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Bibliometric and Scientometric Trends in Structural Health Monitoring Using Fiber-Optic Sensors: A Comprehensive Review

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Abstract: The construction, maintenance, and repair of civil infrastructure demand substantial economic investment, underscoring the necessity of structural health monitoring (SHM) to mitigate property loss resulting from structural failures. Within the domain of SHM systems, the integration of fiber-optic sensors (FOS) is distinguished by their diminutive size, lightweight nature, resistance to corrosion, and straightforward installation procedures, thus garnering widespread recognition. Despite the voluminous publications addressing this subject, comprehensive surveys employing bibliometric and scientometric methodologies remain scarce. This review scrutinizes 1066 publications spanning the past decade through scientometric examination, delineating publication trends, journals of significant contribution, leading researchers, foremost affiliations, and the prevalence of keywords. The analysis reveals a consistent upward trajectory in research activity, with the United States and China emerging as pivotal contributors. Employing VOS viewer for clustering visualization, the study categorizes keywords into discrete clusters, elucidating the breadth of applications and the interconnectedness of topics based on the strength of their associations. This investigation stands as a novel contribution, furnishing a holistic overview of FOS research within SHM, charting historical and current trends, and pinpointing emergent research avenues. The findings are poised to serve as an invaluable repository for scholars endeavoring to incorporate SHM systems equipped with FOS into their forthcoming investigations.

Keywords: Fiber-Optic Sensors (FOS); Fiber Bragg Grating (FBG); Structural Health Monitoring (SHM); Scientometric analysis; Bibliometric review

1 Introduction

Civil engineering encompasses many projects, including buildings, roads, railways, bridges, tunnels, dams, harbors, airports, and even undersea structures [1, 2]. These infrastructure facilities require significant economic investments during the manufacturing process and are connected to maintenance and repair [3]. Typically, the service life of these infrastructures spans decades or even centuries [4]. Infrastructure is susceptible to various disasters and damages during use, such as environmental loads and fatigue effects. These damages can occur in different degrees and types, potentially resulting in severe human accidents and losses of property [5]. Therefore, it is very important to ensure the long-term safety of these structures to prevent potential disasters and advance the safety of the infrastructure. The condition of engineering structures must be monitored and evaluated in real-time.

SHM can identify cumulative damage to the main structure and evaluate its performance and service life in real-time [6]. SHM can also establish safety early warning mechanisms to respond to potential disasters. It has good applications in improving the safety and reliability of structures and reducing the cost of their operation and maintenance [7]. SHM is an essential aspect of future engineering, although it is challenging to address immediately [8, 9]. SHM is a critical application of intelligent material structures, enabling online monitoring of the structure's 'health' condition. SHM employs sensors embedded in or bonded to the surface, acting as a neural system to detect and predict internal and structural damage [10]. The SHM system can assess conditions such as global and local deformation, steel corrosion, and a lack of structural support. In cases of sudden accidents or dangerous environments, this system can restore the structural system to its optimal function.

The SHM process involves obtaining measured values of the dynamic response through a series of sensors [11]. From these values, characteristic damage-sensitive factors are extracted and statistically analyzed to determine the current state of the structure. Large-scale infrastructure is usually characterized by its large capacity, large distribution area, long service life, and long span [12]. To comprehensively monitor displacement, strain, temperature, and vibration in large-scale structures, even hundreds of sensors are typically required [13]. Systems utilizing SHM may face challenges in obtaining, relaying, and storing substantial data volumes. The significance of sensors has notably risen across diverse domains [14, 15]. In SHM systems, commonly used sensors include piezoelectric elements [16], strain elements [17], and FOS [18, 19]. Piezoelectric elements can be used as sensors and actuators due to their high sensitivity, good dynamic performance, and wide range of applications. However, they also have disadvantages, such as fragility, difficulty embedding them in structures, and low-frequency characteristics. The strain element exhibits high sensitivity, good static performance, and stable characteristics. However, traditional resistive strain gauges are inadequate for intelligent SHM of engineering structures due to their stability, durability, and other issues. FOS has been developing the damage to the structure through signal processing techniques and advancing sensing technology. FOS has rapidly grown and gained worldwide application due to its small size, lightweight, anti-corrosion properties, and ease of embedding [20].

FOS can measure changes in one or more light beams, most based on changes in light intensity [21]. These changes can be detected using either a single-point method or a point distribution (multichannel) method. To be effective and reliable in monitoring key parameters such as pressure, corrosion, temperature, crack formation, humidity, vibration, and chemical measurements, traditional sensors must be replaced with high-performance smart sensor technology [22]. The characteristics required for a high-performance smart sensor include sharp accuracy of the optical sensor, affordability of the commercial sensor, compact size, long service life, ease of operation, and real-time data retrieval. FOS technology is well-suited to meet these requirements. It uses fiber as either an optical sensing element or as a means of transmitting signals between remote sensors [23].

The use of FOS techniques in SHM systems for civil infrastructure is widespread due to its ability to identify defects and evaluate service performance for sustainable infrastructure. A review of this area is necessary to gain a comprehensive overview of its development, given the high volume of published articles and increasing research trends [24].

2 An Overview

2.1 FOS Principles

The operational process of the FOS includes monitoring and evaluating external factors and transmitting the signal [25]. As light travels through an optical fiber, its key attributes like intensity, polarization state, wavelength, and frequency undergo alterations. Consequently, FOS is categorized into intensity modulation, phase modulation, polarization modulation, and frequency modulation. Within an FOS setup, modulation takes place within the optical fiber itself as light moves from its source to a detector, referred to as intrinsic FOS. Modulation external to the fiber is termed extrinsic FOS. FOS is further divided into coherent and non-coherent types based on the interference characteristics of light. Furthermore, FOS can be classified into points (local), pseudo-distributed, and distributed. The most used in civil infrastructure are the Fabry-Perot Fiber Optic Sensor (FPFOS) [26], Fiber Bragg Grating (FBG) [27], Optical Time Domain Reflectometer (OTDR) [28], and Long Period Fiber Grating (LPFG) [29].

