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Global Perspectives on Structural Monitoring in Civil Engineering

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ABSTRACT: Structural Monitoring (SM) is crucial in civil engineering for ensuring the safety, functionality, and longevity of civil infrastructure, especially bridges. As its importance grows, SM practices are guided mainly by national standards, leading to fragmented approaches and limited global integration. This paper examines SM guidelines, focusing on contributions from Germany, while exploring the broader international framework.

In Germany, key guidelines such as the DGZfP Merkblatt B09 and others offer structured methods and practice examples for long-term monitoring and performance assessment. Internationally, countries have developed their own SM frameworks. Amongst others, Austria's RVS Richtlinie 13.03.01, France's COFREND Livre Blanc, Canada's ISIS Guidelines, the ACI Report 444.2-21 from the USA, the TRB Circular E-C246 and the CIRIA Guideline from the UK contribute to a global understanding of SM. These guidelines address common technical, theoretical, and economic challenges across regions.

This paper highlights the need for international collaboration, identifying synergies and gaps to promote a unified approach to SM. It offers insights into global standards and how successful strategies can foster innovation and cohesion in SM practices worldwide.

KEY WORDS: Structural Monitoring, International Guidelines.

This paper adopts the term structural monitoring (SM) instead of the more commonly used structural health monitoring (SHM), following the definition provided in the Transportation Research Circular E-C246 [1]. While SHM is widely recognized, its interpretation varies across disciplines, leading to ambiguity, particularly regarding the meaning of "health" in an engineering context. By contrast, SM explicitly refers to the automated, technology-driven collection of structural data over time to objectively assess performance, without implying a predefined goal such as "health", thereby broadening its applicability. Adopting this terminology helps ensure clarity and consistency, emphasizing the role of continuous, instrumented monitoring as a valuable complement to conventional structural assessment methods.

1 THE IMPORTANCE OF STRUCTURAL MONITORING IN MODERN INFRASTRUCTURE GUIDELINES

The increasing complexity and age of infrastructure necessitate advanced monitoring techniques to detect and address potential issues proactively. SM is a critical practice for ensuring the safety, functionality, and longevity of civil infrastructure, particularly bridges. By continuously assessing structural conditions, SM enables the early detection of potential issues, allowing for timely maintenance and preventing failures. This proactive approach not only enhances public safety but also contributes to the sustainable development of infrastructure by extending its service life.

The evolution of SM has been marked by significant advancements in sensor technology, data acquisition systems, and analytical methods. Modern SM systems employ a variety of sensors to monitor parameters such as strain, vibration, and temperature, providing comprehensive insights into structural performance. The integration of artificial intelligence and machine learning algorithms further enhances the ability to interpret complex data, facilitating automated damage detection and assessment.

Despite technological advancements, the implementation of SM is often shaped by national standards, resulting in fragmented methodologies and limited global integration. While Germany, for example, has developed comprehensive guidelines like the DGZfP Merkblatt B09 (2022) to standardize monitoring practices, similar guidelines exist in other countries, with many offering largely the same content. This suggests that the diversity in approaches is unnecessary. However, factors such as local or strategic interests, language barriers, lack of networking, economic considerations, varying financial framework conditions (such as budget constraints, funding availability, and investment priorities), the local acceptance of structural monitoring, and some isolated differences in scientific perspectives, though less prominent in practical implementation, continue to prevent a unified, global approach to SM. Additionally, the differing levels of acceptance of relatively new and unestablished methods in civil engineering, such as Structural Monitoring, remain a decisive factor, as some regions embrace innovative techniques while others remain hesitant to adopt them.

To address these challenges, there is a need for increased international collaboration and the development of standardized SM protocols. By harmonizing guidelines and sharing best practices, the global engineering community can enhance the effectiveness of SHM systems, leading to more resilient and sustainable infrastructure worldwide.

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2 SM GUIDELINES IN GERMANY

In Germany, the significance of SM has been recognized through the development of a robust monitoring framework through a series of comprehensive guidelines, particularly for bridges and other civil engineering structures and aimed at standardizing monitoring practices. Together, these guidelines emphasize a data-driven approach for maintaining usability and availability of infrastructure and generally the preservation of structures.

These guidelines collectively contribute to a structured approach in SM within Germany, promoting uniformity in monitoring practices. The development of such guidelines is crucial, as it offers building owners and operators a framework for implementing effective monitoring systems, thereby enhancing decision-making processes related to construction and maintenance. By establishing clear protocols and methodologies, the guidelines aim to reduce fragmentation in monitoring approaches and promote a unified strategy for ensuring structural integrity.

