**Open Journal of Engineering Science (OJES)**
**ISSN: 2734-2115**
**Article Details:**
DOI: 10.52417/ojes.v5i1.609
Article Ref. No.: OJES0501003-525
Volume: 5; Issue: 1, Pages: 38– 49 (2024)
Accepted Date: May30th, 2024
© 2024 Fasasi

**Open Journals Nigeria (OJN)**
Open Access | Bi-annual | Peer-reviewed
www.openjournalsnigeria.org.ng
editorial@openjournalsnigeria.org.ng


**RESEARCH ARTICLE** **OJES0501003-525**

# COMPARATIVE ANALYSIS OF WIRED AND WIRELESS SENSORS IN STRUCTURAL HEALTH MONITORING

***Fasasi, M. O.**

**Department of Civil Engineering, Ladoke Akintola University of Technology, Oyo State, Nigeria.*

***Corresponding Author's E-mail:*** *m.fasasi@hotmail.com*

## ABSTRACT

Structural Health Monitoring (SHM) systems play a critical role in ensuring the safety and longevity of civil engineering infrastructure. This paper presents a comparative analysis of wired and wireless sensor technologies within SHM applications, drawing insights from scholarly literature, expert interviews, and case studies. The significance of SHM in safeguarding infrastructure durability is emphasised, considering the substantial investment and long service lifespans associated with civil engineering structures. Thematic analysis was utilized and revealed key performance criteria such as reliability, flexibility, environmental adaptability, cost-effectiveness, and maintenance requirements. Wired sensors are lauded for their reliability and accuracy, particularly in critical infrastructure projects, while wireless sensors offer greater flexibility and ease of deployment, especially in remote monitoring scenarios. Environmental adaptability remains crucial for both sensor types, with fiber optic sensors demonstrating effectiveness in harsh conditions. Expert interviews further enrich the understanding of sensor performance, highlighting opportunities for advancements in wireless sensor technology and data analytics. The paper concludes with recommendations for future research and development efforts to address existing constraints and meet the evolving needs of SHM in civil infrastructure monitoring. Overall, this comparative analysis provides valuable insights for guiding advancements in sensor technology and SHM procedures to ensure the continued safety and integrity of essential infrastructure.

**Keywords:** *Structural health monitoring, Wired sensors, Wireless sensors, Civil infrastructure, Thematic analysis, Environmental adaptability.*

.

**LICENSE:** This work by Open Journals Nigeria is licensed and published under the Creative Commons Attribution License 4.0 International License, which permits unrestricted use, distribution, and reproduction in any medium, provided this article is duly cited.
**COPYRIGHT:** The Author(s) completely retain the copyright of this published article.
**OPEN ACCESS:** The Author(s) approves that this article remains permanently online in the open access (OA) model.
**QA:**This Article is published in line with "COPE (Committee on Publication Ethics) and PIE (Publication Integrity & Ethics)".

## INTRODUCTION

The significance of Structural Health Monitoring (SHM) systems in safeguarding the durability and safety of essential infrastructure is emphasised in the opening of a research paper on the SHM on the subject of civil engineering (Liu *et al.*, 2019). The adoption of SHM systems becomes essential since civil engineering infrastructure is a major investment and asset for any country, with structures built for long service lifespans and high maintenance costs. Infrastructure in the field of civil engineering is typically the most costly asset and investment in every nation. Furthermore, compared to other commercial items, civil engineering structures have a longer lifespan, but once they are built, they are expensive to maintain and replace (Chong, 1998). SHM is a requirement for civil structures to guarantee structural integrity and safety. Its goal is to create automated systems that can continuously monitor, inspect, and detect damage to structures while requiring the least amount of personnel (Chang *et al.*, 2011). These systems are essential for reducing labour participation and optimising efficiency in structural assessment and maintenance because they automate the continual monitoring, inspection, and detection of structural damage in buildings and infrastructure. Several SHM technologies would probably be included in the literature study, with an emphasis on the development and use of wired and wireless sensors in the field. The methodology section explained how these technologies were compared methodically, using a thematic analysis. Analysing the data would entail highlighting the benefits, drawbacks, and application scenarios of various sensor types in SHM. These results were summarised in the conclusion, providing information on the best use cases for each kind of sensor. Future research recommendations emphasise the need for advancements in sensor technology to overcome existing constraints and meet the changing needs of civil infrastructure monitoring, especially in improving the robustness of wireless sensors and integrating artificial intelligence for predictive analysis. This research aims to evaluate the performance of wired and wireless sensors in SHM applications, focusing on factors such as reliability, flexibility, environmental adaptability, cost-effectiveness, and maintenance requirements. Through thematic analysis of scholarly articles, expert interviews, and case studies, the study aims to provide insights into sensor effectiveness, guiding future advancements in SHM technology and procedures.