FBG sensors are most active in SHM applications due to their low manufacturing cost, high-quality demodulation system, and convenient installation [30]. FBG sensors can be mounted on the surf structure's surface and embedded in the structure to achieve real-time monitoring of the structure and monitor the formation of structural defects [31]. The pseudo-distributed FBG sensor connects multiple fibers or sensors with signal transmission fibers. It uses the multiplexing principle to separate the optical signals of different sensors so that the monitoring data of different sensors can be analyzed [1], as shown in subgraph (a) of Figure 1. FBG has several limitations, including being discrete rather than continuous, being sensitive to temperature changes, having transverse strain sensitivity, and difficulties in demodulating wavelength shifts for multiple FBG sensors.

FPFOS utilizes an interference cavity core. There are two types of FPFOS based on the structure of the interference cavity: intrinsic and extrinsic. Intrinsic FPFOS typically consists of a single-mode optical fiber and an insulated mirror. The optical fiber's end face, cut by the fiber, can also serve as a mirror [32]. The extrinsic type's interference cavity typically holds air or alternative non-fiber optic materials. Packaging safeguards it by facilitating the transfer of strain from the structure to the sensor [1]. Both types of FPFOS mentioned above use the measured physical parameters to cause a change in phase difference, which in turn changes the optical path difference. This change is then converted into an electrical signal for processing by the detector, as shown in subgraph (b) of Figure 1. The limitations of FPFOS include high fragility, cross-sensitivity, unsuitability for industrial applications and hostile environments, and a complex signal processing and demodulation system.

The OTDR uses light scattered from an optical fiber to provide feedback on its performance [28]. As shown in subgraph (c) of Figure 1, the signal that is reflected is called the Rayleigh signature. It shows an exponential decay over time that is directly related to the fiber's linear attenuation [33]. OTDR allows for measuring fiber attenuation, checking for light continuity, identifying physical defects or break locations, measuring splice loss and position, and determining fiber length [34]. The technology of OTDR monitoring has been widely used in the distributed monitoring of large-scale civil structures [18]. OTDR has limitations such as uncertainty in channel depth, thermal sensitivity, lack of multi-component measurement at the same time, and unsuitability in harsh conditions.

The LPFG, a novel passive optical fiber component, has surfaced in the past few years, generating either a periodic or non-periodic alteration in the refractive index distribution within the fiber core. Due to the internal field coupling effect, LPFG reflects or emits light of a specific wavelength [35–37], as shown in subgraph (d) of Figure 1.

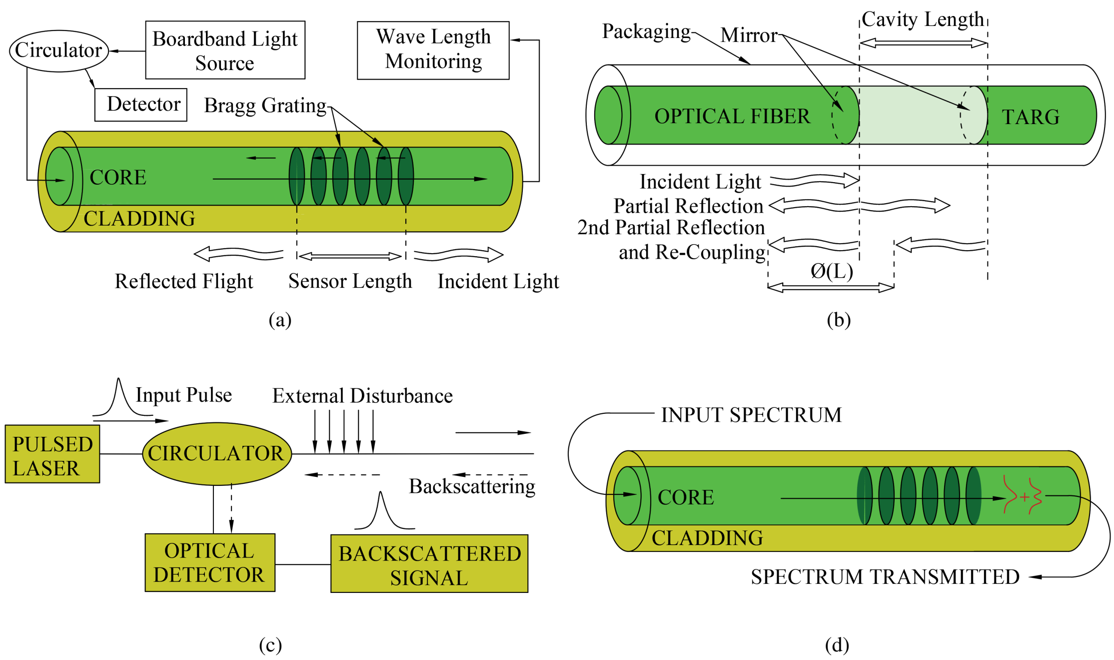

Figure 1. Principles of FOS: (a) FBG sensor principle (modified from [38]); (b) FPFOS principle (modified from [1]); (c) OTDR principle (modified from [37]); (d) LPFG sensor principle (modified from [36])

2.2 FOS Typical

FOSs are widely used in various fields, such as crack detection, temperature monitoring, mechanical strain, and deformation level identification [26, 39–41]. FOSs are used for the detection of cracks. Crack detection using FOSs is used primarily to stabilize reinforced concrete (RC) structures [42]. FOS has applications in the monitoring of bridges, buildings, tunnels, and highways. In crack detection, a significant challenge is the difficulty of monitoring the number and depth of cracks in RC structures due to uneven and heterogeneous materials. In addition to crack detection, temperature and humidity also need to be monitored because their effects are closely related to the health of concrete structures [43, 44]. Zou et al. [45] designed a Fabry-Perot fiber optic temperature sensor to study temperature changes during concrete hydration.