2.1 DGZfP Merkblatt

Notably, the German Society for Non-Destructive Testing (DGZfP) has been instrumental in this endeavor. The publication of the DGZfP Merkblatt B 09 "Dauerüberwachung von Ingenieurbauwerken" [2] provided a cornerstone resource for owners, operators, and planners, detailing established methods for long-term monitoring and performance evaluation of civil engineering structures with a particular focus on concrete and prestressed concrete bridges. The document provides a practical guideline to help stakeholders implement effective monitoring solutions while considering the unique conditions of each structure. It delivers the necessary knowledge for the optimal design, installation, and operation of monitoring systems.

The guideline offers an overview of suitable technical systems and sensors designed for long-term structural monitoring. It differentiates SM from temporary inspection, emphasizing that monitoring does not replace regular structural inspections but serves as a crucial supplement by providing real-time condition assessments and detection of time-varying parameters.

A key focus of the document is the conceptual design of monitoring systems, from preliminary investigations, the definition of measured variables, the decision for or against a monitoring system, basic considerations for safety-relevant monitoring systems, the selection of suitable sensors, definition of measuring points, sensor connection/signal transmission, power supply, control, data verification, data storage, evaluation and alarming to the external communication connection and control of actuators.

It outlines the specific questions that monitoring can help answer. Unlike most other documents, which primarily describe existing sensor technologies and leave it to the reader to determine their applicability to a given monitoring task or rather generally to a question that may be answered with the help of SM, this guideline approaches monitoring from the end user's perspective, making it more accessible. The addressed monitoring tasks range from geometric aspects (strains, displacements, deflections, inclinations) to crack monitoring, force and strain measurements, vibration and shock monitoring, material moisture, corrosion, prestressing wire breakage detection and the influencing factors of temperature, humidity, traffic loads, etc., which must always be taken into account.

Additionally, the leaflet emphasizes data management, ensuring that collected information is effectively processed and utilized. Like many other referenced documents, it also provides detailed examples of real-world implementations. [3], [4]

2.2 DBV Merkblatt

A different focus is set in the DBV Merkblatt "Brücken-monitoring" [5]. Issued by the German Society for Concrete and Construction Technology (DBV), the guideline addresses the monitoring of bridge structures, although it is also applicable to other engineering structures and buildings. It details the services that need to be tendered when implementing a structural monitoring system and highlights the economic considerations involved in such measures. It is less technical than the DGZfP guideline and aims specifically at administrations and engineering offices responsible for preparing tenders, helping them assess whether structural monitoring is a cost-effective option for their specific projects.

The guideline defines relevant actors and comprehensively structures the monitoring process in different phases, beginning with defining the monitoring task, followed by the development of a qualified monitoring concept, implementation planning, installation and operation, data processing, data analysis and concluding with the evaluation of monitoring results. The structured process is supplemented by considerations on quality assurance and information on tendering.

As structural monitoring is not yet a standardized service in civil engineering, the guideline also provides insights into the economic viability of monitoring measures, helping stakeholders evaluate the financial feasibility of these activities in relation to the benefits they bring.

2.3 DIN 1076

In the context of this compilation, the new DIN 1076 [6] is the most authoritative document in terms of recognition, dissemination, acceptance and legal validity. However, as a general standardization document, it takes a more global approach and does not provide detailed guidance on planning, tendering, or implementation of monitoring systems. The standard explicitly permits the use of monitoring systems under specific conditions and for certain purposes, recognizing their value in preventive structural preservation.

DIN 1076 highlights two key applications for monitoring in the context of the standard: supplementing regular structural inspections and addressing special situations, such as the end of a structure's service life or ensuring structural and traffic safety. It mandates that monitoring data must provide clear condition assessments that can be incorporated into overall structural evaluations. In safety-critical applications, the standard requires defining warning or threshold values along with clear instructions for responsible personnel.

Each monitoring application must follow a detailed, structure-specific assessment program covering the entire process (based on the DBV Merkblatt). The selected measurement methods must reliably detect the type, extent, and progression of damage or defects.

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Overall, the standard takes a very conservative and selective approach to monitoring, limiting its scope to structural testing under DIN 1076. However, it leaves room for effective and beneficial use of monitoring in other defined applications.

