buildings

Systematic Review

Structural Health Monitoring of Bridges under the Influence of Natural Environmental Factors and Geomatic Technologies: A Literature Review and Bibliometric Analysis

Virgil Mihai Rădulescu [1], Gheorghe M. T. Rădulescu [1,*], Sanda Mărioara Naș [1], Adrian Traian Rădulescu [1] and Corina M. Rădulescu [2]

[1] Faculty of Civil Engineering, Technical University of Cluj-Napoca, Str. Constantin Daicoviciu nr. 15, 400020 Cluj Napoca, Romania; mihai.radulescu@mtc.utcluj.ro (V.M.R.); sanda.nas@mtc.utcluj.ro (S.M.N.); adrian.radulescu@mtc.utcluj.ro (A.T.R.)

[2] Faculty of Sciences, Technical University of Cluj-Napoca, Str. Victoriei nr. 76, 430122 Baia-Mare, Romania; corina.radulescu@econ.utcluj.ro

* Correspondence: gheorghe.radulescu@mtc.utcluj.ro

Abstract: Throughout their lifetimes, bridges are exposed to various forces that may lead to displacement and deformation, potentially compromising their structural integrity. Monitoring their structural integrity under environmental factors is essential for safety and maintenance under these conditions. This aspect is a fundamental component of Structural Health Monitoring (SHM). Many studies focus on Structural Health Monitoring (SHM), employing various theories, methodologies, and technologies that have advanced rapidly due to the expansion of information technology. The objective of this study is to pinpoint areas where research is lacking in the existing literature on the environmental factors that impact the displacement of bridges, along with the techniques and technology used to monitor these structures. To achieve this objective, the most critical environmental factors and technologies, particularly those that are sensor-based, have been identified through a systematic search of the most popular databases. Subsequently, the study utilized a bibliometric analysis, exploring the challenge and prospective research areas reflected in the specialized literature. The findings indicate a lack of scholarly investigation of environmental factors that influence the Structural Health Monitoring (SHM) of bridges, in particular studies regarding the effect of uneven sunlight on structures. The research provides a comprehensive understanding of the Structural Health Monitoring (SHM) of bridges and has practical implications for developing effective monitoring methodologies.

Keywords: structural health monitoring; bridge; temperature; displacement; unequal exposure to sunlight; extensometers; accelerometers; sensors

Citation: Rădulescu, V.M.; Rădulescu, G.M.T.; Naș, S.M.; Rădulescu, A.T.; Rădulescu, C.M. Structural Health Monitoring of Bridges under the Influence of Natural Environmental Factors and Geomatic Technologies: A Literature Review and Bibliometric Analysis. *Buildings* **2024**, *14*, 2811. https://doi.org/10.3390/buildings14092811

Academic Editor: Wei-Xin Ren

Received: 28 July 2024
Revised: 30 August 2024
Accepted: 3 September 2024
Published: 6 September 2024

1. Introduction

Today, civil engineering faces a significant challenge in the form of supervision and maintenance of long-lasting structures. Because of the complexity and aging of infrastructure worldwide, there is a growing need for continuous assessment and monitoring of structural conditions in order to detect any indications of deterioration, degradation, or potential failure [1–9].

Structural Health Monitoring (SHM) is crucial for bridges, especially when considering environmental influences [10–15]. Continuous monitoring of a bridge's health allows for the timely identification of damage caused by variables such as temperature variations, humidity, wind, precipitation, and seismic activity [16–21]. In addition, they help practitioners understand the influence of different environmental conditions on structural integrity, therefore enabling the creation of more accurate maintenance and repair protocols [22–24].

Moreover, the monitoring of material deterioration might be used to ascertain if environmental causes are accountable for abnormal load patterns over bridges and can assist in evaluating the effects of climate change on bridge safety, thereby directing the development of more resilient structures in the future [25,26]. SHM is also the only technology that removes uncertainty in condition assessment, providing a more accurate illustration of the actual condition of the structure [27,28].

Essentially, SHM provides a proactive strategy for managing environmental impacts, optimizing maintenance strategies, improving safety, and improving transport infrastructure resilience against environmental challenges. As a result, bridge monitoring has intensified SHM research, given its importance and role. However, the implementation of SHM presents several challenges. These are both technical and managerial [29–31].

The technological revolution, digitization, and the introduction of artificial intelligence in all theoretical and applied research fields generate technological challenges, which have numerous effects and implications on innovation and applied re-engineering processes [32–36]. In this sense, SHM techniques, methods, and tools have experienced major innovations in the last decade through the large-scale introduction of non-destructive means [37–39]. Cutting-edge automated methods using smart sensors and artificial intelligence (AI) have supplemented and often replaced current techniques for identifying damage through conventional inspection methods [40–43]. The research implications of SHM of bridges have led to increased innovation and adaptation of advanced technologies in civil engineering and related fields [15,44–46]. Thus, SHM becomes an interdisciplinary field that combines several fields, such as computer science, mechanics, civil engineering, or geomatics [15,40,47–49]. The new scientific advancements need careful observation, systematic categorization, and rigorous analysis [12,15,50–54].

When it comes to the management decision-making process for SHM implementation, it is necessary to make clear which of the primary considerations that support such a choice are now being considered. From a decision-making perspective, the adoption of SHM requires evaluating the conditions for ensuring the safety of people and goods, assessing damage and prioritizing the most serious cases, assessing the operational and environmental conditions of the system under observation, and assessing the constraints on data acquisition in the operational environment.

The recent intensification of research in the SHM field underscores the need for innovative solutions to address both technological and managerial challenges in SHM. Despite the abundance of literature reviews in the SHM field, bibliometric research rarely addresses the comprehensive and integrated analysis of environmental factors' impact on SHM.

The purpose of this research is to investigate the main trends in the scientific approach to structural monitoring of bridges under the influence of environmental factors using non-destructive means, with a special focus on the structural behavior under the influence of uneven sunlight.

The study's specific objectives are to identify new research approaches aimed at analyzing the environmental factors involved in monitoring systems as well as the non-destructive monitoring technologies used. Thus, through a rigorous review of the main research on this topic, the study aims to critically analyze and evaluate the most relevant topics contained in the study area. The study employs the Systematic Literature Review (SLR) methodology, primarily relying on the Scopus database and performing a bibliometric analysis by employing VOSviewer 1.6.20 software; the study highlights both research gaps and trends in this field of research.

After a comprehensive analysis of the factors that can lead to displacement, deformation, and degradation of bridges, as well as the specific technologies and tools used in structural monitoring, this paper seeks to address the following questions:

- RQ1. What are the most important studied environmental factors that affect the structural integrity of bridges?

- RQ2. What are the current methods, techniques, and technologies used in the structural monitoring of bridges?
- RQ3. Can bibliometric analysis identify research gaps?
- RQ4. What are the trends in approaching SHM research?

The study's key contributions include an integrative approach to a comprehensive review of the literature on SHM for bridges, which categorizes the studies based on environmental factors and SHM techniques. Additionally, the study includes a bibliometric analysis of publication trends, prominent authors, institutions, and collaborative networks within the realm of SHM for bridges, emphasizing research gaps and avenues for future research.

Understanding how environmental stresses affect bridge displacement allows engineers to design stronger, more resilient structures [18,55,56]. Monitoring bridge displacement provides crucial data for studies [44,57–62].

- Early detection of potential structural damage;
- Assessment of the need for maintenance;
- Ensuring public safety;
- The infrastructure's life is extended.

2. Research Methodology

2.1. Structure of Research

The study's achievement was determined by the complexity of the research topic, which was related to the analysis of environmental factors and the technologies used to monitor the structural health of bridges. This was achieved through the following stages:

- Conducting a literature review on the most important studied environmental factors that affect the structural integrity of bridges;
- Conducting a literature review on the current methods, techniques, and technologies used in the structural monitoring of bridges;
- Performing a critical assessment of the literature review on methods, techniques, and technologies used in SMH of bridges;
- Performing a scientific mapping and bibliometric analysis of the literature that matches the research criteria of this study by using the scientific database Scopus [12,15,49,63,64];
- Using VOSviewer 1.6.20 software to measure and visualize the scientific network;
- Exploring the challenge and prospective research areas reflected in the specialized literature.

The methodology of the bibliometric research involved a comprehensive search and analysis of the documents available in the Scopus database using the following steps [65,66].

1. The purpose of the search: The objective of the search is to determine the extent to which the issue of uneven sunshine is addressed in the broader context of the Structural Health Monitoring field in the specialty literature cited by Scopus.

2. The iterative process: The methodology involved an iterative process, which went through two stages. The first refers to a thematic sequence of the search, and the second includes other criteria such as the addition in the Scopus search to "bridge monitoring system" domain search, search limitation for the period 2010–2024, or the number of citations. This iterative process ensured comprehensive coverage of relevant literature and emerging trends in the field to achieve the research objective.

3. Subject of the literature search: A thorough search was performed using keywords and phrases related to Structural Health Monitoring (SHM), Bridge (B), Temperature (T), and Deformations (D), and finally, Bridge Deformations and Temperature Variations (BDTV). The search was limited to the Scopus database which has an acclaimed, independent, and transparent selection process to determine which publications will be indexed on its platform.

4. Inclusion criteria: The study fields were confined to the following subjects: Engineering and Earth and Planetary Sciences, all of which are relevant to the research field. Only materials classified as either "Article" or "Conference paper" were kept (Filter 1).

5. Filtering the results: This was performed in four stages using Filters 2, 3, 4, and 5, as follows:

- Filter 2. Addition in Scopus search to bridge monitoring system domain search;
- Filter 3. Limited to 2010–2024;
- Filter 4. Limited to search on a minimum number of citations;
- Filter 5. Limited to the field of Structural Health Monitoring, specifically focusing on Bridge Deformations and Temperature Variations.

VOSviewer 1.6.20 software, which is a tool for the construction and visualization of bibliometric networks, was used to conduct the analysis. For example, these networks may encompass individual publications, researchers, or journals, and they can be established through citation, bibliographic coupling, co-citation, or co-authorship relationships. Additionally, VOSviewer 1.6.20 provides text mining capabilities that enable the creation and visualization of co-occurrence networks of significant terms that have been extracted from a corpus of scientific literature.VOSviewer 1.6.20 generates a map by employing a co-occurrence matrix. The process of constructing a map is comprised of three distinct stages.

→ The co-occurrence matrix is used to calculate a similarity matrix.
→ The VOS mapping technique is applied to the similarity matrix to construct a map.
→ The map is translated, rotated, and reflected [67].

Figure 1 represents the roadmap of the methodology that answers the four research questions, the conclusions, and the proposals for future research.

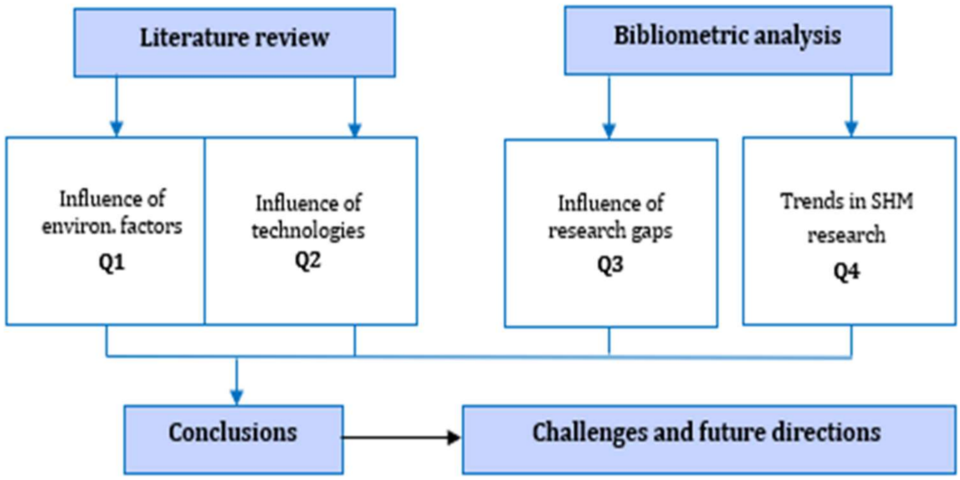


Figure 1. The roadmap of the methodology.

2.2. *Environmental Factors Influencing the Displacement/Deformation/Degradation of the Bridge Structure (RQ1)*

Bridges are essential components of infrastructure in modern society, facilitating transportation and connectivity [68–73]. However, their exposure to environmental forces can introduce challenges in structural integrity. Unequal exposure to sunlight causes differential heating, which results in unequal expansion of materials, which can lead to structural stress and deformation [74–80]. The mechanisms of this phenomenon and methodologies for tracking and mitigating its effects are present in several studies.

In their paper [14], authors Li et al. perform an analysis of cartesian effects (lateral, longitudinal, and vertical displacement) correlating their production with the loads of different environmental factors. The study reveals that wind direction significantly impacts lateral displacement, while temperature negatively impacts vertical displacement. Environmental loads influence longitudinal displacement, with positive correlations between air pressure, temperature, and vertical wind.

Recent studies note that the increase in environmental loads on structures is a major concern that has an impact on the serviceability of engineering structures [40,81–83].

Koo et al. (2013) [84] discuss the practical use of structural health monitoring on the Tamar Bridge in Plymouth, UK. Opened in 1961, the Tamar Bridge is a suspension bridge spanning 335 meters. A structural monitoring system was installed to analyze wind and temperature parameters, as well as the effects on anchor cables and deck, to monitor the behavior of the bridge during and after its 2001 modernization, highlighting potential frequency variations for structural deterioration.

Other writers looked at how different environmental factors affect bridges over time and suggested a modeling method that can connect different environmental factors with modal frequencies while taking nonlinearity and uncertainty into account. Using monitoring data [85–89], the model can precisely characterize the environmental influences on frequencies.

Xu [90] published a study in 2021 that focuses on the environmental impacts of prestressed concrete members in bridges, concluding that the primary environmental elements that affect the lifespan of prestressed concrete members in bridges establish the standard categories of environmental actions, degrees of action, and zoning. This information serves as the foundation for designing the expected lifespan of prestressed concrete members.

Another conclusive research aims to develop a Structural Health Monitoring system for bridge safety evaluation in cold, remote regions using fiber optic sensors with temperature compensation. The system studies bridge temperature behavior using real-time field measurements, revealing the relationship between thermal loading and bridge response [91].

A study that aims to predict the severity of damage to bridge boards considering the effects of traffic and weather reveals that deep neural networks (DNNs) were built with 32 factors to be able to predict different kinds of deck damage. The authors maintain that in doing so, it was possible to accurately identify seven types of damage that could affect bridge decks: linear cracking, map cracking, scaling, breaking, leaking, efflorescence, and rusting of exposed rebar [92].

The study carried out by Xiao, et al. [93] introduces a stiffness separation method for large-scale space truss structure damage identification, simplifying the objective function. The method splits the global stiffness matrix into sub-stiffness matrices, reducing iteration steps and ensuring accuracy in two types of space truss structures.

Zhu et al. [94] analyzed the temperature distribution and related reactions of a suspended rail bridge utilizing Structural Health Monitoring (SHM) as well as field testing and numerical analysis. The research revealed that changes in ambient temperature significantly affect rail-track irregularity on bridges. A modeling system was developed to predict temperature influences on bridges, proving its efficiency by comparing observed data to projected values. The method was also used to investigate seasonal temperature influence on cable-stayed bridges. Heat flow intensity varied on horizontal and vertical surfaces, and temperature changes significantly affected deformation.

Xiao, et al. [95] investigated the impact of thawed frozen soil on the dynamic performance of pile structures in cold regions. The research uses a free-decay response approach to estimate the dynamic properties of a pile partially embedded in Fairbanks silt. Results show two dominant modes: pile rocking and structural bending. The rocking mode exhibits strong soil nonlinearity, while the structural modes show weak nonlinear characteristics. The study also identifies damping ratios and develops a theoretical nonlinear model to correlate with the experimental results, including damage identification of large-scale space truss structures based on the stiffness separation method.

The possible effects of earthquakes of different degrees on bridges are analyzed in the paper "Earthquake-induced residual displacement analysis of simply supported beam bridge based on numerical simulation" [96]. The authors propose mitigation solutions and provide a theoretical basis for improving the disaster resistance of bridge structures.

Progress in the knowledge of the effects of temperature differences on bridges was actively analyzed by Bo and Jianping (2010) [97]. The paper explains the problems in the investigation of thermal effects on bridges, explores some crucial problems to be solved, and predicts development trends in the field.

For example, in the case of high-speed trains, when investigating the effects of deformation in response to temperature in different structural elements of the bridge, it is essential to control the specific deforming effect [98].

Another work by the authors Tan et al. [99] deals with the problem of separating the temperature effect in the signal monitoring the deformation of a bridge and proposes a method that combines VMD and SVD. The application of the method is illustrated by the case of a long-range truss bridge in Wuhan. It is shown that after the monitoring signals are removed by the SVD, the accuracy of separating the effect of the temperature difference is significantly improved.

The work of the authors Xu et al. [100] presents the Wind and Structural Health Monitoring System (WASHMS) that was installed on the Tsing Ma Bridge in Hong Kong. This was designed to monitor the state of the environment, traffic loads, bridge characteristics, and bridge responses.

The SHM system, which consists of a sensor system, a data acquisition and transmission system, and a data processing and control system, is presented in the paper of Zhi-Wen Wang et al. [101], recently published (2024).

"Optimal static strain sensor placement for truss bridges" is another relevant study that presents a numerical optimization method for identifying optimal strain sensor placement for structural static responses. It aims to minimize the number of static strain sensors and layouts needed to evaluate a bridge's structural condition. The method includes automatic model parameter identification, damage detection, and application to an actual bridge [102].

In 2013, Koo and his collaborators published a paper [103] in which the authors state that the most destructive effects on bridges (the main cables and the additional supports) are variations in the structural temperature leading to the thermal expansion of the structure. This is a major factor for global deformation, while the vehicle load and wind are usually secondary factors.

The possible effects of earthquakes of varying degrees on bridges have been intensely analyzed since 2002. Soong and Spencer Jr (2002) published an article [104], which is the most cited work that addresses the problem of the influence of earthquakes on bridges. This paper includes a short historical sketch of the development of passive and active structural control systems, with particular emphasis on the mitigation of wind and seismic response on bridges, being an assessment of the state-of-the-art and practice of these constantly evolving technologies.