When water is combined with cement, it initiates a chemical reaction that releases heat, known as hydration heat. The initial temperature fluctuation caused by this reaction, which varies with different water-to-cement ratios, is directly linked to the formation of cracks and thermal stress within the concrete framework. Hence, vigilant temperature monitoring becomes indispensable, particularly for extensive structures such as bridges and dams [46]. The heat generated during hydration, post-pouring of substantial concrete volumes, underscores the significance of observing cement temperature trends and peak temperatures. These metrics serve as predictive indicators for structural integrity in the long term [47]. Identifying the stress applied to ensure the structure's health is important. FOSs have been used to measure the internal strain of structures in recent years [40, 47].

2.3 FOS Applications

Predicting the life cycle of bridges accurately is challenging due to a limited understanding of complex bridge structures that are aged, corroded, fatigued, or impacted by natural disasters such as earthquakes, floods, and storms [41, 48]. Therefore, monitoring the structure's health in real time is crucial to ensuring the bridge's safety and durability. To comprehensively monitor the performance of large-scale bridges during operation, it is necessary to strengthen maintenance efforts [49]. Monitoring bridge structures in real-time using FOS has been extensively studied by experts from different countries to guarantee both safe and regular functioning while also prolonging the lifespan of the bridges [50]. In 2017, Xiao et al. [51] monitored the dynamic response of the bridge using an FBG inclinometer. The inclinometer records rotation, deflection, and dynamic characteristics through signal processing technology. It's placed on the swing bearing to oversee the rocking movement of the lower roller. In 2018, Ye et al. [52] proposed an orthotropic steel bridge stress monitoring program using FBG sensing technology. FBG sensors were installed at fatigue-prone rib-to-deck and rib-to-diagram welded joints at the mid-span and quarter-span of the bridge. Monitoring the state of the force on the suspension bridge cables is crucial [53]. Hu et al. [54] developed an FBG vibration sensor for real-time monitoring of the vibration characteristics of suspension bridge cables. Based on the sensor-monitored dynamic force distribution results, we can identify which cables require repair due to critical conditions.

FOS-based monitoring systems have been of interest in the field of tunneling. FOS systems were used to monitor structural loads in highway tunnels [55] and to monitor the strain distribution and temperature of optical fibers in railway tunnels affected by active ground flow [56]. Sewer tunnels are susceptible to damage from blockages, corrosion, displacement, mechanical stress, and plant root penetration. This damage can cause flooding, landslides, and groundwater pollution. To prevent these events, it is crucial to implement effective SHM systems in sewer tunnels. The most used SHM technique in sewer tunnels is remote inspection using video camera-based systems. However, this technique only allows for periodic tunnel inspections due to the complexity of the process and the need for prior cleaning, which is both costly and time-consuming. Bremer et al. [57] utilized FOS in their research to introduce a new approach to monitoring the structural health of sewer tunnel structures quickly and simply. The SHM system for sewer tunnels is based on fiber optic moisture and fiber optic tilt sensors located at the interface between two sewer pipes.

3 Methodology

To conduct a comprehensive review, an accurate collection and identification of articles published in the field under review were conducted. We limited our study to publications with titles, objectives, methodologies, and significant contributions within the scope of our research. Our analysis consisted of two stages: bibliometric and scientometric analysis.

To conduct bibliometric analysis, we searched the database using keywords related to the research area [55]. The selected keywords were "SHM", "FOS", "infrastructure", and "building". We customized these keywords in the title and abstract to enable searching for all publications. The search was conducted between January 2013 and December 2023, covering a 10-year screening process that filtered the research sequentially. Because other subject areas such as physics and astronomy also appeared in the SHM and FOS search results, these irrelevant items were excluded. Articles that pass the screening process are then analyzed using bibliometrics.

For the scientometric stage, bibliometric data from published papers was used for the network map and related topic evaluation using VOS viewer software (version 1.6.19). This software utilizes the Visualization of Similarity (VOS) technique, where it filters keyword similarities from the abstract and title of an article to other articles. VOS provides mapping of knowledge fields to analyze their intellectual landscape [21]. This survey utilized scientometric analysis to give young researchers a global perspective on research trends in infrastructure SHM using FOS. The analyses were conducted to reveal these trends: publication year, journal participation and country, co-authorship and affiliation analysis, title word clustering, and cluster networks.

4 Results and Discussion

Following the steps and screening outlined earlier, we opted for 1066 articles for an extensive examination within the study's designated area. Subsequently, we scrutinized multiple facets, such as yearly publication patterns, contributions from research sources, trends in country participation, affiliations' contributions, co-authorship, and the clustering of keywords.

4.1 Annual Publication Trends

Firstly, it is interesting to review the history of articles published on using FOS techniques for SHM in infrastructure buildings over the past decade. Figure 2 shows the distribution of articles published using FOS for SHM from January 2013 to December 2023. The figure shows a fluctuating trend until 2019, which did not exceed 122 articles per year. The number of articles decreased to only 49 in 2020, possibly due to the COVID-19 pandemic making research more difficult. However, 2021 saw the peak of the decade with 140 articles, followed by a decrease in the last 2 years with 107 and 110 articles. The total number of citations fluctuated over the decade. The number of citations in 2017 reached its highest point, indicating the continued relevance of the FOS technique up to that year.