In summary, DIN 1076 is very conservative and exclusive with regard to monitoring. Yet, it does not mandate the use of monitoring but defines specific applications where monitoring can be considered "in accordance with DIN 1076". However, the scope and reasons for using SM extend far beyond these applications, which are not covered by the standard but still remain valid and necessary. This flexibility allows for other approaches to use monitoring sensibly, effectively and profitably, which are defined in other documents within this compilation.

2.4 BASt Leitfaden

The recent BASt "Leitfaden Strategischer Einsatz von Monitoring für Ingenieurbauwerke" [7] offers strategic recommendations for the use of monitoring in engineering structures. It summarizes the state of the art, limits and potentials for monitoring in Germany, taking particular account of the three documents [2], [5] and [6]. In addition, it explicitly addresses why the possibilities of monitoring have not yet been used to the extent that they could be and how acceptance could be improved.

Data management considerations form a large part of the guideline, as the sustainable storage of monitoring data, easy accessibility and systematic evaluation are central to effective monitoring projects.

2.5 BASt Erfahrungssammlung

The complementary BASt "Erfahrungssammlung Monitoring für Brückenbauwerke" [8], compiled by the Federal Highway Research Institute (BASt), provides a comprehensive collection of practical experiences in bridge monitoring, complementing previous documents. It offers insights into the application, capabilities, and limitations of monitoring systems.

In its general section, the document outlines the state-of-the-art in bridge monitoring, reflecting the contents of the DGZfP and DBV Merkblatt. It follows a similar structure to the DGZfP Merkblatt, addressing key aspects from an end-user perspective, such as deformation, inclination, temperature, and crack monitoring, among others. It explains how different measurement techniques align with monitoring objectives and discusses their reliability, limitations, and quality assurance. The second part presents real-world examples, detailing the reasons for monitoring, the methods used, and key findings.

3 INTERNATIONAL SM FRAMEWORKS

SM practices have evolved worldwide to address regional infra-structure challenges and priorities. Despite variations in methodologies, national guidelines share common goals of ensuring safety, reliability, and long-term functionality of civil structures. This section explores international SM frameworks, focusing on selected approaches adopted in countries such as Austria, France, the US, Canada, and the UK.

3.1 Austria

Austria's RVS guideline RVS 13.03.01 "Monitoring von Brücken und anderen Ingenieurbauwerken" [9] provides a structured framework for the monitoring of bridges and other civil engineering structures, reflecting the country's commitment to SM. Compared to other referenced documents, it is relatively concise, comprising 32 pages, with a structure comparable to the DGZfP Merkblatt. One notable feature of the guideline is its classification of monitoring into local vs. global and static vs. dynamic approaches, each accompanied by a brief summary outlining the objectives and applicable sensor technologies. While this classification provides a structured perspective, it remains open to debate whether it offers significant practical advantages in the retrievability of information.

A novel aspect that distinguishes the RVS guideline from other standards is its Safety Management Plan (SMP), which defines action sequences, assigns responsibilities, and references pre-established warning and alarm thresholds. The guideline specifies the content of such a plan and introduces a process scheme incorporating a traffic light system (green, orange, red) to represent different alert levels, ranging from normal operation (green) to immediate intervention, such as bridge closure (red).

Additionally, an annex provides an overview of various measurement instruments referenced in the guideline, briefly explaining their principles of operation. A second appendix explores the role of the Internet of Things (IoT) in structural monitoring, emphasizing its relevance for data acquisition and management in modern SHM systems.

3.2 France

The COFREND "Le Livre Blanc du SHM" [10] has a different focus and approach than other referenced international SHM guidelines. Rather than detailing the technical implementation of monitoring systems, it addresses overarching challenges associated with SM, including scientific and technological hurdles, regulatory concerns, and intellectual property issues.

This white paper is the result of discussions within COFREND's SM branch to develop a national strategy for SM in France. The document outlines key aspects of the field, such as its historical background, market potential, and major scientific and industrial challenges. It highlights the growing demand for SM in sectors like civil engineering, aerospace, and industrial equipment, where aging infrastructure and safety concerns drive the need for continuous monitoring solutions.

A central theme of the Livre Blanc is the necessity for structuring an SM industry in France. It emphasizes the need for standardized methodologies, interoperable systems, and regulatory frameworks to enable widespread adoption. Additionally, it discusses how digital technologies such as IoT, AI, and digital twins are transforming SM by enabling real-time monitoring and predictive maintenance.

