5(e)).

3.3. PZT and triboelectric response

PZT and triboelectric metamaterials convert mechanical deformation directly into electrical signals or harvested energy, enabling self-powered sensing and autonomous monitoring without external power sources [56]. Slabý *et al* [57] developed a reentrant auxetic metamaterial integrated with embedded PZT transducers, enabling simultaneous load-bearing and self-sensing functionality (see figure 6(a)). The proposed architecture enhanced structural stiffness and generated measurable voltage signals under impact and vibration loading, demonstrating considerable potential for vibration-based SHM, impact localization, and real-time structural integrity monitoring of wings and wind turbines.

Beyond static strain amplification, recent applications have increasingly exploited metamaterials that integrate vibration sensing, energy harvesting, and wireless communication. Xia *et al* [58] proposed an elastic origami-based triboelectric nanogenerator array for self-powered bridge health monitoring (see figure 6(b)). The stacked origami architecture converts low-frequency vibration energy into electrical output through interactions between an elastic ball and multiple triboelectric layers, with integrated power management and narrowband-internet of things (NB-IoT) communication for autonomous wireless bridge vibration data transmission, offering a promising route toward battery-free and long-term monitoring of infrastructures.

Complementing these self-powered approaches, Zhao *et al* [66] developed an electromechanical metamaterial node that integrates mechanical metamaterials with PZT interface circuits to simultaneously

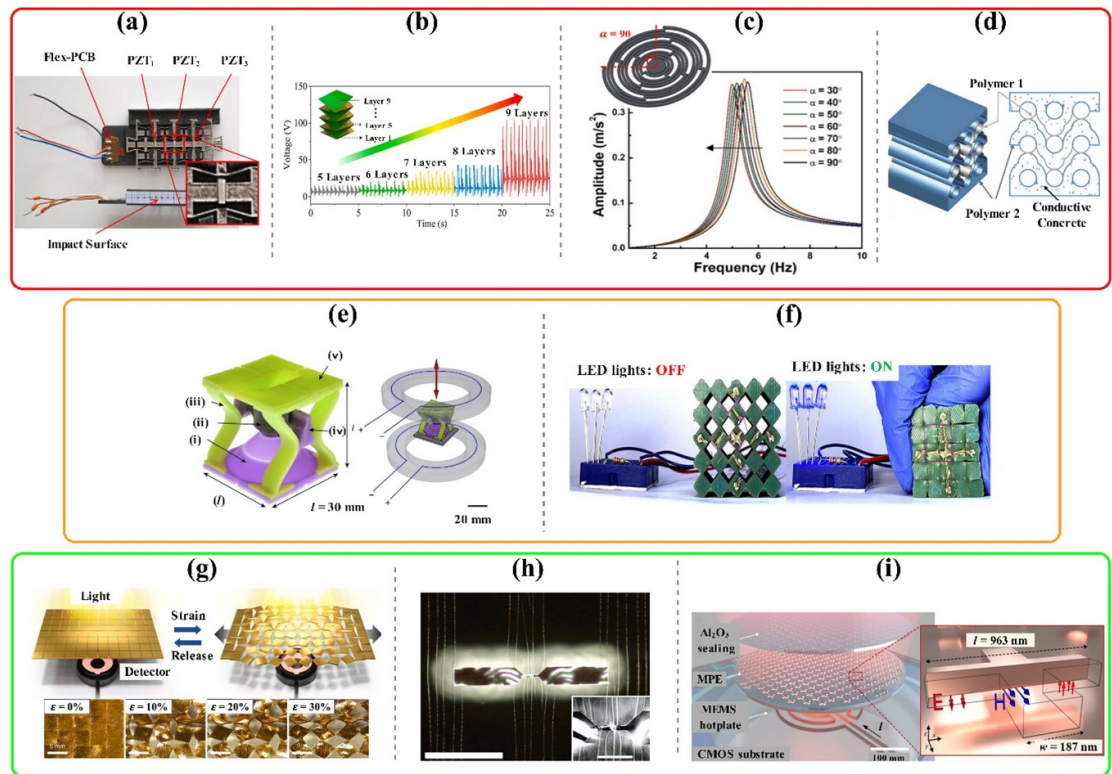


Figure 6. Multifunctional metamaterial systems for SHM. (a) Reentrant auxetic wall with embedded PZT sensors (PZT₁–PZT₃) for impact and vibration sensing [57]. (b) Triboelectric output performance as a function of triboelectric layer count for self-powered energy harvesting [58]. (c) VK structure and harmonic response for varying structural angles (α) in vibration sensing applications [59]. (d) Nanogenerator-integrated metamaterial concrete with conductive and non-conductive polymer layers for self-powered infrastructure monitoring [60]. (e) Reprogrammable m-bit showing components: bistable shell (i), magnetic cap (ii), curved columns (iii), stoppers (iv), and top lid (v); electromagnetic actuation switches bistable states for passive structural memory [61]. (f) Metamaterial switching functionality: uncompressed (open circuit, LED off) vs compacted (closed circuit, LED on) for direct mechanical-to-electrical signal conversion [62]. (g) Rotating square-pattern strain sensor under stretching ($\varepsilon = 0\%$ – 30%) for optical transmittance-based strain monitoring [63]. (h) Dark-field optical image of a strained meta-atom showing microcracks at stress concentration points for high-sensitivity strain detection [64]. (i) Metamaterial perfect emitter (MPE) light source: exploded view of MEMS hotplate with resonant electric (E) and magnetic (H) field lines for gas and corrosion sensing [65].

achieve self-powered sensing and broadband vibration attenuation. The system leverages electromechanical friction induced by synchronized switching interface circuits, which facilitates energy harvesting and enhanced nonlinear dynamic behavior, manifested through expanded bandgaps and higher-harmonic vibration attenuation. Experimentally, the metamaterial node was realized for self-powered sensing of temperature and acceleration data, demonstrating strong potential for SHM and IoT applications where autonomous, energy-aware sensing is required. Maharjan *et al* [67] developed a compact self-powered vibration-monitoring module integrating a circular Z-shaped spring with electromagnetic and triboelectric energy harvesters, where the architected spring geometry enhances vibration-induced deformation over a broad frequency range to simultaneously improve energy harvesting and sensing performance. Integrated with power management, energy storage, and wireless communication, the system enables autonomous vibration monitoring and real-time data transmission without external power, as demonstrated on industrial machinery and automobile engines for IoT-enabled structural and machinery health monitoring.

Complementing this approach, Kim *et al* [59] developed a 3D-printed Vorticella–Kirigami (VK)-inspired vibration sensor exploiting programmable 2D-to-3D morphing to tailor dynamic response for low-frequency vibrations. The capacitive sensor achieved stable operation over 6000 cycles, with field demonstrations on bridge structures successfully detecting impact-induced vibrations and quantifying vibration transmission through structural components (see figure 6(c)).

A transformative direction involves integrating sensing with energy harvesting, enabling structures to become self-aware without external power. Barri *et al* [68] introduced self-aware composite mechanical metamaterials where deformation-induced snapping of triboelectric microstructures generates electrical signals proportional to applied loading while simultaneously harvesting energy, reducing dependence

on dense sensor networks and external power sources for autonomous, continuous, and early damage detection. In another study, Barri *et al* [60] extended this concept to large-scale civil infrastructure by embedding auxetic polymer lattices with snap-through buckling into a conductive cement matrix, achieving significant compressibility and power output, with damage detection experiments showing voltage increases correlating with stiffness reduction (figure 6(d)). Li *et al* [69] developed an auxetic PZT bimorph where a 2D auxetic substrate with elliptical voids is sandwiched between two PZT layers, generating NPR behavior that increases transverse stress and engages both 31- and 32-modes for electric power generation, demonstrating the potential of auxetic geometries for enhanced self-powered applications.

