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Review Article

Integrating self-sensing nano composite and fiber optic sensors technologies for advancing structural monitoring: A mini review

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Abstract

Concrete structures are susceptible to various damages due to ageing and natural hazards. The growing research focus in civil engineering systems is Structural Health Monitoring (SHM). Meanwhile, advanced sensing technologies play an eventual role in SHM, enhancing safety and maintenance by providing real-time data on concrete structures. This review represents the characteristics of advancing sensing technology, such as self-sensing sensors based on nanomaterials and fiber optic sensors. Further, the investigation has been performed to comprehend the evolving field of sensing technology related to several aspects, such as the principal mechanism, practical application, and challenges pertain to SHM. The advantages and limitations of integrating self-sensing multifunctional sensors with nanotechnology as an alternative to fiber optic sensors is discussed. In addition, the analogy of these two sensors is detailed to understand the efficiency of advanced sensing technology using nanotechnology. Both types of sensors exhibit the capability to monitor the changes in the structures. Self-sensing technology provides a straightforward solution, thus leading to cost-effective and simplified structural integrity compared to complex and fragile fiber optic sensors. Self-sensing multifunctional sensors offers an efficient integrated approach while fiber optic sensors provide comprehensive solution for structural monitoring. Particularly, self-sensing sensors offers direct data collection and large-scale applications for extensive projects due to their ease of installation. Therefore, the highly advanced self-sensing sensors with Level 5 technology will eventually be an ideal choice over FOS for SHM.

1. Introduction

Concrete is an extremely versatile and composite material, that has been used globally for buildings, bridges, highway pavements, dams, tunnels, railway roads, sewers, and other infrastructure for over 200 years because of its durability, strength, and affordability [1]. Despite this, due to a lack of advanced technologies in concrete and limited maintenance of infrastructures [2,3], the concrete is subjected to extreme conditions, including chemical and physical effects, changes in the environmental conditions due to concrete shrinkage, stress, and pressure due to overloads leads to cracking, freeze-thaw cycle, corrosion, abrasions, and deterioration [4–7]. Thus, SHM would be of great scientific importance in detecting early signs of deterioration to extend the life of structures and reduce maintenance costs in existing structures [8]. Furthermore, it greatly adapts to the challenges of a dynamic building environment. An innovative approach to SHM involves real-time and continuous monitoring of structures to assess the performance, condition, and integrity of civil infrastructures [9,10]. The SHM collects data about the structural behavior and

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identifies irregularities to allow insights that makes the decision [11]. A major component involved in SHM is advanced sensing technology that is based on various types of sensors. However, employing advanced sensing technology such as fiber optic sensors (FOS) [12] and self-sensing multifunctional sensors (SSMS) [13] for SHM has become comprehensive research interest. Due to these recent advancements in SHM, non-destructive techniques (NDT) of foretelling structural damage have significantly reduced [14].

The FOS play a crucial role in SHM due to their durability, accuracy, and ability to provide real-time data on various parameters of structures [15]. In SHM, the FOS involves in monitoring the changes in properties of structural elements by utilizing optical fibers with the interaction of light frequency and strain within the structure [16]. Such FOS is highly sensitive to detect small structural changes due to environmental conditions. Therefore, multiple sensors are required to be multiplexed along a single optical fiber to reduce the complexity and cost during installation. Moreover, it gives the possibility of monitoring using remote control for structures where the data can be transmitted over long distances. In the context of SHM, fiber-optic sensors are applied to monitor the strain and stress, temperature, crack detection, vibration, pressure, and load distributions in critical areas of structures [17,18], that extends the lifespan of infrastructures. It ultimately leads to improved infrastructure resilience by reducing unnecessary manual inspections and repair.

Noticeably, Intrinsic self-sensing sensors or SSMS are cement-based sensors which could be an alternative to fiber optic sensors but with different mechanism which is competitive and challenging in SHM to analyze the integrity and condition of the structures. SSMS are placed directly in different forms such as embedded, coating, sandwich, and bulk form into the structural material [19] to measure various parameters, such as strain, humidity, and temperature, without any external sensors [20]. The principle of self-sensing sensors is typically based on piezoelectric [21] and capacitive sensors. These self-sensing sensors are built directly into the structure without external attachments and highly sensitive to small changes in the behavior of the structure, respond quickly, and allow for immediate assessment of structural health. It has limited measurement range compared to some other external sensors. Additionally, developing and embedding SSMS can be expensive depending on the sensing material and challenging, respectively [22]. This mini state-of-the-art discusses the complete characteristics of FOS and SSMS with their features for dominant SHM application.

2. Characteristic of Advanced Sensing Technologies

2.1 Fiber optic sensors

In the field of civil engineering, the integration of FOS has emerged as an advanced technology for monitoring the structural integrity and complexity of various structures [23]. FOS are becoming more popular for SHM because they have a high level of sensitivity, accuracy, and can measure parameters like as strain, temperature, and vibration without significant signal loss. Due to their resilience to electromagnetic interference and lightweight characteristics, they are well-suited for integration into different structures without affecting their qualities. FOS possess durability, resilience under challenging conditions, and the ability to facilitate multiplexing, allowing for the simultaneous monitoring of several sensors using a single fiber. In addition, their ability to sense and gather data from multiple locations allows for continuous monitoring of a whole structure, providing real-time information. The extended longevity and little upkeep of FOS also contribute to its cost-effectiveness in the context of extensive, vital infrastructures. FOS is adopted for condition assessment of concrete piers which is subjected to impact load [24] as well as in static and dynamic monitoring of large structures [25]. Typically, FOS are classified in varieties as shown in Figure 1, including Fabry-Perot type interferometers (FP-I), Fiber Bragg grating (FBG), microbend, wavelengths, and Brillouin [16,17,26] with special coatings and strain mechanisms which are useful in detecting various parameters such as stress, pressure, length, crack width, temperature, and chemical changes. The aforementioned advanced sensor technology provides engineers and researchers with real-time data, allowing them to comprehensively understand how structures behave under different conditions. For instance, Figure 2 shows the overview of FOS with deep learning techniques for SHM. However, the installation of these sensors poses many challenges, especially ensuring their proper integration into structural components. To overwhelm such setback, it is associated with fiber escape, strain relief conduits, and wireless telemetry solutions to improve the reliability and efficiency of installation [27,28]. The FOS is unsusceptible to radio and electromagnetic interference owing to its dielectric material [29]. Among FOSs, the use of FBG sensor and Stimulated Brillouin Scattering (SBS) sensors has become prevalent in measuring temperature and strain with exceptional sensitivity and accuracy [30]. Besides the change in wavelength of FBG, the change in strain and temperature can be determined using the Equation (1) and modelled by using equation (2) – (5) [31–35].