The document also examines international approaches, comparing France's SM landscape with that of the US, Germany, and the UK. By advocating for a coordinated effort among stakeholders, the Livre Blanc aligns with the ambitions of the present paper, which aims to structure international efforts in SM. It reinforces the necessity of global collaboration, regulatory alignment, and knowledge exchange to drive innovation and ensure the reliability of SM systems worldwide.

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3.3 Italy

The MIT guideline "Linee guida per la classificazione e gestione del rischio, la valutazione della sicurezza ed il monitoraggio dei ponti esistenti" [11], that has been continuously updated since its first publication, presents a discussion on the permanent and continuous monitoring of bridges, outlining the key principles, necessary technologies, and critical applications of SM systems. The chapter on monitoring is framed within a broader context of visual inspections, risk assessment, and safety evaluations, positioning SM as a complementary tool alongside routine inspections, load testing, and numerical degradation analysis. Rather than being an isolated process, continuous monitoring is presented as an integral component of a comprehensive strategy for bridge management, enhancing both preventive maintenance and decision-making processes.

The document carries a strong authoritative tone by advocating for the mandatory use of SM in high-risk scenarios, particularly for aging or strategically important bridges. It emphasizes the importance of long-term surveillance, particularly for large, complex, or high-risk structures, and highlights the operational requirements for implementing effective monitoring strategies.

The text underscores the necessity of carefully designing SM systems to ensure durability, accuracy, and maintainability. It addresses fundamental aspects such as sensor selection, network architecture, power supply, and data processing, with a strong emphasis on integrating SM data into a broader bridge management system. The document also details specific applications of SM, including structural, seismic, geotechnical, hydraulic, and landslide monitoring. For each of these, it describes the most suitable technologies and analytical methods, ranging from dynamic response measurements for structural assessments to advanced remote sensing techniques for landslide detection.

A key argument is that continuous monitoring enables early detection of structural deterioration, environmental hazards, and other risk factors, facilitating data-driven maintenance and decision-making. The discussion particularly stresses the value of integrating SM with real-time communication networks and automated data analysis to provide accurate, actionable insights into bridge behavior over time.

The UNI/TR 11634 guideline "Linee guida per il monitoraggio strutturale" [12], by reference of [13] and [14], establishes a structured approach to SM, emphasizing its role in supporting asset management decisions. It outlines the entire monitoring process, covering system design, implementation, and data analysis. The document provides criteria for developing SM systems and identifies appropriate methodologies for evaluating structural conditions based on different classes and types.

An aspect of the guideline is its focus on data processing methods, which leverage both data-driven and model-based techniques to assess structural integrity. It also defines the essential components of an SM system, detailing the processes for detecting structural damage and material degradation. Furthermore, the report discusses best practices for system installation, maintenance, and data acquisition to ensure effective monitoring and long-term performance.

3.4 United States

The ACI PRC-444.2-21 report "Structural Health Monitoring Technologies for Concrete Structures" [15] provides a comprehensive examination of structural monitoring (SM) technologies applicable to concrete structures. Building upon an in-depth discussion of relevant material properties and the unique characteristics of concrete, the report systematically explores available sensor types, their underlying physical principles, and the specific monitoring objectives they serve. Additionally, it outlines the necessary measurement equipment, deployment methodologies, and existing standards and codes of practice.

The report adopts an academic approach, extensively referencing scientific literature, thus enabling readers to deepen their understanding of the subject matter. Rather than presenting information in a condensed form, the document offers a thorough insight into sensor technologies, categorizing them into three main types: structural response sensors, environmental condition and load sensors, and supporting technologies.

Complementing this perspective, the Transportation Research Board's Circular E-C246 "Structural Monitoring" [1] provides a broader, application-oriented discussion of SM. Unlike the ACI report, which focuses on technical aspects, this document addresses the practical implementation of monitoring systems from the perspective of potential clients rather than monitoring specialists. It highlights synergies between SM and traditional visual inspections, discusses key considerations for deciding when monitoring is warranted, and outlines the expected benefits.

The circular briefly introduces relevant sensor types based on their measured parameters, such as inclination, acoustic emission, and temperature. A notable aspect is the emphasis on a progressive diagnostic approach, wherein monitoring is continuously refined to determine whether more extensive data collection is necessary in a cost-effective manner. This process accounts for multiple factors, including preliminary information gathering, structural criticality, financial constraints, installation feasibility, durability, and data management. Moreover, the document distinguishes itself by addressing the financial return of SM investments, outlining strategies for evaluating cost-effectiveness in advance. A dedicated FAQ section further enhances its practical utility by succinctly answering common questions related to SM implementation.