Considered one of the most relevant studies to address the effect of earthquakes on bridges, "Multi-hazard Earthquake and Tsunami Effects on Soil-Foundation-Bridge Systems" [105] provides a bridge modeling approach for the individual effects of earthquake hazards and tsunamis, which includes the effects of soil–foundation–structure interaction, developed with finite elements to quantify the sequential damage caused by the quake and tsunami.

The paper, written by Wandji Zoumb and Patrick Arnaud [106], analyses the effect of earthquakes on high-speed trains circulating over railway bridges crossing the sea with deep-water areas. The authors state that when studying the effects of hydrodynamics on train–bridge interactions, accurately modeling and understanding the impact of earthquake-induced hydrodynamic pressure is a crucial issue that has yet to be resolved.

The results of a recent study [107] offer solutions to limit the effects and can provide a theoretical basis for improving the disaster resistance of bridge structures.

In regard to wind effects, a simple search with the terms "wind AND effect AND on AND bridge" conducted in the Scopus database found 1861 documents.

A landmark of this topic is Emil Simiu's manual "Wind Effects on Structures: An Introduction to Wind Engineering", which addresses the overall problem of the structural response (including bridges) to wind actions [108].

A highly cited paper is "Energy Dissipation Systems for Seismic Applications: Current Practice and Recent Developments" [109]. This paper presents a summary of current practice and recent developments in the application of passive energy dissipation systems for seismic protection of structures.

One of the most recent developments in the field is a paper [110] that highlights the fact that the analysis of the influence of wind on bridges in mountain areas should be viewed differently and not by conventional methods of wind speed distribution. This paper suggests a semi-parametric mixed technique to describe the distribution of average wind speeds. The method combines nonparametric Kernel Density Estimation (KDE) and Generalized Pareto Distribution (GPD).

Another study [111] highly cited in the Scopus database is considered the most relevant for the search. This research aims to simulate the wind conditions at the Rose Fitzgerald Kennedy Bridge in Ireland using full-scale three-dimensional computational fluid dynamics (CFD) simulation models.

An analysis of the efficiency of the wind barrier installed for the protection of a road bridge in one of the works that appeared in the field [112] finds that the wind–vehicle–bridge system can be evaluated using a progressive testing approach to comprehend the wind protection capability of the bridge tower.

Starting from the remark that offshore bridges, especially in deep-water environments, are significantly endangered by earthquakes and extreme waves, which pose significant safety risks, Chen et al. (2024) aimed to fill the knowledge gap in the field by conducting a comprehensive series of physical tests on a deep-water bridge dig [113].

Fujiu, Minami, and Takayama (2022) proposed a general approach to the influence of environmental factors correlated with the characteristics of the structure monitored (surface materials, bridge length, and year of construction). The paper concludes that examining environmental elements that might impact degradation is anticipated to assist in the creation of more efficient and effective bridge maintenance strategies [114].

2.3. Technologies, Methods, and Tools for Monitoring SHM of Bridges (RQ2)

Structural Health Monitoring (SHM), as a non-destructive method of in situ structural detection and evaluation, employs a variety of sensors attached or embedded in a structure to monitor structural response, analyze structural characteristics to estimate the severity of damage/damage, and assess their effects on the structure in terms of response, capacity, and lifespan [6,115,116].

Various sensors, technologies, and equipment collect data, which are then consolidated, transferred, analyzed, and evaluated to continually assess the building's health. SHM comprises equipment, approaches, and procedures formerly known as Non-destructive Testing (NDT) and Non-Destructive Evaluation (NDE) [115–124]. These technologies offer different levels of sensitivity, accuracy, and applicability depending on environmental conditions and the specific requirements of the monitoring project.

Key sensor technologies include the following:

Extensometers measure the deformation of the deck material under load [125–127]. Traditional foil extensometers and more advanced fiber optic extension meters are commonly used [128–130]. Installed at critical points, extensometers measure the deformation of bridge materials in response to thermal dilation [131–134].

The researchers Magne et al. [135] presented the implementation of structural monitoring for bridges with the aid of extensometers. The work concludes that such systems can generate both tensile strain and torsional strains simultaneously when a sample is subjected to combined torsion and tensile stress.

A monitoring system consisting of a total topographic station, extensometers, and several sensors was used to monitor "the longitudinal movement of the road deck on Tamar Suspension Bridge in Plymouth in the UK, under changing environmental conditions, over six months" [136]; the transmission of data from the system directly mounted on the structure to the datalogger was wireless. The study is important, too, because it also makes the comparison between the data obtained with the total topographic station (TPS) and the extensometer, a comparison that reveals the usefulness of using this type of sensor in the structural monitoring of this kind of civil construction.

Accelerometers detect vibrations and dynamic shifts [137,138]. They are essential for monitoring fast-acting tensions, such as wind or seismic activities. MEMS (Micro-Electro-Mechanical Systems) accelerometers, with their compact dimensions and high precision, are often used in modern bridge monitoring systems [139–142].

The use of accelerometers coupled with GNSS systems in the structural monitoring of bridges was addressed by the work of Roberts, Meng, and Dodson (with 268 citations) [143]. The study takes into account the multipath limitations of the GNSS systems installed on bridges, finally proposing a hybrid monitoring system (GNSS-accelerometers) that limits the disadvantages of each type of sensor individually, largely offsetting the errors that would result from the use of a single type of monitoring sensors.

Omidalizarandi et al. (2020) propose in their paper [144] "a robust and automatic vibration analyses procedure that is so-called robust time domain modal parameter identification (RT-MPI) technique using low numbers of cost-effective micro-electro-mechanical systems (MEMS) accelerometer". The work concludes that MEMS types are extremely suitable for identifying movements, including those of sub-millimeter type, depending on a certain type frequency chosen.

The use of accelerometers in Structural Health Monitoring (SHM) of bridges is also addressed in the paper of Yang, Wang, and Yang [145], which proposes a new Rauch–Tung–Striebel (RTS) adaptive multi-rate device that merges the measurement signals of the GNSS and accelerometers to improve both accuracy and sampling rate.

An interesting approach from the point of view of the cost of bridge monitoring systems based on accelerometers is presented in the work of Komarizadehasl et al. [146]. For conducting the study, a type of accelerometer called a Low-Cost Adaptable Reliable Accelerometer (LARA) is used. The bridge analyzed in this study is Polvorines' Footbridge in Barcelona, Spain. Finally, using four independent LARA systems, the premises of the study are validated, with certain limitations that mainly relate to the density of the so-called "noise points".

High-precision GPS sensors monitor the static and dynamic movements of bridges. GPS technology is useful for long-term monitoring of large-scale movements but may be less effective for detecting small and rapid changes. They provide precise location data, helping to track the movement of bridge sections with high accuracy.

A simple search for the terms "bridges and GPS(GNSS)" in the Scopus database reveals 495 titles, the most recent appearance being the work of Rossi et al. [147], which highlights the utility of using an Unscented Kalman Filter (UKF) to gather data from GNSS and accelerometers, taking into account and incorporating data of the torsion of the components of the analyzed structure.

A case study of bridge monitoring using multi-GNSS observations [148] focuses on three main aspects: it proposes multisystem-type GNSS for monitoring bridges; for field data collection, the authors use combined signals type GPS, Glonass and Beydou (GPS/BDS/GLONASS); finally, the study demonstrates that, with the choice of larger altitude angles (40 degrees) for the collection of GNSS data, millimeter accuracy can be obtained, but only for planimetric data, those related to the third component (quota) being affected by larger, centimeter error.

A paper by Vazquez-Ontiveros et al. [149] focuses on the real-time performance evaluation of bridges, specifically the measurement technologies using PPP-GNSS in Structural Health Monitoring (SHM) systems. It also involves the signal processing of displacement measurement data and the assessment of structural dependability in terms of the chance of failure.

Doppler Laser Vibrometers (LDVs) measure the speed and displacement of a surface without physical contact. They provide high accuracy and are suitable for monitoring dynamic responses to environmental demands, such as wind loads.

The paper of Garg et al. [150] presents a case study that focuses on mounting a Doppler laser vibrometer (LDV) on an unmanned aerial system (UAS) to allow contactless dynamic cross-sectional movement of a railway bridge. The accuracy of the UAS–LDV measurements is compared with the measures traditionally used, LVDT (Linear Variable Differential Transducer).

The paper of Yu, Tang, and Vinayaka [151] is the most recent appearance that focuses on the use of Doppler laser vibrometers (LDV) for the structural monitoring of bridges. The work starts from the premise that a "single-point portable LDV can measure background noise relatively between the bridge and the LDV", concluding that the speed of a train may be measured by measuring the displacement caused by the train-induced forced vibration.

If we refer to another type of structure monitored with the help of LDV, namely a cable-stay bridge structure, in the study by Kordatou et al. [152], a 2D Doppler laser vibrometer system is used, both in the static system and in the dynamic charging system, to identify a possible correlation between these non-destructive evaluation techniques during the static and dynamic response of different demand situations. The results obtained can be used to improve and facilitate bridge design and allow the detection of distributed failures during a multifactorial load system.

Laser scanning and LiDAR: These technologies allow high-precision measurements of the bridge surface, detecting tiny deformations over time. Recent technological advances in land scanning systems and LiDAR technologies have enabled their use for the structural monitoring of bridges. A representative number of case studies in the literature focus on this aspect [51,153,154].

Thus, a cumulative search for the terms "bridges and LiDAR" in the SCOPUS database reveals several 629 published papers. An example of this is the paper of Kaartinen, Dunphy, and Sadhu [51], which analyzes the use of LiDAR-type sensors to detect structural defects or changes over time, as well as cracks and deformations. Both mobile (MLS) and terrestrial laser scanning systems (TLS) are analyzed, and the existing limitations of each of the two types of systems analyzed are discussed and highlighted.

The most cited work relating to LiDAR terrestrial scanning technology in the structural monitoring of bridges (166 citations in Scopus) is the work of Riveiro, DeJong, and Conde [155]. This work aims to develop a method of fully automated segmentation of point clouds taken with LiDAR sensors in the case of bridges with arc forging. The main advantages of the method presented by the authors are related to its validation in a representative number of cases, as well as the fact that the method does not require special training and expertise in the collection of data from the field with TLS and also extremely powerful computers for data processing.

There are limitations on the use of each type of LiDAR scanning sensor (terrestrial, mobile, aerial, underground, etc.) each of which has its advantages and disadvantages. Each type of sensor must, therefore, be used, taking into account the constructive characteristics of the structure under study, temperature and external environment factors, accessibility, and hazard factors existing in the study area. A study that proposes a comparison between the use of different LiDAR sensors in the structural monitoring of bridges was carried out by Lin et al. [156]. The research starts from the premise that to obtain the right quality of the LiDAR data it is necessary to consider not only the degree of the on-board LiDAR scanners but also the accuracy of the direct geo-referencing data as well as the calibration of the system.

A SHM method that involves the use of a terrestrial laser scanner (TLS) to obtain high-resolution geo-referenced point clouds of bridge grinds, point clouds that are filtered to identify four possible classes of damage, is "Preliminary Test on Structural Elements Health Monitoring with a LiDAR-Based Approach" [157].

Thermal imaging cameras: These cameras can identify temperature variations along the bridge structure, highlighting areas that receive more intense sunlight.

The use of thermal chambers for monitoring bridges is important, especially for the analysis of temperature-related factors and their influence on the movements of the component structures of these types of constructions. The work by Jin Lim et al. [158] analyzes and presents a type of convolutional neuronal network based on regions, which is faster, with the advantage that it is constructed and applied to thermographic images combined with visual images for the automatic detection and classification of phenomena related to surface and underground corrosions of steel bridges. The uniqueness of this study is due to the combination of the classic images (RGB-red, green, blue) and those obtained with the thermal camera, a combination that offers significant improvements in the monitoring of the corrosion phenomena of steel bridges.

Wireless sensor networks (WSNs) consist of spatially distributed sensors that communicate wirelessly to collect and transmit data. They are advantageous for scalability and ease of installation, reducing the need for extended wiring and allowing real-time data acquisition.

The study by Zh Ali et al. [159] presents "a localized information processing approach for long-term automated online Structural Health Monitoring (SHM) using wireless sensor network (WSN)". This paper analyzes the vibration data collected by accelerometers in several locations of a strongly loaded old pre-tensioned bridge that included healthy as well as unhealthy parts using signal processing techniques.

Robotic total stations (RTS) with high sampling rates are becoming increasingly popular for monitoring the displacement responses of bridge structures, both in semi-static and dynamic conditions. This is due to rapid improvements in data sampler rates and tracking speeds [160]. Through both laboratory and in situ studies on a 328 m bridge, the authors demonstrate the feasibility of the system by comparing it with the data obtained with precision accelerometers.

When evaluated by geomatic means, these technologies offer various benefits and trade-offs in terms of effectiveness, cost, ease of implementation, and reliability. Table 1 presents a comparison of different geomatic SHM technologies:

Table 1. Comparison of Geomatic SHM technologies. Source: adapted from [161].

Geomatic Technology	Effectiveness	Cost	Ease of Implementation	Reliability
Global Navigation Satellite System (GNSS) Monitoring	Provides precise measurements of displacement and deformation over large areas. It is effective for continuous monitoring of structural movements, especially for high-rise buildings and long-span bridges.	GNSS can be expensive due to the cost of high-precision equipment and the need for extensive data processing.	Installation can be complex, requiring clear lines of sight to satellites and often specialized knowledge for accurate data interpretation.	Highly reliable with real-time monitoring capabilities, but dependent on satellite signals, which can be affected by environmental conditions.
Total Station Measurements	Excellent for high-precision monitoring of static points, providing accurate deformation and displacement data.	Generally lower than GNSS, but costs can escalate with increasing coverage area and number of monitored points.	Implementation can be manageable, though it requires manual line-of-sight setups and ongoing maintenance.	Reliable for short to medium ranges, but effectiveness decreases with distance and in poor weather conditions.
Laser Scanning (LIDAR)	Offers high-resolution data for surface geometry and can capture a wide area rapidly, making it suitable for detailed structural inspections.	Moderate to high, depending on the scope of the project and equipment used.	Fairly easy to implement with proper equipment. Data processing and interpretation require expertise.	Highly reliable for surface deformations but may have limitations in penetrating structures or areas with obstructions.

Table 1. *Cont.*

Geomatic Technology	Effectiveness	Cost	Ease of Implementation	Reliability
InSAR (Interferometric Synthetic Aperture Radar)	Ideal for monitoring large areas and detecting millimeter-level displacements. Effective for identifying subsidence, landslides, and other gradual changes.	Generally cost-effective for large-scale applications with low marginal costs once the baseline data is acquired.	Highly technical; requires specialized skills for data processing and interpretation.	Very reliable for long-term monitoring over extensive areas, but dependent on satellite availability and revisit frequency.
Drones	Useful for capturing and analyzing structures using photographic methods. Good for assessing visible surface changes.	Relatively low, particularly with advancements in drone technology and software.	Quite straightforward to implement with proper equipment, drones facilitate access to hard-to-reach areas.	Dependable for visual inspections but may have limitations in accuracy for detailed deformation analysis.

2.4. Critical Assessment of Literature Review on Methods, Techniques, and Technologies Used in SMH of Bridges

2.4.1. Assessment of Natural Environmental Factors

From a broad perspective on the study of SHM, the importance of researching environmental factors as triggering factors of various problems regarding the integrity and safety of structures has recently been concentrated on in a very large number of studies. By identifying the most relevant research in the field (assessed by their degree of recognition, respectively, the number of citations), the analysis of these works allowed their synthesis, using the criteria to group the research. The type of factors studied, the research methods used, and the results expected after the research is carried out are criteria that define the intensive character of recent research. These are presented in Table 2.

By analyzing this information, it can be observed that there is a wide variety of approaches in the research on natural environmental factors that affect the integrity of bridge structures. Statistics models use statistical methods to analyze data from sensors placed on or within structures to monitor environmental conditions that may affect structural health. Algorithms for machine learning are used to analyze and model environmental factors that affect structural health; this can be performed with artificial neural networks. Finite-element models simulate structure behavior in various environmental conditions to predict damage from temperature changes, wind speed, or seismic events. Data fusion are algorithms that help understand how environmental factors affect structural integrity by integrating data from more sources. However, a combination of these models and algorithms is intensely used by researchers and engineers to track and evaluate environmental factors' effects on structural health in real-time, enabling proactive management and improving safety and reliability.

Table 2. Natural environmental factors, methods of analysis, and mitigation/monitoring mode, results.

Factor of Influence/Effect	Method of Analysis	Mitigation/Monitoring Mode Results of the Studies
Temperature Temperature variation is manifested in bridges through expansion and contraction. In hot weather, the materials expand, while in cold weather, they contract. This cycle can lead to displacements and potential structural stresses if not properly managed through expansion joints. Moreover, differing temperatures within different parts of the bridge can cause uneven expansion, leading to differential movements and potential misalignments. **Earthquakes and seismic forces** Earthquakes and seismic forces can cause immediate and significant stress to a bridge, potentially leading to cracks, joint failures, or even collapse. Seismic events can generate horizontal and vertical movements that require a seismic resilience design, including flexible joints and energy-dissipating devices. Even minor seismic activities can lead to ground settlements or shifts, affecting bridge foundations and causing displacements. **Wind** High-speed winds apply significant lateral forces on bridge structures, especially on long-span bridges. This can cause displacements, oscillations, and even aeroelastic instabilities such as flutter. Sustained wind can induce vibrations and resonance, particularly in suspension and cable-stayed bridges, leading to fatigue and displacement over time. **Waves** High water levels and fast-moving water during floods, storms, and tsunamis impose significant forces on bridge piers and abutments, leading to scour around foundations and potential displacement or settlement. **Uneven sunlight** Uneven exposure to sunlight can lead to differential thermal expansion and contraction of bridge structural elements. **High humidity** High humidity can lead to moisture ingress in concrete and steel components, potentially causing corrosion of steel reinforcements and degradation of concrete. Over time, this can weaken the bridge's structural integrity and load-bearing capacity. **Precipitation** Excessive precipitation can lead to surface runoff, flooding, and soil erosion around bridge foundations, potentially undermining them. Additionally, water buildup and poor drainage can cause hydrostatic pressure and waterlogging, affecting the bridge's durability.	Statistical analysis; Data analysis; Modeling; Machine learning Finite element analysis; Network analysis. Numerical analysis; Signal monitoring; Simulation; Numerical simulation. Methodologic approach; Control system analysis; Semi-parametric mixed technique; Simulation models; Experimental research. Structural control systems Finite element model; Statistical analysis.	Displacement assessment; Deformation; Serviceability assessment; Life span assessment; Standardization of environmental actions; New research directions in bridge engineering, in particular for applications such as the form-finding of innovative long-span structures, structural reinforcement, and structural optimization. Continuous monitoring allows for real-time damage assessment and early warning systems to close bridges to traffic, if necessary, during seismic events; Post-seismic evaluations to ensure structural safety and identify necessary repairs; Ongoing data analysis can be used to improve the design of future bridges; Efficient, effective bridge maintenance strategies. Assessment of structural response; Assessment of wind influence on bridge structure; Prediction of wind influence; Wind protection capability; Mitigation of wind and earthquake response. Impact of uneven temperature on the bridge tower. Collecting continuous data on the ambient moisture levels using hygrometers and other moisture sensors. Monitoring precipitation helps design effective drainage systems and planning for extreme weather events.
Relevant studies: [162–171]		

2.4.2. Assessment of SHM Technologies

Structural Health Monitoring (SHM) technologies are critical to keeping bridges safe and long-lasting. Regarding the technologies most used in current research, sensors-based technology represents a viable alternative for addressing the complexity of structural monitoring activities.