Also, Farhangdoust *et al* [70] developed a kirigami-auxetic hybrid metamaterial substrate for PZT energy harvesters, achieving significant power enhancement over conventional harvesters, sufficient to power wireless sensor nodes for autonomous, battery-free structural monitoring of bridges, aircraft, and other strain-exposed infrastructure. For extreme impact environments, Zhang *et al* [71] developed an elliptical sandwich curved beam structure mechanical metamaterial that provides high-energy absorption (over 50% reduction in impact peak) and high recoverability (above 90% structural integrity) under extreme impacts up to 25 000 g, with an embedded triboelectric self-powered sensor for real-time impact monitoring. This combined impact protection and self-powered sensing offers a promising solution for intelligent vehicle helmets and fuze systems where autonomous alarming is critical.

3.4. Mechanical logic and memory

While kirigami and origami architectures excel at amplifying and guiding deformation, mechanical logic metamaterials introduce a fundamentally different capability: the ability to encode, store, and process mechanical information through geometry-driven changes in electrical or electromagnetic properties. Through deformation-induced switching between stable configurations, these architectures can perform logical operations and maintain persistent memory states while simultaneously altering their structural behavior, providing a promising foundation for autonomous systems capable of embedded interpretation of mechanical stimuli and adaptive structural responses [72].

Demonstrating this capability, Chen *et al* [61] developed a reprogrammable mechanical metamaterial where each unit cell (m-bit) stores a stable binary state via a bistable shell switched by magnetic actuation, with state changes being elastic, reversible, and persistent without power. The ON and OFF states exhibit markedly different mechanical responses; stiffness and strength differ by approximately an order of magnitude, and each m-bit can be read non-destructively using magnetic sensing, enabling passive structural memory systems that record deformation and damage events as stable mechanical states and allow reprogramming of mechanical properties in response to changing conditions (see figure 6(e)). Extending these memory capabilities toward time-dependent information processing, Kwakernaak and van Hecke [28] developed a programmable mechanical metamaterial capable of counting loading cycles and storing loading history through irreversible state transitions of interacting bistable unit cells. By exploiting mechanically encoded transient memories, the architecture distinguishes loading magnitude, recognizes sequential loading patterns, and performs mechanical information processing, offering an intriguing direction for SHM where repeated overloads, fatigue cycles, or specific loading sequences could be directly recorded within the structural material itself.

Further advancing the structure-as-sensor concept, El Helou *et al* [62] developed soft conductive mechanical metamaterials in which elastic buckling reconfigures embedded conductive networks, producing reversible transitions between insulating and conductive states (see figure 6(f)). The deformation-induced electrical switching enables direct conversion of mechanical loading into discrete electrical outputs without conventional sensing electronics, suggesting considerable potential for intelligent SHM systems capable of autonomous event detection and condition assessment. This approach demonstrates how mechanical deformation can be directly transduced into electrically interpretable signals, bridging the gap between mechanical logic and electronic information processing, while maintaining the passive, electronics-free operation that is particularly attractive for applications in harsh environments.

3.5. Mechano-optical and photonic metamaterials

Following the development of mechanical logic metamaterials, recent research has increasingly explored optical responses as an alternative medium for mechanical information processing. By coupling deformation-induced structural reconfiguration with engineered photonic responses, these systems extend mechanical logic into the optical domain. Park *et al* [73] developed a logic-device-inspired mechanical computing system based on three-dimensional cracked optical fibers embedded within a highly stretchable elastomeric substrate. Mechanical deformation reversibly alters crack morphology,

modulating light transmission and enabling rapid ON/OFF switching at a threshold strain of approximately 180%. By combining multiple cracked optical fibers, the system performs NOT, NAND, and NOR logic operations directly from deformation inputs while simultaneously providing multiaxis vibration sensing. The deformation-controlled optical response enables passive, electromagnetic-interference-free strain sensing and embedded decision-making, with tolerance to harsh environments including temperatures from $-55\text{ }^{\circ}\text{C}$ to $+70\text{ }^{\circ}\text{C}$ and radiation exposure. The optical response of these systems is governed by the geometry of the cracks within the optical fiber, with the threshold strain determined by the crack morphology, while the elastomeric substrate provides the necessary stretchability through its low modulus and high elongation.

Expanding mechano-optical sensing to strain measurement, Gu *et al* [63] proposed a self-powered photonic metamaterial strain sensor combining an auxetic rotating-square architecture with an optical transmittance-based sensing mechanism (see figure 6(g)). Unlike conventional piezo-transmittance sensors relying on stochastic crack propagation, the design employs a deterministic gap-opening mechanism governed by a NPR structure, where tensile loading induces uniform gap expansion and predictable transmittance increase, offering reliable long-term sensing.

A complementary approach to strain-field mapping was presented by Everitt *et al* [64], who developed a terahertz metamaterial for strain-field mapping and strain-history recording in composite structures. The bilayer design contains aluminum strip dipole antennas with strain-severable bowtie junctions that irreversibly fracture when local stresses exceed a predefined threshold, altering the terahertz response. This mechanism enables both visualization of strain distributions and permanent recording of critical stress events for long-term composite delamination monitoring (see figure 6(h)). For wireless strain sensing, Yoo *et al* [74] developed a stretchable screen-printed metasurface where mechanical deformation induces a resonance frequency shift, enabling remote, passive strain monitoring without complex wiring.

Metamaterial-based photonic emitters have also been extended toward highly integrated mid-infrared sensing platforms. Lochbaum *et al* [65] developed a CMOS-compatible metamaterial perfect emitter integrating MEMS heating with a resonant metasurface, achieving NB thermal emission and near-unity emissivity (see figure 6(i)). The device enables compact, filter-free gas sensing, adaptable for environmental monitoring where chemical changes such as corrosion-induced emissions or gas leaks indicate structural degradation. Beyond sensing, the versatility of metamaterials extends to adaptive mechanical response under varying service conditions. Complementing such adaptive systems, Imran *et al* [75] developed a thermal metamaterial integrating thermal cloaking with passive convective cooling via surface fins, achieving significant temperature reduction within the cloaked region through natural convection without disturbing cloaking performance. This strategy protects heat-sensitive sensors and embedded electronics under varying conditions, extending operational lifespan and reducing thermally induced measurement errors, reinforcing the trend toward self-sufficient, multifunctional metamaterials for a variety of civil infrastructures and aerospace applications. The electromagnetic and electric information transduction mechanisms discussed in this section, ranging from impedance changes and dielectric permittivity variation to PZT/triboelectric response, mechanical logic, and mechano-optical platforms, are mentioned in table 2, which highlights their corresponding applications.

Across the electromagnetic and electric information transduction mechanisms summarized in table 2, impedance- and dielectric-based sensors offer the highest reported sensitivity (gauge factors exceeding 1000 and sensitivity enhancements of up to 24-fold) and are the most mature for quantitative strain monitoring, but generally require an external power source and wired data acquisition. PZT and triboelectric metamaterials trade some sensitivity for self-powered, wireless operation, making them attractive for autonomous or inaccessible structures, though their output remains sensitive to loading frequency and amplitude. Mechanical logic and memory architectures uniquely provide passive, power-free information storage that records loading history without continuous sensing, but currently operate at coarse (binary or few-state) resolution rather than continuous measurement. Mechano-optical and photonic platforms combine electromagnetic-interference immunity with wide environmental tolerance (demonstrated from $-55\text{ }^{\circ}\text{C}$ to $+70\text{ }^{\circ}\text{C}$), at the expense of requiring optical interrogation hardware. Selecting among these mechanisms therefore involves a direct trade-off between sensitivity, power autonomy, resolution, and interrogation complexity, which should be guided by the accessibility and power availability of the target structure.

Table 2. Summary of electromagnetic and electric information metamaterials for SHM applications, highlighting the underlying mechanisms, corresponding functionalities, material types and manufacturing/implementation methods.