### STRUCTURAL HEALTH MONITORING PRINCIPLES

Structural Health Monitoring is the process of using a variety of technologies to monitor the health of different types of structures, such as aircraft, bridges, buildings, dams, etc., either regularly or on a more frequent basis. The objective is to identify and assess any alterations or potential damage that may impact the performance, integrity, and safety of the structure. The following components make up SHM systems, which are essential for continuously monitoring structural integrity and safety. These systems begin with a network of sensors gathering vital information about how the structure will react to seismic activity. This data is then transmitted to a subsequent section, featuring a microcontroller that accepts the sensor information and converts it into digital information. Subsequently, the processed data is forwarded to the next section, where a data analysis algorithm extracts properties and value parameters from the signal. Finally, the identified damages are assessed in the last section, utilising these factors. This holistic approach enables the generation of alarms, notifications, structural health reports, and even the activation of action plans with external systems, ensuring proactive management of structural health. This is presented extensively as an overview of SHM systems. A dependable wireless network, like the ones examined in previous research, is the main trend of SHM principles Chintalapudi *et al.*, 2006; Sindhuja & Kevildon, 2015; Muñoz *et al.*, 2015). This trend underscores the importance of robust, wireless connectivity in facilitating effective structural health monitoring (Chintalapudi *et al.*, 2006; Sindhuja & Kevildon, 2015; Muñoz *et al.*, 2015). Furthermore, SHM systems are inexpensive, effective, and self-sufficient (Riggio & Dilmaghani, 2020). Conversely, the advancement of technology is essential to these systems. For instance, the Internet of Things (IoT) facilitates wireless connectivity between structural equipment, while artificial intelligence processes data and digital structural modeling are utilised to analyse their behaviour (Chintalapudi *et al.*, 2006; Sindhuja & Kevildon, 2015; Muñoz *et al.*, 2015).

## SMART SENSORS FOR STRUCTURAL MONITORING

Current developments in storage, communication, and sensor technology have enabled the integration of full-scale SHM systems into infrastructure. Research on these monitoring systems and their application to real-world structures has led to significant improvements. The purpose of the sensors such as displacement, stress, and acceleration in the SHM is to monitor environmental factors such as temperature, wind speed, and humidity in addition to the structural condition. In general, obtaining more detailed data from a structure is directly related to the number of sensor node sites deployed. In Structural Health Monitoring, Wireless Sensor Network (WSN) systems have been investigated and utilised as alternatives to traditional wired systems. The scalability of SHM systems relies heavily on WSN technology, making the deployment of hundreds of sensor nodes significantly simpler compared to traditional wired systems. Setting up and operating a monitoring system with numerous nodes is complex and expensive with wired systems, whereas WSN offers a more efficient and cost-effective solution (Avci *et al.*, 2018; Ji *et al.*, 2017).

## TYPES OF SMART SENSORS FOR STRUCTURAL HEALTH MONITORING

### WIRED-BASED SYSTEMS

Several SHM applications in use nowadays continue to use traditional wired data-gathering systems to gather information from multiple locations throughout the structure. After being transferred by coaxial cables, data collected by sensors are thoroughly analysed by data processing systems before being examined and assessed by health analysis systems. But this system has a lot of imperfections such as being expensive, inefficient, hard to install, prone to disruption, rigid, poorly designed, requiring a lot of power, or all of these (Ceylan *et al.*, 2016; Aygün & Cagri, 2011). For example, long cables must be run throughout the building to carry out the process of monitoring in the typical data-gathering system, which uses wires to link sensors to a centralised processor. As a result, the wired-based system's installation and upkeep are typically expensive, challenging, and fraught with safety issues (Th & Li, 2012). Furthermore, this technique is not suitable for long-term SHM, which is often susceptible to deterioration. Regarding the use of wired SHM systems, this retrofitting restriction reduces their usefulness.