$$\frac{\Delta\lambda_B}{\lambda_B} = P_e \varepsilon_{zz} + \left(P_e \left(\alpha_s - \alpha_f\right) + \zeta\right) \Delta T \qquad (1)$$

Where P_e is coefficient of strain optic α_s is thermal expansion of material; α_f thermal expansion of optic fibre; ε_{zz} is axial strain; ζ is coefficient of thermo-optic;

$$\Delta\lambda_B = K_\varepsilon \varepsilon + K_T \Delta T + K_p P \qquad (2)$$

$$K_\varepsilon = [1 - 0.5 n_{eff} \left(\rho 12 - \nu(\rho 11 - \rho 12)\right)]\lambda_B \qquad (3)$$

Where;

$$K_T = [\alpha + \xi]\lambda_B \qquad (2)$$

$$K_P = [-\frac{1-2\nu}{E} + \frac{n^2}{2E} (1-2\nu)(2\rho 12 + \rho 11)]\lambda_B \qquad (3)$$

But the FBG sensors that is attached to the structures using adhesives, failing to which errors due to temperature [36]. Also, Moyo et al. compared the static and tensile test results of concrete beam and steel bar, respectively. The investigation exhibit that the FBG can be effectively used for strain measurement because the system having an accuracy of 5με and sensitivity of 1με [32]. Whereas, FBGs are particularly suitable for distributed sensing, while SBS sensors enable distributed sensing capabilities [37].

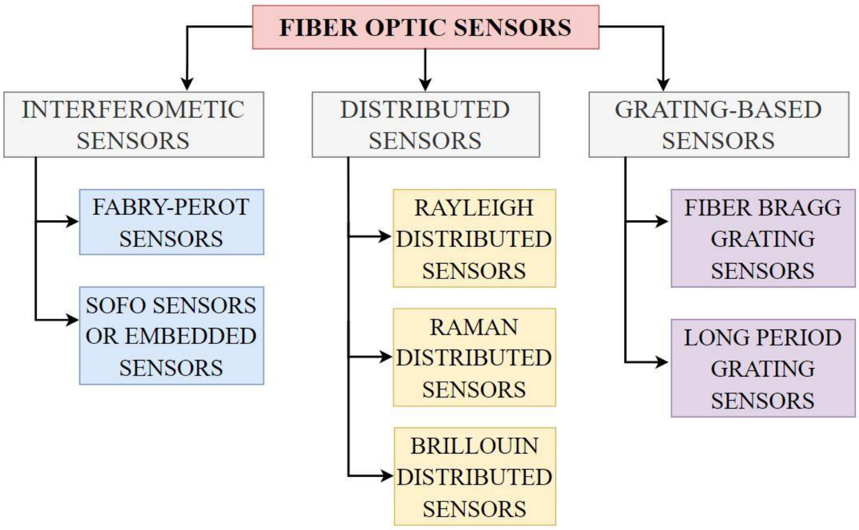


Fig. 1. Classification of fiber optic sensors

The distributed FOS enables the automatic interpretation of crack measurement using machine learning techniques [38]. Such FOS technologies offer reliable and precise solutions to various technical challenges making them invaluable tools for monitoring and data collection in a wide range of civil engineering applications like infrastructure monitoring [39] and marine structures [40]. Consequently, a significant innovation in the field of smart optical fiber (SOF) is the development of FOS pre-embedded in concrete (PEC) as shown in Figure 3 a) and 3 b). The particular sensors are specifically designed to analyse the temperature characteristics of various cementitious matrix materials and pre-stressed bars. Despite the practical challenges associated with the sensitivity and fragility of FOS [25], the implementation of PEC sensors represents a significant leap forward in the quest for enhanced structural monitoring and safety within the construction industry [41,42].

