

Applications of Smart and Self-Sensing Materials for Structural Health Monitoring in Civil Engineering: A Systematic Review

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Abstract: Civil infrastructures are constantly exposed to environmental effects that can contribute to deterioration. Early detection of damage is crucial to prevent catastrophic failures. Structural Health Monitoring (SHM) systems are essential for ensuring the safety and reliability of structures by continuously monitoring and recording data to identify damage-induced changes. In this context, self-sensing composites, formed by incorporating conductive nanomaterials into a matrix, offer intrinsic sensing capabilities through piezoresistivity and various conduction mechanisms. The paper reviews how SHM with self-sensing materials can be applied to civil infrastructure while also highlighting important research articles in this field. The result demonstrates increased dissemination of self-sensing materials for civil engineering worldwide. Their use in core infrastructure components enhances functionality, safety, and transportation efficiency. Among nanomaterials used as additions to produce self-sensing materials in small portions, carbon nanotubes have the most citations and, consequently, the most studies, followed by carbon fiber and steel fiber. This highlight identifies knowledge gaps, benchmark technologies, and outlines self-sensing materials for future research.

Keywords: self-sensing materials; carbon nanotubes; carbon fiber; steel fiber; smart composites; SHM

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1. Introduction

Civil infrastructure, such as bridges, buildings, water supply lines, offshore platforms, and oil tanks, are exposed to a dynamic and complex environmental condition, with extreme fluctuations in temperature and high levels of CO₂, accelerating their deterioration over time [1–3]. Fractures, crevices, and an unavoidable decaying in structural strength ensue. Early detection of the damage location and size is crucial to prevent catastrophic failures. Traditional methods of periodic visual inspections and manual evaluations are restricted in their capacity to detect early structural degradation or damage, emphasizing the necessity for improved monitoring approaches. Nevertheless, most destructive, and non-destructive techniques do not provide continuous health monitoring data requiring the use of smart materials to help to solve this problem [4,5].

Significant research efforts to address these limitations have focused on developing smart materials that can detect damage through vibration-impedance and piezoresistivity, for example [6]. There has been interest in local health monitoring for critical members of a host structure by utilizing smart sensors such as fiber optic sensors and piezoelectric

sensors during the last decades. All the commercially viable sensors require an external power source, either battery or solar power. Additionally, many of these sensors have shown limitations of excessive cost and low durability, as well as limited detection capacity and area [7].

Thus, the use of SHM systems is crucial for a rapid assessment of the health status of these structures, ensuring their safety and reliability. SHM systems, responsible for monitoring and recording data over time, are essential for understanding the health status of structures and identifying changes resulting from damage. It consists of three sequential stages: global damage detection, classification, and estimation. In Stage 1, a global occurrence of damage is detected through monitoring changes in structural systems. In Stage 2, types of damage are classified, recognizing patterns and behavioral characteristics. In Stage 3, the location and extent of the damage are estimated using a method based on experimental or numerical shape [8,9]. An efficient SHM should involve and integrate the following features: accurate, reliable, and distributed strain measurements; the possibility of assessing shape and displacements; detection of local damages; reliable protection of the sensors; no need for surface installations; high durability; measurements from the real zero state of the structural element [10].

In general, the utilization of smart structural materials solely as sensors, without the need for additional sensor components, is termed self-sensing. Self-sensing materials are formed by dispersing electrically conductive nanomaterials (i.e., conductive phase) into a mixture matrix to create a continuous conductive network and provide intrinsic sensing properties to the composite. The formation of an extensive conductive pathway is governed by various mechanisms, such as contacting conduction, tunneling effect, field emission effect, and ionic conduction [11–13]. In this context, composite sensors capable of self-monitoring their deformation state through piezoresistivity are developed, providing electrical variations when mechanically deformed [5]. These composites can be manufactured using diverse types of conductive additives, which reduce their electrical resistivity, such as carbon fiber, steel fiber, graphene, and carbon nanotubes [7,14].

The present article utilizes the systematic review methodology, following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses approach. Through this rigorous review process, the aim is to track the progression of selected articles over time, offering a visual representation of studies conducted in different countries. The principal objective of this study is to comprehensively review and synthesize existing research on SHM applications in civil infrastructure, with a specific emphasis on the potential of self-sensing materials. By analyzing the target journal's scope and readership, this article aims to elucidate the study's significance, identify leading SHM techniques, and discern global trends. This research will offer valuable insights into the practical applications and limitations of self-sensing materials in the field of civil engineering.

2. Research Methods

To investigate the applications of SHM in civil engineering in terms of smart and self-sensing materials, a systematic literature review was conducted. From there, it will be possible to ascertain the relevance of the study and applications of SHM in civil engineering, as well as distinguish the main smart and self-sensing techniques more suitable for future studies. For the development of this review, the PRISMA (Preferred Reporting Items for Systematic Review and Meta-Analysis) methodology was adopted, which guided the selection of studies for this systematic review. Thus, the methodological process involves three distinct phases [15,16]:

1. Accessing vast scientific and academic databases through keyword techniques and searching;
2. Screening for inclusion and exclusion criteria;
3. Implementing an eligibility process to assess relevant material and evaluate study data.

The bibliographic search took place in February 2024, covering the following databases: ScienceDirect, Scopus, and Springer. To search in the repositories, the descriptors used were: (“Civil engineering” AND “SHM”) AND (“smart materials” AND “self-sensing”), aiming to identify and investigate articles exploring the application of self-sensing smart materials in the context of civil engineering, specifically concerning structural health monitoring. Review articles, encyclopedias, book chapters, conference abstracts, editorials, and other materials were excluded.

The articles were classified for relevance through a selection procedure. Initially, 764 research articles were identified and exported from the databases, containing title, author, publication year, and abstract in the “.RIS” format for the Mendeley Reference Manager version 2.110.0 software. The screening phase involved reading the title, abstract, and keywords of each record in the text file, resulting in the selection of 344 articles.

The eligibility criteria were chosen to include an article in the main dataset after full reading. Three criteria were established for the inclusion of an article in this review:

- The article must explicitly relate to the implementation of SHM in the field of civil engineering;
- The article must focus on at least one analysis linked to SHM, whether experimental, methodological, numerical, or mathematics;
- The article must include a characterization of the smart and self-sensing materials used.

After the complete reading and advanced search based on the above criteria, 229 articles were disqualified for not meeting the research criteria. Finally, after checking for duplicate studies, a final number of documents included in the systematic review was obtained, totaling 33. A visual representation of the PRISMA search phases is available in Figure 1.