A comparative analysis of the various techniques and technologies recently used in SHM research is shown in Table 3.

Table 3. Comparison of SHM technologies.

Technology	Pros	Cons
Sensors	Direct measurement of specific parameters like strain, displacement, and acceleration. Can be integrated into a real-time monitoring system. High sensitivity and accuracy. Suitable for long-term monitoring.	Requires physical installation on the structure. Maintenance can be challenging. Limited to the points where sensors are installed.
High Precision GPS Sensors	Provide accurate displacement and deformation measurements over a wide area. Real-time data collection. Non-contact method (no need for modifications to the structure).	Limited by satellite visibility and signal obstructions. Relatively high cost.
Doppler Laser Vibrometers	Non-contact measurements of vibration and displacement. High precision and resolution. Can measure dynamic responses and modal properties.	Limited to line-of-sight distance measurements.
Laser Scanning and LIDAR	Provides detailed 3D models of the structure. High spatial resolution and coverage. Non-contact and rapid data acquisition	High initial equipment cost. Data processing can be complex and time-consuming. Performance is affected by environmental conditions, such as rain and fog.
Thermal Imaging Cameras	Detect temperature variations that can indicate structural issues. Can be used to identify moisture ingress, voids, and delamination. Non-contact and can cover large areas quickly.	Require interpretation of thermal data. Only detect surface defects and anomalies.

2.4.3. New Insights into SHM Methodologies for Bridges: Eigen Perturbation Strategies

The industry has recognized recent approaches, such as those using eigen perturbation strategies, as the industry standard. By analyzing changes in the bridge's dynamic properties, eigen perturbation, a mathematical approach, can innovate real-time Structural Health Monitoring (SHM) for bridges. The use of eigen perturbation strategies in SHM represents a sophisticated approach that offers advantages and differences compared to traditional methods. Application of eigen perturbation strategies in real-time SHM can lead to the development of models of the bridge's dynamics. These serve as a reference for detecting structural changes and continuously measuring their dynamic response using sensors such as accelerometers and strain gauges distributed across the bridge. Advanced data acquisition systems can process this information in real time. Changes in eigen parameters can help localize potential damage areas. Specific algorithms can quantify the severity and nature of the detected changes, allowing for more targeted inspections and maintenance.

Three key features contribute to the novelty of eigen perturbation strategies:

- Sensitivity to structural changes means that eigen perturbation methods are particularly sensitive to small changes in structural parameters, which can be advantageous for the early detection of damage. They allow for precise detection of shifts in a structure's vibrational characteristics that indicate potential issues.

- Mathematical rigor consists of the fact that these methods rely on perturbation theory, which offers a rigorous mathematical framework for analyzing changes in eigenvalues and eigenvectors of a system's structural matrix. This makes them highly reliable for theoretical modeling.
- Model updating, which means that they facilitate better model updating, which is crucial when the existing model of a structure needs refinement based on observed data. By observing how eigenvalues react to perturbations, we can make adjustments more accurately.

A comparison of eigen perturbation strategies with standard strategies is presented in Table 4:

Table 4. Comparison of eigen perturbation strategies vs. standard strategies.

Strategy	Type	Eigen Perturbation Strategies vs. Standard Strategies
Traditional Modal Analysis	Detection Capabilities	While traditional modal analysis techniques also utilize the structure's vibrational modes, eigen perturbation methods provide enhanced sensitivity to small changes. This can lead to earlier detection and more accurate localization of damage.
	Complexity and Computation	Eigen perturbation methods can be computationally more complex given their mathematical demands, though modern computational power often mitigates this challenge.
Data-Driven Approaches	Machine Learning and Statistical Methods	While data-driven approaches like machine learning are becoming more popular due to their ability to handle vast amounts of data and learn patterns, eigen perturbation techniques offer a more physics-based approach, which can be more robust in situations with limited data.
	Interpretability	Eigen perturbation methods offer clearer insights into structural behavior since they are grounded in physics, unlike some black-box data-driven approaches.
Relevant studies: [172–178]		

The practical applications of eigen perturbation strategies present innovative solutions and opportunities for future development of Structural Health Monitoring.

- ○ They can be particularly beneficial for monitoring complex structures such as bridges, high-rises, and buildings where precise detection and localization of damage are critical.
- ○ Eigen perturbation strategies can be integrated seamlessly with sensor technologies and IoT for real-time monitoring, enhancing their effectiveness and practicality in ongoing operations.
- ○ Although potentially more costly due to computational demands, the investment in higher precision for damage detection can lead to savings by preventing costly repairs and downtime through early intervention.

A Comparative Analysis of Different Eigen Perturbation Strategies

When performing a comparative analysis of different eigen perturbation strategies, scholars focus on the effectiveness in damage identification and computational efficiency of the eigen perturbation strategies. These strategies utilize changes in the modal properties (such as natural frequencies and mode shapes) of a structure to identify damage. In a similar way, while comparing real-time eigen perturbation strategies with traditional methods, highlighting their advantages and limitations must be a compulsory action [179].

Lin and Ng [180] discuss two main eigen perturbation approaches: direct and iterative methods. The direct method computes changes in eigenvalues and eigenvectors directly, while the iterative method updates these properties over successive iterations. Fan and Qiao [181] evaluate both methods based on their accuracy in detecting different types and locations of damage in a simulated structure.

Firstly, the effectiveness of each eigen perturbation strategy can be assessed using a benchmark structure subjected to various damage scenarios. Performance metrics include sensitivity to small damages, localization accuracy, and the ability to differentiate between multiple damage sites. Results show that certain strategies offer superior accuracy in identifying and localizing damage, though with varying requirements on computational resources [182].

Secondly, ref. [183] argues that computational efficiency is critical for real-time applications of SHM. The authors compare the time complexity and resource requirements of each strategy. Iterative methods generally offer better real-time performance due to lower computational costs per iteration, whereas direct methods may require more resources but can be more straightforward for simpler structures. The differences in performance highlight trade-offs between computational efficiency and damage detection; accuracy reveals that iterative methods offer enhanced efficiency, while direct methods may provide more precise damage estimation under specific conditions.

The choice of strategy may depend on the complexity of the structure and the specific requirements of the SHM system [184].

In conclusion, real-time eigen perturbation strategies provide a promising approach for structural health monitoring, offering a balance between accuracy in damage identification and computational efficiency. Future developments could include hybrid models that combine the strengths of both methods to optimize SHM systems further. This comparative analysis offers insights that can guide the selection and development of effective SHM strategies to ensure the structural integrity and safety of critical infrastructure.

2.4.4. Using Artificial Intelligence (AI) and Smart Sensors for SHM

Recent studies argue that integrating advanced technologies like AI and smart sensors into SHM systems enhances their efficiency and accuracy. Table 5 exhibits detailed examples of how these technologies are integrated.

Table 5. Integration of AI and smart sensors in SHM.

Advanced Technology	Technology Type	Integration Description
Smart Sensors	**Wireless Sensor Networks (WSNs)**	Bridges are often equipped with wireless smart sensors to collect data on various parameters such as strain, temperature, acceleration, and displacement. The wireless nature simplifies installation and reduces costs. For instance, accelerometers and strain gauges can be placed at critical points to monitor movements and stress changes in real-time.
	Fiber Optic Sensors	These sensors can measure strain and temperature along the length of the bridge. They are highly sensitive and can cover long distances with minimal signal loss, making them ideal for large structures.
AI and Machine Learning	**Pattern Recognition Algorithms**	AI can analyze sensor data to detect patterns or anomalies that might indicate structural damage or deterioration. Machine learning models are trained to recognize the normal behavior of the bridge and identify deviations in real time.
	Predictive Maintenance Models	Using historical data and AI, predictive models can forecast potential failures or necessary maintenance tasks, allowing for proactive management of bridge health.

Table 5. *Cont.*

Advanced Technology	Technology Type	Integration Description
Data Integration and Analysis	Data Fusion Techniques	Combining data from various types of sensors (e.g., acoustic, vibration, thermal) provides a more comprehensive understanding of the bridge's condition. AI algorithms can process and integrate this multi-source data to offer more accurate assessments.
	Cloud-Based Platforms	Data from smart sensors can be streamed to cloud-based platforms where AI algorithms analyze them continuously. This allows for remote monitoring and immediate alert systems in case of a detected anomaly.
Drones and Robotics	**Autonomous Inspection**	Drones equipped with cameras and sensors can conduct visual inspections of hard-to-reach areas of a bridge. They can detect surface damage, corrosion, or misalignment, complementing data from stationary sensors.
	Robotic Crawlers	Robotic Crawlers can traverse difficult parts of the bridge to perform detailed inspections and collect high-resolution data, which are then analyzed using AI techniques.
Digital Twins	Real-Time Simulation Models	A digital twin of the bridge can be developed using data from AI and sensors. This virtual model allows for real-time simulations and stress testing of different scenarios, helping engineers predict the bridge's response to various stressors and environmental conditions.
Relevant studies: [185–198]		

By integrating these technologies, SHM systems can provide a continuous, real-time overview of bridge health, resulting in timely interventions and extended bridge lifespan, ultimately enhancing public safety and infrastructure reliability.

2.4.5. Discussion

Studies reveal that Structural Health Monitoring systems use models or data. For a data-driven approach to be effective, a model is needed. A model-based approach of different methods, specified previously, creates a real model of the structure. The choice of algorithm or model for analyzing environmental factors in Structural Health Monitoring of bridges depends on factors such as data availability, computational resources, desired level of detail, and specific goals of the monitoring program. The best and most accurate results are often obtained using a hybrid approach that combines several models and algorithms.

Eigen perturbation strategies offer a highly sensitive and mathematically robust approach to SHM, providing advantages in terms of detection precision and model validation over traditional methods. While computationally intensive, their integration with modern computational tools and technologies makes them a feasible option for complex Structural Health Monitoring tasks.

By using different technologies, the realization of health monitoring devices is added to the model, following the tracking and calculation of losses.

There are some cases in which these processes of data collection, data processing, modeling, and analysis are not carried out separately but are combined. For example, a data collection device is used to request and transmit information in both cases. The data collection system can be moved or fixed on the structure as required by the user. These systems capture data constantly or intermittently and transmit them to a central location via a wired or wireless connection. Health monitoring tools typically collect information and compare it to predictions made by a computer model.

3. Bibliometric Analysis of Research Carried Out in the SHM of Bridges Realm

The current research utilizes the Systematic Literature Review (SLR) methodology, primarily relying on the Scopus database. The findings are analyzed using the VOSviewer application.

To find references in the literature about the implementation of the four words, namely, SHM, Bridge, Temperature, and Deformations, documents were searched by associating them in different combinations: first the first two terms, then the first three terms, and lastly all four terms together.

To conduct a thorough literature review, articles that discuss the application of the mentioned terms in research were chosen. The selection process followed the search methodology recommended by Scopus, using specific keywords entered in the code of the article title, abstract, and keywords. The keywords used were "SHM", "SHM and bridge", "SHM and bridge and temperature", and "SHM and bridge and temperature and deformations".

By analyzing the findings obtained from Scopus, the documents in RIS format were introduced into the VOSviewer program [199]. This analysis helped identify the publications that specifically addressed the research questions RQ3 and RQ4 in the relevant domains. Ultimately, our research examines how the primary elements that have been found interact with each of the aforementioned words. The search results from Scopus were as follows:

❖ Inclusion criteria: The study fields were confined to the following subjects: Engineering and Earth and Planetary Sciences, all of which are relevant to the research field. Only materials classified as either "Article" or "Conference paper" were kept (Figure 2, Filter 1). The results of the first search round were as follows:
  - SHM, 12,573 documents found;
  - SHM, Bridge, 9346 documents found;
  - SHM, Bridge, Temperature, 1356 documents found;
  - SHM, Bridge, Temperature, Deformations, 143 documents found.

❖ Filtering the results was performed using the next three filters (Figure 2), Filters 2, 3, and 4, as follows:
  - Filter 2. Addition in Scopus search to bridge monitoring system domain search;
  - Filter 3. Period limited to 2010–2024;
  - Filter 4. Limited to search on a minimum number of citations.

❖ After applying the four previously mentioned search filters, the results were reduced to:
  - SHM, Bridge, 1191 documents found;
  - SHM, Bridge, Temperature, 496 documents found;
  - SHM, Bridge, Temperature, Deformations, 71 documents found.

When considering the field of Structural Health Monitoring, specifically focusing on Bridge Deformations and Temperature Variations (Filter 5), only 14 articles were found in Scopus that directly examined the impact of uneven sunlight on bridges. Relevant for these searches are "Insights into temperature effects on structural deformation of a cable-stayed bridge based on Structural Health Monitoring" [200], along with a literature review conducted by Borah and co-authors titled "The effect of temperature variation on bridges" [201]. These two are among the limited number of works that discuss this particular topic.

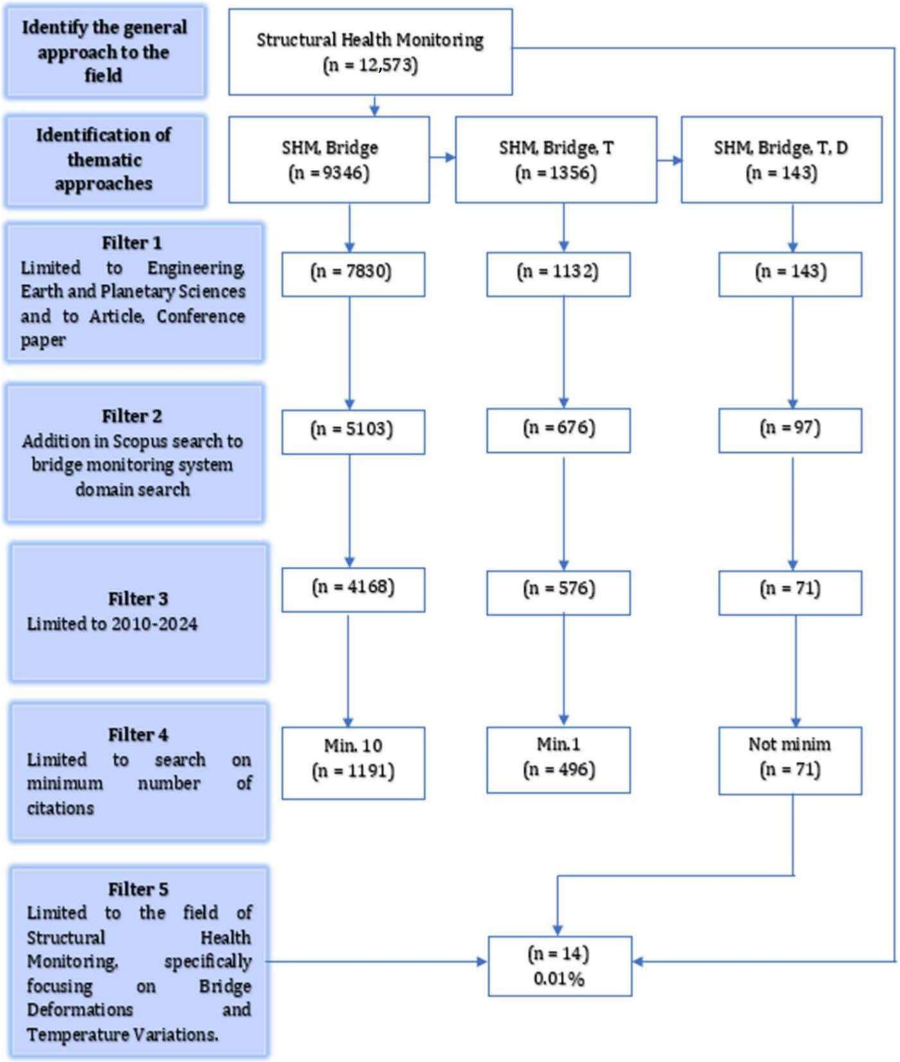


Figure 2. PRISMA flow diagram illustrating the identification, screening, and inclusion of studies Source: by authors adapted from Çevikbaş [65].

3.1. Identifying Relevant Research and Research Gaps (RQ3)

Through bibliometric analysis, we aimed to identify important research and research needs in the field of structural monitoring of bridges. The main issue we intended to answer was, "What are the most relevant keywords in structural monitoring in SHM, Bridge, Temperature, and Deformation studies (Coded: SHM-B-T-D), and how do they connect in network maps"?

Table 6 displays the primary keywords related to the correlation between Structural Health Monitoring (SHM) terms. The table first focuses on the link with bridges, then expands to include temperature, and finally adds the term deformations. The primary search terms, SHM and Bridge, consistently rank top in all three searches. In the first search, they yielded 3426/1652 results out of a total of 8876. In the second search, they yielded 345/256 out of 1198 results. In the third search, they yielded 112/102 out of 415 results. In the footer of Table 6, we explain how we organized the data thematically. For instance, under the category of Non-destructive Examination, we included the many research-monitoring methodologies used, such as Modal Analysis, Finite Element Method, Structural Analysis, Structural Dynamics, and Vibration Analysis.

Table 6. The most relevant keywords regarding the association of SHM terms, respectively Bridge, Temperature, and Deformations.