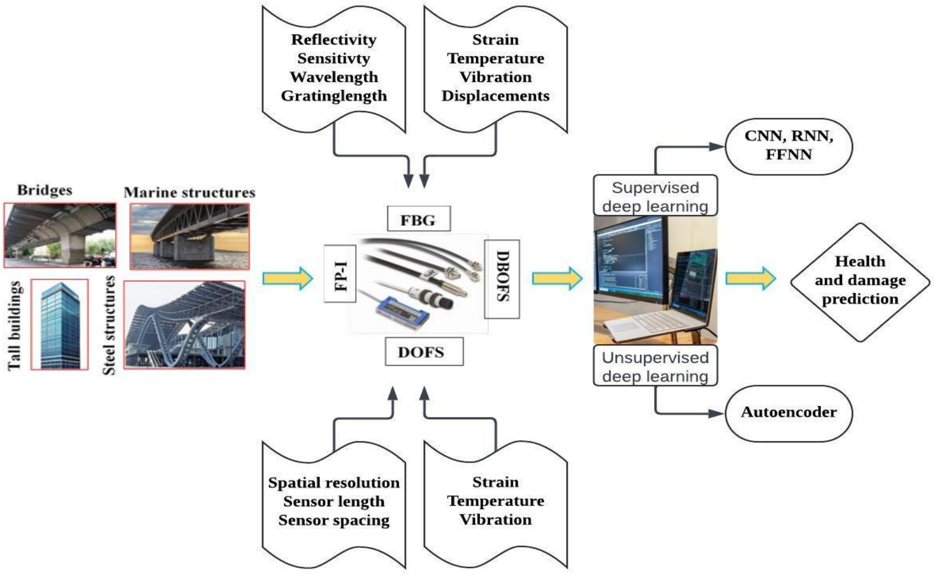
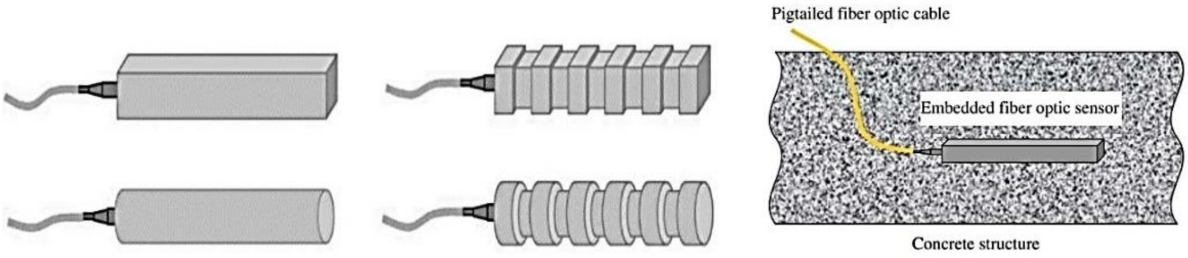


Fig. 2. Overview of FOS with deep learning technique for SHM



(a) (b)

Fig. 3. (a) Shapes of PEC sensors [42], (b) Embedded FOS in concrete structure [41]

In addition, the FOS has led to the discovery and use of plastic optical fibers (POF) in crack and monitoring applications due to its traditional fragility. The POFs exhibit light intensity changes at the initial crack growth stage, making them suitable for early detection. The experimental results using crack simulation samples and concrete beams exhibit that the sensitivity of POF in crack monitoring decreases as the angle between POF and crack increases [43]. Moreover, lens based POF is used to monitor the rebar corrosion due to impressed current [44]. Eventually, the advances towards POF is by highlighting the adaptability and flexibility of FOS technology associated with structural health monitoring [43,44]. Besides the crack and corrosion monitoring, the real-time analysis of temperature and strain of the pavement slabs are monitored using distributed FOS. It has the capability of providing a comprehensive analysis of longitudinal temperature distributions, heat flux transfer from top to bottom, and strain patterns in both vertical and longitudinal orientations.

The immediate insights derived from these results aid in assessing potential deformation patterns within the pavement slab, contributing to game changer of structural assessments and maintenance [45,46]. Additionally, FOS continue to evolve and offers a recent advancement capability for SHM. For instance, the recent insights such as smaller, flexible FOS enabling integration into diverse structure; improved spatial resolution for detecting minute changes over long distances; and wireless communication enhancing the real-time data transmission. In addition, FOS integrated with AI and IoT analytics for predicting and assessing the damages in the structure.

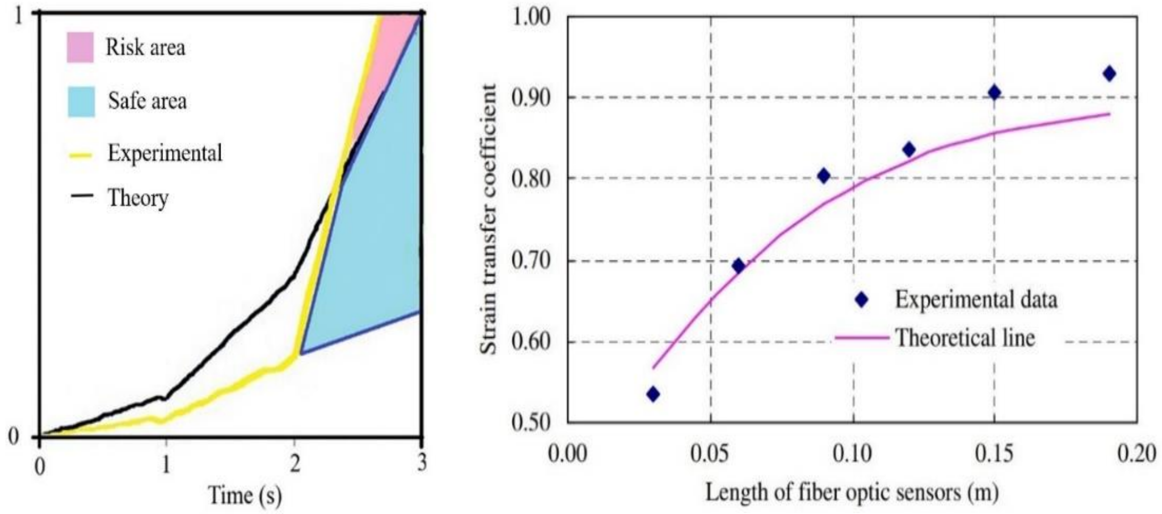


Fig. 4. Graphical representations of experimental and theoretical results for SHM using FOS [16,41]

The FOSs can assess various parameters, including strain, temperature, refractive index, chloride ion concentration, and pH value for all type of reinforced concrete. The Figure 4 represents the graphical interpretation of experimental and theoretical results obtained using FOS, where the structural integrity is determined between two curves. The FOS has the advantage in offering real-time information on structural deformation and stress, which can improve safety by detecting potential problems before they occur. In this regard, the real-time data obtained using linear regression curve between the corrosion penetration and deformation measured using optical fiber is depicted in the Figure 5 for an elementary observation. Furthermore, the continuous monitoring supported by FOS technology contributes to the development of predictive maintenance strategies, minimizing the risk of structural failure, and optimizing the lifespan of critical infrastructure.