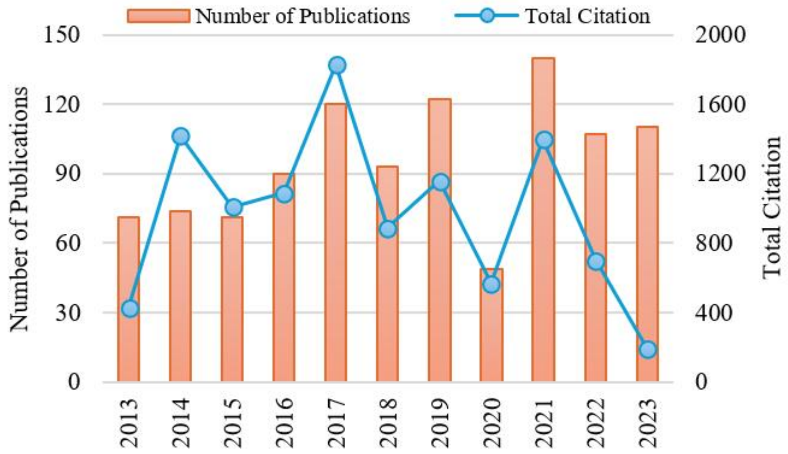

Figure 2. Total number of publications and total number of citations from 2013 to 2023

4.2 Most Contributing Source

Table 1 lists the publisher information for the leading journals that have published over 10 articles on using FOS techniques in infrastructure SHM. Among these journals, "Lecture Notes in Civil Engineering" has published the highest number of articles at 59, significantly more than the other journals. The second-highest number of articles was published in "SHM," with 31 articles, while the remaining journals have published less than 20 articles. Figure 3 illustrates the annual distribution of articles published by each journal. It is evident that "Lecture Notes in Civil Engineering" is the most contributing journal in recent years.

Table 1. Most relevant journals

Sources	Publisher	Articles	SJR 2022
Lecture Notes in Civil Engineering	Springer Nature	59	0.147
SHM	Sage Journals	31	1.877
Composite Structures	Elsevier	19	1.455
Structural Control and Health Monitoring	Hindawi	18	1.755
Engineering Structures	Elsevier	17	1.607
Journal Of Intelligent Material Systems and Structures	Sage Journals	17	0.635
Construction And Building Materials	Elsevier	15	1.888
Mechanical Systems and Signal Processing	Elsevier	15	2.475
Journal Of Civil SHM	Springer Nature	13	0.938
Automation In Construction	Elsevier	11	2.443

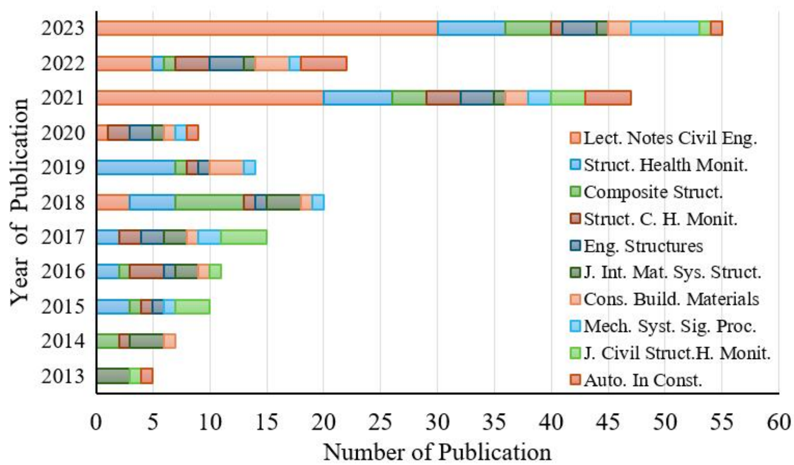

Figure 3. Distribution of the number of articles published annually in the most relevant journals

Additionally, “SHM” has consistently contributed articles every year since 2015. Therefore, analyzing research resources can help researchers quickly find relevant articles and select suitable journals for future manuscript publication. Table 1 lists the best scientific literature resources, promoting the understanding and further development of SHM using FOS in the construction industry. The inclusion of the SJR ranking allows for the selection of journals based on their level of influence and scientific impact. It is worth noting that Elsevier, a well-known publisher, has a dominant presence in terms of both accumulated publications and SJR scores.