SHM, Bridge	Nr. Keywords	SHM, Bridge, Temperature	Nr. Keywords	SHM, Bridge, Temperature, Deformations	Nr. Keywords
SHM [1]	3426	SHM [1]	345	SHM [1]	112
Bridges [2]	1652	Bridges [2]	256	Bridges [2]	102
Non-destr. Exam [3]	1250	Non-destr. Exam. [3]	147	Non-destr. Exam. [3]	24
Damage detection	686	Temperature	82	Damage detection	10
Sensors	503	Sensors	77	Sensors	83
Monitoring	508	Structural Analysis	72	Temperature	32
Decision Making	132	Monitoring	69	Damage Detection	10
Maintenance	158	Damage Detection	68	Maintenance	9
Life Cycle	142	Maintenance	26	Deform. Monitoring	7
Machine Learning	110	Life Cycle	16	Deflection (structures)	7
Deterioration	108	Long-Term Monitor.	15	Costs	7
Info. Management	101	Data Handling	13	Deterioration	6
Civil Infrastructures	100	Thermal Effect	12	Wind	6
Total Keywords	**8876**	**Total Keywords**	**1198**	**Total Keywords**	**415**

[1] SHM, Structural Health Monitoring Systems, etc., [2] Bridges, Cable Stayed Bridge, Steel Bridges, Bridge Decks, etc. [3] Modal Analysis, Finite Element Method, Structural Analysis, Structural Dynamics, Vibration Analysis, etc.

Table 6 depicts that only the number of keywords changes in SHM and Bridge, SHM and Bridge and Temperature, and SHM and Bridge and Temperature and Deformations, type searches, not the types of keywords. Since we intended to continue the research on the structural behavior of bridges under the effect of uneven sunlight, we continued the bibliometric analysis, focusing on the last four-term associations.

Next, using the VOSviewer 1.6.20 software, we performed a keyword co-occurrence analysis and networking based on data from the Scopus database.

The generated map is a distance-based network, and the space between nodes indicates the strength of the relationship between keywords [202]. The closest distance between nodes generally represents the strongest relationship between keywords, and the size of the node is directly proportional to the number of documents that contain those keywords. The VOSviewer 1.6.20 tool provides a grouping technique to set keywords associated with the same group with the same color [203]. Only keywords with high occurrence numbers are selected to map the network, respectively, for the combination of terms SHM, Bridge, Temperature, and Deformations, minimum number of occurrence of keywords =5, number of keywords to be selected = 22. (Table 7).

Figure 3 shows the density of the items by the association "structural AND health AND monitoring, AND bridge, AND temperature AND deformations". The more important an item is, the larger its label and its circle. This map contains 22 selected keywords. In this view, each point on a map is assigned a color based on the density of items present. That is, the color of a point on a map is determined by the number of items in its immediate vicinity as well as the relevance of those items. The density view is very beneficial for getting a sense of a map's overall structure and highlighting the most relevant areas [204].

The five most dense items were Structural Health Monitoring, damage detection, nondestructive examination, modal analysis, and fiber optic sensors.

The co-occurrence network shows the collective interconnection of terms based on their presence in pairs within the text of the works found through the search. Networks are generated by connecting pairs of terms using a set of criteria that defines co-occurrence, i.e., the 5 keywords. These appear simultaneously two by two, if both are contained within a certain article. The co-occurrence network is particularly useful because by mapping it, one can determine the intensity of the connections between terms. Figure 4 shows the keywords co-occurrence network (the intensity of the links) after reducing the selection of terms to 22 keywords, i.e., the main ones found in the works selected for the literature review and the introduction in the VOSwiewer analysis of the previously mentioned terms.

Table 7. Mapping Repeated Items in Papers (adapted from [65]).

ID	Items	Cluster	Occurrences	Total Link Strength	Field of Study	Rate of Occurences	Rate of Link Strength
1.	Structural Health Monitoring	1	38	132	Research field	0.27	0.23
2.	Structural Health Monitoring (SHM)	1	5	20			
3.	Structural Health Monitoring Systems	1	6	25			
4.	Bridge	2	6	30	Monitored structure	0.07	0.06
5.	Bridges	3	7	18			
6.	Bridge structure	3	6	24	Category of monitored element/structure	0.22	0.26
7.	Cable-stayed bridges	1	10	50			
8.	Cable-stayed bridge	1	5	25			
9.	Cables	1	7	36			
10.	Arch bridges	2	7	36			
11.	Arches	2	6	30			
12.	Finite element method	2	5	23	Calculation/forecasting methodology of structural behavior	0.03	0.03
13.	Interferometry	2	6	27	Monitoring methodology	0.08	0.08
14.	Synthetic aperture radar	2	9	34			
15.	Deformation monitoring	2	5	26	Reason for request	0.12	0.11
16.	Health monitoring	2	5	26			
17.	Forecasting	1	7	18			
18.	Damage detection	3	5	14			
19.	Temperature	3	8	36	Stressors	0.07	0.08
20.	Wind	1	5	21			
21.	Thermal deformation	2	7	27	Effect of Stressors Factors	0.14	0.15
22.	Deformations	1	18	80			
	Total	**-**	**183**	**758**	**-**	**1**	**1**

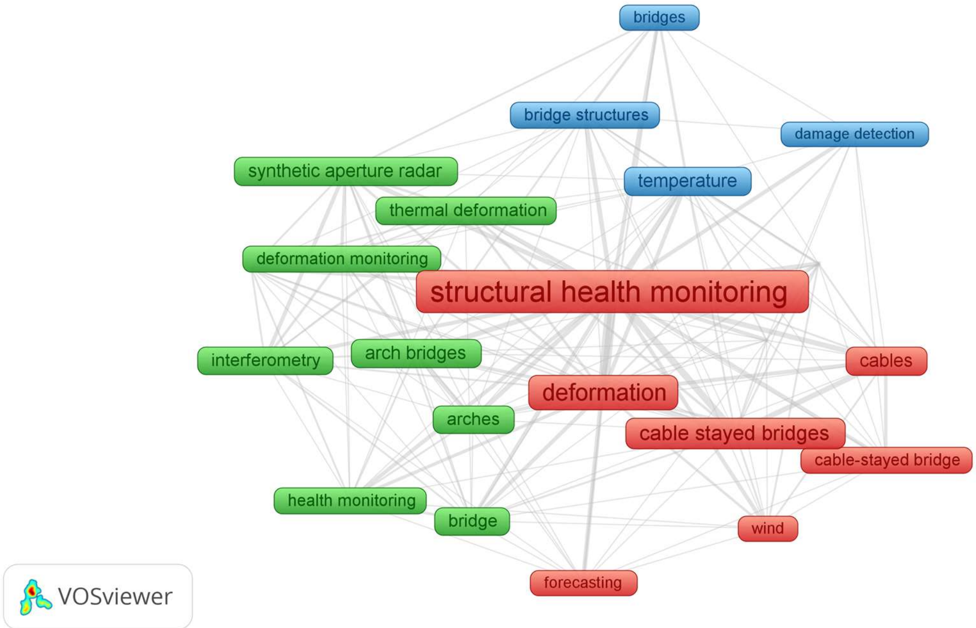


Figure 3. Density of the items: SHM, Bridge, Temperature, Deformations (minimum number of occurrence of keywords = 5, number of keywords to be selected = 22).

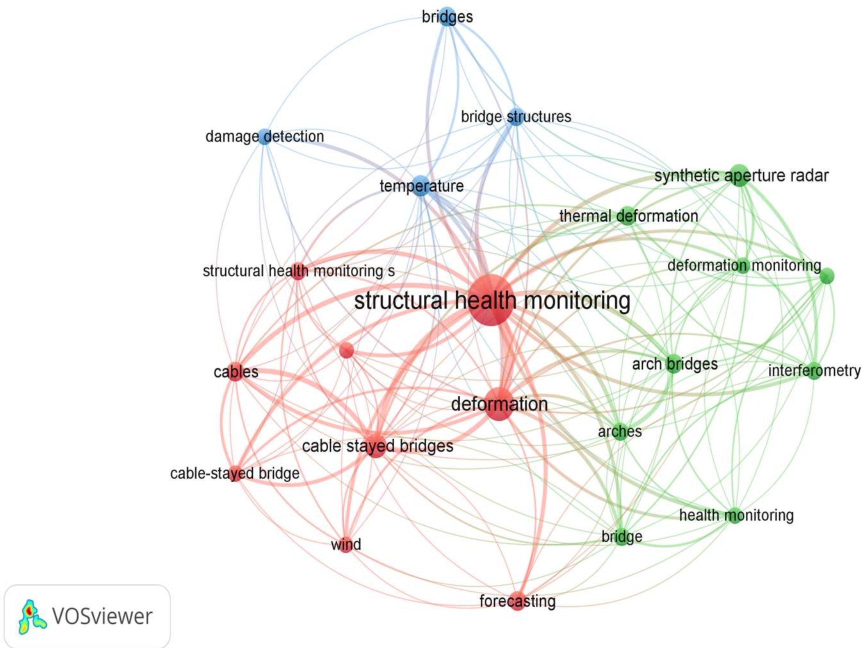


Figure 4. Keyword co-occurrence network SHM, Bridge, Temperature, Deformations (minimum number of occurrence of keywords = 5, number of keywords to be selected = 22).

Through the last-mentioned association of terms, three clusters are formed, as follows (Figure 5):

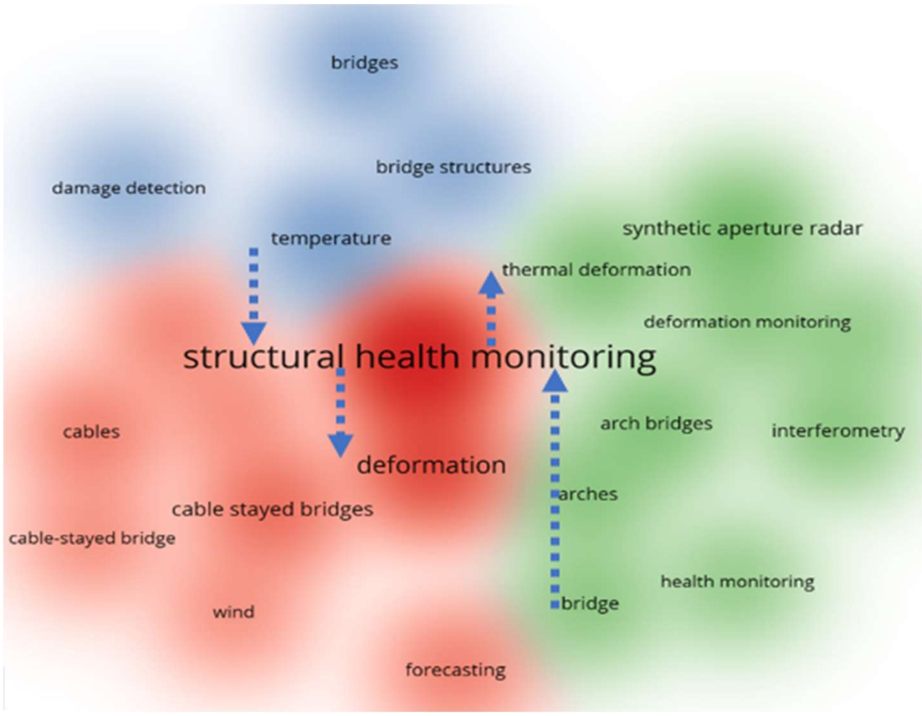


Figure 5. Density of clusters and the inter-cluster association between SHM, Bridge, Temperature, and Deformations.

The five most dense items were Structural Health Monitoring, damage detection, nondestructive examination, modal analysis, and fiber optic sensors.

- Cluster 1, represented by the color red, consists of an analytical axis that encompasses topics such as cable-stayed bridges/cable-stayed bridge, cables, deformation, forecasting, Structural Health Monitoring/Structural Health Monitoring SHM)/ Structural Health Monitoring system, wind;
- Cluster 2, indicated in green, ranks second in terms of density and consists of the following components: arch bridges, arches, bridge, deformation monitoring, finite element method, health monitoring, interferometry, synthetic aperture radar, thermal deformation;
- Cluster 3, shown by the color blue, has significance in the study due to its inclusion of items such as bridge structure, bridges, damage detection, and temperature.

Figure 4 displays the density of clusters and the inter-cluster association between the most important themes regarding SHM of bridges found in the literature review.

The five most dense items were Structural Health Monitoring, damage detection, nondestructive examination, modal analysis, and fiber optic sensors.

Upon examining the graph, it becomes evident that the crucial connection in the study is between bridges/temperature, Structural Health Monitoring, and deformation/thermal deformation monitoring.

Figure 6 displays the most robust connections among the words referenced in the networking examined in the specialized literature. The hypothesis is validated that there exist robust connections among the fundamental concepts of the study, namely Structural Health Monitoring, bridges, temperature, deformation, and thermal deformation. Additionally, there are associations with monitoring technologies, albeit not the most pertinent ones for the investigated domain, such as interferometry or synthetic aperture radar.

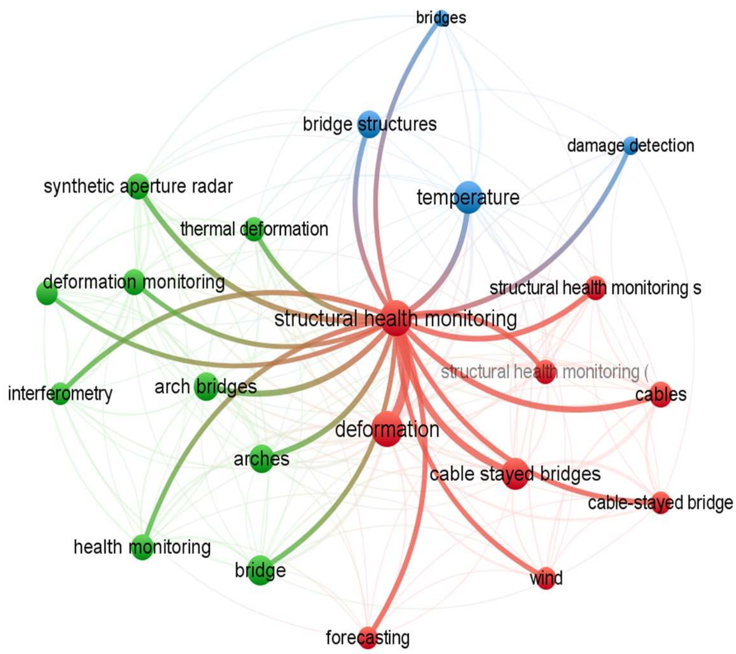


Figure 6. Importance of links in the SHM network.

Synthesizing the prior data, convergence of themes and essential domains of approach may be discovered via regions of investigation, as shown in Table 7. This displays the research areas, categorized into eight categories, in the order of significance presented, connected to the rate of occurrences: research field: 27%; category of monitored element/structure: 22%; effect of stresses factors: 14%; reason for request: 12%; monitoring technique: 8%; monitored structure: 7%; stressors: 7%; and calculation/forecasting methodology of structural behavior: 3%. These fields of study are the most relevant issues that make up the field's research scope. The percentages provided for the rate of connection strength are comparable.

3.2. Gaps in the Research on the Influence of Uneven Sunlight on Bridges

To determine the gaps in the literature regarding the influence of uneven sunlight on bridges, we conducted further research by using the keywords "sunlight AND on AND the AND bridge AND structure" in the Scopus database. At first, a total of 135 results were acquired. The searches were restricted to Engineering (44), Earth and Planetary Sciences (4), and Multidisciplinary (3), resulting in a total of 51 matches. The study was restricted to the time frame of 2020–2024 and focused only on publications categorized as "Article" (19) and "Conference Paper" (6). This yielded a total of 25 results. After analyzing much research deemed to be the most pertinent to the search topic, namely "the impact of uneven sunlight on bridges", it was discovered that although several studies indirectly touch upon this issue, none directly address it. However, the following studies stand out among the few works found.

Ko et al. [204] examined the impact of temperature fluctuations on the structural parts of a bridge during construction, specifically focusing on the deformations caused by temperature changes. Based on estimates, when there is a maximum temperature differential of 21 °C, the vertical displacement of a structural element may vary by roughly 87 mm daily.

Another study [205] examined the influence of temperature on the vertical alignment of slender bridge support piers with thin walls. The study utilizes actual temperature data collected from within the piers during their construction.

Zhu et al. discuss the intricacy of temperature distribution in different structural elements of bridges in their study published in *Advances in Structural Engineering* [186]. The authors employ a temperature field analysis algorithm that takes into account geo-meteorological factors and the relationship between shielding elements to simulate the transient temperature field and thermal deformation of the structure. They then analyze the temperature distribution characteristics and thermal deformation under the influence of different seasons.

One intriguing study [206] examines the impact of the color of metallic bridge components on the distribution of temperature inside the structure. For this purpose, steel samples of standard sizes with different colors were placed horizontally and exposed to sunlight to measure the temperature changes during the day in different places. Based on the observation of the temperature change of steel specimens with different colors, it was observed that direct sunlight had an obvious influence on the temperature of the steel specimens, and the temperature variation between different colors was very large.

Concluding Remarks

Bridges are susceptible to a variety of strains, both natural (resulting from environmental variables) and anthropogenic (resulting from human activities). Environmental factors might arise unexpectedly, such as earthquakes, abrupt flooding of watercourses, tornadoes, and other such events. The most constant strain is uneven sunshine. The current study suggests that this particular component is not extensively discussed in the literature. There are many factors contributing to this gap. Firstly, a significant portion of the primary data collected during monitoring activities is confidential. Secondly, only a limited number of buildings are continuously monitored during their entire lifespan, mostly due to the high expenses involved. The most recent studies suggest that there are efforts to improve the accessibility of monitoring by reducing the cost of the entire monitoring system. This can be achieved by equipping bridges with intelligent structures, such as artificial intelligence and smart sensors, which enable continuous monitoring throughout their lifespan.

4. Trends in Approaching SMH Research (RQ4)

To effectively analyze the trends in research on Structural Health Monitoring (SHM) about environmental elements and technology, it is necessary to identify the key subjects that address these issues. It is crucial to accurately understand the trends in the growth of the Structural Health Monitoring (SHM) field, specifically about the research of bridge behavior. This includes focusing on the significant influence of temperature as a continuous stress source, its variations, and the resulting expansion of structural components. Consequently, the subsequent research subjects may be addressed.