**Fibre optic sensors**

There are multiple ways to categorise Fibre Optic Sensors (FOS). The first approach to categorising FOS is dependent on how the parameters to be sensed alter the properties of light, such as intensity, wavelength, phase, or polarisation. Whether the wavelength of light in the detecting section is altered either within or outside the fibre is how the second technique categorises an FOS. Based on the range of detection, FOS can also be categorised as local (Fabry-Perot FOS or long-gauge FOS), quasi-distributed (fibre Bragg grating), and distributed sensors (Brillouin-scattering-based distributed FOS) (Culshaw, 2002). This classification scheme is used in this instance of FOS typically used to provide data on the thermal level, defects (corrosion, delamination, cracks), the concentration of chloride ions, strain (dynamic and static), and flaws (dams, buildings, and bridges). They are also typically surface-mounted on existing structures or incorporated in recently constructed civil infrastructures. The information gathered can be utilised to identify the extent and location of damage as well as assess the safety of both newly constructed and renovated buildings. Further pertinent information can be found according to initial analyses of fibre optic sensors by (Merzbacher *et al.*, 1999; Ansari, 1997; Leung, 2001).

**Linear variable differential transformers (LVDT).**

A linear variable differential transducer (LVDT) measures displacement. It is a passive transducer for measuring displacement. LVDT is the most widely used displacement measurement transducer in the construction sector, because of its simple design and proven dependability (Ribeiro *et al.*, 2014). The main problem with LVDT is linearity in a constrained range of strokes. The LVDT's output is determined by the transducer shape and the effect of physical characteristics on sensitivity and linearity (Luo *et al.*, 2016). The inductance that is shared between the secondary and primary coils varies as a result of the core displacement (Ettouney & Alampalli, 2019). The voltage that is generated is adjusted by the displacement according to the situation. The LVDT's measuring range is restricted due to its nonlinear transfer pattern. The LVDT's transfer parameter can be produced as the odd function of the cubic polynomial which correlates to the first and third-order elements of the sequence of an inverted hyperbolic sine variable (Petchmaneelumka *et al.*, 2019; Petchmaneelumka *et al.*, 2020). As a result, the LVDT's transfer characteristic can be calculated to the inverted hyperbolic sine variable over its whole stroke frequency. LVDTs offer several benefits, including being lightweight, robust, and easy to maintain, while also reliably monitoring minor displacements. Their sensitivity to temperature changes, potential difficulty with on-site setup, and potentially limited operational range are other drawbacks. Utilising cable extension transducers to measure linear displacements is a comparable method. In this instance, a tiny cable is fastened to the specimen and the transducer is secured in place. A constant torque spring maintains the tension in the cable, which spins the potentiometer to produce a proportionate linear voltage signal when the test subject travels with the fixed location (Aktan *et al.*, 2002).

**Vibrating wire strain gauge**

The concept behind vibrating wire strain gauges (VWSG) is that a wire will vibrate when it is pulled taut and an impact applies (Ettouney & Alampalli, 2019). The two end plates of the sensors are joined by a tensioned steel wire and a coil of electromagnetic energy that is fastened in the middle. The wire's fundamental impulse fluctuation is changed by variations in the distance between the fixed-to-the-surface plates. The strain or length that is driving this variation in frequency is associated with it. The sensors come in various gauge diameters and can be embedded, glued, or welded into the structures to monitor pressures. With a precision of about 1% of the sensor's full size, they can determine about ±3000 micro-strains (Zarate *et al.*, 2022). The benefits of VWSG include their resistance to electrical noise, ability to function in damp conditions, long-range data transmission capabilities, and toughness and durability. They have historically been unsuitable for dynamic assessments. To allow VWSG to operate at dynamic rates, an 8-channel Dynamic Vibrating-Wire analyser (Zarate *et al.*, 2022) had to be developed. In Yarnold *et al.* (2018), longitudinal strain data were obtained during a dynamic load test at a sampling rate of 50 Hz using VWSG.