4.3 Country Participation Trends

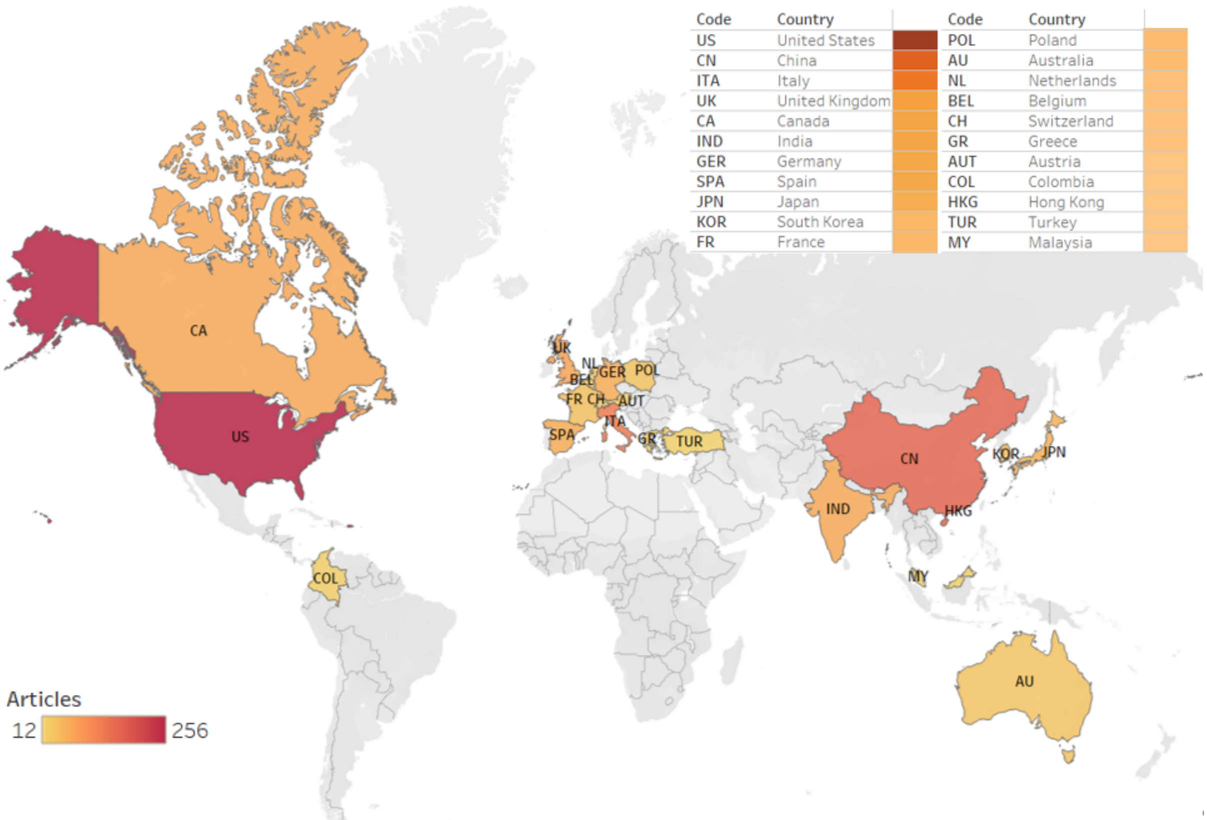

Figure 4. Top countries in FOS usage in infrastructure SHM over the last decade

Table 2. Top 10 countries in the last decade

Country	Code	Articles	Percentage
United States	US	256	24.4 %
China	CN	160	15.3 %
Italy	ITA	125	11.9 %
United Kingdom	UK	71	6.8 %
Canada	CA	65	6.2 %
India	IND	64	6.1 %
Germany	GER	61	5.8 %
Spain	SPA	61	5.8 %
Japan	JPN	52	5.0 %
South Korea	KOR	38	3.6 %

To help readers understand which countries contribute the most research publications in the current field, Figure 4 shows a map of corresponding author country distribution for countries with over 10 articles in infrastructure SHM studies using the FOS technique over the last decade. Table 2 shows that the United States has contributed the most research, with 256 published articles (24.4%), followed by China and Italy with 160 (15.3%) and 125 (11.9%), respectively. These three countries have contributed more than a third of the research in this area. Moreover, nations on the rise within this domain encompass the United Kingdom, Canada, India, Germany, Spain, Japan, and South

Korea. Delving into the map depicting actively engaged countries presents a chance to foster international research partnerships and share innovative concepts.

4.4 Most Contributing Affiliates

This study delves deeper into the rich field of FOS research, highlighting the most influential papers published in peer-reviewed journals. These articles provide access to innovative developments and groundbreaking research in the field. This study identifies institutions that make important contributions to the field in terms of quantity and quality, as well as the impact of academic research. Figure 5 illustrates the top 10 contributing institutions by number of publications. Princeton University leads the way with the world's most extensive academic and library collection related to the field, with 43 articles in the last decade. The University of Tokyo, Dalian University of Technology, and the University of Cambridge have contributed more than 20 articles, totaling 25, 24, and 22, respectively. These citations demonstrate that their research has played an important role in shaping today's understanding of using FOS in SHM. By evaluating the results, researchers can gain a brighter picture of which research areas are receiving attention and may be most beneficial to their respective audiences. This research bridges the gap between academia and industry, providing insights that can drive informed decision-making and strategic planning in both fields.