3.5 Canada

Canada's ISIS "Guidelines for Structural Health Monitoring" [16] represents one of the foundational references on SM included in this compilation. As an early comprehensive guideline outside the academic context, it contextualizes modern SM within the broader framework of various testing methodologies used to assess the in-situ condition and performance of structures under different load scenarios and potential damage conditions. The document systematically categorizes these methodologies based on the frequency and duration of measurements, distinguishing between static field testing, dynamic field testing, periodic monitoring, and continuous monitoring, the latter of which is now commonly referred to as structural monitoring.

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Each of these testing approaches is introduced in detail, outlining its specific objectives, practical implementation strategies, and the potential benefits it offers for structural assessment. Moreover, the guideline provides multiple real-world case studies to illustrate the practical application and effectiveness of the described methods in diverse structural contexts.

The appendices of the manual offer additional technical depth, including explanations of the operational principles of selected sensor technologies, an introduction to data acquisition systems, and an overview of various algorithms used for vibration-based damage detection. While the sections on sensor technology and data acquisition have become somewhat outdated due to significant technological advancements since the publication of the manual, they still serve as a valuable foundation for understanding fundamental principles.

3.6 United Kingdom

The CIRIA guide "Structural Health Monitoring in Civil Engineering" [17] provides a comprehensive, low-level introduction to SM for various stakeholders, including infrastructure owners, operators, and engineers. The guide begins by defining SM and explaining its role in risk management for civil infrastructure. It highlights how SM can support intervention planning by providing valuable data to enhance safety, reduce costs, and extend the lifespan of assets.

A key focus of the guide is distinguishing between traditional visual inspections, periodic manual assessments, and automated continuous monitoring, emphasizing the advantages of sensor-based SM. The document underscores the importance of data quality, modeling, and redundancy in effective monitoring systems, recognizing data as the "currency" of SM.

The guide discusses the business and technological drivers behind SM adoption, outlining both proactive and reactive applications. It provides guidance on conceptual design and implementation, including sensor selection and system integration. A dedicated chapter addresses data management, storage, security, ownership, and analysis, ensuring the effective use of collected information.

Procurement considerations, risk assessment, and specification requirements are also covered in detail, offering a structured approach for organizations planning to implement SM. Additionally, the guide presents real-world case studies that illustrate the practical applications of SM, detailing the sensors used, data acquisition strategies, and resulting insights.

3.7 China

The accessibility of Chinese SM standards to the international community is often hindered by language barriers and differences in normative frameworks. Unlike widely adopted international standards, Chinese regulations and guidelines are primarily available in Mandarin, making it challenging for non-Chinese researchers and practitioners to engage directly with them. However, it is possible to gain indirect insight into the scope of Chinese SM standards by referencing available review documents, such as [18] or [19].

The extent of standardization efforts in China is remarkable, with a vast array of documents addressing various aspects of SM at multiple regulatory levels. These include national standards, which apply nationwide, professional standards that govern specific industry sectors, as well as provincial and company-level regulations. An often-cited national standard in this context is the GB 50982 technical code [20], that is discussed in detail in [21].

Instead of detailing the full list of normative documents available in China in a reproduction of the aforementioned articles, it is noteworthy to highlight the early adoption and impressive breadth of topics already addressed within their SM standards. These standards begin with foundational aspects, including the definition of basic terms and concepts, and extend to more specific areas such as SM design standards, operational maintenance, and management practices for SM systems. Additionally, there are guidelines governing the construction and acceptance of SM systems, as well as those focused on massive data processing for SM applications. Notably, China's SM standards also include regulations tailored to specific infrastructure types, such as bridges, with comprehensive technical codes and specifications. These bridge-related standards cover critical aspects such as fiber optic monitoring systems, concrete bridge monitoring, threshold levels for intervention, and the selection and placement of sensors.

The breadth and depth of this standardization effort suggest a strong institutional commitment to SM, reflecting the country's large-scale infrastructure development and emphasis on long-term structural safety and reliability.

3.8 Others

One relevant document outside national application, of a very general nature, is the FIB Bulletin 109 [22]. One of the chapters is devoted to certain aspects of structural monitoring, in the wider context of structural condition survey (in particular NDT and load testing), condition assessment and sensor placement.