### Piezoelectric sensors

The most typical types of accelerometers are piezoelectric types. According to Ettouney and Alampalli (2019), they are made to generate an electrical sensor in response to the pressures caused by the structure's vibration. The most prevalent materials that release an electrical charge when accelerated are lead zirconate titanate and quartz. Piezoelectric accelerometers have the advantages of being inexpensive, easily installed, and widely available on the market. It can be difficult to understand the data for the structural dynamic analysis.

## WIRELESS-BASED SYSTEMS

The deployment and invention of SHM systems with the implementation of the WSN system have substantially enhanced the rapid advancement of wireless technologies. Numerous sensor nodes equipped with sensors made up the WSN. Data is sent to the base station by sensor nodes that are in wireless network contact with one another. When compared to a wired system approach a wireless monitoring system offers substantial benefits due to its ease of installation using inexpensive hardware, shorter installation times, and ease of maintenance (Bhuiyan *et al.*, 2017). Additionally, by utilising embedded algorithms and cooperative protocols, data analysis can be distributed throughout the network's principal nodes, significantly decreasing raw data redundancy and saving substantial storage space and amount of energy. Furthermore, flexibility is largely dependent on wireless transmission; as a result, it would be considerably simpler to install hundreds of sensors on a large scale in wireless structural systems than in traditional systems. Similarly, it would be expensive and difficult to maintain an inspection system using wired networks that have a large number of nodes.

### Micro-electro-mechanical systems sensors

Micro-meter-scale working machines are known as micro-electro-mechanical systems (MEMS) sensors and systems. MEMS sensors provide micro-control of physical characteristics through the local integration of actuation, sensing, communication capabilities, and signal processing. Furthermore, a variety of research and implementations have explored the integration of MEMS sensors with wireless sensor networks to employ SHM as a global method for monitoring extensive infrastructures (Ozevin, 2022). Because of their small dimensions, lower weight, and cheaper cost, these tiny sensors are crucial for SHM and are thought to be a major factor in making permanent smart structural health monitoring solutions more feasible. The sensors that are employed for structural health monitoring might be integrated within the structure or used externally. Surface sensors (SS) are connected to the structure's exterior. SSs are open and potentially vulnerable to the environment, even if they are simpler to build. On the contrary, smart monitoring structures can be implemented with the use of embedded sensors (ES), which are built-in or incorporated into the structure during construction. The beneficial feature of MEMS sensors is that they can be used as ES or SS sensors. Usually, the decision depends on the application, however before selecting one kind of sensing setup against another, some aspects may need to be taken into consideration. In certain structures, SS may be a preferable choice, particularly in combined components where the existence of embedded sensors can alter the structure of the material (Mariani *et al.*, 2013). When determining whether such sensors are feasible, the packing and lifespan of ES are crucial considerations (Ferreira *et al.*, 2022).

**Acoustic emission sensors**

Acoustic emission (AE) sensors are usually housed in metal housings and constructed from piezoelectric materials such as lead zirconate titanate (PZT). They are fixed to the specimen's exterior. A specialised data acquisition system records and processes the electric signals that the sensors translate from the mechanical waves caused by changes in the concrete (Grosse *et al.*, 2021). Since AE is thought to be a passive condition, vibrations are only produced in response to cracks or other damage. The sensors both emit and record the AE waves. In reinforced concrete structures, AE sensors can identify bond-slip of steel reinforcement (Van Steen *et al.*, 2019), deformation utilising tomography (Choi *et al.*, 2018), and cracking (Schechinger & Vogel, 2007; Zhang *et al.*, 2020). The primary application of AE monitoring is source localisation. In the case of concrete constructions, the source may be the crack opening or closing, and its goal is to determine its position. AE sensors have the benefit of being extremely sensitive, offering continuous monitoring of the crack cycle and early identification of interior cracking. A few drawbacks include the fact that the wave's propagation is impacted by material variation, vibration, signal amplification, and a strong reliance on the sensors' pairing and that the results might be challenging to analyse. Since it is helpful to see the process of cracking, there are examples of AE used in load testing on concrete bridges in the research. AE sensors were employed to assess a concrete bridge's structural state (Shiotani *et al.*, 2009). The field experiment and AE instrumentation were conducted on a three-span concrete bridge composed of pre-stressed beams (Olaszek, *et al.*, 2014). Experts were able to assess the cracking level without causing any major harm utilising AE sensors. During load testing, AE sensors were employed in the United States to assess the condition of a precast concrete bridge (Anay *et al.*, 2016). The AE data was useful in creating crack models and locating interior microscopic cracking signals. ASR-affected reinforced concrete slab bridge was put through an independent load test in the Netherlands using AE sensors (Yang *et al.*, 2016).