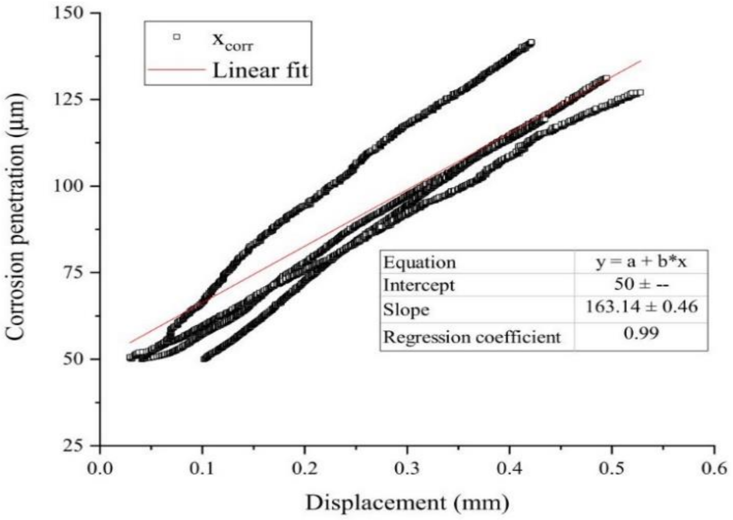
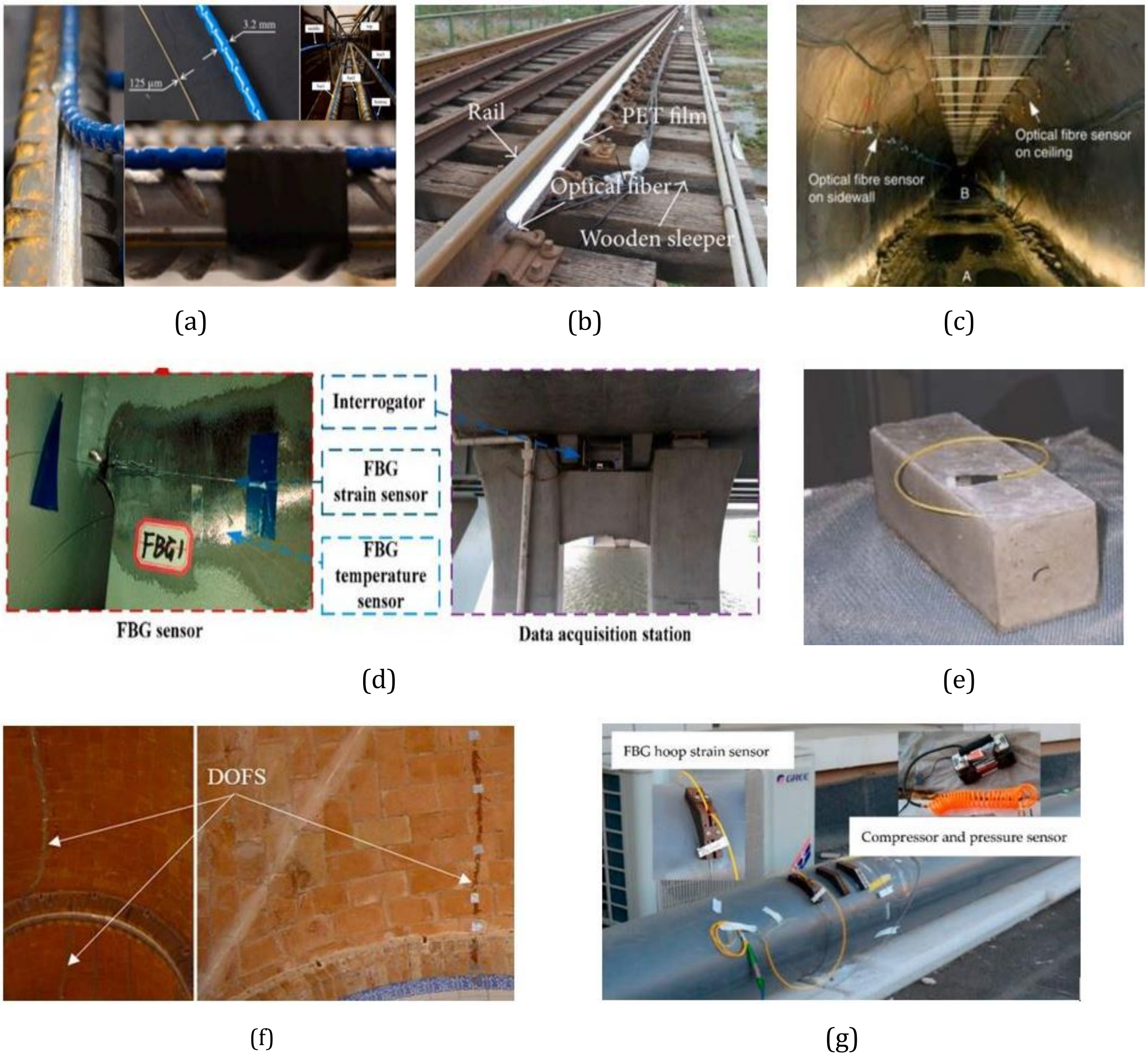