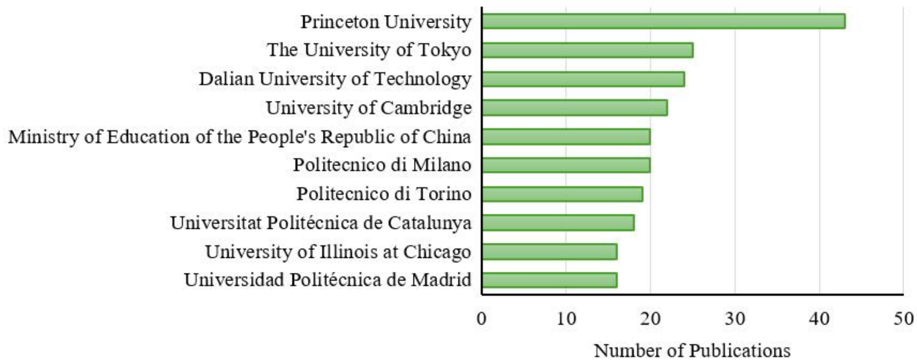

Figure 5. Most relevant affiliations

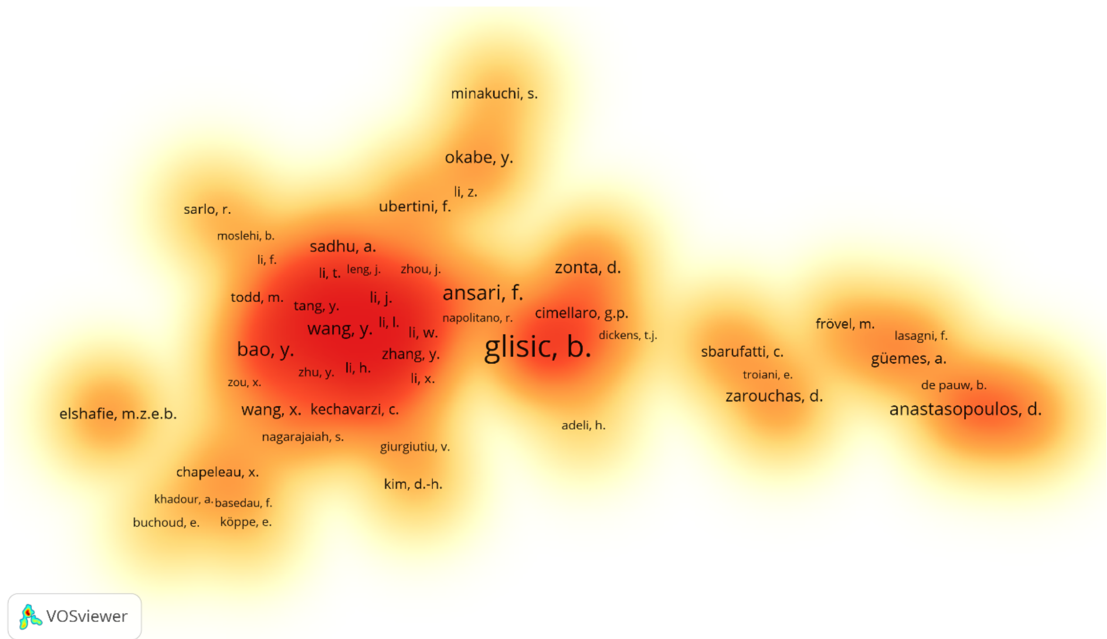

Figure 6. Density visualization of co-authorship

4.5 Co-Authorship Analysis

Figure 6 illustrates the density of authorship within the field, showcasing at least two articles related to the utilization of FOS in SHM. Notably, familiar authors within this domain are identifiable, with Glisic, B., making the most significant contribution by having the highest number of published articles, followed by Ansari, F., Casas, J.R., and Bao, Y. For a more comprehensive insight, Figure 7 presents a visualization detailing the publication years and authorship connections of each author. The color gradient denotes the publication year, ranging from blue for the oldest studies to red for the most recent ones. Additionally, the node sizes indicate the frequency of articles authored by each one, with Panagiotis Glisic, B., standing out as the most prolific contributor over the last decade. Furthermore, the most recent research endeavors are attributed to Zarouchas, D., and Li, T. This visualization analysis facilitates the recognition of other active and noteworthy researchers in the FOS field within the SHM infrastructure.