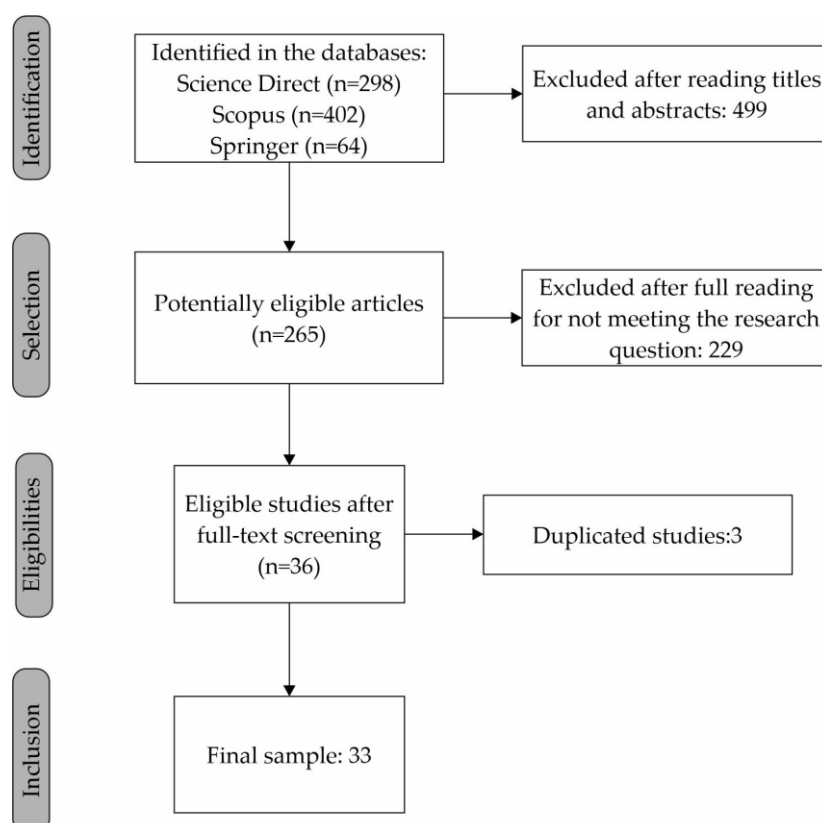


Figure 1. PRISMA flowchart of the systematic review process.

3. Descriptive Analysis Results

In this section, a comprehensive analysis of the reviewed articles is presented, covering various dimensions and utilizing tables and figures to illustrate the results. Figure 2 illustrates the chronological distribution of research papers over the specified period, following applying the criteria adopted to define the articles. The data analysis reveals a growing trend in using self-sensing materials in civil engineering, beginning in 2014 and continuing to increase over the years, as indicated by the upward trend line. Additionally, the results reveal that approximately 78% of the publications were disseminated over the last five years. Moreover, the number of articles on the subject reached 9 in 2023, reinforcing the ongoing relevance of these materials. This suggests that self-sensing materials are becoming an effective tool for monitoring the structural integrity of critical infrastructures in real-time.

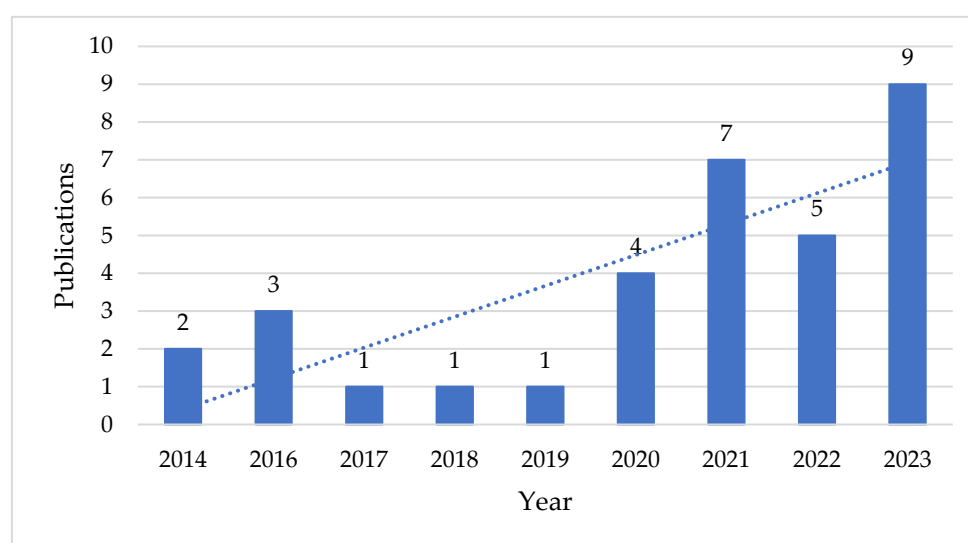


Figure 2. Distribution of research papers by year.

The analysis of the geographical distribution of publications, illustrated in Figure 3, highlights the universality of self-sensing materials in civil engineering, with representations in various countries. It is observed that the articles cover a diversity of countries distributed across different continents, including South America, North America, and Europe. A significant portion of the studies on the subject comes from China, the United States, and Italy, which contributed 15%, 13%, and 13% of the total published articles, leading in this field. Highlighted are the countries conducting studies on smart and self-sensing applications: India, Spain, the United Kingdom, and Portugal. Countries such as Israel, Germany, Australia, and Brazil are also emerging with smaller contributions from authors in the field. This selection is due to the substantial number of publications during this period, reflecting the growing interest in this topic. The broad geographical representation underscores the diverse perspectives and methodologies influencing advancements in civil engineering and self-sensing materials.

The broad geographical representation underscores the diverse perspectives and methodologies influencing advancements in civil engineering and self-sensing materials. This prevalence reflects the leadership of these countries in the field, characterized by significant investments in research and infrastructure, as well as a robust community of experts and academic institutions dedicated to this area of study.