—Structural Health Monitoring (SHM) using wireless sensor networks (WSN) has gained research interest due to its ability to reduce costs associated with the installation and maintenance of SHM systems [207].

—Development and testing of a serial multiplexed fiber optic sensor system [208].

—Experimental evidence on the use of the impedance-based health monitoring technique on components typical of civil structures [209]. The basic principle behind this technique is to use high-frequency structural excitations (typically > 30 kHz) via a surface-bonded piezoelectric sensor/actuator to detect structural point impedance changes due to the presence of damage.

—Modeling the effects of temperature on modal frequencies for the Ting Kau Bridge (Hong Kong), which was fitted with a long-term Structural Health Monitoring system. Based on one year of measurement data obtained from 45 accelerometers and 83 temperature sensors permanently installed on the bridge, the modal frequencies of the first ten modes and temperatures at different locations of the bridge were obtained at hourly intervals [210].

—Simultaneous recovery of temperature and voltage over a single sensor length was demonstrated using information recovered from polarimetric measurements on LP01 and

LP11 polarization-maintaining modes of the fiber. Temperature information was retrieved at 2 °C, and strain retrieval was better than 10 με. The measurement method is fully compatible with distributed measurement methods. A new generic form of sensor capable of performing distributed measurements on a chemical species has been devised [211].

—The relationship between temperature changes and the resulting deformations and displacements of the structure to create a unique numerical and graphical baseline in an SHM framework [212].

—A structural monitoring system comprising wind, temperature, cable tension, and deck level sensors to monitor bridge behavior during and after retrofitting [213].

—The temperature-induced deformations of a cable bridge using multiple linear superpositions of the thermal expansion effects of the individual components [214].

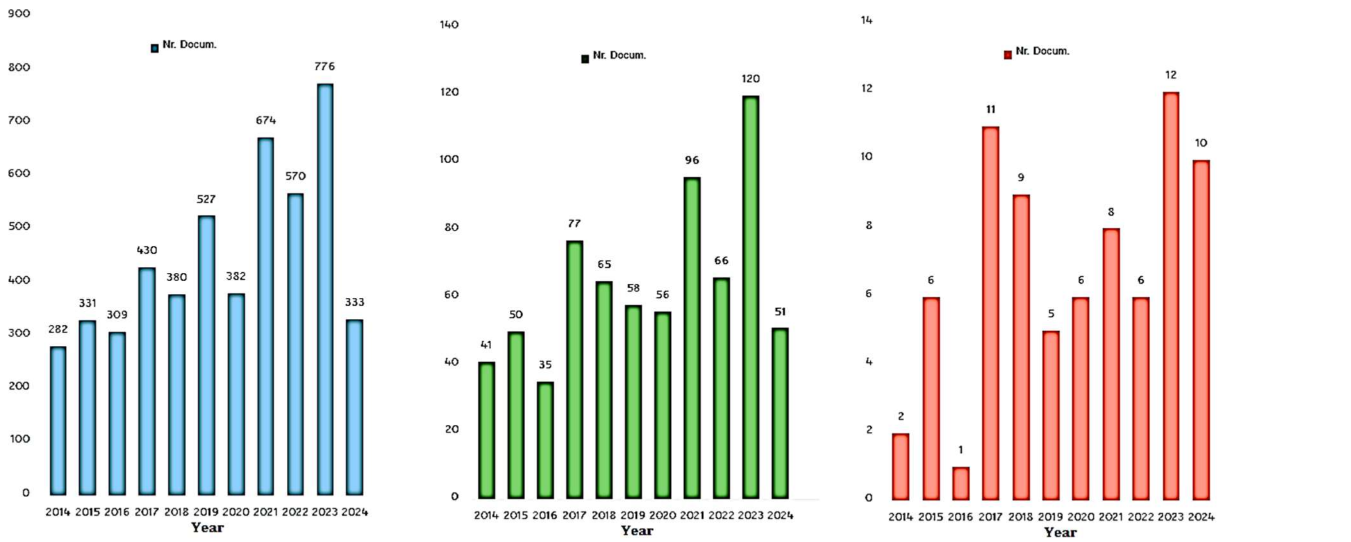
—The effect of temperature-induced beam deformation on train-induced beam deformation is analyzed using the train-bridge dynamic model. The results demonstrated that the influence of the temperature-induced beam deformation on the train-induced beam deformation is relatively small compared to the train-induced beam deformation itself, the increasing amplitude is not more than 3% [186].

—Optical technology using Bragg gratings was used to develop a fiber optic strain sensing system. The system can be used as a design tool for engineers, for monitoring the cleaning of composites, the installation of platforms, etc., or it can be used as a health monitoring tool to periodically monitor the loading of bridges, buildings, and pipelines [215].

The common focus of all these studies is the significance of developing a comprehensive monitoring system for bridges. This system plays a crucial role in assessing the structural integrity, durability, and reliability of the bridge throughout its entire lifespan.

4.1. Latest Research Progress in the SHM Realm

Although between the years 2014 and 2024, the number of papers addressing the SHM/Bridge/Temperature/Deformations concepts has increased, the process remains slow, especially at the level of the simultaneous approach of the four terms, with only 22 papers before 2014 and then, at most, 12 works in 2023 (Figure 7).



(**a**) (**b**) (**c**)

Figure 7. Evolution in time of SHM-B-T-D publications, (**a**). SHM, B; (**b**). SHM, B. T; (**c**). SHM, B, T, D. (Source: by authors adapted from [65]).

The graphs shown in Figure 7 present the evolution of occurrences related to the searches Structural Health Monitoring, Bridge, (SHM, B), Structural Health Monitoring, Bridge, Temperature, (SHM, B, T), respectively, Structural Health Monitoring, Bridge, Temperature, Deformations, (SHM, B, T, D).

Although between the years 2014 and 2024, the number of works addressing the SHM/B/T/D concepts increased, the process remains slow, especially at the level of the simultaneous approach of the four terms.

Although the concern of analyzing the structural monitoring of bridges (search SHM, B.) has a history of more than 60 years, the oldest publication mentioned in the Scopus database is by the authors Moyo and Brownjohn [216]. In the period before 2014, 2532 works had appeared, and the trend was of fluctuating growth with a maximum of 776 in 2023.

The oldest occurrence related to the search SHM, B, T are by the authors Giurgiutiu and Lin [217], and until 2014, 384 works had appeared in the Scopus index. The evolution was slow, with a few tens of papers published annually, with a maximum of 120 in 2023. Many fewer papers result from the SHM, B, T, D search. The oldest mention in Scopus is from 2005, by the authors Bastianini et al. [218]. Only 22 papers were published before 2014, and a maximum of 12 papers in 2023.

A scientometric analysis is needed to gain insight into the state of research in the field of structural monitoring of bridges. This will enable researchers and practitioners to make better decisions regarding future research directions [65].

In order to update the analysis, through the VOSviewer 1.6.20 software, we reduced the period to the level of the last five years, 2020–2024, and Figure 8 shows the association of the analyzed concepts in their evolution by years. The color spectrum is from blue, the beginning years of the analysis, to yellow, the end years. It can be noted that the introduction of another wind request factor appeared recently, as well as the very advanced interferometry or synthetic aperture radar methods.

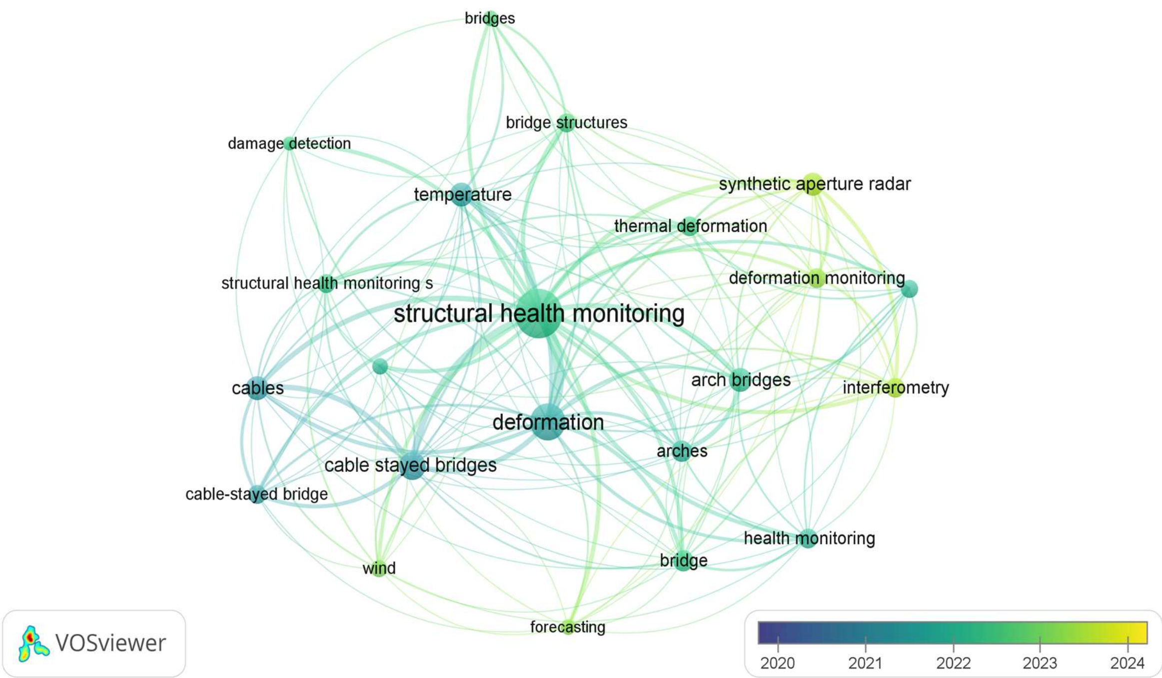


Figure 8. Association of the analyzed concepts “SHM, Bridge, Temperature, Deformations” in evolution over the period 2020–2024.

A S.W.OT Approach for Future Research

The development of the SHM discipline, like any other field, is contingent upon the advancement of the underpinning science. This truth is derived from the examination of publications in the discipline. Consequently, the future tendencies of publications on structural monitoring can be better analyzed in order to organize various aspects by performing an analysis, i.e., identifying strengths, weaknesses, opportunities, and threats in the research of the SHM realm.

✓ From the point of view of environmental influencing factors

Scholarly literature provides an extensive overview of environmental factors, such as temperature fluctuations, wind, earthquakes, or a combination of these, that can impact the health of bridge structures. This broad coverage is crucial for developing a nuanced understanding of SHM. However, the study of the effect of uneven sunlight is rarely approached. Uneven exposure to sunlight poses significant challenges for deck structures through differential thermal expansion. By using advanced tracking and monitoring technologies, engineers can better understand these dynamics and implement effective mitigation strategies, thereby increasing the longevity and safety of bridge structures. Future research should focus on developing sustainable materials and construction techniques to improve structural durability. The interdisciplinary approaches of the majority of studies integrate knowledge from civil engineering, environmental science, and information technology to offer well-rounded perspectives on SHM, enhancing the robustness of monitoring strategies.

Some of the weaknesses are related to the limited empirical data on the long-term effects of environmental factors on bridge structures and potential gaps in research regarding specific geographical locations or types of bridges. Climate change-induced extreme weather events putting additional strain on bridge infrastructure is a major challenge in the research work.

✓ From the point of view of methods, techniques, and tools

The literature often highlights advanced non-destructive methods such as the development and testing of a serial multiplexed optical fiber sensor system, wireless sensor networks (WSN), and the development of optical technology that uses Bragg gratings. The main risks are environmental sensitivity, such as fluctuations in temperature, humidity, and exposure to pollutants that can affect the accuracy and reliability of non-destructive methods; however, continued advances in materials science and sensor technologies can lead to more robust and accurate NDT methods, improving the overall effectiveness of SHM.

✓ From the point of view of data collection

Through the use of sensors and Internet of Things (IoT) devices, continuous monitoring is enabled, providing comprehensive and real-time data on the structural integrity of bridges. Although NDT techniques often require specialized knowledge and training that may not be widely available, which leads to challenges in implementation and data interpretation, this weakness can be countered by incorporating AI and machine learning techniques for data analysis. This can enhance predictive maintenance capabilities, enabling proactive management of structural health. The problem reported by many researchers is that unexpected environmental and climate changes could introduce new variables that existing nondestructive methods are not designed to handle, potentially compromising their effectiveness.

Another risk reported in the papers is that as SHM systems become more connected via IoT, they face increased risks of cyber-attacks, which could compromise the integrity of monitoring data and lead to misinformation or missed detections.

✓ From the point of view of safety improvement

Most studies highlight the fact that early detection of possible structural failures can significantly increase the safety and reliability of bridges, potentially preventing catastrophic failures. However, handling and processing large volumes of data from continuous monitoring can be complex and require sophisticated data analysis tools and expertise. This negative aspect is lessened through international collaboration that can facilitate the exchange of best practices, technological innovations, and standardization of methods in different regions.

In this sense, the researchers point out that inconsistent regulations and standards in different regions can represent challenges in the widespread adoption and standardization of non-destructive methods for SHM.

✓ From the point of view of cost-effectiveness

As shown in many works, non-destructive monitoring methods can be cost-effective in the long run due to the reduced need for extensive manual inspections and the avoidance of extensive downtime for repairs and maintenance. High initial installation costs for advanced monitoring systems can be an obstacle, especially for projects or regions with limited budgets. By increasing awareness and government policies focused on infrastructure security, more funding and support can be obtained for research and implementation of advanced techniques by SHM. For example, the inclusion in the investment cost of the costs related to the structural monitoring of the entire structure throughout the service life, where appropriate, is emphasized in many researches.

5. Conclusions

By combining the literature review and the bibliometric analysis, we succeeded in evaluating the current state of research and identifying gaps, trends, and future directions in the integration of environmental factors and geomatics technologies in SHM of bridges. Through a comprehensive literature review on SHM for bridges, we classified and analyzed 218 studies based on environmental factors and SHM techniques. The bibliometric analysis, which initially included 1191 works regarding publication trends, prominent authors, institutions, and collaborative networks published between 2010 and 2024, was conducted for the identification of underexplored areas and proposals for future research paths to address these gaps.

The literature provides a comprehensive overview of environmental factors affecting Structural Health Monitoring of bridges. It covers a wide range of non-destructive technologies used in bridge monitoring. Offering insights into the latest advancements and trends in the field helps bridge engineers and researchers to make informed decisions based on the latest research. At the bridge level, the works demonstrate the widespread application of the SHM approach. The majority of the papers suggest that the field is crucial in that the development of a long-term monitoring system for a bridge is genuinely capable of providing information for the assessment of structural integrity, durability, and reliability throughout the bridge's life cycle.

In this domain, integrating natural environmental factors and geomatic technologies offers both theoretical and practical implications. Our main findings indicate the following:

- Theoretical models can be developed to predict how various natural environmental factors like temperature, humidity, wind, precipitation, and seismic activity affect the structural integrity of bridges.
- The integration of geomatic technologies such as GNSS and smart sensors into SHM enables researchers to develop advanced algorithms for data collection, processing, and analysis that can be implemented in real-time SHM. These algorithms can accommodate the variability introduced by environmental factors, leading to more accurate monitoring systems.
- Combining SHM with geomatic technologies enables improved simulation of bridge behavior under different environmental scenarios. This can lead to advancements in predictive modeling, offering insights into potential failure mechanisms and improving strategies for preventive maintenance.
- The use of geomatic technologies facilitates the development of robust SHM systems that can operate in real time and under a variety of environmental conditions. These systems can provide continuous, precise data about the structural state, enhancing decision-making regarding bridge maintenance and safety.

- Practical applications of these technologies allow for more precise diagnosis of bridge health, identifying specific areas at risk of failure. This precision allows for targeted maintenance efforts, minimizing disruption and optimizing resource allocation.

With better monitoring and predictive capabilities, the risk of catastrophic bridge failures due to environmental impacts can be significantly reduced. This enhances public safety and supports effective risk management strategies.

Challenges and Future Directions

The field of Structural Health Monitoring for all categories of structures that require it is in full development, as evidenced by the increasing number of works that address it.

Despite significant progress, some challenges remain in the field of bridge displacement monitoring. Thus, the most pressing problems to be solved at the general level are as follows:

- Data integration: Combining data from different types of sensors and managing large amounts of generated data;
- Environmental interference: Addressing the impact of environmental factors on sensor performance;
- Costs: Reduction of sensor deployment and maintenance costs.

By intensifying research in SHM of bridges, new perspectives will be opened, such as:

- Potential for further research and innovation in combining different technologies for more accurate bridge health monitoring;
- Increasing interest in sustainable infrastructure can lead to more funding opportunities for research in this area;
- Collaboration between academia and industry for practical implementation of monitoring techniques;
- Emerging technologies such as IoT and AI could revolutionize the field of bridge monitoring.

Author Contributions: All authors contributed equally to this work. Conceptualization and methodology G.M.T.R. and C.M.R. resources and data collection V.M.R. software and validation of data S.M.N. investigation and formal analysis A.T.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research benefited from funding through the Research Development Program HCA57/15.06.2021 of the Technical University of Cluj-Napoca, Romania.