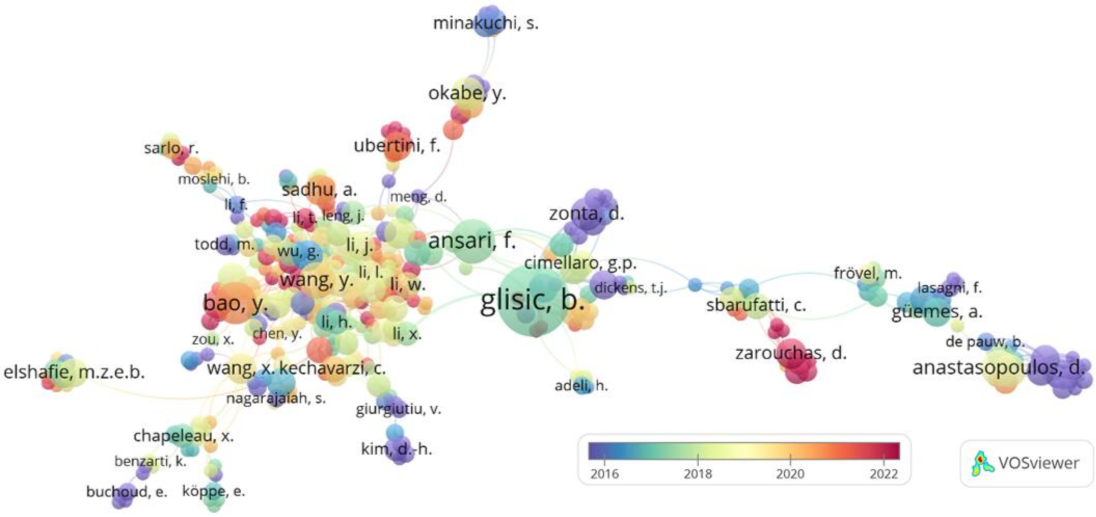

Figure 7. Visualization of co-authorship

4.6 Keyword Occurrence and Connectivity

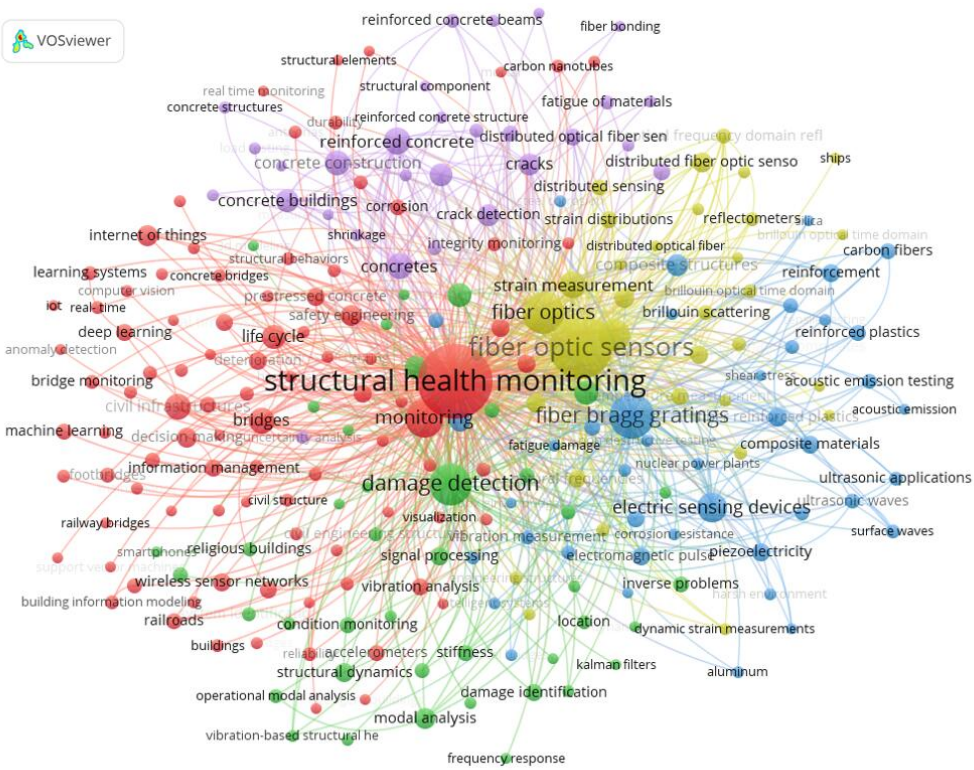

Figure 8. Clustering connectivity and co-occurrence of title words

The first thing that comes to mind when searching for and encountering an article is its title. It can be inferred that the title words of the article are related to the main theme of the research. Therefore, mapping the title words in clustering provides a comprehensive view of AI techniques used in SHM on infrastructures using FOS. Figure 8 illustrates the co-occurrence of keywords, with at least six co-occurrences for each keyword in the 1066 articles collected by the VOS viewer. The keyword co-occurrence map shows that keywords such as SHM, fiber optic sensors, FBG, damage detections, and fiber optics have larger nodes than other title words. Each keyword is connected to different keywords by branches of a certain color, while branches of the same color indicate the occurrence of keywords in clusters. In the following, the top five keywords related to FOS techniques used in SHM technology on infrastructure will be surveyed.

4.6.1 Red cluster analysis

This red cluster has the most keywords, which is 93 words. SHM is the most common keyword in the red cluster, abbreviated as "SHM." By filtering out other keywords, the artificial neural network formed the largest cluster, with several intra-clusters to connect it to the broad field of SHM techniques. The number of occurrences of "SHM" is 1001, which means that almost all articles use this word. More specifically, the selection of the top five keywords based on the number of occurrences from the SHM field is: "monitoring" (179), followed by "bridges" (70), "civil infrastructures" (69), "life cycle" (57), and "safety engineering" (43), illustrating the most frequent co-occurrence.

4.6.2 Yellow cluster analysis

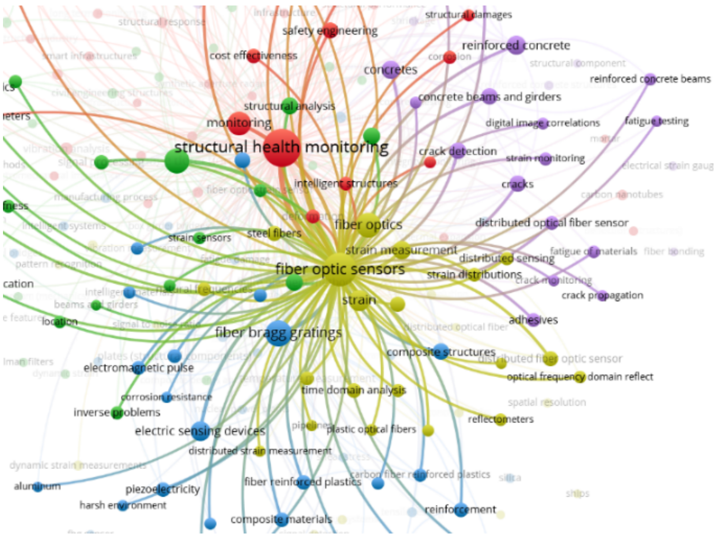

Figure 9. The yellow clustering network

The yellow cluster has 32 keywords. Figure 9 shows the clustering network of “fiber optic sensors” with 636 occurrences. FOSs are one of the sensors used in SHM that have received more attention in the fields of SHM, fiber optics, and FBG, with a number of co-occurrences of 634, 220, and 261, respectively. These results show that most of the research that uses fiber optic sensors focuses on the principles of these methods, such as reflectometers, optical frequency domain reflection, and strain measurement. The keyword fiber optic sensors will also frequently appear in studies such as SHM, FBG, and crack detection.

4.6.3 Blue cluster analysis

The blue cluster has 42 keywords. Figure 10 shows the clustering network of “FBG”, which has a total of 278 occurrences and is the largest in this cluster. FBGs are one of the working principles of FOS itself, so these two keywords have a strong link relationship of 261 links. Other keywords focusing on FBG are SHM, damage detection, and bridges, with 277, 71, and 11 occurrences, respectively. These results show that most FBG research focuses on electrical sensing devices, reinforcement, and composite structures.

4.6.4 Green cluster analysis

Cluster analysis detection is usually used as one of the functions of SHM using FOS. Figure 11 illustrates the commonly used title words in published articles with damage detection. The most frequently occurring words are SHM and fiber optic sensors, with 27 and 137 occurrences, respectively.