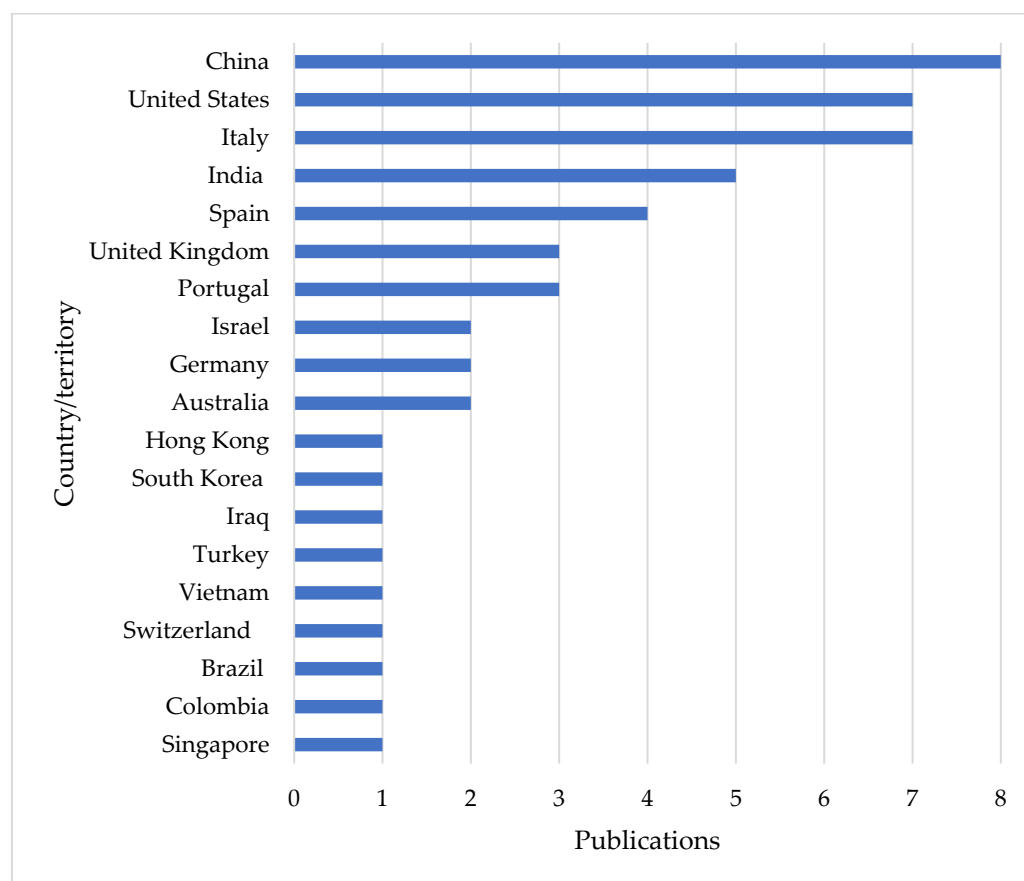


Figure 3. Publications by country of the authors.

Figure 4 highlights the particular emphasis of SHM applications in beams and columns, followed by transportation and geotechnics. This suggests a predominance of the use of smart materials in fundamental components of infrastructures, such as elements of safety and durability of these constructions, as well as functionality, safety, and operational efficiency in transportation. However, there are gaps in the development of self-sensing in the areas of bridges and metal structures, building structures, and historic buildings. This indicates an opportunity for researchers to further explore the potential of SHM in these specific areas and develop solutions more tailored to the demands and challenges associated with civil construction and the structural integrity of buildings.

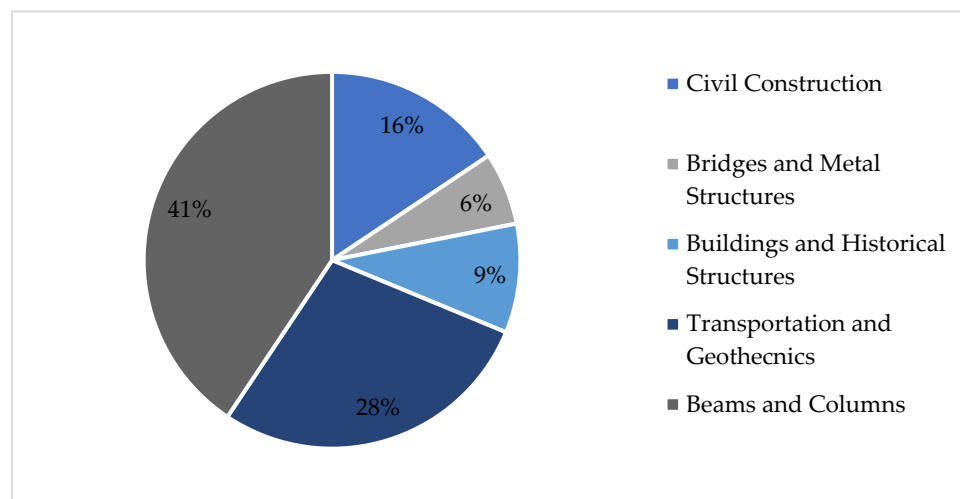


Figure 4. Publications by subject area.

Furthermore, in the analysis of bridges and metallic structures, the predominant presence of commercial sensors is highlighted, especially fiber optic sensors and fiber Bragg grating sensors. These local sensors are integrated into global SHM systems [17–19]. While there is a technology base for SHM in these components, there is still significant room for innovation and ongoing research aimed at enhancing these systems and adapting them to self-sensing materials for more precise and effective monitoring.

Finally, Figure 5 provides an overview of the distribution of publications across various engineering journals. The journal *Construction and Building Materials* stands out, accounting for approximately 30% of experimental and numerical studies, significantly serving as a platform for scientific dissemination in this field. Additionally, journals such as *Sensors and Actuators A: Physical*, with three publications, *Composites Part B: Engineering*, and *Cement and Concrete Composites*, also notably contribute to the discourse, each representing a substantial portion of the analyzed publications.

This diversity of scientific communication vehicles reflects the breadth of the discourse and the importance attributed to advancing knowledge about self-sensing materials in civil engineering. Therefore, it is emphasized that the higher number of publications in certain journals indicates not only quantity but also the quality and prestige of these outlets in the specific field of self-sensing materials in civil engineering.