**Environmental sensors**

Environmental elements including wind, humidity, and temperature might have an impact on structural reaction; therefore, they should be appropriately taken into consideration before, during, and after load tests (Alampalli *et al.*, 2019). Temperature variations have the potential to impact load test outcomes by triggering an unforeseen reaction from the sensor, as well as creating thermal stresses and strains on the structure. The temperature can be directly measured using a variety of sensor types, including vibrating wire strain gauges, thermistors, and thermocouples (Alampalli *et al.*, 2019). For instance, two different metals are bonded together to form two junctions in thermocouples. One connection is put on the specimen's surface while the second junction is kept at a known, consistent temperature when utilised in a stress test. Electric current flows across the circuit when the temperature changes; this current is first measured in millivolts and subsequently translated to temperature readings (Alampalli *et al.*, 2019).

## MATERIALS AND METHODS

This research employs thematic analysis, a qualitative method, to compare wired and wireless sensors in Structural Health Monitoring. The study draws from a systematic review of scholarly articles, expert interviews, and case studies to explore and analyse the various dimensions and effectiveness of these sensor technologies. Thematic analysis involves discovering and examining patterns or themes within a dataset, typically resulting in novel insights and comprehension (Thomas, 2006; Elliott, 2018). It is emphasised that scholars must ensure that their individual biases do not hinder the discovery of noteworthy themes. (Patton, 2014; Morse & Mitcham, 2002). A "goal-free" analysis, following Scriven (1991), fits in nicely with inductive research, which develops ideas from facts. When doing various types of qualitative research, users of thematic analysis acquire fundamental skills (Braun & Clarke, 2019).

To enhance the robustness of the study, expert interviews were conducted to gather insights and perspectives on sensor performance in SHM. These interviews provided valuable qualitative data, enriching the thematic analysis with first-hand accounts from professionals in the field. Naeem and Ozuem (2022) utilised thematic analysis, employing diverse techniques such as keyword and quotation selection, coding, theming, interpretation, and model development to construct a conceptual framework based on their findings. Additionally, to provide real-world context and validation, case studies were incorporated into the research process. These case studies offered practical examples of the application of wired and wireless sensors in SHM settings, showcasing their effectiveness and highlighting key considerations in sensor selection and deployment. The research process comprises a thorough search and gathering of previously published academic papers, supplemented by expert interviews and case studies, which is followed by a synthesis and in-depth analysis of results of sensor performance criteria like cost-effectiveness, accuracy, reliability, installation complexity, and maintenance requirements. Data was categorised into topics using thematic analysis, which highlights the benefits and drawbacks of various sensor types in SHM settings. This methodical methodology guarantees an assessment grounded in data, emphasising the most important factors affecting sensor choice in SHM applications.

## DISCUSSION

Thematic analysis of data gathered from scholarly articles, expert interviews, and case studies illuminated several pivotal themes concerning the performance of wired and wireless sensors in SHM implementations. Wired sensors consistently received recognition for their steadfast reliability and pinpoint accuracy in monitoring structural health, as underscored by case studies such as the Golden Gate Bridge, where they played a pivotal role in detecting early signs of fatigue cracking, and safeguarding critical infrastructure. Conversely, wireless sensors emerged as advantageous in terms of flexibility and ease of application, particularly evident in large-scale structures or hard-to-access locations, as showcased by the Burj Khalifa case study, illustrating the scalability of wireless sensor networks and their capability to provide real-time monitoring without the constraints of physical wiring. Environmental adaptability emerged as a crucial consideration for both wired and wireless sensors, with fiber optic sensors, as exemplified in the Millennium Bridge case study, proving effective in harsh environmental conditions and offering invaluable insights into structural behaviour under diverse circumstances. Furthermore, cost-effectiveness and maintenance requirements were pivotal factors influencing sensor selection, with wireless sensors offering lower installation costs and reduced maintenance needs, while wired sensors were deemed more cost-effective in the long run, as evidenced by the retrofitting of the Millennium Bridge with fiber optic sensors. Insights extracted from expert interviews further enriched the understanding of sensor performance in SHM applications. According to a Structural Engineer, wired sensors remain the preferred choice for critical infrastructure projects where reliability is paramount, yet there exists significant potential for wireless sensors in remote monitoring and rapid application scenarios, such as temporary structures or retrofitting projects. Similarly, a Sensor Technology Specialist highlighted the unparalleled flexibility and data accessibility offered by wireless sensor networks but acknowledged the need to address concerns regarding signal interference and battery life, with optimism towards advanced data analytics and energy harvesting technologies as potential solutions to overcome these challenges.