Metamaterial Design/Mechanism	SHM application	Constituent material(s)	Manufacturing/implementation
Hypersensitive strain sensor [41]	Deformation sensing	Mo/MoO ₃ sensing layer on PBAT; PLA auxetic layer	PBAT spin coating; MoO ₃ /Mo sputtering and pre-cracking; PLA spin coating and UV-laser patterning; thermal bonding
Auxetic metamaterial with negative Poisson's ratio [42]	Deformation sensing	Conductive SWCNT network on PDMS thin film	3D printing-assisted molding SWCNT self-pinning method
Auxetic crack-based strain sensor [43]	Deformation sensing of flexible architectures	Pt-coated silicone rubber	Silicone casting/spin coating and curing; Pt sputter coating; auxetic architecture produced by laser fabrication
Kirigami graphene architecture [45]	Deformation sensing of curved structures	Monolayer graphene; polyimide; gold electrodes	CVD graphene synthesis; spin-coating; photolithography; sacrificial layer etching
Millimeter-wave metamaterial [46]	Deformation sensing	Copper; thermoplastic polyurethane (TPU)	Copper foil laminated on TPU; unit cell structures etched; second TPU layer laminated; woven glass fiber layers added for fixation
Flexible capacitive sensor with topological dielectric nanocomposites [47]	Deformation sensing of curved structures	Dielectric elastic nanocomposite (3D nanofiller networks; multilayered heterogeneous films)	Nanocomposite synthesis; spin-coating; electrode deposition (sputtering/evaporation/printing);
Auxetic bilayer conductive mesh [44]	Deformation sensing	SWCNT sensing layer; carbon-black-doped Ecoflex mesh	Direct-ink-writing 3D printing of conductive Ecoflex mesh; SWCNT deposition by ink spraying
Chiral metamaterial with omnidirectional amplification [49]	Multidirectional deformation sensing	Polyimide (CAM); Ecoflex (elastomer substrate); MWCNT (sensing layer)	CAM fabricated by laser cutting; bonded to Ecoflex via APTES treatment; MWCNT network deposited; elastomer encapsulation
Elastic origami-based triboelectric nanogenerator array [58]	Bridge monitoring	Paper/Kapton triboelectric layers with integrated electrodes	Origami-inspired multilayer assembly integrated into an elastic triboelectric nanogenerator array
Composite mechanical metamaterials [68]	Autonomous damage detection	PLA (conductive layers); TPU (non-conductive/dielectric layers); Au/Pd (metal coating for cardiovascular stent)	FDM 3D printing (dual extruder); Nanoscribe 3D laser writer
Polymer lattices in conductive cement matrix [60]	Infrastructure monitoring	Auxetic polymer lattice; graphite-modified conductive cement matrix	Architected polymer lattice fabricated and embedded within conductive cement matrix
Reprogrammable m-bit with bistable shell [61]	Fatigue monitoring	VPS silicone; NdFeB particles; cyanoacrylate	SLA 3D-printed moulds; casting; assembly; magnetization
Photonic metamaterial with auxetic rotating-square architecture [63]	Strain monitoring	Dragon Skin elastomer; Chromium adhesion layer; Gold light-blocking film	Spin-coating and curing of elastomer; plotter cutting of auxetic pattern; e-beam deposition of Chromium
Terahertz metamaterial with strain-severable bowtie junctions [64]	Composite delamination monitoring	Aluminum strip-dipole meta-atoms with strain-severable bowtie junctions	Multilayer aluminum meta-atom arrays fabricated and integrated/laminated with the composite structure
CMOS-compatible metamaterial perfect emitter with MEMS heating [65]	Corrosion monitoring	CMOS-compatible materials (dielectric membrane; heater structure; metamaterial resonator layers)	CMOS-compatible resonant metasurface integrated with a MEMS hotplate

4. Mechanical wave information

Mechanical-wave information is one of the most established information carriers in SHM, where structural integrity is assessed through the propagation and scattering of elastic waves. Acoustic metamaterials provide unprecedented opportunities to manipulate these waves through architected subwavelength structures, enabling enhanced control over wave transmission, amplification, focusing, filtering, mode conversion, and energy localization. As summarized in figure 7, current applications of acoustic metamaterials in mechanical-wave-based SHM can be broadly classified into active and passive monitoring paradigms. While active SHM has matured through advances in damage detection enhancement, damage