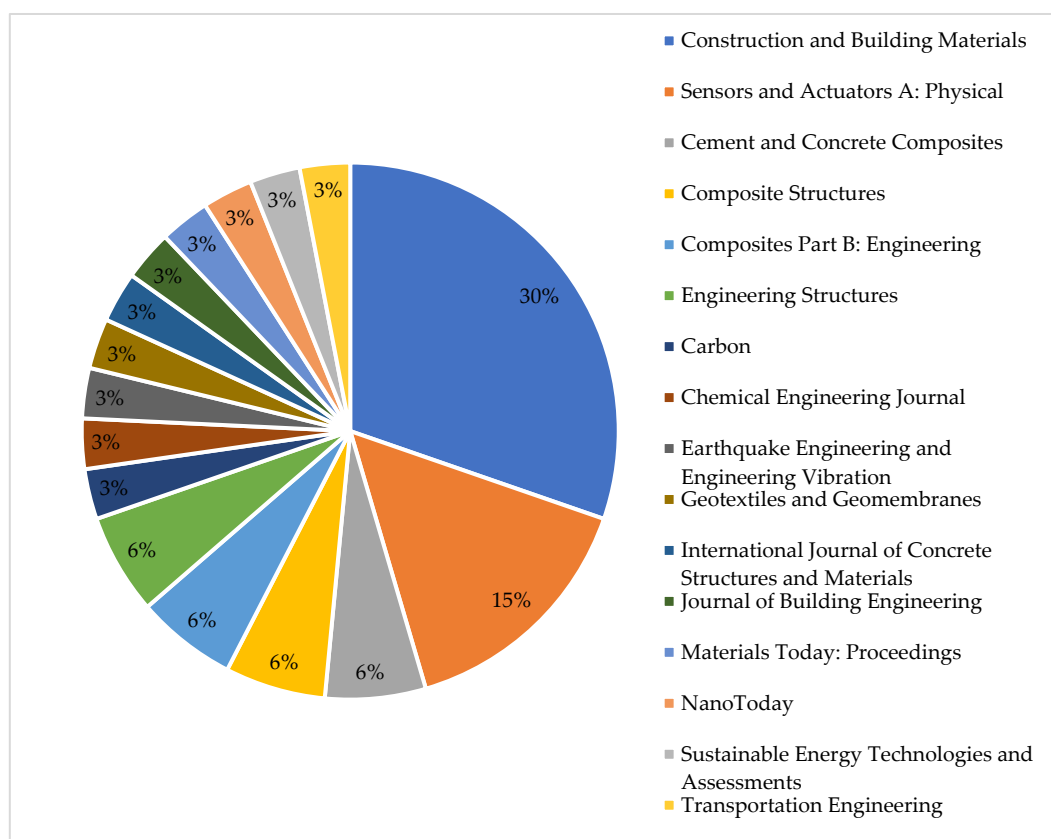


Figure 5. Percentage distribution of reviewed articles according to journal name.

4. SHM for Civil Infrastructure

Recently, many researchers have focused on the possibility of using variations in the properties of a structure as an indication of its structural damage and as an uncertain impact due to varying ambient conditions [9]. Hence, the SHM of structures is widely used for the evaluation of the condition of the infrastructure based on measuring real-time strain values as a crucial parameter of the structure [20]. Global research trends in smart and self-sensing materials are applications in various aspects of civil infrastructure. These include civil construction, bridges, metal structures, buildings (including historical ones),

transportation systems, geotechnics, as well as beams and columns. Figure 6 illustrates the comprehensive fields of SHM in civil engineering.

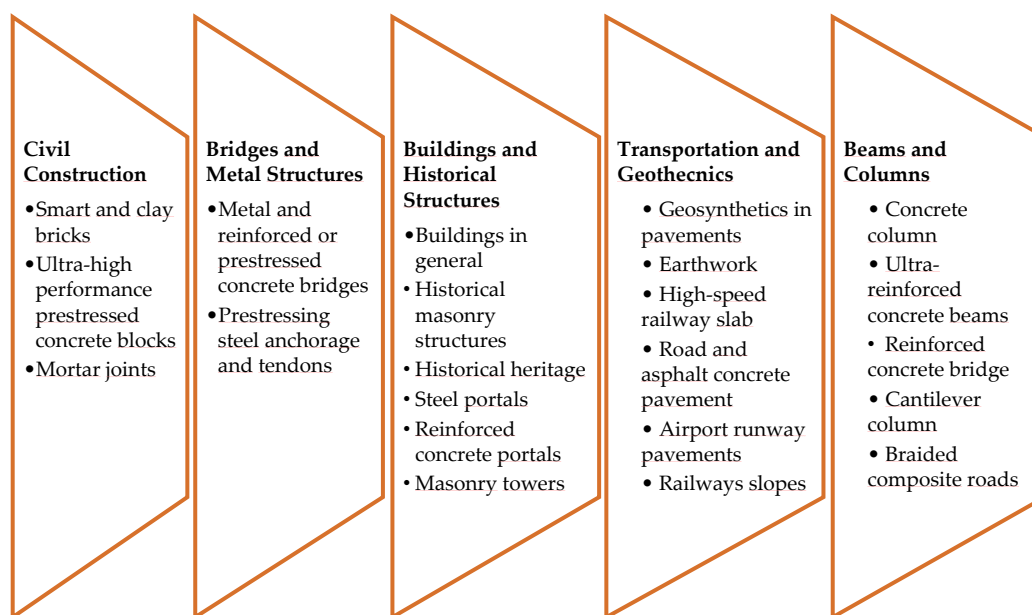


Figure 6. SHM application of smart material and self-sensing in civil engineering.

4.1. Civil Construction

The civil construction industry is susceptible to structural issues such as settlements, heavy loads, and material aging. Inadequate maintenance can result in dangerous collapses. Smart bricks, mortar joints, and ultra-high-performance concrete blocks have been developed to monitor deformations and identify damages, assisting in preventive maintenance [21–24]. These intelligent materials have become more popular for detecting structural problems. However, integrating these technologies into existing infrastructures presents challenges, including compatibility with conventional construction practices, cost-effectiveness, and long-term durability.

4.2. Bridges and Metal Structures

Bridges and other civil infrastructures are designed to safely bear loads, but they face degradation from operational and environmental factors over time. Most failures involve steel member fractures, often due to fatigue cracking, a progressive process involving initiation, slow growth, and abrupt failure phases [6,25,26]. Early detection of damage is vital to prevent catastrophic failures. Prestressed concrete bridges, along with anchorage and tendons for prestressing steel, and structural bridges on pedestrian walkways, steel, enhanced with the incorporation of nanomaterials, serve as self-sensing components in SHM for evaluation and assessment purposes [10].

4.3. Buildings and Historical Structures

The monitoring of structures encompasses two phases: early construction and long-term post-construction. During early construction, factors like hydration temperature and moisture content influence concrete properties and shrinkage. This phase is critical due to high energy consumption and emissions from raw materials extraction and transportation. In the long term, structures face severe weather and environmental conditions, necessitating SHM to detect and prevent corrosion caused by water penetration and chloride ingress, serving as a key practice in conservation engineering [27,28]. Preservation and rehabilitation of valuable historic heritage buildings require effective and efficient monitoring systems to ensure proper maintenance of durability and functionality of the

building structures and materials. Moisture transportation and retention in building infrastructure are some of the most common problems, often inducing structural damage and resulting in harmful microbial growth that affects human health [29,30].