Other specific national standards or guidelines for SM in civil engineering are not prominently documented in the available literature. While [23] references a withdrawn Russian standard [24], comprehensive national frameworks remain scarce. Some ISO standards address related aspects, such as vibration monitoring, but do not specifically focus on structural monitoring as a whole. Instead, much of the existing knowledge is found in scientific literature and technical reports. Notable examples of research results include, amongst others, and without assessing their value above others without further review, the SAMCO report [25], the Sustainable Bridges Report [26], the SMooHS Report [27], or the recent IM-SAFE Reports [28], which provide valuable insights into monitoring methodologies, system design, and long-term structural assessment. However, these documents primarily originate from research initiatives rather than regulatory bodies, highlighting the ongoing need for standardized international guidelines in structural monitoring.

4 SYNERGIES AND CHALLENGES

A shared objective in structural monitoring (SM) guidelines is to ensure the safety, reliability, and longevity of civil infrastructure. These guidelines reflect the diverse needs, priorities, and technical capabilities of different countries, addressing common challenges and promoting best practices globally.

4.1 Synergies

Despite differences in local infrastructure conditions, economic constraints and environmental factors, there are surprisingly no

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significant differences, only variations in focus, in methodologies, performance metrics and monitoring technologies. One reason for this may be that the technical challenges are comparable, which ultimately leads to similar guidelines. This basic agreement helps efforts to develop a unified approach. Therefore, a list of key aspects can be extracted from the different guidelines, which are relevant to be taken into account in a common effort for a harmonized monitoring strategy.

- Definition of terms and notations: While terminology is often similar across guidelines, differences exist. For example, the distinction between SM and structural health monitoring (SHM) varies. A clear definition of terms is crucial to ensure consistency and avoid ambiguity in communication and implementation.
- Promoting the benefits of SM: Guidelines highlight achievable goals, such as enhanced safety and risk reduction, while also acknowledging scientific technological challenges, i.e., what can not be achieved by employing SM. They emphasize early detection and prevention of structural degradation through continuous monitoring, proactive measures to mitigate risks, and data-driven strategies for assessing infrastructure health and performance.
- SM in civil engineering and other industries: Structural monitoring in civil engineering is placed in the broader context of its application in other industries, such as aeronautics, space, mechanical engineering, energy, and automotive sectors. These comparisons provide insights into cross-sector best practices and technological advancements.
- Locally governing codes, standards, and practices: SM guidelines must align with national and international regulatory frameworks, integrating with existing structural assessment methods such as visual inspections, load tests, and non-destructive testing. They also play a role in maintenance planning and intervention strategies.
- Criticality and asset value considerations: The relevance of SM depends on factors such as a structure's criticality, asset value, and degradation state. Guidelines help prioritize monitoring efforts based on risk assessment and long-term economic benefits.
- Monitoring-relevant characteristics of structures and materials: Guidelines address the unique monitoring needs of different structures and materials, considering their physical properties, environmental influences, and long-term durability. The focus is often on bridges, especially those of reinforced and prestressed concrete, most likely because a large proportion of the monitoring systems installed to date have been applied to such structures, and therefore a wealth of experience is available and the need for regulation is particularly great.
- Preliminary research and assessment: Prior investigations are necessary to determine monitoring scope, relevant parameters, priority structures, and measurement locations. NDT techniques play a crucial role in identifying potential vulnerabilities and optimizing monitoring strategies. Based on these investigations, numerical models and simulations play an essential role in the further planning of monitoring systems for complex structures, broadly defined problems and unclear structural behaviour, in order to be able to estimate the sensitivity of SM systems with regard to the desired objectives.
- Cost-benefit analysis of SM implementation: Guidelines provide methodologies for estimating financial benefits, considering cost-effectiveness and the value chain. Decision-makers can evaluate whether implementing SM is justified for specific projects.
- Monitoring process and stakeholder responsibilities: Information is provided on the entire monitoring process, including relevant stakeholders, their responsibilities, the division of tasks, and the coordination required to ensure effective decision-making.
- Procurement and tendering processes: Guidelines outline necessary specifications for tendering SM systems to ensure meaningful, comparable, and complete bids. They also address procurement considerations from a technical and administrative perspective.
- Conceptual design of SM systems: Developing an effective SM system requires extensive considerations, ensuring alignment with project requirements and stakeholder expectations. Guidelines offer insights into designing target-oriented systems tailored to specific infrastructure needs.
- Technical information on sensors and applications: Guidelines detail available sensor technologies, their capabilities, and the types of structural insights they provide. This includes both resistance- and load-related monitoring for comprehensive assessment. There are generally two different approaches: the (technical) contractor's view – what sensors are available and what can be achieved with them, and the (administrative) client's view – what tasks can be accomplished and what sensors are available to do so.
- Supporting technologies: Integration of local and global data transmission, communication systems, and energy supply and harvesting technologies plays a crucial role in ensuring effective SM system functionality.
- Practical implementation considerations: Guidelines address real-world challenges in SM deployment, including installation, maintenance, exchangeability, expandability, remote access and operational reliability, ensuring that systems function as intended over time.
- Ensuring data quality and management: Strategies for maintaining consistent data quality, handling short- and long-term storage, and ensuring accessibility and visualization are essential components of SM guidelines.
- Extracting meaningful insights for decision-making: Automated data analysis methods, i.e. how to (automatically) extract relevant knowledge about the monitored structure at the relevant time (preferably in real time) from the data for decision making, often referred to as “intelligence” in this context, i.e. feature extraction instead of mere data collection. This enables the detection, characterization, prognosis and risk assessment of degradation and damage and thus proactive maintenance. Some recent guidelines include artificial intelligence as a keyword.
- Alarm processes and safety considerations: Guidelines provide ways of establishing alarm chains, escalation