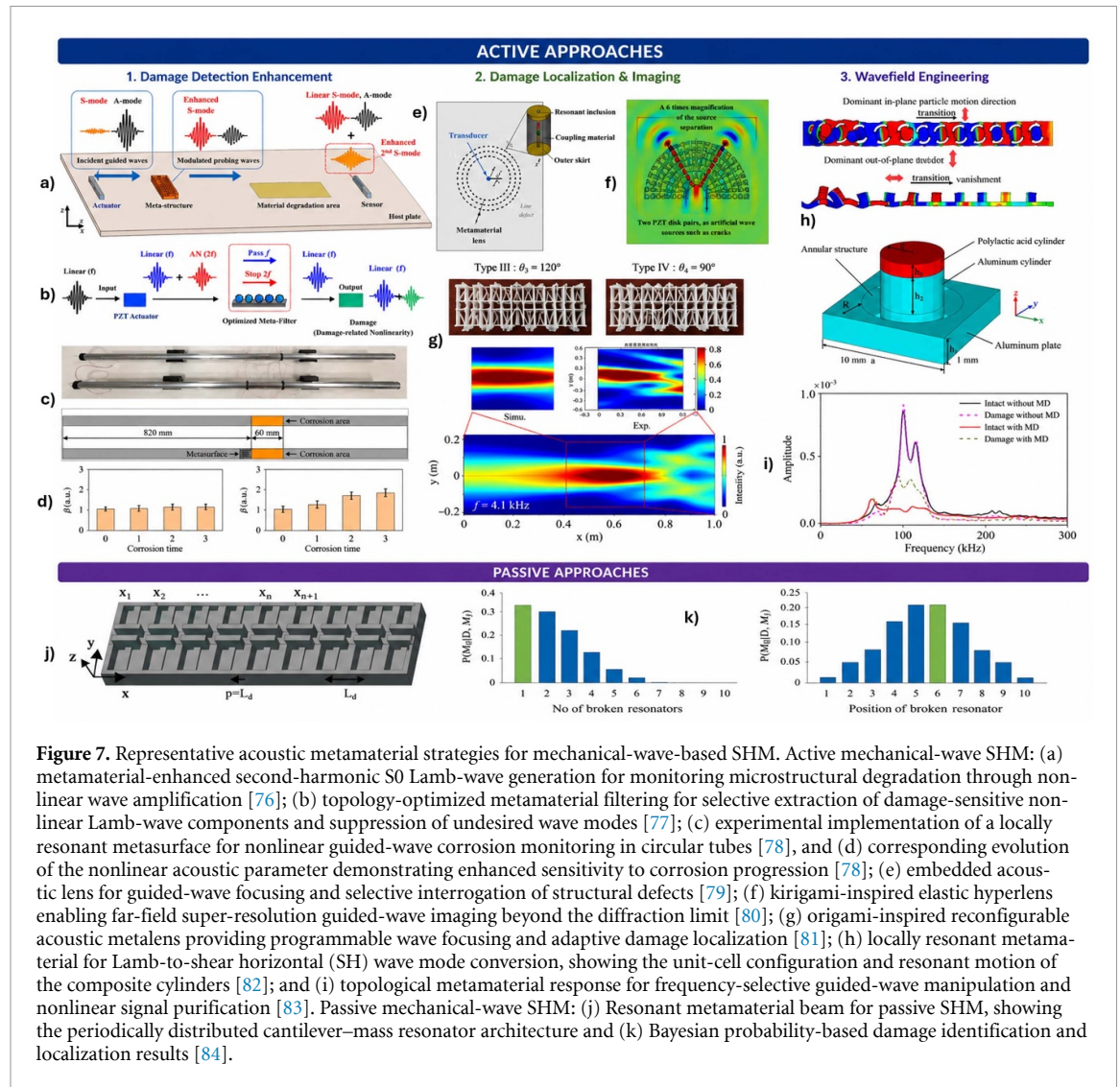


Figure 7. Representative acoustic metamaterial strategies for mechanical-wave-based SHM. Active mechanical-wave SHM: (a) metamaterial-enhanced second-harmonic S0 Lamb-wave generation for monitoring microstructural degradation through nonlinear wave amplification [76]; (b) topology-optimized metamaterial filtering for selective extraction of damage-sensitive nonlinear Lamb-wave components and suppression of undesired wave modes [77]; (c) experimental implementation of a locally resonant metasurface for nonlinear guided-wave corrosion monitoring in circular tubes [78], and (d) corresponding evolution of the nonlinear acoustic parameter demonstrating enhanced sensitivity to corrosion progression [78]; (e) embedded acoustic lens for guided-wave focusing and selective interrogation of structural defects [79]; (f) kirigami-inspired elastic hyperlens enabling far-field super-resolution guided-wave imaging beyond the diffraction limit [80]; (g) origami-inspired reconfigurable acoustic metalens providing programmable wave focusing and adaptive damage localization [81]; (h) locally resonant metamaterial for Lamb-to-shear horizontal (SH) wave mode conversion, showing the unit-cell configuration and resonant motion of the composite cylinders [82]; and (i) topological metamaterial response for frequency-selective guided-wave manipulation and nonlinear signal purification [83]. Passive mechanical-wave SHM: (j) Resonant metamaterial beam for passive SHM, showing the periodically distributed cantilever–mass resonator architecture and (k) Bayesian probability-based damage identification and localization results [84].

localization and imaging, and wavefield engineering, passive SHM remains an emerging research direction with comparatively fewer reported applications. The following sections review representative developments within each paradigm.

4.1. Mechanical wave-based metamaterial for active SHM

Active mechanical-wave SHM employs externally generated elastic waves, most commonly ultrasonic guided waves, to interrogate structural integrity under controlled excitation. By tailoring wave propagation before, during, or after interaction with damage, acoustic metamaterials significantly expand the capabilities of conventional guided-wave inspection. As summarized in figure 7, recent developments can be broadly categorized into three complementary research directions: damage detection enhancement, damage localization and imaging, and wavefield engineering.

Nonlinear ultrasonic techniques offer strong sensitivity to incipient damage, but the weak amplitude of higher-order harmonic components and their susceptibility to interference often limit practical implementation. Acoustic metamaterials overcome these challenges by selectively amplifying damage-sensitive nonlinear features while suppressing others. Early demonstrations of metamaterial-assisted nonlinear ultrasonic damage detection were reported by Tian *et al* [85], who developed a locally resonant aluminum-lead bandgap metamaterial for fatigue crack monitoring. The metamaterial acted as a mechanical frequency filter that suppressed undesired wave components while preserving damage-sensitive second-harmonic responses generated by fatigue-crack breathing, thereby improving the extraction and reliability of nonlinear damage indicators. Building upon this concept, Tian *et al* [86] proposed a defect-mode metamaterial (DMM) consisting of a pillared elastic structure with an embedded defect cavity that localized elastic-wave energy and amplified weak second-harmonic signals associated with incipient fatigue cracks. The approach was subsequently developed and experimentally validated by Tian

et al [87], who implemented the DMM at the sensing terminal to localize the Lamb-wave response and enhance crack-induced nonlinear signatures, achieving a 6.3-fold increase in the damage index compared with the conventional pitch-catch configuration. Unlike the filtering strategy adopted in the earlier work, the DMM enhanced damage sensitivity through wave-energy localization and harmonic amplification. Collectively, these studies established two complementary strategies for metamaterial-assisted nonlinear damage detection: frequency-selective bandgap filtering to improve the extraction of nonlinear signatures and defect-mode energy localization to amplify weak damage-induced harmonic responses.

Subsequent research expanded these concepts from fatigue crack detection to the monitoring of distributed material degradation and microstructural evolution. Liu *et al* [76] developed a meta-structure specifically designed to enhance second-harmonic S0 Lamb-wave generation for monitoring microstructural changes in materials. Unlike fatigue-crack-focused approaches that rely on localized contact non-linearity, this work targeted distributed microstructural degradation through nonlinear wave interactions occurring throughout the material volume. As illustrated in figure 7(a), the proposed meta-structure significantly increased the amplitude of the generated second-harmonic S0 wave while preserving its propagation characteristics. The enhanced second-harmonic response enabled clearer separation of nonlinear damage-sensitive features from the fundamental wave, improving sensitivity to subtle material-state variations that are often difficult to detect using conventional guided-wave techniques. The study demonstrated that acoustic metamaterials can be employed not only for localized defect detection but also for monitoring progressive material degradation and structural health evolution through enhanced nonlinear wave interactions.

Complementary to harmonic amplification, topology-optimized metamaterials have also been developed as frequency-selective nonlinear wave filters. Rather than directly enhancing harmonic generation, these structures manipulate wave transmission characteristics to isolate damage-sensitive nonlinear features from background signals. As illustrated in figure 7(b), the topologically designed metamaterial filter selectively suppresses undesired signal components while preserving nonlinear harmonic information, thereby improving the extraction of damage-sensitive indicators. Liu *et al* [83] demonstrated the effectiveness of this approach for nonlinear Lamb-wave-based plastic damage detection, enabling the identification of material plasticization before the formation of macroscopic cracks, while subsequent work further established the underlying filtering mechanism and signal evolution characteristics of the metamaterial filter (Liu *et al* [77]). By improving the signal-to-noise ratio of weak nonlinear features, topological metamaterial filters offer a promising strategy for nonlinear feature extraction and early-stage damage assessment.

A related challenge is the contamination of damage-sensitive nonlinear features by harmonics generated within the actuation system. Aslam *et al* [88] developed a metallic ring-shaped metasurface filter to suppress both instrumentation-induced harmonics and nonlinear components arising from PZT debonding, while preserving the guided-wave components required for damage interrogation. Experimental validation using a 3D-printed metafilter demonstrated its effectiveness in improving nonlinear guided-wave SHM. Extending this signal-purification concept, Xu *et al* [89] proposed a bidirectional purification strategy employing metamaterial filters at both the excitation and sensing stages of a nonlinear guided-wave SHM system. The excitation-side filter suppresses spurious second-harmonic components generated by instrumentation and transducer nonlinearities, while the sensing-side filter selectively removes the dominant fundamental wave and preserves damage-induced harmonic responses. Through this dual-filter configuration, nonlinear damage indicators can be extracted with significantly reduced interference, improving the fidelity and reliability of nonlinear measurements. This study demonstrates that acoustic metamaterials can function not only as wave amplifiers and filters but also as physical signal-conditioning devices that enhance the robustness of nonlinear SHM systems.

The application of metamaterial-assisted nonlinear ultrasonics has also been extended to engineering structures with more complex wave propagation characteristics. Gao *et al* [78] developed a locally resonant metasurface for nonlinear guided-wave-based damage detection in circular tubes, where the metasurface was designed to selectively attenuate undesired second harmonics through bandgap filtering while allowing the fundamental wave to propagate. As illustrated in figure 7 (c,d), the approach was validated using a controlled corrosion region introduced on the surface of a circular tube. By suppressing irrelevant harmonic components generated by instrumentation and wave excitation, the metasurface improved the reliability of second-harmonic generation measurements and increased sensitivity to incipient corrosion damage. The resulting nonlinear acoustic parameter exhibited a clear increase with corrosion progression when the metasurface was employed, whereas the conventional configuration showed limited sensitivity to damage evolution. These results demonstrate the potential of metamaterial-assisted nonlinear guided waves for corrosion monitoring in tubular structures and represent an important step toward practical SHM applications in engineering components with complex wave propagation characteristics.