4.4. Transportation and Geotechnics

In the fields of transportation geotechnics, the availability of reliable conditions and performance data is paramount, whether concerning pavement/railway/coastal engineering or directly affecting the provision of accurate and precise information [31–33]. Rail and road infrastructure deteriorates over time due to various factors, including material fatigue, overloading, ground movement, and environmental effects [7,34]. Cemented stabilized sand or geosynthetics have found wide application in different infrastructure constructions but exhibit low ductility and susceptibility to cracking. Maintenance and renewal costs for typical railway tracks and substructures represent 50–60% of the total costs of such infrastructure over its entire service life [35,36]. Distresses such as nanocracks, which evolve into microcracks and eventually macrocracks, significantly contribute to the degradation of pavement structures over time. Factors like material aging, environmental conditions, heavy usage, and overloading accelerate this process [37,38]. Amongst all SHM methods, self-sensing composites incorporating nanomaterials provide a more integrated, real-time, and practical solution for infrastructure damage detection, considering geomaterial properties and smart pavements [39].

4.5. Beams and Columns

In the case of structural components, such as beams, columns, and connections, which are typically subjected to different external and internal loads, deterioration may occur due to exposure to severe conditions associated with the environment, loading, effects of aggressive actions, corrosion of embedded metal, frost, overload, concretes resistance to volume changes, abrasion/erosion, and chemical actions [40,41]. Ultra-reinforced, prestressed beams or columns like concrete-filled steel tubular columns tended to undergo more intense deterioration processes. Additionally, it is well-founded that corrosion of steel reinforcement and fatigue damage lead to degradation of concrete structural performance. Therefore, reduced durability and shortened service life are evident in these structural components [42]. However, it is challenging to assess during their service life through visual inspection and direct core sampling examination. Beams and columns doped with nanoparticles constitute robust materials capable of transducing strain into changes in electrical resistance [41,43].

5. Smart and Self-Sensing Materials for Advanced SHM

Sensor-based health diagnostic methods can be replaced with conventional non-destructive techniques due to their robustness, reliability, and ease of implementation. SHM sensors collect data from structures when subjected to external forces, either permanently or temporarily attached to the structure [20,21]. Multisensing, reusable, and non-bonded configurations of piezoelectric sensors, transducers piezoceramics, Fiber Bragg grating, fiber optic sensors, and lead zirconate titanate are gaining popularity [9,14,22].

Taheri (2019) classifies four advanced sensor technologies currently used in SHM:

- Fiber optic sensors detect changes in light signals transmitted along optical fibers. These sensors, primarily made of glass fibers, offer advantages such as high sensitivity and immunity to electromagnetic interference, with fiber optic Bragg grating (FBG) sensors being prominent [10,24,28,29];
- Piezoelectric sensors detect parameters like acoustic emission, temperature, and strain by converting them into electrical charges. Piezoelectric materials, such as ceramics like Lead Zirconate Titanate (PZT), act as sensors, actuators, and transducers [6,14,22,31,32]. These sensors are small in size, lightweight, low cost, available in a variety of formats, have high sensitivity, and so on [44,45]. Integrated into smart

materials, piezoelectric patches and “smart patches” have been utilized for rehabilitation and vibration damping due to their ability to detect subtle changes in structural integrity, making them invaluable in preventing catastrophic failures and ensuring the longevity of bridges, buildings, and aircraft [34–36,46];

- Electrochemical sensors fall into three main categories: potentiometric, amperometric, and conductometric. Their ability to provide real-time, accurate data on the corrosion of steel reinforcement bars in concrete, either directly or indirectly, based on the changes in the properties of the concrete cover and maintenance practices, ultimately extending the service life of infrastructure [47]. In corrosion monitoring of reinforced concrete structures, electrochemical sensors such as those measuring open circuit potential, surface potential, concrete resistivity, polarization resistance, noise analysis, and galvanic current are employed [48–50];
- Wireless sensors are increasingly replacing traditional wired systems in structural monitoring, offering the potential for advanced data processing, such as early detection of structural damage [51,52]. These sensors are nodes and platforms for autonomous data acquisition rather than traditional sensors. They enable the attachment of sensors like piezoelectric pads, leveraging mobile computing and wireless communication capabilities. Wireless technology reduces wiring needs, lowers installation costs, and allows flexible system configurations [37].

They generally enable early damage detection, vibration control, and distributed monitoring of stress, temperature, and deformation [23,24]. However, their intrinsic fragility limits their application and can be difficult to install due to their extremely small dimensions [7,38,53]. Such sensors must be integrated into smart materials to create advanced structural global monitoring systems in various applications [22,25]. There are advanced non-destructive evaluation techniques, such as ground-penetrating radar, spectral analysis of surface waves, DIC and three-dimensional laser scanning. The system must interface and integrate the original practice principally based on traditional sensors and combine the response of several diffuse sensors installed on the structure to monitor the progress of changes and damage with improved degradation [6,26,27]. This convergence facilitates the development of sophisticated global monitoring systems, exemplified by the innovative use of FDM to create high-performance multi-material 3D and 4D printed composite structures with smart materials [54,55].

In scientific literature, sensors developed through traditional methods have faced constraints in meeting the increasing requirements for precise sensing. These sensors often exhibit characteristics that compromise data quality, such as packet loss during communication, errors in time synchronization, and slow communication speeds. Even with advancements in materials involving intricate multi-scale structures and complex multi-rare-earth doping, conventional development and characterization techniques continue to present considerable challenges. Moreover, these sensors lack integrated intelligence, which limits their adaptability and responsiveness to dynamic environmental changes [45,56,57].

Given the existence of such complex and integrated systems, there is an effort to develop materials that can effectively be used as building materials while acting as sensors to monitor the health of structures [58]. Thus, a new generation of multifunctional building materials has emerged for SHM approaches: smart materials with self-monitoring and detecting damage. These self-sensing composites can be produced with various types of conductive fillers that reduce their electrical resistivity. The electrical properties of nanocomposites are significantly influenced by nanomaterial concentration. At low concentrations, conductivity primarily occurs through quantum tunneling between isolated nanostructures. As concentration increases, direct contact between nanomaterials becomes more prevalent, resulting in a conductive network. This transition is marked by the percolation threshold. When subjected to external stimuli such as deformation or microcracking, changes in inter-nanomaterial distances alter conductivity patterns, inducing a piezoresistive response [59–61]. Consequently, they demonstrate detectable changes in

electrical resistivity in response to variations in voltage/deformation and crack propagation resulting from monotonic and cyclic loads, making them promising alternatives for SHM architectures [31,62]. This electrical sensitivity to external physical parameters makes nanocomposites candidates for SHM applications [36,63,64].