Data Availability Statement: The data used to support the findings of this study can be made available by the corresponding author upon request.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. Frangopol, D.M.; Soliman, M. Life-cycle of structural systems: Recent achievements and future directions. In *Structures and Infrastructure Systems*; Routledge: London, UK, 2019; pp. 46–65. [CrossRef]
2. Mishra, M.; Lourenço, P.B.; Ramana, G.V. Structural Health Monitoring of civil engineering structures by using the internet of things: A review. *J. Build. Eng.* **2022**, *48*, 103954. [CrossRef]
3. Artagan, S.S.; Bianchini Ciampoli, L.; D'Amico, F.; Calvi, A.; Tosti, F. Non-destructive assessment and health monitoring of railway infrastructures. *Surv. Geophys.* **2020**, *41*, 447–483. Available online: https://link.springer.com/article/10.1007/s10712-019-09544-w (accessed on 16 April 2024). [CrossRef]
4. Rădulescu, A.T.G.; Rădulescu Gheorghe, M.T. Geometric Structural Monitoring in Cinematic Regime—Dynamic Surveying as Means to Assure a Structure Safety, PAPER (3945). In Proceedings of the FIG Congress 2010—Facing the Challenges—Building the Capacity, Sydney, Australia, 11–16 April 2010.
5. Sikorsky, C.; (Senior Bridge Engineer, California Department of Transportation, Sacramento, CA, USA). Identification of Gaps in Structural Health Monitoring Technologies for Bridges. Personal Communication, 1999.
6. Rizzo, P.; Enshaeian, A. Challenges in bridge health monitoring: A review. *Sensors* **2021**, *21*, 4336. [CrossRef]
7. Vagnoli, M.; Remenyte-Prescott, R.; Andrews, J. Railway bridge structural health monitoring and fault detection: State-of-the-art methods and future challenges. *Struct. Health Monit.* **2018**, *17*, 971–1007. [CrossRef]

8. Speckmann, H.; Henrich, R. Structural Health Monitoring (SHM)–Overview on Technologies under Development. In Proceedings of the 16th World Conference on NDT-2004—Montreal (Canada) (WCNDT 2004); Special Issue of e-Journal of Nondestructive Testing (eJNDT) ISSN 1435-4934, Session: Aerospace. Available online: https://www.ndt.net/search/docs.php3?id=2084 (accessed on 16 April 2024).
9. Farrar, C.R.; Worden, K. An introduction to Structural Health Monitoring. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2007**, *365*, 303–315. [CrossRef]
10. Balageas, D.; Fritzen, C.P.; Güemes, A. (Eds.) *Structural Health Monitoring*; John Wiley & Sons: Hoboken, NJ, USA, 2010; Volume 90.
11. Chowdhury, F.H.; Raihan, M.T.; Islam, G.M.S. Application of different Structural Health Monitoring system on bridges: An overview. In Proceedings of the IABSE-JSCE Joint Conference on Advances in Bridge Engineering-III, Dhaka, Bangladesh, 21–22 August 2015; Volume 10, p. 10.
12. Radulescu, G.M.; Stefan, O.; Radulescu, A.T.G. Dynamic Surveying as a Means to Ensure Structural Safety. In Proceedings of the CIB W99 International Conference on Global Unity of Safety and Health in Construction, Beijing, China, 22–30 June 2006; Tsingua University Press: Beijing, China, 2006; pp. 346–355, ISBN 7302132364/9787302132363.
13. Dixit, S.; Sharma, K. A review of studies in Structural Health Monitoring (SHM). In Proceedings of the Creative Construction Conference, Creative Construction Conference 2019, CCC 2019, Budapest, Hungary, 29 June–2 July 2019; pp. 84–88. [CrossRef]
14. Li, J.; Meng, X.; Hu, L.; Bao, Y. Quantifying the impact of environment loads on displacements in a suspension bridge with a data-driven approach. *Sensors* **2024**, *24*, 1877. [CrossRef] [PubMed]
15. Bisby, L.A. ISIS Canada Educational Module No. 5: An Introduction to Structural Health Monitoring, ISIS Canada. 2006. Available online: www.isiscanada.com (accessed on 18 June 2024).
16. Wang, G.; Ke, J. Literature Review on the Structural Health Monitoring (SHM) of Sustainable Civil Infrastructure: An Analysis of Influencing Factors in the Implementation. *Buildings* **2024**, *14*, 402. [CrossRef]
17. Liu, Y.; Nayak, S. Structural Health Monitoring: State of the art and perspectives. *JOM J. Miner. Met. Mater. Soc.* **2012**, *64*, 789–792. [CrossRef]
18. Heiza, K.; Khalil, A.; Hawas, M. State of the art review on bridges structural health monitoring-iii (applications and future trends). *Int. Conf. Civ. Arch. Eng.* **2015**, *11*, 1–25. [CrossRef]
19. Chen, H.P. *Structural Health Monitoring of Large Civil Engineering Structures*; Wiley-Blackwell: Hoboken, NJ, USA, 2018; 336p, ISBN 978-1-119-16643-6. [CrossRef]
20. Inaudi, D.; Glisic, B. Continuous monitoring of concrete bridges during construction and service as a tool for data-driven Bridge Health Monitoring. In *Proceedings of the 3rd International Conference on Bridge Maintenance, Safety, Management, LC Performance and Cost*; Taylor & Francis: Abingdon, UK, 2006.
21. Arangio, S.; Gkoumas, K.; Bontempi, F. Slow and high speed structural monitoring of suspension bridges. In Proceedings of the 4th International ASRANet Colloquium: Integrating Structural Analysis, Risk & Reliability, Athens, Greece, 25–27 June 2008; pp. 1–10.
22. Seo, J.; Hu, J.W.; Lee, J. Summary review of structural health monitoring applications for highway bridges. *J. Perform. Constr. Facil.* **2016**, *30*, 04015072. [CrossRef]
23. Zhou, Y.L.; Abdel Wahab, M.; Figueiredo, E.; Javier Cara Cañas, F. Bridge structural health monitoring and damage identification. *Sensors* **2019**, *19*. Available online: http://hdl.handle.net/1854/LU-8607358 (accessed on 18 July 2024).
24. Fiandaca, D.; Di Matteo, A.; Patella, B.; Moukri, N.; Inguanta, R.; Llort, D.; Pirrotta, A. An integrated approach for Structural Health Monitoring and damage detection of bridges: An experimental assessment. *Appl. Sci.* **2022**, *12*, 13018. [CrossRef]
25. Habeeb, B.; Bastidas-Arteaga, E. Assessment of the impact of climate change and flooding on bridges and surrounding area. *Front. Built Environ.* **2023**, *9*, 1268304. [CrossRef]
26. Van Genuchten, E. How Climate Change Impacts the Safety of Bridges. In *A Guide to a Healthier Planet: Scientific Insights and Actionable Steps to Help Resolve Climate, Pollution and Biodiversity Issues*; Springer Nature: Cham, Switzerland, 2023; pp. 25–34. [CrossRef]
27. Alderson, D.L.; Brown, G.G.; Carlyle, W.M. Operational models of infrastructure resilience. *Risk Anal.* **2015**, *35*, 562–586. [CrossRef] [PubMed]
28. Domaneschi, M.; Martinelli, L.; Cucuzza, R.; Noori, M.; Marano, G.C. Structural Control and Health Monitoring Contributions to Service-life Extension of Bridges. *Life-Cycle Struct. Infrastruct. Syst.* **2023**, *6*, 741–745. [CrossRef]
29. Labossière, P.; Newhook, J. Will sustainable development objectives increase the need for Structural Health Monitoring in civil engineering. In Proceedings of the SHMII-2 Conference, Shenzhen, China, 16–18 November 2005.
30. AlHamaydeh, M.; Ghazal Aswad, N. Structural Health Monitoring techniques and technologies for large-scale structures: Challenges, limitations, and recommendations. *Pract. Period. Struct. Des. Constr.* **2022**, *27*, 03122004. [CrossRef]
31. Mustapha, S.; Lu, Y.; Ng, C.T.; Malinowski, P. Sensor networks for structures health monitoring: Placement, implementations, and challenges—A review. *Vibration* **2021**, *4*, 551–585. [CrossRef]
32. Weihnacht, B.; Tschöke, K. Smart monitoring and SHM. In *Handbook of Nondestructive Evaluation 4.0*; Springer International Publishing: Cham, Switzerland, 2021; pp. 1–16.
33. Sharma, V.B.; Tewari, S.; Biswas, S.; Lohani, B.; Dwivedi, U.D.; Dwivedi, D.; Jung, J.P. Recent advancements in AI-enabled smart electronics packaging for Structural Health Monitoring. *Metals* **2021**, *11*, 1537. [CrossRef]

34. Taheri, H.; Gonzalez Bocanegra, M.; Taheri, M. Artificial intelligence, machine learning and smart technologies for nondestructive evaluation. *Sensors* **2022**, *22*, 4055. [CrossRef]
35. Johnson, P.C.; Laurell, C.; Ots, M.; Sandström, C. Digital innovation and the effects of artificial intelligence on firms' research and development–Automation or augmentation, exploration or exploitation? *Technol. Forecast. Soc. Chang.* **2022**, *179*, 121636. [CrossRef]
36. Haefner, N.; Wincent, J.; Parida, V.; Gassmann, O. Artificial intelligence and innovation management: A review, framework, and research agenda☆. *Technol. Forecast. Soc. Chang.* **2021**, *162*, 120392. [CrossRef]
37. Shibu, M.; Kumar, K.P.; Pillai, V.J.; Murthy, H.; Chandra, S. Structural Health Monitoring using AI and ML based multimodal sensors data. *Measurement: Sensors* **2023**, *27*, 100762. [CrossRef]
38. Kot, P.; Muradov, M.; Gkantou, M.; Kamaris, G.S.; Hashim, K.; Yeboah, D. Recent advancements in non-destructive testing techniques for Structural Health Monitoring. *Appl. Sci.* **2021**, *11*, 2750. [CrossRef]
39. Hassani, S.; Dackermann, U. A systematic review of advanced sensor technologies for non-destructive testing and Structural Health Monitoring. *Sensors* **2023**, *23*, 2204. [CrossRef] [PubMed]
40. Keshmiry, A.; Hassani, S.; Mousavi, M.; Dackermann, U. Effects of environmental and operational conditions on Structural Health Monitoring and non-destructive testing: A systematic review. *Buildings* **2023**, *13*, 918. [CrossRef]
41. Preethichandra, D.M.G.; Suntharavadivel, T.G.; Kalutara, P.; Piyathilaka, L.; Izhar, U. Influence of Smart Sensors on Structural Health Monitoring Systems and Future Asset Management Practices. *Sensors* **2023**, *23*, 8279. [CrossRef]
42. Sony, S.; Laventure, S.; Sadhu, A. A literature review of next-generation smart sensing technology in Structural Health Monitoring. *Struct. Control Health Monit.* **2019**, *26*, e2321. [CrossRef]
43. Tanveer, M.; Kim, B.; Hong, J.; Sim, S.H.; Cho, S. Comparative Study of Lightweight Deep Semantic Segmentation Models for Concrete Damage Detection. *Appl. Sci.* **2022**, *12*, 12786. [CrossRef]
44. Smarsly, K.; Lehner, K.; Hartmann, D. Structural Health Monitoring based on artificial intelligence techniques. In Proceedings of the International Workshop on Computing in Civil Engineering 2007, Pittsburg, PA, USA, 24–27 July 2007; pp. 111–118. [CrossRef]
45. Karakostas, C.; Quaranta, G.; Chatzi, E.; Zülfikar, A.C.; Çetindemir, O.; De Roeck, G.; Döhler, M.; Limongelli, M.P.; Lombaert, G.; Apaydın, N.M.; et al. Seismic assessment of bridges through structural health monitoring: A state-of-the-art review. *Bull. Earthq. Eng.* **2024**, *22*, 1309–1357. [CrossRef]
46. Wu, T.; Liu, G.; Fu, S.; Xing, F. Recent Progress of Fiber-Optic Sensors for the Structural Health Monitoring of Civil Infrastructure. *Sensors* **2020**, *20*, 4517. [CrossRef]
47. Glišic, B.; Yao, Y.; Tung, S.; Wagner, S.; Sturm, J.; Verma, N.; Magoun, A.B. Structural Health Monitoring: Technological Advances to Practical Implementations. *Proc. IEEE* **2016**, *104*, 2016.
48. Long, Y.; Guo, W.; Yang, N.; Dong, C.; Liu, M.; Cai, Y.; Zhang, Z. Research progress of intelligent operation and maintenance of high-speed railway bridges. *Intell. Transp. Infrastruct.* **2022**, *1*, liac015. [CrossRef]
49. Aktan, E.; Bartoli, I.; Glišić, B.; Rainieri, C. Lessons from Bridge Structural Health Monitoring (SHM) and Their Implications for the Development of Cyber-Physical Systems. *Infrastructures* **2024**, *9*, 30. [CrossRef]
50. Neves, A.C. Structural Health Monitoring of Bridges: Data-Based Damage Detection Method Using Machine Learning. Doctoral Dissertation, KTH Royal Institute of Technology, Stockholm, Sweden, 2020. [CrossRef]
51. Kaartinen, E.; Dunphy, K.; Sadhu, A. LiDAR-based Structural Health Monitoring: Applications in civil infrastructure systems. *Sensors* **2022**, *22*, 4610. [CrossRef]
52. Zinno, R.; Haghshenas, S.S.; Guido, G.; Rashvand, K.; Vitale, A.; Sarhadi, A. The state of the art of artificial intelligence approaches and new technologies in Structural Health Monitoring of bridges. *Appl. Sci.* **2022**, *13*, 97. [CrossRef]
53. Alokita, S.; Rahul, V.; Jayakrishna, K.; Kar, V.R.; Rajesh, M.; Thirumalini, S.; Manikandan, M. Recent advances and trends in Structural Health Monitoring. In *Structural Health Monitoring of Biocomposites, Fibre-Reinforced Composites and Hybrid Composites, 5 Woodhead Publishing Series in Composites Science and Engineering*; Elsevier: Amsterdam, The Netherlands, 2019; pp. 53–73. [CrossRef]
54. Maraveas, C.; Bartzanas, T. Sensors for Structural Health Monitoring of agricultural structures. *Sensors* **2021**, *21*, 314. [CrossRef]
55. Vijayan, D.S.; Sivasuriyan, A.; Devarajan, P.; Krejsa, M.; Chalecki, M.; Żółtowski, M.; Koda, E. Development of Intelligent Technologies in SHM on the Innovative Diagnosis in Civil Engineering—A Comprehensive Review. *Buildings* **2023**, *13*, 1903. [CrossRef]
56. Hibbeler, R.C.; Tan, K.H. *Structural Analysis*; Pearson Prentice Hall: Upper Saddle River, NJ, USA, 2006.
57. Brownjohn, J.M. Structural Health Monitoring of civil infrastructure. *Philos. Trans. R. Soc. A Math. Phys. Eng. Sci.* **2007**, *365*, 589–622. [CrossRef]
58. Elmi, M.; Ghafory-Ashtiany, M.; Bahar, O. Integrated Bridge Structural Health Monitoring System. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2024**, *48*, 149–168. [CrossRef]
59. Yun, C.B.; Lee, J.J.; Kim, S.K.; Kim, J.W. Recent R&D activities on Structural Health Monitoring for civil infra-structures in Korea. *KSCE J. Civ. Eng.* **2003**, *7*, 637–651. [CrossRef]
60. Sridhar, S.; Sankar, K.R.; Sreeshylam, P.; Parivallal, S.; Kesavan, K.; Murthy, S.G.N. Remote Structural Health Monitoring of civil infrastructures-recent trends. *Int. J. COMADEM* **2008**, *11*, 25.
61. Ni, Y.Q.; Ye, X.W.; Ko, J.M. Fatigue reliability analysis of a suspension bridge using long-term monitoring data. *Key Eng. Mater.* **2006**, *321*, 223–229. [CrossRef]

62. Phares, B.M.; Washer, G.A.; Rolander, D.D.; Graybeal, B.A.; Moore, M. Routine highway bridge inspection condition documentation accuracy and reliability. *J. Bridge Eng.* **2004**, *9*, 403–413. [CrossRef]
63. Abdallah, A.M.; Atadero, R.A.; Ozbek, M.E. A state-of-the-art review of bridge inspection planning: Current situation and future needs. *J. Bridge Eng.* **2022**, *27*, 03121001. [CrossRef]
64. Ali, K.N.; Alhajlah, H.H.; Kassem, M.A. Collaboration and Risk in Building Information Modelling (BIM): A Systematic Literature Review. *Buildings* **2022**, *12*, 571. [CrossRef]
65. Çevikbaş, M.; Işık, Z. An Overarching Review on Delay Analyses in Construction Projects. *Buildings* **2021**, *11*, 109. [CrossRef]
66. Han, D.; Hosamo, H.; Ying, C.; Nie, R. A Comprehensive Review and Analysis of Nanosensors for Structural Health Monitoring in Bridge Maintenance: Innovations, Challenges, and Future Perspectives. *Appl. Sci.* **2023**, *13*, 11149. [CrossRef]
67. Van Eck, N.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef]
68. Gonzalez, A.; Schorr, M.; Valdez, B.; Mungaray, A. Bridges: Structures and materials, ancient and modern. In *Infrastructure Management and Construction*; IntechOpen: London, UK, 2020. [CrossRef]
69. Mitoulis, S.A.; Domaneschi, M.; Cimellaro, G.P.; Casas, J.R. Bridge and transport network resilience–A perspective. In Proceedings of the Institution of Civil Engineers-Bridge Engineering; Thomas Telford Ltd.: London, UK, 2021; Volume 175, pp. 138–149. [CrossRef]
70. Srinivasu, B.; Rao, P.S. Infrastructure development and economic growth: Prospects and perspective. *J. Bus. Manag. Soc. Sci. Res.* **2013**, *2*, 81–91.
71. Calderón, C.; Servén, L. *Infrastructure, Growth, and Inequality: An Overview*; World Bank Policy Research Working Paper 7034; Policy Research Working Paper Series 7034; The World Bank: Washington, DC, USA, 2014.
72. Chin, M.Y.; Ong, S.L.; Wai, C.K.; Kon, Y.Q. The role of infrastructure on economic growth in belt and road participating countries. *J. Chin. Econ. Foreign Trade Stud.* **2021**, *14*, 169–186. [CrossRef]
73. Yang, D.Y.; Frangopol, D.M. Bridging the gap between sustainability and resilience of civil infrastructure using lifetime resilience. In *Routledge Handbook of Sustainable and Resilient Infrastructure*; Routledge: London, UK, 2018; pp. 419–442.
74. Davies, J.H.; Davies, D.R. Earth's surface heat flux. *Solid Earth* **2010**, *1*, 5–24. [CrossRef]
75. Kleidon, A. How does the Earth system generate and maintain thermodynamic disequilibrium and what does it imply for the future of the planet? Philosophical Transactions of the Royal Society A: Mathematical. *Phys. Eng. Sci.* **2012**, *370*, 1012–1040. [CrossRef] [PubMed]
76. Georgieva, K.; Veretenenko, S. Solar influences on the Earth's atmosphere: Solved and unsolved questions. *Front. Astron. Space Sci.* **2023**, *10*, 1244402. [CrossRef]
77. Wang, B.L.; Mai, Y.W.; Zhang, X.H. Thermal shock resistance of functionally graded materials. *Acta Mater.* **2004**, *52*, 4961–4972. [CrossRef]
78. Jiang, L.; Yang, H.; Liu, W.; Ye, Z.; Pei, J.; Liu, Z.; Fan, J. Early Warning for Continuous Rigid Frame Bridges Based on Nonlinear Modeling for Temperature-Induced Deflection. *Sensors* **2024**, *24*, 3587. [CrossRef]
79. González, I. Study and Application of Modern Bridge Monitoring Techniques. Doctoral Dissertation, KTH Royal Institute of Technology, Stockholm, Sweden, 23 November 2011.
80. Jančula, M.; Vičan, J.; Spiewak, A. Experimental measurement of environmental actions on structural steel members. *Transp. Res. Procedia* **2019**, *40*, 46–50. [CrossRef]
81. KC, S.; Gautam, D. Progress in sustainable structural engineering: A review. *Innov. Infrastruct. Solut.* **2021**, *6*, 68. [CrossRef]
82. Gatti, M. Structural Health Monitoring of an operational bridge: A case study. *Eng. Struct.* **2019**, *195*, 200–209. [CrossRef]
83. Mei, L.; Wang, Q. Structural optimization in civil engineering: A literature review. *Buildings* **2021**, *11*, 66. [CrossRef]
84. Koo, K.Y.; Brownjohn, J.M.W.; List, D.I.; Cole, R. Structural Health Monitoring of the Tamar suspension bridge. *Struct. Control Health Monit.* **2013**, *20*, 609–625. [CrossRef]
85. Ma, K.C.; Yi, T.H.; Yang, D.H.; Li, H.N.; Liu, H. Nonlinear uncertainty modeling between bridge frequencies and multiple environmental factors based on monitoring data. *J. Perform. Constr. Facil.* **2021**, *35*, 04021056. [CrossRef]
86. Mu, H.Q.; Zheng, Z.J.; Wu, X.H.; Su, C. Bayesian network-based modal frequency–multiple environmental factors pattern recognition for the Xinguang Bridge using long-term monitoring data. *J. Low Freq. Noise Vib. Act. Control* **2020**, *39*, 545–559. [CrossRef]
87. Bertola, N.; Küpfer, C.; Kälin, E.; Brühwiler, E. Assessment of the environmental impacts of bridge designs involving UHPFRC. *Sustainability* **2021**, *13*, 12399. [CrossRef]
88. Du, G. Life Cycle Assessment of Bridges, Model Development and Case Studies. Doctoral Dissertation, KTH Royal Institute of Technology, Stockholm, Sweden, 23 March 2015.
89. Radulescu, G.M.; Radulescu, A.T. Kinematic Surveying A New Concept For Monitoring The Stability Of Mining Construction. In Proceedings of the 11th International Multidisciplinary Scientific GeoConference of Modern Management of Mine Producing, Geology and Environmental Protection (SGEM 2011), Albena, Bulgaria, 20–25 June 2011; Volume 2, Part A. pp. 279–287.
90. Xu, Q.L. Analysis of typical environmental effects on the surface of prestressed concrete members of bridges. In *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations*; CRC Press: Boca Raton, FL, USA, 2021; pp. 1021–1027. [CrossRef]
91. Xiao, F.; Hulsey, J.L.; Balasubramanian, R. Fiber optic health monitoring and temperature behavior of bridge in cold region. *Struct. Control Health Monit.* **2017**, *24*, e2020. [CrossRef]