Fig. 5. Linear regression curve for the real-time data using optical fiber [44]

It is used to monitor the shrinkage and creeps of the concrete, loads on cable bridges, rebar corrosion and crack detection, rail tracks, underground mines, water pipelines for leakages, masonry structures, steel and concrete bridges. The implementation of optical fiber in various forms for SHM of different civil structures and elements is shown in the Figure 6. However, there are still certain shortcomings in FOS such as expensive interrogation system, need for specialist expertise and several repeaters for signal boosting. Moreover, to understand the working principal of FOS, it is necessary to know the basics of light propagation in fiber optical cables where the entire process is based on the principle of total internal reflection. This phenomenon is particularly noticeable when the shell material has a lower refractive index than the core material. The proper application of these principles is essential for the successful design and deployment of fiber optic sensing systems. Nonetheless, the FOS is commonly employed for SHM, the operative service and durability of sensors is quite a disadvantage and requires an alternative with multifunctional properties.



(a) (b) (c)

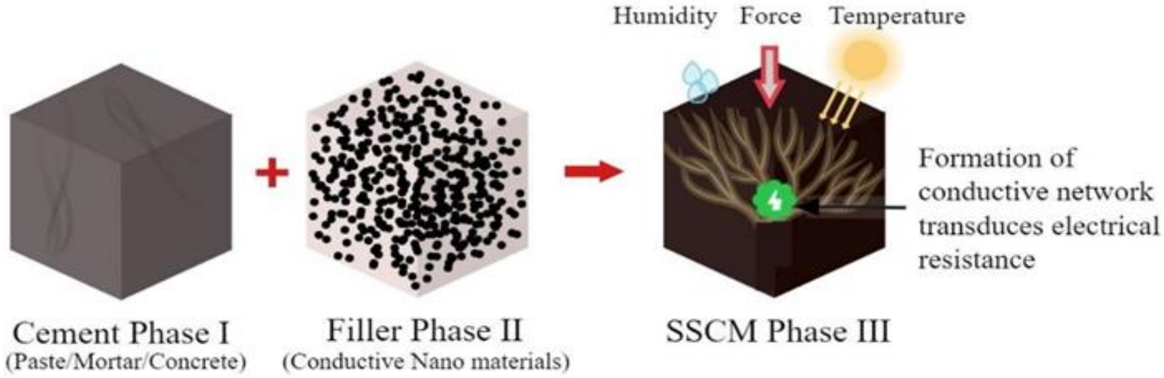
(d) (e)

(f) (g)

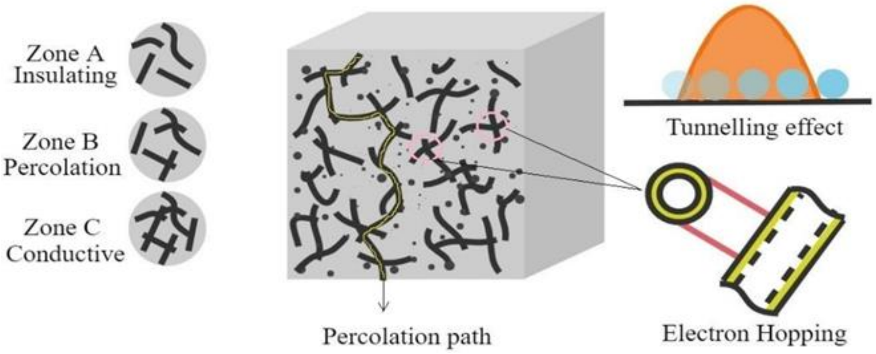
Fig. 6. Implementation of FOS is various forms for system of civil SHM a) Crack detection in rebar [47] b) Monitoring rail tracks [48] c) Strain monitoring in underground mining tunnel [49] d) Monitoring steel bridge crossing in china [50] e) Embedded sensors in concrete element for SHM [41] f) Crack detection in masonry walls [51] g) Monitoring leakage in the water pipeline [52]

2.2 Nano Self-Sensing Composites/Multifunctional Sensor

The cement matrix is not a conductive material without sensing parameters. Therefore, a conductive filler is dispersed effectively into the cementitious matrix to develop SSMS composite [53–57]. The structure of SSMS composites is depicted in Figure 7 a). This technique is based on the principle of the piezo resistivity effect, where the nano functional filler creates a conductive network resulting in conductivity [58–60]. While incorporating nano conductive fillers, the electrical resistivity of composites will reduce to 1 ohm cm. The conductivity network formed by the effective electron hopping and percolation path attributes to the sensitive particles inside the cement matrix, which is called as percolation threshold (Φ_c). Figure 7 b) depicts the formation of conductive networks in the matrix. The different conduction theories for SSMS composites includes, percolation theory [61], the tunneling effect [62], electric field emission [63], and effective medium theory [64]. The behavior of SSMS depends on the nature of electrical conductivity in the matrix as a function of filler concentration (Φ), during the process of percolation. There are different zones of conductive mechanisms during the formation of conductive networks. In the zone A ($\Phi < \Phi_c$) mechanism, the conductive filler or nanofiller percentage is less compared to the percolation threshold. Here, the cement matrix will tend to have high resistivity due to the more movement of electrons which resist creating a conductive network. It is also called an insulation zone showing ionic conduction. In zone B ($\Phi = \Phi_c$), percolation indicates that the conductive filler amount is equal to the percolation threshold. Therefore, the distance between the fillers will be reduced and the conductive link will start resulting in tunnelling conduction. In zone C ($\Phi > \Phi_c$), the filler concentration will be greater than the percolation threshold and the mechanism itself stabilizes the sensing property inside the matrix.