Self-sensing composites contribute to SHM in civil infrastructure by improving the durability, safety, and efficiency of civil infrastructure through enhanced monitoring capabilities. Their ability to provide continuous, real-time data, embedded sensing and performance evaluation on structural conditions contributes significantly to the maintenance and management of infrastructure assets [65,66]. One of the main benefits of these materials is the reduced cost. Sensors embedded in structural components during construction may have lower installation costs compared to traditional [67]. This is crucial because, while a SHM system improves safety and lowers management/inspection costs, it becomes unfeasible for large-scale infrastructures if material production and integration costs are too high [24].

Conductive particles, fibrous, powder, and nanoplatelets, offer a lot of conductive channels for the development of self-sensing materials [13,68]. Among nanomaterials used as composite additives to produce self-sensing materials, carbon nanotubes have the most citations and, consequently, the most studies, followed by carbon fiber and steel fiber. There is a notoriety regarding graphite powder, graphene nanoplatelet, and carbon black nanoparticles. In smaller quantities, there are rubber fiber, Ni nanofiber and fine steel slag aggregate. For reasons of relevance, those most applied in civil engineering SHM will be explained.

Furthermore, with the increasing complexity of modern infrastructures, the durability of civil infrastructures has received significant attention [69,70]. In assessing the environmental effects and the durability of intelligent and self-sensing materials used in SHM, the need to develop multifunctional materials, such as those incorporating carbon nanotubes, arises. These materials are subject to various deterioration factors, such as chloride attacks, carbonation, freezing and thawing conditions, chloride ion penetration, and sulfate attack. These factors are known to be the main causes of damage to concrete. Therefore, understanding the durability of these materials is crucial for their practical applications in civil structures [71–73].

Carriço et al. [74] analyzed the resistance to carbonation and chloride penetration in concretes with CNT, observing an improvement of approximately 16% in carbonation resistance, while the resistance to chloride penetration was little affected by the presence of CNT. Yoon et al. [75] compared cement pastes containing CNT, carbon fibers, and a combination of both. They concluded that the combination of CNT and CF played a crucial role in reducing the increase in electrical resistivity after exposure to deterioration conditions due to synergistic effects, such as the bridging effect between CNT and CF.

5.1. Carbon Nanotubes (CNT)

Carbon nanotubes have garnered significant interest as one of the most promising conductive nanoparticles for SHM applications over the past 15 years [76]. Multi-walled carbon nanotubes (MWCNTs) consist of concentric cylinders of graphene sheets arranged around a hollow core of carbon atoms [77,78]. These nanotubes are formed by rolled layers of graphite consisting of walls with hexagonal carbon rings. They often aggregate into large bundles, with their ends closed by dome-shaped structures where hexagonal rings are capped by pentagonal rings [79]. They exhibit a high aspect ratio, low bulk density, and an extremely high specific surface area. MWCNTs exhibit exceptional mechanical, thermal, and electrical characteristics, with Young's modulus reaching up to 1 TPa and fracture deformations of approximately 6%. These nanoscale fibers with superior stiffness, strength, and aspect ratio, making them reinforcements in composite materials [58,80]. One of the great challenges of this material is related to its dispersion, which directly affects the piezoresistive behavior [60,81,82].

In addition to their remarkable properties, CNTs can be expensive to produce due to the complexity of their synthesis and purification processes. The cost varies depending on the type and the purity required. However, for large-scale applications, continuous production of CNTs from low-cost sources has taken a closer step to overcoming the problem of the high cost of synthesis [67,83,84]. CNT-based sensors are generally durable and have a long operational lifespan, reducing frequent replacement costs, too [78,85].

Table 1 presents a review of studies using CNT and MWCNT (eight articles) and with a combination of Ni nanofiber (CNT_Ni, with one article). The applications include in-situ pavement, concrete airport runway pavements, railway sleepers, building construction, high-speed rail infrastructure, and reinforced concrete beams, among others. The weight percentages of CNT relative to the binder vary according to the specific application, with an average of around 0.5 to 2%. Experimental methods include monotonic compression tests and dynamic loads, as well as electrical measurements to assess properties such as compressive strength and electrical resistance. Additionally, numerical modeling has emerged as a valuable tool for understanding the behavior of structures enhanced with CNT. This diversity of applications reflects the growing interest in using CNT to enhance the properties of concrete structures and pavements. The remarkable mechanical and sensing properties of CNT suggest that they are ideal candidates for high-performance and self-sensing cementitious composites.

Table 1. Review of studies using carbon nanotubes for civil engineering SHM.

Filler Type	Application	Content	Num.*	Exp.**	Method	Reference
CNT	In-situ pavement	0.2 wt% of the epoxy resin weight		X	Cyclic compressive, temperature, and roller compaction	[37]
CNT	Concrete airport runway pavements	2 wt% of the aqueous solution weight		X	Electrical impedance tomography in cycles of loading	[86]
CNT	Concrete railway sleeper	0.5 to 1 wt% of the cement weight	X	X	Static and dynamic loading with dynamic modeling	[36]
CNT_Ni	Building	0.1% and 0.5% to 1.9% (respectively) of the cement weight		X	Monotonic compression and cyclic compression	[28]
CNT	High-speed rail infrastructure	0 to 25 wt% of the cement weight		X	Compressive strength and electrical resistance	[87]
CNT	Reinforced concrete beams	0.2 to 0.8 wt% of the cement weight		X	Compression test and electric measurement	[23]
CNT	Reinforced concrete beams	0 to 2 wt% of the cement weight		X	Compressive strength and electrical resistance	[78]
CNT	Large structures	0.1 to 0.75 wt% of the cement weight		X	Dynamic loads	[25]
CNT	Reinforced concrete beams	2 wt% of the cement weight		X	Dynamic loads and electric measurement	[26]
CNT	Reinforced plates	-	X		Stochastic uncertainties	[88]

* Numerical; ** Experimental.

5.2. Carbon Fibers (CF)

Composites reinforced with carbon fibers, which have a high aspect ratio, exhibit enhanced self-sensitivity. Studies have shown significant improvements in durability, especially in corrosive environments [89,90]. For piezoresistivity-based detection in composites, the optimal fiber length is generally up to 10 mm, as longer fibers tend to agglomerate, making dispersion more difficult [91–94]. Therefore, carbon fibers (CFs) are considered superior to steel fibers for enhancing the electrical conductivity and piezoresistive properties of cementitious composites [95].