Beyond harmonic amplification and nonlinear feature filtering, acoustic metamaterials have also been utilized to increase wave–damage interaction through the manipulation of multiply scattered wavefields. Shan *et al* [90] introduced a metamaterial-enhanced coda wave interferometry framework based on customized artificial frequency-space boundaries. The proposed metamaterial architecture modified elastic-wave scattering and energy redistribution within the structure, thereby increasing the sensitivity of coda waves to local perturbations caused by weak structural damage. Unlike conventional nonlinear ultrasonic approaches that primarily rely on harmonic generation, the method exploits the cumulative sensitivity of multiply scattered waves to amplify subtle damage-induced changes. The results demonstrated significantly improved detection capability for weak damage and highlighted an alternative pathway through which acoustic metamaterials can enhance SHM performance by strengthening wave–damage interactions.

Metamaterial-assisted mode discrimination has also been extended to structural discontinuities with complex guided-wave behavior. Xu *et al* [91] developed a locally resonant metasurface for integrity monitoring of right-angle structures, exploiting the characteristic mode conversion occurring at geometric discontinuities. The metasurface selectively suppressed the interfering A0 mode while preserving the defect-sensitive S0 response, enabling structural discontinuities to be detected and quantitatively evaluated from guided-wave measurements. Experimental validation on a T-shaped aluminum profile demonstrated the applicability of this mode-selective approach to geometrically complex structural regions.

Collectively, these studies demonstrate that acoustic metamaterials enhance guided-wave damage detection through complementary mechanisms, including harmonic amplification, frequency-selective filtering, signal purification, mode discrimination, and strengthened wave–damage interactions. Together, these advances have significantly improved the detection of early-stage structural degradation, establishing acoustic metamaterials as a powerful platform for next-generation nonlinear SHM.

Beyond enhancing damage sensitivity, acoustic metamaterials have also enabled significant advances in damage localization and imaging through wave focusing, energy localization, and wavefront manipulation, improving the spatial resolution and accuracy of guided-wave SHM. The earliest demonstrations focused on acoustic metamaterial lenses capable of concentrating guided-wave energy into subwavelength regions. Semperlotti and Zhu [79] introduced an embedded acoustic lens based on locally resonant metamaterials that selectively focused Lamb waves toward predefined inspection regions, thereby improving damage interrogation and spatial resolution beyond that achievable with conventional guided-wave techniques. By exploiting locally resonant unit cells, the acoustic lens enabled selective wave focusing without requiring complex phased-array excitation, demonstrating the potential of metamaterial-assisted wave control for high-resolution structural inspection. A representative acoustic lens configuration is shown in figure 7(e).

Building upon the concept of guided-wave focusing, subsequent developments extended acoustic metamaterials from energy concentration to super-resolution imaging. Zhu *et al* [80] developed a kirigami-inspired elastic hyperlens that exploited anisotropic wave propagation to convert evanescent wave components into propagating waves, enabling imaging beyond the diffraction limit. As illustrated in figure 7(f), the hyperlens successfully resolved two closely spaced PZT wave sources that would otherwise appear indistinguishable using conventional guided-wave imaging. The effective separation between the wave sources was magnified by approximately six times, demonstrating the potential of metamaterial-enabled hyperlenses for future high-resolution damage localization and imaging.

More recently, wave-focusing concepts have been extended toward adaptive and reconfigurable imaging systems. Liu *et al* [81] proposed an origami-inspired reconfigurable acoustic metalens capable of dynamically tailoring wavefront propagation through programmable structural reconfiguration. Unlike conventional acoustic lenses with fixed focusing characteristics, the proposed metalens enabled adaptive wave focusing under different operating conditions, providing additional flexibility for guided-wave inspection and damage localization. The work demonstrates a transition from static metamaterial devices toward reconfigurable wave-control platforms for next-generation SHM applications, as illustrated in figure 7(g).

Fu *et al* [92] further extended metamaterial-assisted focusing toward broadband and spatially selective microcrack interrogation by developing a nondestructive elastic metasurface with moderately broadband and wide-field focusing capabilities. The metasurface focused A0 Lamb waves over 100–150 kHz and incident angles from -20° to 20° , enabling the focal region to be shifted through incident-angle control. By concentrating wave energy at the microcrack, the approach enhanced the local contact-acoustic-nonlinearity response, producing up to a 235% increase in second-harmonic amplitude. This demonstrates how wave focusing can simultaneously improve damage sensitivity and provide spatial selectivity for guided-wave SHM.

The application of metamaterial-assisted imaging has subsequently expanded toward practical engineering structures. Chen *et al* [93] developed a gradient acoustic focusing metamaterial that enhanced ultrasonic guided-wave energy concentration for detecting minor structural damage, while Du *et al* [94] incorporated bandgap metamaterials into Lamb-wave inspection of aero-engine blades to improve damage assessment under complex wave propagation conditions. These studies demonstrate the growing applicability of metamaterial-assisted wave focusing and imaging concepts to realistic engineering components.

Collectively, these developments demonstrate that acoustic metamaterials extend guided-wave SHM beyond enhanced damage detection toward high-resolution damage localization and imaging. Through wave focusing, super-resolution imaging, and programmable wavefront control, metamaterial architectures provide powerful tools for improving the spatial accuracy, flexibility, and robustness of guided-wave inspection.

Beyond damage localization, acoustic metamaterials provide a broader capability through wavefield engineering, enabling deliberate control of wave modes, frequencies, propagation directions, and wavefront characteristics. Rather than solely enhancing damage-sensitive features or imaging performance, these approaches tailor guided-wave propagation itself to optimize structural interrogation and improve the versatility of active SHM systems.

One of the earliest demonstrations of metamaterial-based wavefield engineering was reported by Tian *et al* [82], who developed a resonance-based locally resonant metamaterial capable of converting Lamb waves into shear horizontal (SH) waves. As illustrated in figure 7(h), the proposed unit-cell architecture exploited local resonance to achieve efficient mode conversion while preserving wave energy transmission. Since SH waves exhibit different sensitivities to specific damage mechanisms and are less affected by surrounding media, this approach provides additional flexibility for selecting the most suitable guided-wave mode for structural inspection.

Building upon mode control, subsequent studies explored topology-optimized metamaterials for frequency-selective wave manipulation. Liu *et al* [83] designed metamaterial devices capable of filtering guided-wave frequency components through topology optimization, enabling selective transmission of damage-sensitive wave modes while suppressing unwanted frequencies. Further developments demonstrated the effectiveness of these topological filters for nonlinear guided-wave monitoring, material degradation assessment, and signal purification, highlighting their versatility across a range of SHM applications (Liu *et al* [77]). Representative frequency-selective wave manipulation strategies are shown in figure 7(i).

The principles of metamaterial-assisted wavefield engineering have also been extended beyond conventional guided-wave SHM. Zhao *et al* [95] demonstrated the application of acoustic metamaterials to pulse-echo ultrasonic evaluation of thick hybrid composite laminates, where metamaterial-assisted wave manipulation improved defect interrogation under challenging inspection conditions. This study illustrates the broader applicability of metamaterial concepts to active ultrasonic inspection beyond guided-wave systems.

4.2. Mechanical wave-based metamaterial for passive SHM

Compared with active SHM, the application of acoustic metamaterials in passive SHM remains relatively limited. This disparity arises because most acoustic metamaterial concepts have been developed to manipulate externally generated ultrasonic or guided waves, naturally aligning them with active inspection strategies. In passive SHM, however, structural condition is inferred from changes in the dynamic response of a structure under ambient or operational excitation, without the need for dedicated wave actuation. Existing passive metamaterial-based approaches primarily exploit the high sensitivity of resonant and bandgap architectures to local changes in stiffness, mass, and damping, enabling damage detection through variations in resonance characteristics, vibration transmission, and frequency-response behavior. Although the field remains relatively immature compared with active SHM, these studies demonstrate the potential of acoustic metamaterials to enhance damage detection, quantification, and localization through engineered dynamic responses.