92. Lim, S.; Chi, S. Damage prediction on bridge decks considering environmental effects with the application of deep neural networks. *KSCE J. Civ. Eng.* **2021**, *25*, 371–385. [CrossRef]
93. Xiao, F.; Sun, H.; Mao, Y.; Chen, G.S. Damage identification of large-scale space truss structures based on stiffness separation method. *Structures* **2023**, *53*, 109–118. [CrossRef]
94. Zhu, Y.; Sun, D.; Shuang, M. Investigation of temperature-induced effect on rail-road suspension bridges during operation. *J. Constr. Steel Res.* **2024**, *215*, 108542. [CrossRef]
95. Xiao, F.; Chen, G.S.; Hulsey, J.L.; Davis, D.; Yang, Z. Characterization of the viscoelastic effects of thawed frozen soil on pile by measurement of free response. *Cold Reg. Sci. Technol.* **2018**, *145*, 229–236. [CrossRef]
96. Gu, Z.-W.; Zhang, P.; Lyu, D.-Y.; Wu, C.-L.; Yang, Z.; Tan, G.-J.; Huang, X.-M. Earthquake-induced residual displacement analysis of simply supported beam bridge based on numerical simulation. *J. Jilin Univ. (Eng. Technol. Ed.)* **2023**, *53*, 1711–1718. [CrossRef]
97. Bo, C.; Jin, Z.; Jianping, W.J. State-of-the-art of the temperature effects of bridges. *J. Wuhan Univ. Technol.* **2010**, *32*, 79–83.
98. Hao, H.; Zhang, C. Research of the temperature effects on strain response in the steel-truss arch railway bridge using FIR filtering: HW Zhao & YL Ding AQ Li. In *Mechanics of Structures and Materials*; CRC Press: Boca Raton, FL, USA, 2019; Volume XXIV, pp. 1337–1342. [CrossRef]
99. Tan, D.; Guo, T.; Luo, H.; Ji, B.; Tao, Y.; Li, A. Dynamic Threshold Cable-Stayed Bridge Health Monitoring System Based on Temperature Effect Correction. *Sensors* **2023**, *23*, 8826. [CrossRef] [PubMed]
100. Xu, Y.L.; Chen, B.; Ng, C.L.; Wong, K.Y.; Chan, W.Y. Monitoring temperature effect on a long suspension bridge. *Struct. Control Health Monit.* **2010**, *17*, 632–653. [CrossRef]
101. Wang, Z.-W.; Xu, L.-P.; Ding, Y.-L.; You, R.-Z.; Zhu, J.-B.; Shan, S. Structural Health Monitoring System for a Complicated Long-Span Continuous Girder Bridge: Implementation and Demonstration. *Int. J. Distrib. Sens. Netw.* **2024**, 1–15. [CrossRef]
102. Xiao, F.; Hulsey, J.L.; Chen, G.S.; Xiang, Y. Optimal static strain sensor placement for truss bridges. *Int. J. Distrib. Sens. Netw.* **2017**, *13*, 15501477177. [CrossRef]
103. Koo, K.Y.; Sung, S.H.; Jung, H.J. Damage quantification of shear buildings using deflections obtained by modal flexibility. *Smart Mater. Struct.* **2011**, *20*, 045010. [CrossRef]
104. Soong, T.T.; Spencer, B.F., Jr. Supplemental energy dissipation: State-of-the-art and state-of-the-practice. *Eng. Struct.* **2002**, *24*, 243–259. [CrossRef]
105. Carey, T.J.; Mason, H.B.; Barbosa, A.R.; Scott, M.H. Multihazard earthquake and tsunami effects on soil–foundation–bridge systems. *J. Bridge Eng.* **2019**, *24*, 04019004. [CrossRef]
106. Zoumb, P.A.W.; Li, X.; Wang, M. Effects of Earthquake-Induced Hydrodynamic Force on Train–Bridge Interactions. *J. Bridge Eng.* **2022**, *27*, 04022010. [CrossRef]
107. Okem, E.S.; Nwokediegwu, Z.Q.S.; Umoh, A.A.; Biu, P.W.; Obaedo, B.O.; Sibanda, M. Civil engineering and disaster resilience: A review of innovations in building safe and sustainable communities. *Int. J. Sci. Res. Arch.* **2024**, *11*, 639–650. [CrossRef]
108. Simiu, E.; Scanlan, R.H.; Sachs, P.; Griffin, O.M. *Wind Effects on Structures: An Introduction to Wind Engineering and Wind Forces in Engineering*; Wiley: New York, NY, USA, 1980.
109. Symans, M.D.; Charney, F.A.; Whittaker, A.S.; Constantinou, M.C.; Kircher, C.A.; Johnson, M.W.; McNamara, R.J. Energy dissipation systems for seismic applications: Current practice and recent developments. *J. Struct. Eng.* **2008**, *134*, 3–21. [CrossRef]
110. Cheng, C.; Luo, B.; Jiang, Y.; Liu, J. Study on the distribution of average wind speeds at a mountainous bridge site for structural durability design. *Adv. Bridge Eng.* **2024**, *5*, 16. [CrossRef]
111. Zhang, Y.; Sweeney, C.; Cardiff, P.; Cahill, F.; Keenahan, J. Quantifying the impact of bridge geometry and surrounding terrain: Wind effects on bridges. In *Proceedings of the Institution of Civil Engineers-Bridge Engineering*; Thomas Telford Ltd.: London, UK, 2023; pp. 1–18. [CrossRef]
112. Xiang, H.; Zhang, B.; Li, Z.; Li, Y.; Zhang, M.; Zhu, J.; Li, L. Field measurement of wind shielding effect of bridge tower for wind-vehicle-bridge system. *Adv. Struct. Eng.* **2022**, *25*, 2076–2088. [CrossRef]
113. Chen, Y.; Huang, X.; Wu, K.; Li, Z.X. Experimental research on dynamic responses and hydrodynamic pressures of deep-water bridge piers under seismic and wave actions. *Eng. Struct.* **2024**, *313*, 118276. Available online: https://ui.adsabs.harvard.edu/link_gateway/2024EngSt.31318276 (accessed on 25 June 2024). [CrossRef]
114. Fujiu, M.; Minami, T.; Takayama, J. Environmental Influences on Bridge Deterioration Based on Periodic Inspection Data from Ishikawa Prefecture, Japan. *Infrastructures* **2022**, *7*, 130. [CrossRef]
115. Housner, G.W.; Bergman, L.A.; Caughey, T.K.; Chassiakos, A.G.; Claus, R.O.; Masri, S.F.; Skelton, R.E.; Soong, T.T.; Spencer, B.F.; Yao, J.T.P. Structural control: Past, present, and future. *J. Eng. Mech.-ASCE* **1997**, *123*, 897–971. Available online: http://www.iitk.ac.in/nicee/wcee/article/2217.pdf (accessed on 25 June 2024). [CrossRef]
116. Dong, Y. *Bridges Structural Health Monitoring and Deterioration Detection, Synthesis of Knowledge and Technology*; Final Report; Alaska University Transportation Center: Fairbanks, AK, USA, 2010.
117. Pallarés, F.J.; Betti, M.; Bartoli, G.; Pallarés, L. Structural Health Monitoring (SHM) and Nondestructive testing (NDT) of slender masonry structures: A practical review. *Constr. Build. Mater.* **2021**, *297*, 123768. [CrossRef]
118. Vilhena, C.R.; Souza, I.T. The non-destructive testings technician formation. In *Non-Destr. Testing'92*; Elsevier: Amsterdam, The Netherlands, 1992; pp. 219–223.
119. Niezrecki, C.; Baqersad, J.; Sabato, A. Digital image correlation techniques for non-destructive evaluation and Structural Health Monitoring. In *Handbook of Advanced Non-Destructive Evaluation*; Springer: Cham, Swizerland, 2018. [CrossRef]

120. Dolati, S.S.K.; Mehrabi, A.; Dolati, S.S.K.; Caluk, N. NDT methods for damage detection in steel bridges. In *Health Monitoring of Structural and Biological Systems XVI*; SPIE: Bellingham, WA, USA, 2022; Volume 12048, pp. 385–394. [CrossRef]
121. Scutaru, M.C.; Ţăranu, N.; Comisu, C.C.; Boacă, G.; Ungureanu, D. Sensors for bridge Structural Health Monitoring. *Bul. Institutului Politeh. Din Lasi. Sect. Constr. Arhit.* **2018**, *64*, 25–39. [CrossRef]
122. López-Higuera, J.M.; Cobo, L.R.; Incera, A.Q.; Cobo, A. Fiber optic sensors in Structural Health Monitoring. *J. Light. Technol.* **2011**, *29*, 587–608. [CrossRef]
123. Brannstrom, R.; Granlund, D. Sensor monitoring of bridge movement: A system architecture. In Proceedings of the IEEE 36th Conference on Local Computer Networks, Bonn, Germany, 4–7 October 2011; LCN 2011. IEEE: Piscataway, NJ, USA, 2011; pp. 793–796. [CrossRef]
124. Liu, P.; Zhou, C.; Huang, Y.; Zhang, L. Structural health monitoring of underground structures in reclamation area using fiber bragg grating sensors. *Sensors* **2019**, *19*, 2849. [CrossRef]
125. Convergence Extensometer. Available online: https://sisgeo.com/products/discontinued/convergence-extensometer (accessed on 12 July 2024).
126. Strain-Gauge-Extensometers. Available online: https://www.shimadzu.ro/products/materials-testing/uni-ttm-consumables/ssg-series-strain-gauge-extensometers/index.html (accessed on 5 July 2024).
127. Rod-Type-Borehole-Extensometer. Available online: https://roctest.com/en/product/bor-ex-rod-type-borehole-extensometer (accessed on 10 March 2024).
128. Bertulessi, M.; Bignami, D.F.; Boschini, I.; Brunero, M.; Ferrario, M.; Menduni, G.; Zambrini, F. Monitoring Strategic Hydraulic Infrastructures by Brillouin Distributed Fiber Optic Sensors. *Water* **2022**, *14*, 188. [CrossRef]
129. Delepine-Lesoille, S.; Merliot, E.; Boulay, C.; Quétel, L.; Delaveau, M.; Courteville, A. Quasi-distributed optical fibre extensometers for continuous embedding into concrete: Design and realization. *Smart Mater. Struct.* **2006**, *15*, 931. [CrossRef]
130. Cumunel, G. Long-Gage Fiber Optic Extensometers for Dynamic Structural Monitoring. Doctoral Dissertation, Ecole des Ponts ParisTech, Champs-sur-Marne, France, 2008. Available online: https://www.researchgate.net/publication/281598698_Long-gage_fiber_optic_extensometers_for_dynamic_structural_monitoring. (accessed on 10 June 2024).
131. Yuan, L.; Zhou, L.M.; Lau, K.T.; Jin, W.; Demokan, M.S. Fiber optic extensometer for concrete deformation measurements. *Rev. Sci. Instrum.* **2002**, *73*, 2469–2474. [CrossRef]
132. Qin, X.; Zhang, L.; Yang, M.; Luo, H.; Liao, M.; Ding, X. Mapping surface deformation and thermal dilation of arch bridges by structure-driven multi-temporal DInSAR analysis. *Remote Sens. Environ.* **2018**, *216*, 71–90. [CrossRef]
133. Lyu, M.; Ke, Y.; Li, X.; Zhu, L.; Guo, L.; Gong, H. Detection of seasonal deformation of highway overpasses using the PS-InSAR technique: A case study in Beijing urban area. *Remote Sens.* **2020**, *12*, 3071. [CrossRef]
134. Howiacki, T.; Sieńko, R.; Bednarski, Ł. Structural concrete measurements: New distributed approach for standard specimens. *Measurement* **2024**, *235*, 115003. Available online: https://ui.adsabs.harvard.edu/link_gateway/2024Meas.23515003 (accessed on 25 June 2024). [CrossRef]
135. Magne, S.; Boussoir, J.; Rougeault, S.; Marty-Dewynter, V.; Ferdinand, P.; Bureau, L. Health monitoring of the Saint-Jean bridge of Bordeaux, France using fiber Bragg grating extensometers. In *Smart Structures and Materials 2003: Smart Sensor Technology and Measurement Systems*; SPIE: Bellingham, WA, USA, 2003; Volume 5050, pp. 305–316. [CrossRef]
136. De Battista, N.; Westgate, R.; Koo, K.Y.; Brownjohn, J. Wireless monitoring of the longitudinal displacement of the Tamar Suspension Bridge deck under changing environmental conditions. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems*; SPIE: Bellingham, WA, USA, 2011; Volume 7981, pp. 469–483. [CrossRef]
137. Chaudhuri, D.; Singh, R. Applications of accelerometer as a vibration detector. *Int. J. Emerg. Trends Sci. Technol.* **2015**, 2084–2092.
138. Hassan, I.U.; Panduru, K.; Walsh, J. An In-Depth Study of Vibration Sensors for Condition Monitoring. *Sensors* **2024**, *24*, 740. [CrossRef]
139. Gautschi, G. *Piezoelectric Sensorics—Force Strain Pressure Acceleration and Acoustic Emission Sensors Materials and Amplifiers*; Springer: Berlin/Heidelberg, Germany, 2002. [CrossRef]
140. Albarbar, A.; Badri, A.; Sinha, J.K.; Starr, A. Performance evaluation of MEMS accelerometers. *Measurement* **2009**, *42*, 790–795. [CrossRef]
141. Judy, J.W. Microelectromechanical systems (MEMS): Fabrication, design and applications. *Smart Mater. Struct.* **2001**, *10*, 1115. [CrossRef]
142. Bao, M.; Wang, W. Future of microelectromechanical systems (MEMS). *Sens. Actuators A Phys.* **1996**, *56*, 135–141. [CrossRef]
143. Roberts, G.W.; Meng, X.; Dodson, A.H. Integrating a global positioning system and accelerometers to monitor the deflection of bridges. *J. Surv. Eng.* **2004**, *130*, 65–72. [CrossRef]
144. Omidalizarandi, M.; Herrmann, R.; Kargoll, B.; Marx, S.; Paffenholz, J.A.; Neumann, I. A validated robust and automatic procedure for vibration analysis of bridge structures using MEMS accelerometers. *J. Appl. Geod.* **2020**, *14*, 327–354. [CrossRef]
145. Yang, A.; Wang, P.; Yang, H. Bridge dynamic displacement monitoring using adaptive data fusion of GNSS and accelerometer measurements. *IEEE Sens. J.* **2021**, *21*, 24359–24370. [CrossRef]
146. Komarizadehasl, S.; Huguenet, P.; Lozano, F.; Lozano-Galant, J.A.; Turmo, J. Operational and analytical modal analysis of a bridge using low-cost wireless Arduino-based accelerometers. *Sensors* **2022**, *22*, 9808. [CrossRef] [PubMed]
147. Rossi, Y.; Tatsis, K.; Hohensinn, R.; Clinton, J.; Chatzi, E.; Rothacher, M. Unscented Kalman Filter–Based Fusion of GNSS, Accelerometer, and Rotation Sensors for Motion Tracking. *J. Struct. Eng.* **2024**, *150*, 05024002. [CrossRef]