Carbon fibers are especially attractive to engineers due to their low density, high thermal conductivity, and ability to mitigate issues such as drying shrinkage and cracking. Extensive research has explored the benefits of carbon fibers in concrete, as used in a study by Zhao et al. [96]. They are widely used as reinforcement in concrete due to their light weight, high modulus of elasticity, and excellent thermal conductivity [97,98].

Table 2 presents a review of studies that utilize CF and combinations of carbon fibers with carbon nanotubes (CF_CNT) for SHM in civil engineering applications. This summary includes seven articles focused on CF and two articles that investigate the combined use of CF and CNT. This diversity of applications and the consistent improvements observed across various studies reflect the growing interest and potential in using carbon fibers and their composites to enhance the properties and longevity of concrete structures.

Table 2. Review of studies using carbon fibers for civil engineering SHM.

Filler Type	Application	Content	Num.*	Exp.**	Method	Reference
CF	Weigh-in-motion system in pavement	1 wt% of the binder weight	X	X	Compression load and electromechanical model	[39]
CF_CNT	Beams and columns	0 to 0.75 wt% of the cement weight		X	Compressive strength and electrical measurements	[99]
CF	Support Structures	56 vol% of the fiber volume		X	Cycle loading test	[100]
CF	Tendon of the prestressed bridge	15.9% and 23.8 vol% fiber fractions in CFRP		X	Tensile and electrical resistance tests	[101]
CF	Reinforced concrete beams	1 wt% of the total mass weight		X	Tensile and compressive strains	[21]
CF	Reinforced concrete beams	Throughout the area		X	Compression test and electric measurements	[24]
CF_CNT	Reinforced concrete beams	0.55 wt% of the total mass weight		X	Static flexural loading	[27]

* Numerical; ** Experimental.

5.3. Steel Fibers (SF)

Steel fibers are gradually replacing traditional steel bars, providing significant reinforcement to structures. SFs are known for their high energy absorption capacity and durability, improving the mechanical properties of composite materials [2,87,102,103]. Compared with other fibers, carbon steel fibers are more effective in improving the deformation and sensing ability of ultra-high performance. They have a good response regarding the effects of temperature, relative humidity, and storage age on the electrical properties of composites [104–106]. Dalvand et al. [107] show the evaluation of the impact failure mechanism and mechanical characteristics of self-compacting cementitious composites reinforced with steel fibers containing silica fume, SFs, SEM, and surface topography.

Table 3 presents a review of studies using SF (5 articles) and with combination of FSSA (SF_FSSA, with 1 article) in various structural contexts, primarily with smart bricks, in addition to prestressed concrete block, columns, and masonry buildings. The weight percentages of SF in relation to clay or cement highlight the adaptable nature of these materials, around 0.5%. Experimental methods encompass eccentric axial compression, temperature and humidity variation studies, piezoresistive testing under monotonic loading, and life cycle analysis. The numerical method refers to the nonlinear stress-strain model. These experiments reveal the multifaceted nature of SF applications, ranging from structural reinforcement in masonry buildings to innovative uses in smart brick technology. The incorporation of nonlinear modeling and rigorous testing underscores a comprehensive approach to understanding SF behavior under different conditions, indicative of ongoing research aimed at enhancing structural durability, efficiency, and sustainability.

Table 3. Review of studies using steel fibers for civil engineering SHM.

Filler type	Application	Content	Num.*	Exp.**	Method	Reference
SF	Smart Bricks	0.5 wt% of the clay weight		X	Eccentric axial compression	[21]
SF_FSSA	Prestressed concrete block	0.5 wt% and 2 wt% of the cement weight		X	Eccentric axial compression	[1]
SF	Smart Bricks	0.5 wt% of the clay weight	X	X	Nonlinear model and eccentric compression	[22]
SF	Smart bricks	0.25 wt% of the clay weight		X	Temperature and humidity variation	[23]
SF	Columns tubular	0.5 wt% of the cement weight		X	Piezoresistive in monotonic loading	[108]
SF	Masonry buildings	0.25 w% of the total mass weight		X	Life cycle analysis	[53]

* Numerical; ** Experimental.

5.4. Graphene Nanoplatelets (GNPs)

Graphene nanoplatelets are a type of carbon nanomaterial composed of small stacks of graphene sheets. These sheets are obtained from graphite layers through a process involving the intercalation of small molecules followed by mechanical or thermal exfoliation [31]. Additionally, GNPs offer cost efficiency and superior dispersibility, a significant advantage over other nanomaterials or pure graphene, simplifying their incorporation into various matrices [12,38]. They exhibit distinct geometric variations in their two-dimensional structure. Therefore, hybrid nanomaterials, such as GNP_CNT with different dimensions (2D/1D), can produce a synergistic enhancing effect and impart excellent properties to cementitious composites [109,110]. Through mechanisms such as crack bridging and deflection, they hinder crack propagation at the nanoscale [20,111]. Baomin et al. [112] study the effect and mechanism of GNPs on the hydration reaction, mechanical properties, and microstructure of cement composites.

Table 4 provides a review of studies using GNP (two articles) and their combinations with carbon CNT and CF (GNP_CNT and GNP_CNT_CF, adding two articles). GNP is utilized in asphalt mixtures for road pavements and geotextiles for pavements, with distribution ranging from volumetric proportions in asphalt mixtures to widespread use in geotextiles. Experimental methodologies include cyclic compressive stress testing, tensile loading, transverse strains, and electromechanical modeling aimed at evaluating mechanical and electrical properties. The numerical method refers to the electromechanical model. The combination of CNT, GNP, and CF in concrete beams highlights the versatility of these materials in enhancing compressive strength and electrical conductivity.

Table 4. Review of studies using graphene nanoplatelets for civil engineering SHM.

Filler Type	Application	Content	Num.*	Exp.**	Method	Reference
GNP	Asphalt mixtures in road pavements	5 vol% of the binder volume		X	Cyclic compressive stress	[11]
GNP_CNT_CF	Concrete beam reinforced	0.35 to 3 wt% of the cement weight		X	Compressive strength and electrical measurements	[20]
GNP	Geotextiles in pavements	Throughout the area	X	X	Tensile loading, transverse strains, and electromechanical model	[102]
GNP_CNT	Geocomposites in pavements	0.17 wt% of the cement weight		X	Compressive strength and electrical measurements	[103]

* Numerical; ** Experimental.