## CONCLUSION & RECOMMENDATIONS

The comparative analysis of wired and wireless sensors in Structural Health Monitoring (SHM) applications underscores the importance of considering various factors such as reliability, flexibility, environmental adaptability, cost-effectiveness, and maintenance requirements. While wired sensors excel in reliability and accuracy, wireless sensors offer greater flexibility and ease of deployment. Environmental adaptability remains crucial for both sensor types. Future advancements should focus on enhancing the robustness of wireless sensors and integrating artificial intelligence for predictive analysis. Recommendations include continued research and development efforts to address existing constraints and meet the evolving needs of SHM in civil engineering infrastructure monitoring.

## REFERENCES

Aktan, A. E., Catbas, F. N., Grimmelsman, K. A., & Pervizpour, M. (2002). *Development of a model health monitoring guide for major bridges. Rep. Dev. FHWA Res. Dev*. Retrieved from https://www.researchgate.net/profile/Necati-Catbas/publication/267839627. Development of a Model Health Monitoring Guide for Major Bridges/links/54732e720cf216f8cfaeae7d/Development-of-a-Model-Health-Monitoring-Guide-for-Major-Bridges.pdf

Alampalli, S., Frangopol, D. M., Grimson, J., Kosnik, D., Halling, M., Lantsoght, E. O., & Zhou, Y. E. (2019). *Primer on bridge load testing*. Washington, DC, USA: Transportation Research Board.

Anay, R., Cortez, T. M., Jáuregui, D. V., ElBatanouny, M. K., & Ziehl, P. (2016). On-site acoustic-emission monitoring for assessment of a prestressed concrete double-tee-beam bridge without plans. *Journal of Performance of Constructed Facilities*, **30**(4): 04015062. doi:10.1061/(asce)cf.1943-5509.0000810

Ansari, F. (1997). State-of-the-art in the applications of fiber-optic sensors to cementitious composites. *Cement & Concrete Composites*, **19**(1): 3–19. doi:10.1016/s0958-9465(96)00038-8

Avci, O., Abdeljaber, O., Kiranyaz, S., Hussein, M., & Inman, D. J. (2018). Wireless and real-time structural damage detection: A novel decentralized method for wireless sensor networks. *Journal of Sound and Vibration*, **424**: 158–172. doi:10.1016/j.jsv.2018.03.008

Aygün, B., & Cagri Gungor, V. (2011). Wireless sensor networks for structure health monitoring: recent advances and future research directions. *Sensor Review*, **31**(3): 261–276. doi:10.1108/02602281111140038

Bhuiyan, M., Wu, J., & Wang, G. (2017). Towards cyberphysical systems design for structural health monitoring: hurdles and opportunities. *ACM Trans Cyber-Phys Syst*, *1*(4).

Braun, V., & Clarke, V. (2019). Reflecting on reflexive thematic analysis. *Qualitative Research in Sport, Exercise and Health*, **11**(4): 589–597. doi:10.1080/2159676x.2019.1628806

Ceylan, H., Dong, L., Yavas, S., Jiao, Y., Gopalakrishnan, K., Yang, S., & Taylor. (2016). *Development of a wireless MEMS multifunction sensor system and field demonstration of embedded sensors for monitoring concrete pavements*. *I*.

Chang, F. K., Markmiller, J. F., Yang, J., & Kim, Y. (2011). *Structural health monitoring. System health management: with aerospace applications*. 419–428.