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procedures and personnel responsibilities to ensure an effective response to critical structural conditions, particularly in safety-related applications. They provide information on the special features of safety-related monitoring systems, in which considerations such as availability, redundancy, verifiability, etc. play an extremely important role compared to other monitoring systems.

- Integration with broader digital systems: SM results can seamlessly integrate with building information modeling (BIM), digital twins, risk management systems, and structural databases to enhance decision-making and lifecycle management.
- Qualification of monitoring personnel: Training and certification requirements for personnel involved in SM are essential to maintain high-quality data collection, interpretation, and response measures. It should be noted that there are hardly any standardized qualification paths that can be queried or specified.
- Best practices and case studies: Guidelines often include a compilation of real-world monitoring projects, that showcase successful implementations and lessons learned to guide future applications in diverse environments. The technical and scientific depth of planning, execution, data analysis and results achieved in the examples vary widely.

Harmonization of regulatory practices requires a balance between regional needs and global best practice, while ensuring that local priorities are not undermined. Encouraging international collaboration and knowledge sharing can help create adaptable, yet standardized, SM guidelines that meet different infrastructure requirements.

4.2 Challenges

The integration of SM practices on a global scale faces numerous challenges. While SM has proven effective in improving infrastructure safety, functionality, and longevity, achieving a cohesive international framework requires overcoming these obstacles through harmonization, technological accessibility, and policy alignment.

- Data Standardization and Interoperability: A major obstacle to global SM integration is the lack of standardized data formats and protocols. Different monitoring systems employ proprietary technologies, leading to inconsistencies in sensor calibration, data interpretation, and reporting formats. These discrepancies create challenges in comparing and integrating monitoring results. Establishing universal standards for data acquisition, processing, and analysis is essential for facilitating collaboration, ensuring data consistency, and improving the reliability of infrastructure assessments. Industry-wide cooperation and policy-driven initiatives can help create a unified data-sharing ecosystem.
- Economic and resource constraints: Reservations about the long-term economic viability of monitoring systems play an important role, as the costs of designing, implementing and operating a monitoring system on a (presumably) intact structure must be weighed against the future, currently fictitious and elusive, savings of a preventive maintenance strategy using structural monitoring. Expenses related to implementing and maintaining SM systems is a significant barrier, particularly in regions with constrained infrastructure budgets. To mitigate these challenges, cost-effective solutions and scalable monitoring strategies must be developed. Encouraging public-private partnerships and leveraging emerging technologies such as energy-efficient sensors and cloud-based data storage can also help improve affordability and accessibility.
- Qualification of SM personnel: The effectiveness of SM depends on the expertise of personnel involved in data collection, analysis, and interpretation. However, specific training standards – if available at all – vary across regions, leading to inconsistencies in monitoring quality. Establishing global certification programs, standardized training curricula, and skill development initiatives can help ensure that SM personnel possess the necessary expertise to operate and maintain monitoring systems effectively.
- Communication barriers: A fundamental and very essential hurdle are the communication challenges that hinder international cooperation in SM implementation. Even within Europe, the exchange of information on directives is limited because guidelines they are written in national languages and are not available in English. At the international level, language barriers make it much more difficult to exchange information, as it is often not even possible to search for specific national regulations because the necessary keywords are unknown in the relevant language. Although this challenge is lessened by the digital possibilities of translation, it remains, as availability is still limited to individuals. An effort to provide English translations of relevant documents would be desirable. However, multilingual resources are by far the better option, as English is not the "world language" for everyone.
- Cultural barriers: The general openness to new technologies varies from region to region. The construction industry itself stands out as a particularly conservative industry, most likely because the financial investment values are very high and therefore the willingness to innovate is limited. Cultural differences and varying perspectives on risk management, maintenance priorities, and the perceived benefits of SM lead to inconsistencies in adoption and execution strategies. Differences in administrative procedures and organizational structures add to complexity. Effective collaboration requires fostering a culture of cooperation.
- Intellectual property rights and industrial espionage concerns: Fears regarding intellectual property rights and industrial espionage pose challenges in international SM collaboration. Companies and institutions may be reluctant to share proprietary monitoring technologies or data due to concerns over competition and data misuse. Establishing clear legal frameworks and international agreements on IP protection, data ownership, and ethical data sharing can help alleviate these concerns while promoting cooperative advancements in SM technologies.
- Data privacy and security concerns: Sharing sensitive infrastructure data across borders requires stringent cybersecurity measures and clear agreements on data