One of the earliest examples of passive SHM using acoustic metamaterials was reported by Zhu *et al* [84], who investigated damage detection, quantification, and localization in a resonant metamaterial beam comprising periodically distributed cantilever-mass resonators, as shown in figure 7(j). The monitoring concept was based on the fact that damage occurring in individual resonators alters the local resonance characteristics of the metamaterial, leading to measurable changes in the global frequency response of the structure. By exploiting the high sensitivity of the resonant architecture to local stiffness and mass variations, even damage confined to a single resonator could be reflected in the measured frequency response functions. To identify the damaged resonator, the authors combined physics-based Bayesian

inference with data-driven analysis, comparing measured responses against candidate damage scenarios. The resulting posterior probability distributions, shown in figure 7(k), successfully localized the damaged resonator and quantified the likelihood of different damage hypotheses. This study demonstrates how the intrinsic resonance sensitivity of locally resonant metamaterials can be utilized for passive damage detection and localization without requiring active guided-wave interrogation.

Beyond the limited number of passive SHM studies reported to date, the broader acoustic metamaterials literature suggests several promising directions for future structural monitoring applications. Passive acoustic metamaterials have been extensively developed for noise reduction and vibration control through mechanisms such as local resonance, acoustic bandgaps, acoustic black holes, Helmholtz resonators, labyrinthine structures, and phase-engineered metasurfaces (Gao *et al* [96]). These architectures enable strong wave attenuation, energy localization, frequency-selective filtering, and wavefront manipulation while maintaining passive operation. Such capabilities could be leveraged to enhance damage-sensitive features, amplify defect-induced scattering, improve signal-to-noise ratios, and enable more effective wave focusing and localization in SHM systems. Acoustic black holes offer broadband energy concentration and vibration attenuation, whereas resonant and bandgap metamaterials provide highly sensitive dynamic responses to local structural perturbations. Although these concepts have primarily been explored for noise and vibration mitigation, their integration into SHM systems represents a promising research direction for developing multifunctional structures capable of simultaneously controlling and monitoring structural dynamics.

As a final observation, acoustic metamaterials enhance mechanical-wave-based SHM through diverse wave-control mechanisms rather than a single design strategy. Depending on the application, metamaterial architectures exploit nonlinear harmonic amplification, frequency-selective and topological filtering, wave focusing, super-resolution imaging, mode conversion, wavefield engineering, or resonance-based sensing to improve damage detection, localization, and structural interrogation. These functionalities arise from the coupled selection of constituent materials, architected geometry, and manufacturing and integration strategies. Material properties such as density and stiffness, together with geometric features such as local resonators, periodic architectures, defect cavities, and topology-optimized structures, determine the resulting wave-control characteristics, while fabrication and attachment methods govern their physical realization and integration with the host structure. Table 3 therefore summarizes the material choices, geometric features, manufacturing and integration methods, and wave-control mechanisms of representative designs discussed in this review, providing a direct link to the material–architecture–manufacturing framework discussed in section 5. All studies employ aluminum host structures (plates, except for the aluminum tube in Gao *et al* [78]).

From a comparative perspective, the mechanical-wave metamaterial designs reviewed here present different trade-offs in sensitivity, operating range, and implementation complexity. Locally resonant and DMMs provide high sensitivity to incipient damage through harmonic amplification and energy localization, but are inherently frequency-selective. Bandgap and topology-optimized filters improve damage-feature extraction and signal-to-noise ratio, although their operating range is limited by the designed bandgap. Lens-based metamaterials offer improved spatial resolution, with the kirigami-inspired hyperlens achieving an approximately six-fold magnification of source separation, while reconfigurable and wavefield-engineering designs provide greater adaptability at the cost of increased complexity. Passive resonant metamaterials avoid dedicated wave actuation but remain resonance-dependent and comparatively less mature for SHM. Overall, direct quantitative comparison remains challenging because the reported studies employ different structures, damage types, frequencies, and performance metrics.

5. Design and implementation strategies for material-centric SHM

5.1. Materials, architectures and manufacturing

As summarized in figure 8, the functionality of metamaterials for SHM arises from the synergistic interplay between constituent materials, architected geometry, and manufacturing. Unlike conventional SHM, which relies on externally attached sensors and electronic instrumentation, metamaterial-enabled SHM embeds sensing functions directly within the structural architecture. Consequently, the design objective extends beyond achieving high stiffness or strength to transforming structural responses (including strain, vibration, wave propagation, temperature, and damage) into measurable visual, mechanical, electrical, or electromagnetic information. Material selection is therefore driven primarily by the desired information modality rather than mechanical performance alone, with constituent materials providing the required mechanical and functional properties, while architected geometry governs how structural responses are amplified, filtered, and encoded into measurable signals. Manufacturing, in turn, enables

Table 3. Representative applications of acoustic metamaterials for mechanical-wave-based SHM, highlighting the underlying mechanisms, corresponding functionalities, material types and manufacturing/implementation methods.

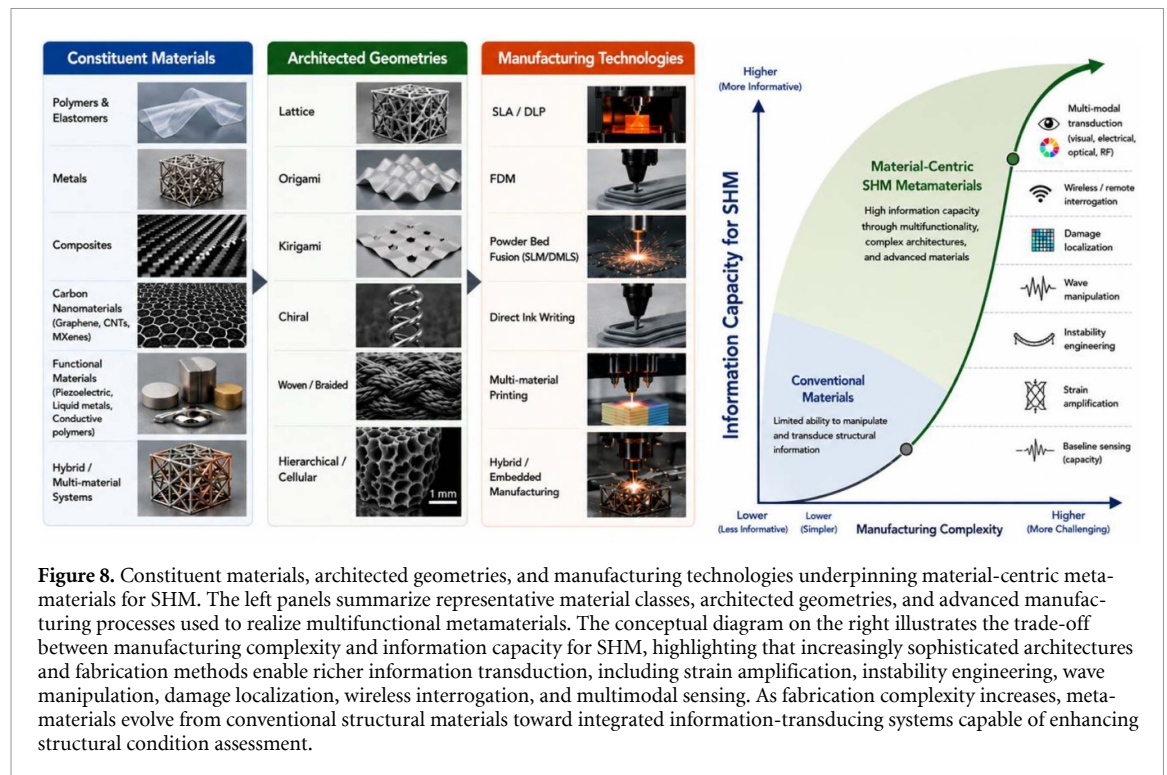
Metamaterial Design/Mechanism	SHM application	Constituent material(s)	Manufacturing/implementation
Locally resonant bandgap filter, local-resonance filtering of unwanted second harmonics [85]	Fatigue crack detection	Al–Pb composite resonators	Fabrication method not specified; 10 × 5 resonator array bonded to Al plate using cyanoacrylate adhesive
Defect-mode metamaterial defect-mode localization and second-harmonic amplification, [86] and [87]	Fatigue crack detection	Steel cylindrical stubs	Numerical design; perfect stub-plate bonding assumed
Second-harmonic-enhancing meta-structure, A0 → S0 mode conversion and enhancement of cumulative second-harmonic S0 waves [76]	Microstructural degradation monitoring	Steel meta-structure	Metal additive manufacturing; surface-mounted on Al plate
Topology-optimized metamaterial filter broadband selective filtering, and second-harmonic waves [83]	Plastic damage detection	Pb meta-filter	Numerical design; adhesively surface-mounted on Al plate using a 0.05 mm adhesive layer
Topological metamaterial filter, selective fundamental-wave transmission and suppression of unwanted second harmonics [77]	Early damage fundamental detection	Pb meta-filter	Fabrication method not specified; adhesively surface-mounted on Al plate using a 0.05 mm adhesive layer
Bidirectional metamaterial filters, bandgap filtering for selective extraction of damage-induced second harmonics [89]	Nonlinear guided-wave SHM	6061-Al (MF1) and Pb (MF2)	Host plate laser-cut; filters symmetrically bonded to both faces using two-component epoxy
Locally resonant metasurface, local-resonance bandgap filtering of undesired second harmonics [78]	Corrosion monitoring	Steel resonators	Steel resonators 3D printed and circumferentially installed using 3D-printed semicircular gears
Artificial frequency-space boundary, bandgap-induced wave confinement and enhanced coda-wave interferometry [90]	Weak damage detection	Pb meta-devices	CNC-machined from a Pb plate as a single entity; epoxy-bonded to Al plate
Locally resonant metasurface, mode-selective bandgap filtering of A0 to isolate defect-sensitive S0 response [91]	Right-angle structural integrity monitoring	Ti-6Al-4 V/brass locally resonant metasurface	Metal additive manufacturing; integrated with T-shaped Al profile
Focusing strip metasurface, moderately broadband A0 focusing and enhancement of local nonlinear second harmonics [92]	Microcrack detection	6061-Al strip metasurface	Monolithic selective laser melting with Al plate