(a)



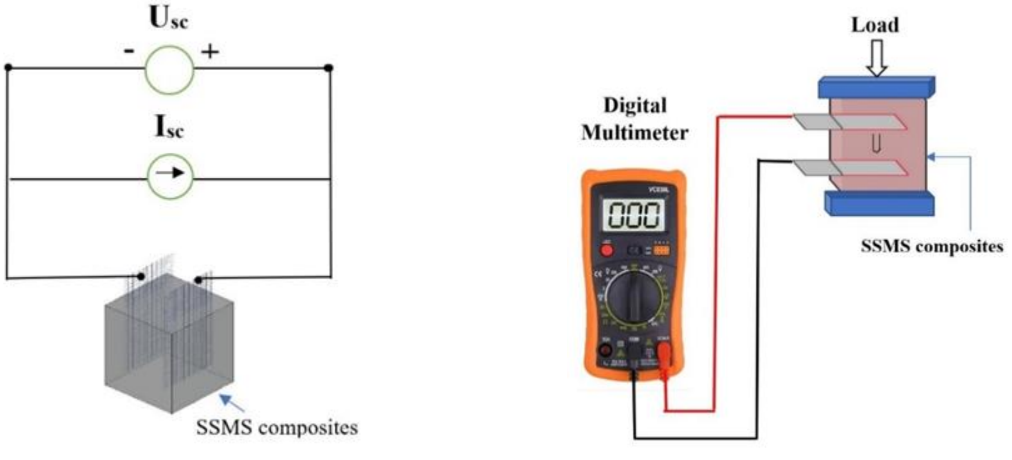
(b)

Fig. 7. a) 3-phase structure of self-sensing [65], b) Formation of conductive network in matrix [65]

When these sensing composites are exposed to the natural ecological process or external forces or loads [53,61], the network inside the matrix is distributed leading to FCR (fractional change in resistivity). By principally adopting this method, electrical property could be measured to determine the cracks, damage, stress, strain, temperature, and humidity in various loading conditions like static or cyclic. This also depends on the contact between the fillers in the composites due to piezo resistivity [59]. The principle of SSMS behaves like a human brain as a nervous system like human action [66]. The cement-based sensors were compared with 10mm foil strain sensor for cyclic compression load by converting to electrical resistivity resulting in less error margin.

The SSMS composite influenced with conductive nanomaterial influence multifunctional properties that are used effectively in the different civil engineering application for SHM. Cement-based sensors are exceptionally efficient for SHM owing to their material compatibility with concrete, which guarantees precise and dependable readings of strain, cracks, and deformation. Their self-sensing capabilities, utilizing variations in electrical resistivity to identify stress and fractures, facilitate the early diagnosis of structural problems. These sensors, embedded directly in concrete, provide durability, long-term stability, and resilience to hostile environments, rendering them suitable for continuous monitoring. Cement-based sensors are cost-effective and easily integrated during construction, offering both local and distributed sensing capabilities to monitor extensive areas or crucial locations. Their adaptability, along with prospective improvements through smart materials, renders them a sustainable and efficient choice for long-term infrastructure monitoring. Concurrently, SSMS composites is also defined as nanocomposites with special properties like sensor application which is used in advanced industries [67]. Moreover, it is appropriately used in many applications to monitor the effects of the reinforced concrete beams [68], stress-strain behavior of concrete using cement sensor by short analysis time [69], beam-column sub-assemblage using embedded SSMS [70], to transform roads into smart pavements by weigh-in-motion (WIM) characterization [71,72], and to detect the traffic of vehicle speed and human motion [73,74]. Moreover, SSMS is used in rail infrastructures for low-cost monitoring, railway sleepers, and aircraft structures for self-diagnostic functionalities [75–77]. In addition, the self-sensing sensors are used to evaluate the temperature and moisture variations of concrete structure [20].

The renaissance of SSMS composites is developed with essential sensing properties such as electrical resistivity, piezo resistivity (FCR, hysteresis, linearity, repeatability, and signal to noise ratio), electrical sensitivity (stress, strain, and force sensitivity), and conductivity. Simultaneously, developing hydrophobic SSMS composites is crucial for maintaining the durability of cement-based composites [78,79]. The schematic illustration of measuring electrical resistivity and piezo resistivity is depicted in the Figure 8 a) and 8 b). In order to measure the multifunctional sensing ability, the following relevant formulae are used, as stated in the equation (6) – (15).



(a) (b)

Fig. 8 a) Electrical resistivity measurement, b) piezoresistivity measurement

2.2.1 Electrical Resistivity (ρ)

$$\rho = \frac{U_{sc} \, . \, R_r \, . \, A}{U_r \, . \, L} \, \Omega.cm \tag{6}$$

where U_{sc} = voltage of the sensor composite (v), U_r = voltage of the resistor (v), R_r = resistance of the resistor (Ω), L = distance between electrodes (cm), and A = area of electrodes (cm^2).

2.2.2 Piezo Resistivity

$$FCR = \frac{\frac{V_{sc} \, . \, R_r}{V_r} - R_i}{R_i} \tag{7}$$

Where V_{sc} = voltage over the sensor composite (v), R_r = resistance of the resistor (Ω), R_i = initial electrical resistance of the sensor composite (Ω), V_r = voltage of the resistor (v);

$$Hysteresis\ (H) = \frac{\Delta\, FCR_{max}}{FCR_f} \tag{8}$$

$$Repeatability\ (L) = 1 - \frac{\Delta\, FCR_{max\,-\,i}}{FCR_f} \tag{9}$$

$$Linearity\ (E) = \frac{\Delta Max}{\Delta \rho_{FS}} \tag{10}$$

$$Signal\ to\ noise\ ratio\ (SNR) = 10log_{10}\left(\frac{P_s}{P_n}\right) = 10log_{10}\left(\frac{A_s^2}{A_n^2}\right) \quad (11$$

Where $\Delta\, FCR_{max}$ = maximum variation of FCR, FCR_f = change in electrical resistance under loading, $\Delta\, FCR_{max\,-\,i}$ = maximum change in FCR, $\Delta\rho_{FS}$ = full scale FCR output value, P_s = signal power, P_n = noise power, A_s = amplitude of signal, A_n= amplitude of noise, and ΔMax = maximum deviation between the piezoresistive.