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ownership and accessibility. Unauthorized access to monitoring data can pose security risks, including cyber threats and infrastructure vulnerabilities. Establishing robust rules for data protection, encryption technologies, and regulatory agreements is crucial for ensuring secure and ethical data exchange between stakeholders.

- The importance of a well-developed SM concept: A properly developed SM strategy is crucial for ensuring that monitoring efforts align with infrastructure needs and long-term maintenance goals. Without a clear conceptual framework, SM implementations lack focus and efficiency, leading to reservations in the implementation in other projects and thus the widespread use of SM.
- Availability of guidelines and standards: The accessibility of SM guidelines and standards significantly impacts their adoption and awareness. Documents that are not open-access or are only available in print form limit their distribution. Promoting open-access policies and digital dissemination can improve the reach and influence of SM best practices, fostering wider implementation and international collaboration.

Addressing these challenges calls for coordinated international efforts. By overcoming these barriers, the global engineering community can unlock the full potential of SM, ensuring safer, more resilient infrastructure for future generations.

To address these gaps, increased international collaboration is essential. It is most viable to appreciate the efforts that have been made by others and then embrace and integrate them in a joint effort, at least referencing and appreciating best practice.

Establishing common protocols, such as data exchange standards and unified terminology, can enhance the interoperability of SM systems. This alignment will not only improve the safety and performance of infrastructure but also pave the way for sustainable development and resilient infrastructure worldwide.

5 CONCLUSION: TOWARDS A UNIFIED GLOBAL APPROACH TO SM

The globalization of SM practices is essential for tackling shared challenges such as aging infrastructure, climate change, and rapid urbanization. While national guidelines serve as critical frameworks for monitoring and maintaining structures, international collaboration presents an opportunity to harmonize practices, facilitate knowledge exchange, and leverage technological advancements across borders.

SM has become a fundamental tool in ensuring the safety, reliability, and longevity of civil infrastructure. However, as infrastructure systems grow increasingly complex and interconnected, a unified global approach to SM is more crucial than ever. By fostering cooperation and standardization, nations can maximize the potential of SM technologies, creating a safer, more resilient, and better-integrated global infrastructure network.

Achieving global cohesion in SM requires a concerted effort to address existing disparities and align diverse methodologies. This endeavor can build upon the wealth of detailed and well-established guidelines outlined in this paper. The missing piece is a comprehensive synthesis that bridges regional differences and integrates best practices into a cohesive framework, fostering interoperability and broader applicability.

Looking ahead, the convergence of SM with emerging technologies holds immense potential for transforming infrastructure management and preservation. The adoption of digital twins, for instance, could enable real-time monitoring, predictive maintenance, and advanced scenario modeling. Additionally, advancements in machine learning and artificial intelligence promise to revolutionize data analysis, providing deeper insights into structural behavior and enhancing decision-making processes.

As infrastructure networks become more complex and the demand for resilient systems continues to rise, SM will play an increasingly pivotal role in the global engineering landscape. The path forward lies in collaboration – sharing expertise, aligning methodologies, and driving innovation together. By embracing these principles, the global engineering community can solidify SM as a cornerstone of modern infrastructure management, ensuring a safer, more sustainable, and future-proof built environment for all.

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