the realization of these architectures, with the required fabrication complexity increasing alongside architectural sophistication and material integration.

A defining characteristic of metamaterials is that their functional behavior is dictated primarily by geometry. Architected lattices, origami, kirigami, woven structures, hierarchical cellular materials, and periodic microstructures manipulate stress distributions, deformation pathways, and wave propagation, thereby controlling how structural information is generated before it reaches the readout system. Geometry therefore acts as both a structural design variable and an information-processing element, capable of amplifying weak structural responses, filtering mechanical signals, concentrating deformation, or tailoring wave propagation to improve damage detectability.

The choice of constituent material is largely determined by the targeted information modality. Polymeric and elastomeric materials dominate visual and electromechanical metamaterials because their large reversible deformation enables instability-driven shape transformations, mechanochromism, mechanoluminescence, and significant strain amplification while remaining compatible with piezoresistive, capacitive, PZT, triboelectric, and radio-frequency transduction. Metallic metamaterials provide higher stiffness, fatigue resistance, and thermal stability, making them attractive for load-bearing structures, wave manipulation, resonant sensing, and harsh operating environments. Composite metamaterials combine structural efficiency with multifunctionality by integrating architected cores, woven reinforcements, conductive networks, or PZT phases, allowing load-bearing components to simultaneously manipulate strain fields and generate measurable outputs. Functional materials such as graphene, MXenes, carbon nanotubes, liquid metals, PZT ceramics, and conductive polymers have further expanded the design space by enabling self-powered sensing, wireless communication, and multi-modal information transduction.

Advances in additive and hybrid manufacturing have been fundamental to the development of metamaterials by enabling complex architectures and the integration of multiple structural and functional



materials. Depending on the information-transduction mechanism, these approaches are complemented by molding, laser processing, lithography, thin-film deposition, machining, and bonding or embedding techniques for integration with the host structure. Techniques such as stereolithography, digital light processing, fused filament fabrication, selective laser melting, direct ink writing, and multi-material printing provide precise control over geometry and material distribution. For material-centric SHM, manufacturing is not merely a fabrication step but a key determinant of sensing performance. Geometric fidelity, material interfaces, and fabrication accuracy directly influence strain localization, wave propagation, resonance, and electrical or optical responses. As metamaterials become more multifunctional and information-rich, achieving higher sensing performance requires increasingly sophisticated manufacturing processes. Future applications are expected to adopt localized and hybrid manufacturing strategies that integrate metamaterial regions only where monitoring is required, improving practicality for large-scale engineering structures.

5.2. Design framework

The design of metamaterials for SHM should be viewed as an information-transduction problem rather than a mechanical optimization problem. External loading, environmental changes, or damage first generate physical fields (including strain, displacement, stress waves, vibration, or temperature) which are subsequently transformed by the architected material into measurable outputs. The design framework is summarized in figure 9. Within this framework, the architecture acts as a physical information encoder. Beyond transduction, architected materials increasingly perform functions traditionally assigned to electronic signal-conditioning circuits, enabling passive wireless and self-powered sensing. For visual sensing, geometry amplifies deformation into observable shape changes, color shifts, luminescence, or surface reconfiguration. For wave-based sensing, periodic architectures manipulate elastic-wave propagation through bandgaps, resonance, localization, and wave focusing to enhance damage-sensitive features. Electrical and electromagnetic metamaterials convert structural responses into measurable resistance, capacitance, PZT, triboelectric, radio-frequency, or metasurface signals.

The vast design space of architected metamaterials makes computational design crucial. Finite element analysis remains the primary tool for predicting deformation, wave propagation, buckling, resonance, and coupled multiphysics behavior, while topology optimization, inverse design, and machine-learning-assisted optimization enable systematic exploration of architectures that would be impractical to develop by intuition alone. Unlike conventional structural optimization, which emphasizes stiffness or weight reduction, metamaterial design for SHM increasingly targets information-transduction performance by maximizing strain amplification, wave sensitivity, optical contrast, wireless signal modulation, or robustness to environmental variations.

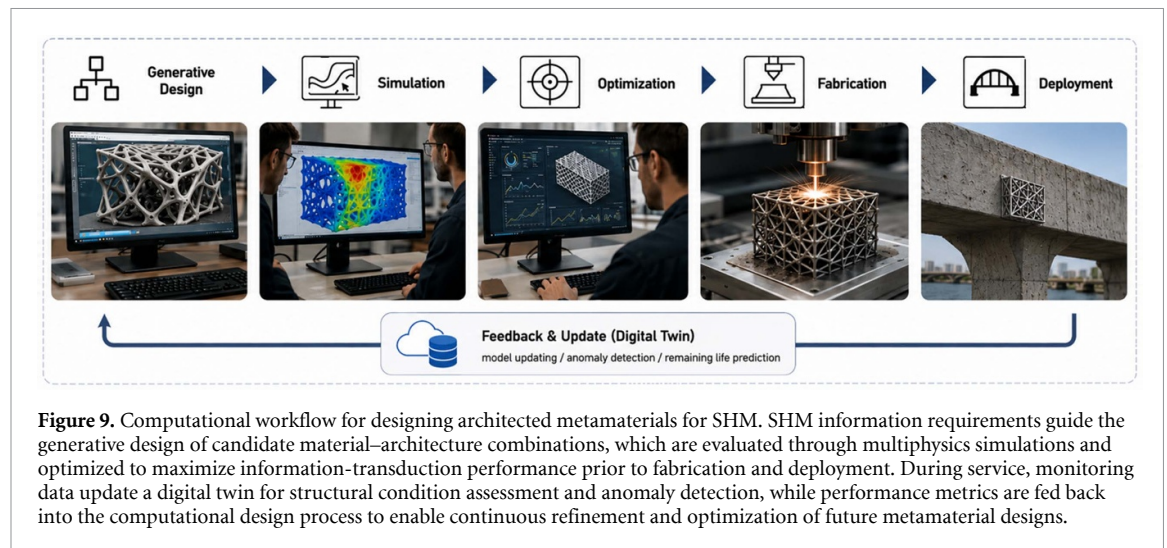


Figure 9. Computational workflow for designing architected metamaterials for SHM. SHM information requirements guide the generative design of candidate material–architecture combinations, which are evaluated through multiphysics simulations and optimized to maximize information-transduction performance prior to fabrication and deployment. During service, monitoring data update a digital twin for structural condition assessment and anomaly detection, while performance metrics are fed back into the computational design process to enable continuous refinement and optimization of future metamaterial designs.