2.2.3 Electrical Sensitivity

$$Strain\ sensitivity\ co: \frac{\Delta R/R_i}{\varepsilon} = \frac{FCR}{\varepsilon} \tag{12}$$

$$Stress\ sensitivity\ coefficient: \quad \frac{\Delta R/R_i}{\sigma} = \frac{FCR}{\sigma} \tag{13}$$

$$Force\ sensitivity\ coefficient: \quad \frac{\Delta R/R_i}{F} = \frac{FCR}{F} \tag{14}$$

Where ΔR = variation in electrical resistance (Ω), ε = strain due to load, σ = stress/load, R_i = initial electrical resistance of SSMS (Ω), ε = strain due to load, σ = stress/load.

2.2.4 Conductivity

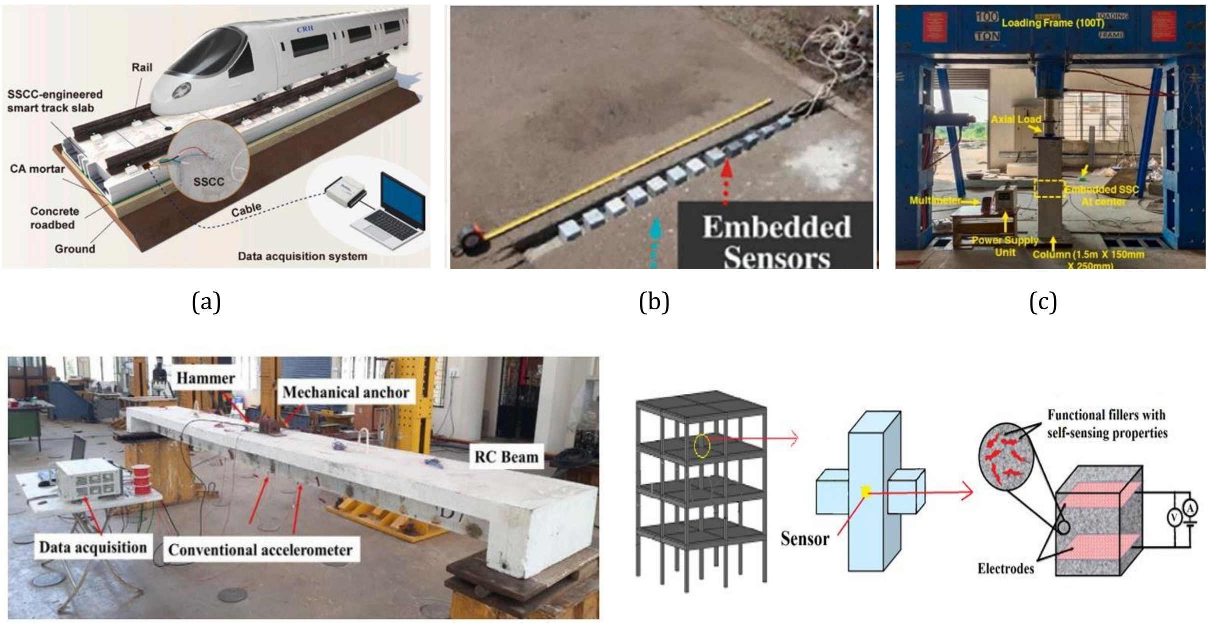
$$\delta = \delta_f \left(\frac{\varphi - \varphi_c}{1 - \varphi_c}\right)^{\gamma} \tag{15}$$

Where, δ_f = filler conductivity, γ = universal exponent, φ = filler concentration, and φ_c = percolation threshold.

The dominant sensing parameters are crucial in self-sensing composites for structural health monitoring application. The Table 1 depicts the various improved parameters to attain smart composites. Whereas, the challenges faced during installation, visualization, and identifying the crack patterns and failures are greatly reduced. The integration of nanomaterials into the SSMS enables it to exhibit versatile characteristics, which can be effectively utilized in a range of applications. These include monitoring high-speed rail infrastructures, detecting traffic, and implementing smart pavements through weigh-in-motion (WIM) sensing. Further, SHM is utilized in several applications, including railway sleepers, vibrations, structure deformations, dynamic load behavior, aviation structures, self-cleaning, stress-strain behavior of concrete, corrosion of steel in concrete structures, and monitoring the operation of large-scale sub-assemblages such as RC beams and beam-columns. This enables the use of SSMS in SHM to achieve intelligent and sustainable infrastructures, with a focus on high accuracy and convenient installation. Figures 9 depict the utilization and implementation of SSMS in various structural contexts to monitor the condition and detect any damage. The high precision self-sensing sensors paves the way for various field applications as an alternate to FOS to attain smart infrastructure.