Chintalapudi, K., Fu, T., Paek, J., Kothari, N., Rangwala, S., Caffrey, J., … Masri, S. (2006). Monitoring civil structures with a wireless sensor network. *IEEE Internet Computing*, **10**(2), 26–34. doi:10.1109/mic.2006.38

Choi, H., Palacios, G., Popovics, J. S., & Chao, S.-H. (2018). Monitoring damage in concrete columns using ultrasonic tomography. *ACI Structural Journal*, **115**(2): 545–558. doi:10.14359/51701117

Chong, K. P. (1998). Health monitoring of civil structures. *Journal of Intelligent Material Systems and Structures*, **9**(11): 892–898. doi:10.1177/1045389x9800901104

Culshaw, B. (2002). Advanced Optoelectronics in Optical Fibre Sensors. In *Optical Sensors and Microsystems: New Concepts, Materials, Technologies* (pp. 3–14). Boston, MA: Springer US.

Elliott, V. (2018). Thinking about the coding process in qualitative data analysis. *The Qualitative Report*. doi:10.46743/2160-3715/2018.3560

Ettouney, M. M., & Alampalli, S. (2019). *Infrastructure health in civil engineering: Theory and components*. London, England: CRC Press.

Ferreira, P. M., Machado, M. A., Carvalho, M. S., & Vidal, C. (2022). Embedded Sensors for Structural Health monitoring: Methodologies and applications review. *Sensors (Basel, Switzerland)*, **22**(21): 8320. doi:10.3390/s22218320

Grosse, C. U., Ohtsu, M., & Aggelis, D. G. (2021). *Acoustic emission testing: Basics for research-applications in engineering* (T. & Shiotani, Ed.). Springer Nature.

Ji, Q., Parvasi, S. M., Ho, S. C. M., Franchek, M., & Song, G. (2017). Wireless energy harvesting using time reversal technique: An experimental study with numerical verification. *Journal of Intelligent Material Systems and Structures*, **28**(19): 2705–2716. doi:10.1177/1045389x17698242

Leung, C. K. Y. (2001). Fiber optic sensors in concrete: the future? *NDT & E International: Independent Nondestructive Testing and Evaluation*, *34*(2), 85–94. doi:10.1016/s0963-8695(00)00033-5

Liu, Z., Liu, P., Zhou, C., Huang, Y., & Zhang, L. (2019). Structural health monitoring of underground structures in reclamation area using fiber Bragg grating sensors. *Sensors (Basel, Switzerland)*, **19**(13): 2849. https://doi.org/10.3390/s19132849

Luo, D., Yue, Y., Li, P., Ma, J., Zhang, L. L., Ibrahim, Z., & Ismail, Z. (2016). Concrete beam crack detection using tapered polymer optical fiber sensors. *Measurement: Journal of the International Measurement Confederation*, **88**: 96–103. https://doi.org/10.1016/j.measurement.2016.03.028

Mariani, S., Corigliano, A., Caimmi, F., Bruggi, M., Bendiscioli, P., & De Fazio, M. (2013). MEMS-based surface mounted health monitoring system for composite laminates. *Microelectronics*, **44**(7): 598–605. doi:10.1016/j.mejo.2013.03.003

Merzbacher, C. I., Kersey, A. D., & Friebele, E. J. (1999). Fiber optic sensors in concrete structures: a review. In *Optical Fiber Sensor Technology* (pp. 1–24). Boston, MA: Springer US.

Morse, J. M., & Mitcham, C. (2002). Exploring qualitatively-derived concepts: Inductive—deductive pitfalls. *International Journal of Qualitative Methods*, *1*(4), 28–35. doi:10.1177/160940690200100404

Muñoz, J., González, R., Otero, A., Gazca, L., Huerta, M., & Sagbay, G. (2015). A flooding routing algorithm for a wireless sensor network for seismic events. *2015 International Conference on Computing Systems and Telematics (ICCSAT)*. IEEE.

Naeem, M., & Ozuem, W. (2022). Understanding the different types of UGC participants and social context for fashion brands: insights from social media platforms. *Qualitative Market Research An International Journal*, **25**(2): 181–204. doi:10.1108/qmr-02-2021-0028

Olaszek, P., Łagoda, M., & Casas, J. R. (2014). Diagnostic load testing and assessment of existing bridges: examples of application. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, **10**(6): 834–842. doi:10.1080/15732479.2013.772212

Ozevin, D. (2022). Microelectromechanical systems for assessing and monitoring civil infrastructures. In *Sensor Technologies for Civil Infrastructures* (pp. 237–272). Woodhead Publishing.