Digital twins provide the natural framework for integrating these materials into practical SHM systems. By continuously updating computational models with monitoring data, they distinguish structural changes from environmental effects, reduce uncertainty, and improve condition assessment throughout the service life of a structure. Rather than replacing digital intelligence, metamaterials enhance it by physically conditioning structural responses into more informative signals before computational interpretation.

6. Future research directions

Although significant progress has been achieved in visual, wave-based, and electromagnetic information transduction, most current demonstrations remain proof-of-concept studies performed under controlled laboratory conditions. Future research should therefore focus on translating these concepts into robust, scalable, and deployable material-centric SHM systems capable of operating reliably throughout the service life of engineering structures.

A major research direction is the development of multifunctional metamaterials capable of combining multiple information modalities within a single architecture. Rather than generating only one sensing output, future metamaterials may simultaneously produce visual, elastic-wave, electrical, and electromagnetic information, providing complementary measurements that improve reliability while reducing dependence on dense sensor networks. Such multimodal architectures could also increase robustness against environmental variability by enabling information fusion directly at the material level.

Another important challenge is the realization of physical information processing within architected materials. Recent demonstrations of mechanical logic, sequential counting, programmable deformation, and mechanically encoded pattern recognition suggest that metamaterials can perform functions traditionally assigned to electronic signal-conditioning circuits. Future research should extend these concepts toward architectures capable of filtering noise, amplifying weak signals, implementing mechanical thresholding, storing loading history, or classifying structural states before electronic acquisition. Such developments would establish metamaterials not only as sensing elements but also as physical processors of structural information.

The integration of artificial intelligence, inverse design, and digital twins will further accelerate the development of material-centric SHM. Machine learning and topology optimization provide powerful tools for navigating the enormous design space of architected materials, enabling simultaneous optimization of structural performance and information-transduction efficiency. Coupling metamaterials with digital twins will allow continuously updated models to interpret material-generated information while accounting for operational and environmental variability, thereby improving diagnosis and prognosis throughout the structural lifecycle.

The practical realization of these concepts will additionally require advances in scalable manufacturing, long-term reliability, standardization, and field integration, as discussed in section 7. Ultimately, the long-term vision extends beyond replacing conventional sensors with architected materials. Instead, future structural systems may become intrinsically intelligent, where geometry, material composition,

and functional constituents operate collectively to sense, process, communicate, and potentially adapt to changing structural conditions. In this paradigm, the distinction between structure, sensor, and processor gradually disappears, giving rise to material-centric SHM systems in which intelligence is embedded directly within the material itself rather than added through external electronics.

7. Practical challenges and limitations for field deployment

Beyond the research opportunities discussed above, several practical challenges must still be overcome before metamaterial-based information-transduction concepts can be reliably deployed in real engineering structures. The first challenge concerns long-term durability and environmental robustness. Many of the visual and electromechanical transduction mechanisms reviewed in this work rely on polymeric, elastomeric, or thin-film functional materials, such as mechanochromic and mechanoluminescent coatings, PZT and triboelectric elements, and instability-driven shape-transforming architectures, whose optical, electrical, and mechanical responses can degrade under prolonged exposure to ultraviolet radiation, moisture, temperature cycling, and repeated mechanical loading. Fatigue of resonant and bandgap architectures, debonding of embedded sensing elements from the host structure, and drift in baseline signal characteristics over time remain largely unquantified for most of the platforms discussed, and long-term, multi-year field validation studies remain scarce.

A second, closely related challenge is the absence of standardized testing protocols and calibration procedures. As noted in section 4, direct quantitative comparison of sensitivity and operating range across the reviewed studies remains difficult because different research groups employ different damage types, excitation frequencies, host structures, and performance metrics. This heterogeneity complicates benchmarking between competing metamaterial platforms and limits the establishment of performance thresholds that engineers and infrastructure owners can rely on for design and acceptance decisions. Establishing common testing standards, reference damage scenarios, and calibration or compensation procedures for environmental and operational variability, analogous to existing standards for conventional strain gauges and PZT sensors, would help translate these technologies from academic demonstrations toward accepted engineering practice, and would also support the development of formal reliability-certification pathways that are currently unavailable for metamaterial-based sensing systems.

A third challenge relates to manufacturing scalability and integration with existing infrastructure. Most of the metamaterial-based SHM concepts reviewed here have been demonstrated at coupon or small-panel scale using additive manufacturing or other laboratory-scale fabrication techniques; extending these architectures to large, curved, or geometrically complex civil, aerospace, and marine structures will require manufacturing processes that are cost-effective, scalable, and compatible with existing construction and maintenance workflows. Potential approaches include hybrid fabrication, textile processing, composite manufacturing, and modular metamaterial inserts. Practical deployment further requires durable bonding or embedding strategies that preserve the structural integrity of the host component, sufficient wireless-interrogation range and power autonomy -twin infrastructure. Manufacturing tolerances under realistic operating conditions, and compatibility with existing data-acquisition and digital and their influence on sensing performance must also be considered to ensure repeatability under realistic production conditions. Retrofitting metamaterial-based sensing into already-built structures, rather than only into newly manufactured ones, remains a largely open problem.

8. Outlook and conclusions

SHM is undergoing a fundamental transition from sensor-centric systems toward material-centric intelligent structures, driven by rapid advances in architected metamaterials. Rather than serving solely as load-bearing components, these materials are increasingly capable of sensing, amplifying, filtering, and encoding structural responses before information reaches external instrumentation. This shift redefines the role of materials from passive structural elements to active participants in structural information processing.

This review presented a comprehensive overview of metamaterials for SHM through the lens of information transduction. The literature was organized according to the type of information generated from structural responses, including visual, mechanical, wave, electrical, and electromagnetic modalities. This perspective establishes a unified framework for comparing diverse metamaterial platforms and highlights the evolution of the field from sensing enhancement toward integrated information transduction and embedded physical intelligence.

Future developments are expected to be driven by the convergence of architected materials, advanced manufacturing, computational design, and digital twins. As the information capacity of metamaterials continues to increase, so too will the demand for sophisticated generative design, multiphysics optimization, multifunctional material integration, and advanced manufacturing. At the operational level, digital twins will enable continuous model updating, performance assessment, and iterative refinement of metamaterial architectures throughout the structural life cycle, creating a closed-loop design framework that links sensing, computation, and material development.

Despite this progress, several challenges remain before widespread engineering implementation becomes feasible. Long-term durability, environmental robustness, scalable manufacturing, standardized performance metrics, and integration into large-scale infrastructure continue to limit practical deployment. Addressing these challenges will require close collaboration across materials science, mechanics, manufacturing, computational engineering, and data science.

Looking ahead, metamaterials are expected to evolve beyond architected structures with enhanced mechanical properties into integrated material systems capable of simultaneously carrying load, sensing structural responses, conditioning information, harvesting energy, and interacting with digital intelligence. Such developments will move SHM beyond distributed sensor networks toward structures in which intelligence is increasingly embedded within the material itself, enabling more autonomous, resilient, and information-rich infrastructure.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Conflict of interest

The authors declare no conflicts of interest.

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