148. Xi, R.; He, Q.; Meng, X. Bridge monitoring using multi-GNSS observations with high cutoff elevations: A case study. *Measurement* **2021**, *168*, 108303. [CrossRef]
149. Vazquez-Ontiveros, J.R.; Vazquez-Becerra, G.E.; Quintana, J.A.; Carrion, F.J.; Guzman-Acevedo, G.M.; Gaxiola-Camacho, J.R. Implementation of PPP-GNSS measurement technology in the probabilistic SHM of bridge structures. *Measurement* **2021**, *173*, 108677. [CrossRef]
150. Garg, P.; Nasimi, R.; Ozdagli, A.; Zhang, S.; Mascarenas, D.D.L.; Reda Taha, M.; Moreu, F. Measuring transverse displacements using unmanned aerial systems laser Doppler vibrometer (UAS-LDV): Development and field validation. *Sensors* **2020**, *20*, 6051. [CrossRef]
151. Yu, T.; Tang, Q.; Vinayaka, S. Identifying structural properties of a steel railway bridge for Structural Health Monitoring using laser Doppler vibrometry. *Autom. Constr.* **2024**, *160*, 105320. [CrossRef]
152. Kordatou, T.Z.; Mpalaskas, A.C.; Tragazikis, I.K.; Matikas, T.E. Monitoring a model cable-stay bridge structure by acoustic emission and laser Doppler vibrometry. In *Smart Structures and NDE for Industry 4.0, Smart Cities, and Energy Systems*; SPIE: Bellingham, WA, USA, 2020; Volume 11382, pp. 161–170. [CrossRef]
153. Maru, M.B.; Lee, D.; Cha, G.; Park, S. Beam deflection monitoring based on a genetic algorithm using LiDAR data. *Sensors* **2020**, *20*, 2144. [CrossRef]
154. Kitratporn, N.; Takeuchi, W.; Matsumoto, K.; Nagai, K. Structure deformation measurement with terrestrial laser scanner at pathein bridge in myanmar. *J. Disaster Res.* **2018**, *13*, 40–49. [CrossRef]
155. Riveiro, B.; DeJong, M.J.; Conde, B. Automated processing of large point clouds for Structural Health Monitoring of masonry arch bridges. *Autom. Constr.* **2016**, *72*, 258–268. [CrossRef]
156. Lin, Y.C.; Liu, J.; Cheng, Y.T.; Hasheminasab, S.M.; Wells, T.; Bullock, D.; Habib, A. Processing strategy and comparative performance of different mobile LiDAR system grades for bridge monitoring: A case study. *Sensors* **2021**, *21*, 7550. [CrossRef] [PubMed]
157. Spadavecchia, C.; Belcore, E.; Di Pietra, V. Preliminary Test on Structural Elements Health Monitoring with a LiDAR-Based Approach. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2023**, *48*, 247–253. [CrossRef]
158. Jin Lim, H.; Hwang, S.; Kim, H.; Sohn, H. Steel bridge corrosion inspection with combined vision and thermographic images. *Struct. Health Monit.* **2021**, *20*, 3424–3435. [CrossRef]
159. Ali, S.H.; Zaid, M.; Abdullah, M.; Khan, T.M.R. *SHM of Concrete Bridge Structures Using Wireless Sensor Networks*; European Conference on Smart Objects, Systems and Technologies: Munich, Germany, 2018; pp. 1–6. Available online: https://ieeexplore.ieee.org/document/8436105 (accessed on 20 June 2024).
160. Yu, J.; Zhu, P.; Xu, B.; Meng, X. Experimental assessment of high sampling-rate robotic total station for monitoring bridge dynamic responses. *Measurement* **2017**, *104*, 60–69. [CrossRef]
161. Kalmar, T.M.; Dîrja, M.; Rădulescu, A.T.G.; Măran, P.D.; Rădulescu, G.M.; Nychvyd, M.; Kalynych, I.; Rădulescu, V.M.; Zaharia, G.; Danku, G. Geospatial technologies for landslide monitoring: A case study of Sighetu Marmației, Romania. *Environ. Earth Sci.* **2024**, *83*, 341. [CrossRef]
162. Hassan, S.H.; Junaiddin, Q.M.; Daud, N.M.; Hamid, M.S.A.; Ismail, S.I.H.; Zakariah, Z. Evaluation Structural Health Monitoring (SHM) in Bridge Assessment. In *Proceedings of the AWAM International Conference on Civil Engineering*; Springer Nature: Singapore, 2022; pp. 121–131. [CrossRef]
163. Slotterback, C.S. Evaluating the implementation of environmental review mitigation in local planning and development processes. *Environ. Impact Assess. Rev.* **2008**, *28*, 546–561. [CrossRef]
164. Ni, Y.Q.; Hua, X.G.; Fan, K.Q.; Ko, J.M. Correlating modal properties with temperature using long-term monitoring data and support vector machine technique. *Eng. Struct.* **2005**, *27*, 1762–1773. [CrossRef]
165. Michie, W.C.; Thursby, G.; Walsh, D.; Culshaw, B.; Konstantaki, M. Distributed sensing of physical and chemical parameters for structural monitoring. In *Proceedings of the IEE Colloquium on Optical Techniques for Smart Structures and Structural Mmonitoring*; Digest No. 1997/033; IET: Stevenage, UK, 1997; pp. 1–13.
166. Yarnold, M.T.; Moon, F.L. Temperature-based Structural Health Monitoring baseline for long-span bridges. *Eng. Struct.* **2015**, *86*, 157–167. [CrossRef]
167. Will, K.M.; Johnson, C.P.; Matlock, H. *Analytical and Experimental Investigation of the Thermal Response of Highway Bridges*; (No. FHWA-TX-77-23-2 Intrm Rpt.); Center for Highway Research, University of Texas at Austin: Austin, TX, USA, 1977.
168. Zhao, H.W.; Ding, Y.L.; Nagarajaiah, S.; Li, A.Q. Behavior analysis and early warning of girder deflections of a steel-truss arch railway bridge under the effects of temperature and trains: Case study. *J. Bridge Eng.* **2019**, *24*, 05018013. [CrossRef]
169. Anastasopoulos, I.; Anastasopoulos, P.C.; Agalianos, A.; Sakellariadis, L. Simple method for real-time seismic damage assessment of bridges. *Soil Dyn. Earthq. Eng.* **2015**, *78*, 201–212. [CrossRef]
170. Fraden, J. Humidity and moisture sensors. In *Handbook of Modern Sensors: Physics, Designs, and Applications*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 507–523.
171. Mondoro, A.; Frangopol, D.M.; Liu, L. Bridge adaptation and management under climate change uncertainties: A review. *Nat. Hazards Rev.* **2018**, *19*, 04017023. [CrossRef]
172. Bhowmik, B.; Tripura, T.; Hazra, B.; Pakrashi, V. First-order eigen-perturbation techniques for real-time damage detection of vibrating sys-tems: Theory and applications. *Appl. Mech. Rev.* **2019**, *71*, 060801. [CrossRef]
173. Golub, G.H.; Van der Vorst, H.A. Ei-genvalue computation in the 20th century. *J. Comput. Appl. Math.* **2000**, *123*, 35–65. [CrossRef]

174. Gomez-Cabrera, A.; Escamilla-Ambrosio, P.J. Review of Machine-Learning Techniques Applied to Structural Health Monitoring Systems for Building and Bridge Structures. *Appl. Sci.* **2022**, *12*, 10754. [CrossRef]
175. Moallemi, A.; Burrello, A.; Brunelli, D.; Benini, L. Model-based vs. Data-driven approaches for anomaly detection in structural health monitoring: A case study. In Proceedings of the 2021 IEEE International Instrumentation and Measurement Technology Conference (I2MTC), Glasgow, UK, 17–20 May 2021. [CrossRef]
176. Li, X.Y.; Guan, Y.H.; Law, S.S.; Zhao, W. Monitoring abnormal vibration and struc-tural health conditions of an in-service structure from its SHM data. *J. Sound Vib.* **2022**, *537*, 117185. [CrossRef]
177. Figueiredo, E.; Brownjohn, J. Three decades of statistical pattern recognition paradigm for SHM of bridges. *Struct. Health Monit.* **2022**, *21*, 3018–3054. [CrossRef]
178. Deng, Z.; Huang, M.; Wan, N.; Zhang, J. The current development of structural health monitoring for bridges: A review. *Buildings* **2023**, *13*, 1360. [CrossRef]
179. Limongelli, M.P.; Manoach, E.; Quqa, S.; Giordano, P.F.; Bhowmik, B.; Pakrashi, V.; Cigada, A. Vibration response-based damage detection. In *Structural Health Monitoring Damage Detection Systems for Aerospace*; Springer: Berlin/Heidelberg, Germany, 2021; Volume 133. [CrossRef]
180. Lin, R.M.; Ng, T.Y. An iterative method for exact eigenvalues and eigenvectors of general nonviscously damped structural systems. *Eng. Struct.* **2019**, *180*, 630–641. [CrossRef]
181. Fan, W.; Qiao, P. Vibration-based damage identification methods: A review and comparative study. *Struct. Health Monit.* **2011**, *10*, 83–111. [CrossRef]
182. Civera, M.; Surace, C. A comparative analysis of signal decomposition techniques for structural health monitoring on an experimental benchmark. *Sensors* **2021**, *21*, 1825. [CrossRef] [PubMed]
183. Avci, O.; Abdeljaber, O.; Kiranyaz, S.; Inman, D. Structural damage detection in real time: Implementation of 1D convolutional neural networks for SHM applications. In *Structural Health Monitoring & Damage Detection, Volume 7: Proceedings of the 35th IMAC, A Conference and Ex-Position on Structural Dynamics 2017*; Springer International Publishing: Berlin/Heidelberg, Germany, 2017; pp. 49–54.
184. Tibaduiza Burgos, D.A.; Gomez Vargas, R.C.; Pedraza, C.; Agis, D.; Pozo, F. Damage identification in structural health monitoring: A brief review from its implementation to the use of data-driven applications. *Sensors* **2020**, *20*, 733. [CrossRef]
185. Hou, S.; Wu, G. A low-cost IoT-based wireless sensor system for bridge displacement monitoring. *Smart Mater. Struct.* **2019**, *28*, 085047. [CrossRef]
186. Zhou, G.D.; Yi, T.H. Recent developments on wireless sensor networks technology for bridge health monitoring. *Math. Probl. Eng.* **2013**, *2013*, 947867. [CrossRef]
187. Casas, J.R.; Cruz, P.J. Fiber optic sensors for bridge monitoring. *J. Bridge Eng.* **2003**, *8*, 362–373. [CrossRef]
188. Matta, F.; Bastianini, F.; Galati, N.; Casadei, P.; Nanni, A. Distributed strain measurement in steel bridge with fiber optic sensors: Validation through diagnostic load test. *J. Perform. Constr. Facil.* **2008**, *22*, 264–273. [CrossRef]
189. Sun, L.; Shang, Z.; Xia, Y.; Bhowmick, S.; Nagarajaiah, S. Review of bridge structural health monitoring aided by big data and artificial intelligence: From condition assessment to damage detection. *J. Struct. Eng.* **2020**, *146*, 04020073. [CrossRef]
190. Bao, Y.; Li, H. Machine learning paradigm for structural health monitoring. *Struct. Health Monit.* **2021**, *20*, 1353–1372. [CrossRef]
191. Futai, M.M.; Bittencourt, T.N.; Carvalho, H.; Ribeiro, D.M. Challenges in the application of digital transformation to inspection and maintenance of bridges. *Struct. Infrastruct. Eng.* **2022**, *18*, 1581–1600. [CrossRef]
192. Luo, J.; Huang, M.; Lei, Y. Temperature effect on vibration properties and vibration-based damage identification of bridge structures: A literature review. *Buildings* **2022**, *12*, 1209. [CrossRef]
193. Xia, Y.; Lei, X.; Wang, P.; Sun, L. Artificial intelligence based structural assessment for regional short-and medium-span concrete beam bridges with inspection information. *Remote Sens.* **2021**, *13*, 3687. [CrossRef]
194. Dang, H.V.; Tatipamula, M.; Nguyen, H.X. Cloud-based digital twinning for structural health monitoring using deep learning. *IEEE Trans. Ind. Inform.* **2021**, *18*, 3820–3830. [CrossRef]
195. Ameli, Z.; Aremanda, Y.; Friess, W.A.; Landis, E.N. Impact of UAV hardware options on bridge inspection mission capabilities. *Drones* **2022**, *6*, 64. [CrossRef]
196. Cano, M.; Pastor, J.L.; Tomás, R.; Riquelme, A.; Asensio, J.L. A new methodology for bridge inspections in linear infrastructures from optical images and HD videos obtained by UAV. *Remote Sens.* **2022**, *14*, 1244. [CrossRef]
197. Halder, S.; Afsari, K. Robots in inspection and monitoring of buildings and infrastructure: A systematic review. *Appl. Sci.* **2023**, *13*, 2304. [CrossRef]
198. Ye, C.; Butler, L.; Bartek, C.; Iangurazov, M.; Lu, Q.; Gregory, A.; Middleton, C. A digital twin of bridges for structural health monitoring. In Proceedings of the 12th International Workshop on Structural Health Monitoring 2019, Stanford University, Stanford, CA, USA, 10–12 September 2019. [CrossRef]
199. Bukar, U.A.; Sayeed, M.S.; Razak, S.F.A.; Yogarayan, S.; Amodu, O.A.; Mahmood, R.A.R. A method for analyzing text using VOSviewer. *MethodsX* **2023**, *11*, 102339. [CrossRef]
200. Zhou, Y.; Sun, L. Insights into temperature effects on structural deformation of a cable-stayed bridge based on Structural Health Monitoring. *Struct. Health Monit.* **2019**, *18*, 778–791. [CrossRef]
201. Borah, S.; Al-Habaibeh, A.; Kromanis, R. The effect of temperature variation on bridges—A literature review. In *Energy and Sustainable Futures: Proceedings of 2nd ICESF 2020*; Springer: Berlin/Heidelberg, Germany, 2021; pp. 207–212. [CrossRef]

202. Perianes-Rodriguez, A.; Waltman, L.; van Eck, N.J. Constructing bibliometric networks: A comparison between full and fractional counting. *J. Informetr.* **2016**, *10*, 1178–1195. [CrossRef]
203. Oraee, M.; Hosseini, M.R.; Papadonikolaki, E.; Palliyaguru, R.; Arashpour, M. Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review. *Int. J. Proj. Manag.* **2017**, *35*, 1288–1301. [CrossRef]
204. Ko, J.M.; Ni, Y.Q. Technology developments in Structural Health Monitoring of large-scale bridges. *Eng. Struct.* **2005**, *27*, 1715–1725. [CrossRef]
205. Li, L.; Shen, A.; Tang, Y.; Sun, Y.; Li, Y.; Dong, L. Study on the Influence of Temperature on the Verticality of Thin-Walled High Pier and the Control Method Based on Measured Temperature. In *Proceedings of the International Conference on Advanced Civil Engineering and Smart Structures*; Springer Nature: Singapore, 2023; pp. 13–21. [CrossRef]
206. Sun, R.; Chang, K.; Sugiura, K. Study of temperature effect on different colored steel specimens by solar radiation. In *Bridge Maintenance, Safety, Management, Life-Cycle Sustainability and Innovations*; CRC Press: Boca Raton, FL, USA, 2021; pp. 3879–3883.
207. Noel, A.B.; Abdaoui, A.; Elfouly, T.; Ahmed, M.H.; Badawy, A.; Shehata, M.S. Structural Health Monitoring using wireless sensor networks: A comprehensive survey. *IEEE Commun. Surv. Tutor.* **2017**, *19*, 1403–1423. [CrossRef]
208. Chen, Z.; Liang, Y.; Ansari, F. Remote Structural Control Health Monitoring with serially multiplexed fiber optic acoustic emission sensors. *Earthq. Eng. Eng. Vib.* **2003**, *2*, 141–146. [CrossRef]
209. Bhalla, S.; Soh, C.K. Structural health monitoring by piezo–impedance transducers. II: Applications. *J. Aerosp. Eng.* **2004**, *17*, 166–175. [CrossRef]
210. Park, G.; Cudney, H.H.; Inman, D.J. Impedance-based health monitoring of civil structural components. *J. Infrastruct. Syst.* **2000**, *6*, 153–160. [CrossRef]
211. Bock, W.J.; Eftimov, T.A. Simultaneous hydrostatic pressure and temperature measurement employing a LP/sub 01/-LP/sub 11/fiber-optic polarization-sensitive intermodal interferometer. In Proceedings of the 1993 IEEE Instrumentation and Measurement Technology Conference, Irvine, CA, USA, 18–20 May 1993; University of Missouri: Columbia, MO, USA, 1993; pp. 426–429. [CrossRef]
212. Reilly, J.P. *A Temperature Driven Method for Structural Health Monitoring*; Princeton University: Princeton, NJ, USA, 2019; p. 13886628. Available online: https://arks.princeton.edu/ark:/88435/dsp01gm80hz200 (accessed on 29 June 2024).
213. He, Z.; Li, W.; Salehi, H.; Zhang, H.; Zhou, H.; Jiao, P. Integrated structural health monitoring in bridge engineering. *Autom. Constr.* **2022**, *136*, 104168. [CrossRef]
214. Behkamal, B.; Entezami, A.; De Michele, C.; Arslan, A.N. Investigation of temperature effects into long-span bridges via hybrid sensing and supervised regression models. *Remote Sens.* **2023**, *15*, 3503. [CrossRef]
215. Han, G.; Yan, J.; Guo, Z.; Greenwood, D.; Marco, J.; Yu, Y. A review on various optical fibre sensing methods for batteries. *Renew. Sustain. Energy Rev.* **2021**, *150*, 111514. [CrossRef]
216. Moyo, P.; Brownjohn, J.M.W. Detection of anomalous structural behaviour using wavelet analysis. *Mech. Syst. Signal Process.* **2002**, *16*, 429–445. [CrossRef]
217. Giurgiutiu, V.; Lin, B. In-Situ Fabrication of Composite Piezoelectric Wafer Active Sensors for Structural Health Monitoring. In Proceedings of the ASME International Mechanical Engineering Congress and Exposition, Anaheim, CA, USA, 13–19 November 2004; Volume 47004, pp. 89–95. [CrossRef]
218. Bastianini, F.; Matta, F.; Galati, N.; Nanni, A. A Brillouin smart FRP material and a strain data post processing software for structural health monitoring through laboratory testing and field application on a highway bridge. In *Smart Structures and Materials 2005: Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems*; SPIE: Bellingham, WA, USA, 2005; Volume 5765, pp. 600–611. [CrossRef]