5.5. Graphite Powder (GP)

Graphite finds various applications, whether in powder form, nanofibers, or reduced from oxides. Graphite powder is attractive due to its lightweight and high conductivity. Nevertheless, GP equips a smooth surface on the microstructural scale, which lessens the surface bonding strength and consequently reduces the mechanical properties [113,114]. Graphite was characterized by ease of application, capable of being dispersed in the mortar binder through mechanical mixing, allowing their application in large quantities without the use of specialized equipment [29]. Due to poor adhesion and low interlocking with cement, GP exacerbated concrete defects, decreasing the elastic modulus, cyclo-hop effect, and compressive strength. The best results could be obtained with optimized contents of self-sensing materials and graphite. Different length scales of GP were used in the work of Dinesh et al. [115]. GP is used to reduce the percolation threshold of the other nanomaterials embedded in cement [53].

Table 5 presents a review of studies using GP in civil engineering for SHM. The reviewed studies include the application of GP in beams and columns, where 5% by weight of the cement was used, resulting in compressive strength and electrical measurements. Another study reviewed the combination of GP with silica fume (SF) in beams and columns, using 0.75% by volume of the cement weight, also focusing on compressive strength and electrical measurements. Additionally, the combination of GP with CF and CNT was applied in historic masonry buildings, with content variations between 0 to 20%, 0.2%, and 0.4% by weight of the binder, respectively, for mechanical and electrical characterization. These studies highlight the versatility and importance of GP and its combinations in different structural contexts, offering improvements in both the mechanical strength and electrical properties of construction materials.

Table 5. Review of studies using graphite powder for civil engineering SHM.

Filler Type	Application	Content	Num.*	Exp.**	Method	Reference
GP	Beams and columns	5 wt% of the cement weight		X	Compressive strength and electrical measurements	[115]
GP_SF	Beams and columns	0.75 vol% of the cement weight		X	Compressive strength and electrical measurements	[68]
GP_CF_CNT	Historic masonry buildings	0 to 20%, 0.2% and 0.4 wt%, respectively, of the binder weight		X	Mechanical and electrical characterization	[29]

* Numerical; ** Experimental.

The weight or volume percentages of the materials relative to the binder demonstrate the variety of proportions used in different application contexts, around 0 to 20%. Experimental methods involve compression strength tests and electrical measurements, aiming to evaluate both the mechanical and electrical properties of the composite materials. Also noteworthy is the detailed mechanical and electrical characterization in historical masonry buildings, reflecting the preservation of cultural heritage while seeking innovative solutions to reinforce their structure.

5.6. Carbon Black Nanoparticles (CBN)

Carbon black nanoparticles are conductive additives commonly used in self-sensitive materials [116]. Formed during the thermal decomposition of hydrocarbons, CBNs have a diameter of less than 300 nm. They fuse to form aggregates during production, with their structure depending on factors such as fuel type and combustion temperature [24,62]. The incorporation of CBN offers high electrical conductivity and can act as a microencapsulation agent, together with lime, providing self-sensing and self-healing properties in composites [117–119].

Table 6 highlights a review of studies using CBN (one article) and a combination with CNT (one article) in masonry structures and concrete columns. The weight percentages of the materials relative to the binder are around 0% to 9% of the binder weight, demonstrating the flexibility of these composites in different structural contexts. Experimental methods include cyclic compression tests, eccentric axial compression, and monotonic compression, emphasizing the variety of loading conditions considered to evaluate the strength and performance of these materials in different scenarios.

Table 6. Review of studies using carbon black nanoparticles for civil engineering SHM.

Filler Type	Application	Content	Num.*	Exp.**	Method	Reference
CBN	Concrete masonry	0% to 9 wt% of the binder weight		X	Eccentric axial compression	[62]
CBN_CNT	Concrete column	6 wt% of the cement weight		X	Cyclic and monotonic loading	[120]

* Numerical; ** Experimental.

5.7. Comparison of Health Monitoring Systems

In this section, a comparison and analysis of the different SHM methods presented in this document were conducted, highlighting their advantages and disadvantages. Table 7 emphasizes aspects such as sensitivity, cost, durability, and ease of implementation for each method.

Table 7. Comparative analysis of different sensing materials for SHM.

Method	Advantages	Disadvantages
Optical Fiber Sensors	High precision, durability	High cost, need for power sources
Piezoelectric Sensors	Moderate sensitivity, easy integration	Limitations in large areas, medium cost
Carbon Nanotubes	High electrical conductivity, good flexibility	Difficulty in uniform dispersion, high cost
Carbon Fibers	High mechanical strength, lightness	Relatively high cost, difficulty in dispersion
Steel Fibers	High mechanical strength, easy incorporation into concrete matrices	Heavy, may affect the properties of the base material
Graphene Nanoplatelets	High conductivity, excellent mechanical properties	Difficulty in large-scale production, high cost
Graphite Powder	Low cost, good conductivity	Lower sensitivity, potential agglomeration
Carbon Black Nanoparticles	High surface area, good conductivity	Difficulty in uniform dispersion, variable cost

Each method has its own characteristics and ideal applications. For instance, fiber optic sensors are accurate and durable, but their cost is high, and they require additional power sources. Piezoelectric sensors, on the other hand, have moderate sensitivity and are easy to integrate, but they have limitations over large areas and a medium cost. Furthermore, CNTs provide high electrical conductivity and flexibility, but they face difficulties with uniform dispersion and are expensive. The analysis presented in the table helps to better understand the trade-offs between different SHM methods, assisting in the selection of the most appropriate method for each specific application.

6. Conclusions

Methods for assessing damage and stress in structures are often expensive and limited-duration techniques. However, the emergence of self-sensing materials presents clear

advantages with respect to traditional monitoring technologies within the smart materials category. These innovative materials, when integrated into load-bearing structures, offer enhanced compatibility and similar durability to civil works. The main outcomes of this work can be summarized as follows:

- PRISMA-based review highlights the increasing integration of self-sensing materials in civil engineering, particularly in advancing SHM practices;
- Significant growth in research publications, notably in journals like *Construction and Building Materials* since 2014, underscores the expanding effectiveness and application scope of self-sensing technologies;
- Contributions from leading nations such as China, the United States, and Italy reflect global interest and investment in leveraging self-sensing materials for enhancing infrastructure resilience and longevity;
- Carbon nanotubes (CNTs) have emerged as pivotal additives, offering exceptional electrical conductivity and stability. Their integration into self-sensing composites enhances performance under harsh environmental conditions, promising long-term monitoring capabilities at reduced costs;
- Finally, significant issues, such as comprehensive analysis of current trends and innovations in self-sensing materials, highlight novel applications that advance SHM practices across diverse civil engineering sectors.

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