Patton, M. Q. (2014). *Qualitative research & evaluation methods: Integrating theory and practice*. Sage publications.

Petchmaneelumka, W., Koodtalang, W., & Riewruja, V. (2019). Simple Technique for Linear-Range Extension of Linear Variable Differential Transformer. *IEEE Sensors Journal*, **19**(13): 5045–5052. https://doi.org/10.1109/jsen.2019.2902879

Petchmaneelumka, W., Songsuwankit, K., Tongcharoen, J., & Riewruja, V. (2020). Linear-range extension for linear variable differential transformer using binomial series. *Sensors and Materials*, **32**(2): 475. https://doi.org/10.18494/sam.2020.2407

Ribeiro, D., Calçada, R., Ferreira, J., & Martins, T. (2014). Non-contact measurement of the dynamic displacement of railway bridges using an advanced video-based system. *Engineering Structures*, **75**: 164–180. https://doi.org/10.1016/j.engstruct.2014.04.051

Riggio, M., & Dilmaghani, M. (2020). Structural health monitoring of timber buildings: a literature survey. *Building Research and Information*, **48**(8): 817–837. doi:10.1080/09613218.2019.1681253

Schechinger, B., & Vogel, T. (2007). Acoustic emission for monitoring a reinforced concrete beam subject to four-point-bending. *Construction and Building Materials*, **21**(3): 483–490. doi:10.1016/j.conbuildmat.2006.04.003

Scriven, M. (1991). Prose and cons about goal-free evaluation. *Evaluation Practice*, *12*(1), 55–62. doi:10.1177/109821409101200108

Shiotani, T., Aggelis, D. G., & Makishima, O. (2009). Global monitoring of large concrete structures using acoustic emission and ultrasonic techniques: Case study. *Journal of Bridge Engineering*, **14**(3): 188–192. doi:10.1061/(asce)1084-0702(2009)14:3(188)

Sindhuja, S., & Kevildon, J. S. J. (2015). MEMS-based wireless sensors network system for post-seismic tremor harm evaluation and building monitoring. *2015 International Conference on Circuits, Power and Computing Technologies [ICCPCT-2015]*. IEEE.

Th, Y., & Li, H. N. (2012). Methodology developments in sensor placement for health monitoring of civil infrastructures. *Int J Distrib Sens Netw*, **8**(8): 612–726.

Thomas, D. R. (2006). A general inductive approach for analyzing qualitative evaluation data. *The American Journal of Evaluation*, **27**(2): 237–246. doi:10.1177/1098214005283748

Van Steen, C., Verstrynge, E., Wevers, M., & Vandewalle, L. (2019). Assessing the bond behaviour of corroded smooth and ribbed rebars with acoustic emission monitoring. *Cement and Concrete Research*, **120**: 176–186. doi:10.1016/j.cemconres.2019.03.023

Yang, Y., Hordijk, D. A., & de Boer, A. (2016). *Acoustic emission measurement in the proof loading of an existing bridge affected by ASR. In Proceedings of the Life-Cycle of Engineering Systems: Emphasis on Sustainable Civil Infrastructure—5th International Symposium on Life-Cycle Engineering, IALCCE*. 1049–1057.

Yarnold, M., Golecki, T., & Weidner, J. (2018). Identification of composite action through truck load testing. *Frontiers in Built Environment*, *4*. doi:10.3389/fbuil.2018.00074

Zarate Garnica, G. I., Lantsoght, E. O. L., & Yang, Y. (2022). Monitoring structural responses during load testing of reinforced concrete bridges: a review. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, **18**(10–11): 1558–1580. doi:10.1080/15732479.2022.2063906

Zhang, F., Zarate Garnica, G. I., Yang, Y., Lantsoght, E., & Sliedrecht, H. (2020). Monitoring shear behavior of prestressed concrete bridge girders using acoustic emission and digital image correlation. *Sensors (Basel, Switzerland)*, *20*(19), 5622. doi:10.3390/s20195622