4.6.5 Purple cluster analysis

The purple cluster is the cluster with the most keywords, namely 29. This purple cluster contains information about the field of concrete, its type, and its properties, with the most occurrences of the keyword reinforced concrete at as many as 81. Figure 12 illustrates the title words commonly used in published articles with reinforced concrete. The most frequently occurring words are SHM and fiber optic sensors, with 81 and 45 occurrences, respectively.

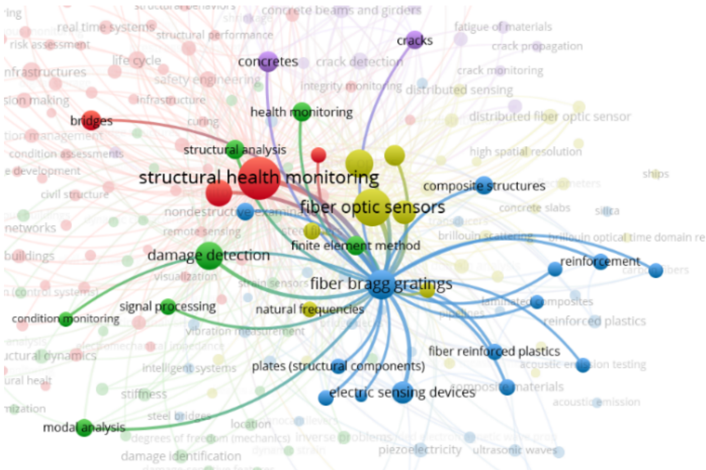

Figure 10. The blue clustering network

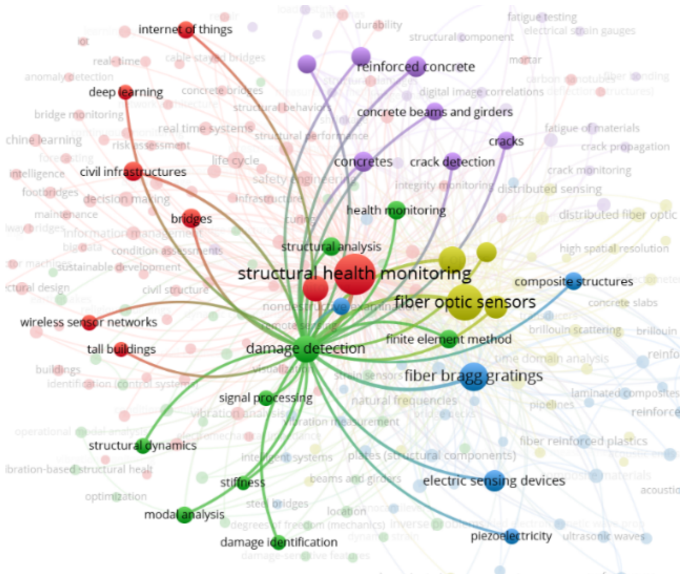

Figure 11. The green clustering network

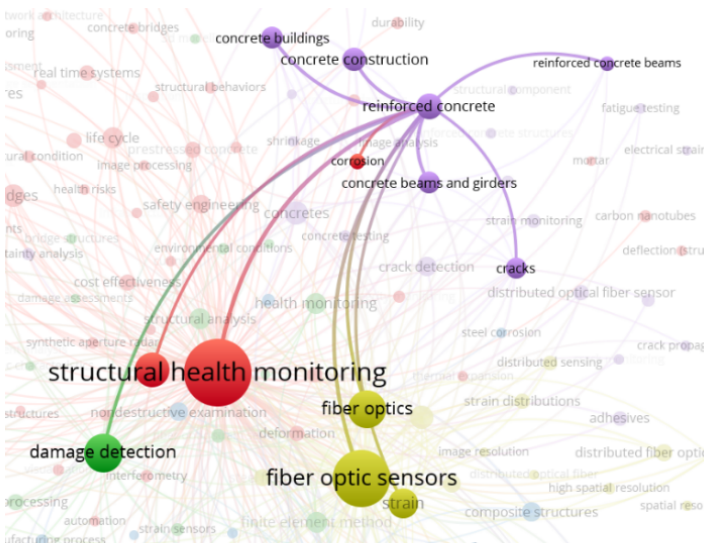

Figure 12. The purple clustering network

5 Conclusions

This study presents a scientometric analysis of 1066 articles published between 2013 and 2023, examining the research trends in the use of FOS in SHM techniques for infrastructure. The annual publication trend shows a significant increase in published articles from 2021 to 2023, with over 100 articles published each year. This trend signifies a significant progression in the advancement of extensive civil engineering, especially within the realm of SHM systems. The introduction of innovative technology in FOS techniques not only enhances functionality and ease of use but also presents technical enhancements and hurdles. The aspiration is for the growth and integration of fiber optic sensing technology within SHM to reach a level of maturity and stability.

Analysis of the research sources reveals that the journal 'Lecture Notes in Civil Engineering' published the most articles and made the greatest contribution in the last three years. This examination enables researchers to swiftly retrieve articles from various origins and presents pertinent journals within this domain for the dissemination of their manuscripts. The leading contributors include the United States, China, and Italy, underscoring the widespread international involvement. This visual representation aids in pinpointing active and noteworthy researchers, fostering opportunities for future collaborative endeavors, and sharing innovative concepts.

In infrastructure SHM technology using FOS, researchers often use FBG due to the complex optimization problems they face. Additionally, FOS clustering is widely used for damage detection and strain measurement. The FBG model has outperformed other models, so it is expected that more research will be conducted in this area in the coming years. Evaluating each technique's strengths and weaknesses is recommended to improve future research. Additionally, planning similar research in the future can help monitor the development of FOS techniques in infrastructure SHM and follow their evolutionary trend.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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