Table 1. Improved parameters of self-sensing multifunctional sensor

Type of composites	Stress Sensitivity (% / MPa)	Strain Sensitivity	Linearity (%)	Repeatability (%)	Hysteresis (%)	Ref. / Year
Paste	1.35	227	4.17	4.05	3.61	[77]/2007
Mortar	2.69	7.4	-	-	-	[80]/2015
Mortar	$2.86*10^{-3}$	30.28	-	-	-	[81]/2017
Mortar	3.12	521	-	-	-	[82]/2018
Mortar	-	155	-	0.95	-	[83)/2020
Mortar	-	-	15.47	28.12	-	[84]/2021
Mortar	-	155.5	0.961	-	-	[85]/2021
Mortar	2.714	-	11.795	13.178	-	[86]/2021
Paste	-	74.90	0.67	-	1.14	[87]/2021
Paste	1.27	408	15.51	11.92	25.86	[88]/2022
Paste	-	30.10	-	0.994	-	[89]/2022
Paste	1.39	463	10.84	10.05	19.32	[90]/2022
Paste	0.49	86.03	-	-	-	[91]/2022
Paste	-	142	0.891	0.750	0.382	[92]/2022



(a) (b) (c)

(d) (e)

Fig. 9. a) High speed rail monitoring [77] b) Traffic monitoring [93] c) Measuring deflection of column using SSMS [94] d) vibration sensing of RC beam [95] e) Application of SSMS in structures [65]

3. Analogy between FOS and SSMS

In contrast to FOS with SSMS technology for SHM, both technologies have their own advantages and limitations. Besides, FOS, developed by the Fiber Bragg grating and Fiber-Perot interferometer, provides versatile and advanced techniques for collecting real-time data on various parameters; automated technology perception is more capable, particularly in certain situations. In SSMS sensing technology, such as smart materials with built-in sensing capabilities directly emerge into structural elements. This inherent characteristic exhibits the process of monitoring, reduces complexity in integrating, and mitigates both fragility and sensitivity. Furthermore, SSMS technology is often integrated with the structural components in order that monitoring can be distributed and continuous without additional instrumentation.

Table 2. Comparative study between different FOS and SSMS composite

Sensors	Type	Material	Working principle	Type of damage detected	Advantages	Limitations
Fiber Optics Sensor	Optical	Optic fiber	Light refractivity	Multiple	Effective for damage detection for entire length of fiber, Free from Electromagnetic Influence	Fragile, hence proper care to be taken while installation
FBG Sensor	Optical	Optic Fiber	Light refractivity	Multiple	Effective for damage detection for entire length of fiber, Free from Electromagnetic Influence	Fragile, hence proper care to be taken while installation
Carbon based graphene sensor	Wired, electrical	Carbon nano material	Change in electronic energy band	Multiple	Lightweight and highly sensitive	In certain applications it is used for particularly for one damage parameter
Cement based sensor	Wired, electrical	Cement with nano material	Change in fractional change in resistivity	Multiple	Parent element which is easy to embed into concrete	In certain applications it is used for particularly for one damage parameter

In practice, SSMS sensing technology can provide a more straightforward solution, particularly when the structural material is capable of sensing. Therefore, it can lead to cost savings and simplified monitoring, compared to the more complex installation processes and potential issues with FOS. Moreover, SSMS sensing technologies provide a more direct and immediate assessment of structural conditions because they are intrinsically embedded within the structural material, providing real-time feedback without any external sensors. However, it’s important to choose between FOS and SSMS sensing technology depending on the requirements of the application. FOS is applied for various parameters, such as temperature, strain, pressure, and environmental changes. Their adaptability and versatility make them convenient for a broad range of applications. Additionally, SSMS sensing technologies can be more advantageous in the SHM applications. The comparative study for different FOS and SSMS sensors used for SHM is shown in Table 2. Concisely, both FOS and SSMS composites exhibit the capability to monitor the changes in their surroundings. Meanwhile, they contribute valuable insights into SHM and environmental conditions through their different physical principles.

4. Conclusion and Future Study

This mini-review gives the retrospective discussion on the characteristics of advanced sensing technologies, such as self-sensing cement sensors developed using nanomaterials and commercially available fiber sensors. The investigation has been performed to perceive the evolving field of sensing technology related to several aspects, such as the principal mechanism, practical application, and challenges pertain to SHM. Eventually, this mini-review guides an understanding of AST for SHM with FOS and SSMS composites with their principles and parameters. The priority of either FOS or SSMS composites in SHM may depend on the specific projects. However, sensitivity and measurement accuracy are the crucial parameter for adopting both FOS and SSMS for detecting the changes during structural integrity. Whereas, selecting right FOS involves balancing the accuracy, reliability, and range on the specific requirement for SHM. While the SSMS technologies offer an efficient integrated approach over the intended service life of the structure with stability, durability, and compatibility with cement. Particularly, SSMS offers simplified data acquisition and higher scalability for extensive projects due to their ease of installation. Notably, FOS only provides a comprehensive solution for monitoring various parameters. Ultimately, the choice between the technologies should also be guided by an understanding of the project's requirements with consideration of factors such as accuracy, sensitivity, cost, and structural environment. Nevertheless, the development of SSMS composites is challenging with complicated nanomaterial that is to be optimized. In this regard, SSMS composites with higher evolution (level 5) technology in SHM will be an ideal choice for early detection of potential issues during structural integrity. Hence the SSMS composites is recommended over FOS in multiple contexts for SHM. The future direction and challenges in the evolution of SSMS is outlined as follows:

- Extensive investigation is necessary to achieve self-healing property in SSMS composites for structural integrity.
- The parameters of SSMS composites could be optimized by decoupling algorithm with circuit measurement method or micro-mechanic modeling.
- In-depth investigation is required to study the synergistic effect of SSMS composites.
- The trend of correlating SSMS composites with concrete structures could be extended beyond the SHM to military vigilance.

Abbreviations

FBG – Fiber bragg grating
FCR – Fractional change in resistivity
FOS – Fiber optic sensor
POF – Plastic optical fibers
SHM – Structural health monitoring
SSMS – Self-sensing multifunctional sensor

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