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SENSOR BASED MONITORING OF BRIDGE ASSETS – A SURVEY OF INDUSTRY AND ACADEMIA

Coveney, Millar[1], Woods, Joshua[2,6], Hoult, Neil[3], Rajlic, Biljana[4], Murray, Philip[5]
[1] Engineer in Training, Klohn Crippen Berger, Canada
[2] Mitchell Professor in Intelligent Infrastructure Monitoring, Queen's University, Canada
[3] Professor, Queen's University, Canada
[3] Engineer, Hatch Ltd., Canada
[3] Engineer, Hatch Ltd., Canada
[6] joshua.woods@queensu.ca

Abstract: Much research has focused on structural monitoring approaches for bridges to collect quantitative data relating to in-service performance (e.g., accelerations, displacements, strains). However significant challenges remain surrounding how this data can be effectively used by asset owners and engineering consultants to assess bridge condition and inform operation and maintenance. As a result, the use of monitoring has largely been limited to academic studies. While it is becoming more common to use sensors to monitor complex bridge structures, it is often still not clear what to do with the data and widespread use of sensor-based bridge monitoring has not been adopted by industry. This raises several important questions: what is preventing widespread use of sensors to monitor bridge infrastructure? And what information would a sensor system need to produce to be useful for bridge owners and engineering consultants? To investigate the answers to these questions, this paper describes the results of an anonymous survey that was circulated amongst industry and academic participants to get their insights into the use of sensors for monitoring bridge infrastructure. Results of the survey demonstrate that most respondents would consider using sensor-based monitoring if it could provide more reliable data than visual inspections. But a lack of knowledge about available sensor technologies and the need for engineering analysis to interpret collected data were limiting factors. The survey also provided insights into other questions surrounding sensor-based bridge monitoring, including the most important types of bridges to monitor and the specific measurement quantities that should be captured.

1 INTRODUCTION

The 2021 American Society of Civil Engineers (ASCE) report card for America's infrastructure found that the national backlog for bridge repair exceeded $125 billion (American Society of Civil Engineers 2021). The report also found that 42% of all bridges were at least 50 years old, and that 46,154 (7.5%) were considered structurally deficient. In Canada, the 2019 Canadian Infrastructure Report Card found that 9, 661 (12.4%) bridge and tunnel structures were in poor or very poor condition (The Canadian Infrastructure Report Card 2019). As North America's bridge infrastructure continues to deteriorate, and a growing population pushes demand for mobility to new highs, researchers have recognized an opportunity to apply technology to support the operation and maintenance of these critical assets.

Much research over the past two decades has focused on the development of structural monitoring approaches to collect quantitative data relating to bridge performance (e.g., accelerations, displacements, strains). However, significant challenges remain surrounding how this data can be effectively used by asset owners and engineering consultants to assess bridge condition and inform operation and maintenance decisions. As a result, the use of monitoring has largely been limited to academic studies and very targeted applications. While it is becoming more common to use sensors to monitor complex bridge structures and bridges in seismically active regions, it is often still not clear what to do with the data and widespread use of sensor-based monitoring (SBM) of bridge assets has not been adopted by industry (Xu et al., 2000).

This raises a number of important questions for the research community including: what is preventing widespread use of sensors to monitor bridge infrastructure? And what information would a sensor system need to produce to prove to be useful for bridge owners and engineering consultants? To investigate the answers to these questions, an anonymous survey was circulated amongst industry and academic participants to get their insights into the current state of the use of sensors for monitoring of bridge infrastructure, which will be discussed in this paper.

1.1 Literature Review

Before answering these questions, it is first important to understand how SBM systems work and what technologies have been used to monitor bridge structures in the past.

Some of the existing data acquisition methods for monitoring structures include using fiber-optic (FO) technologies, vibration-based monitoring, and wireless sensor networks (WSNs) (Webb et al., 2015). More specifically, the following technologies have been widely used in reported SBM studies: electronic resistance strain gauges (ERSGs), vibrating wire strain gauges (VWSGs), laser-based deflection measurements, deflection measurements using GPS, acoustic emission (AE) technology for detection of prestressing wire breaks, and ground-penetrating radar (GPR) for inspection studies.

Some drawbacks for common bridge SBM sensing techniques were reviewed by Reagan et al. (2018) who found that fixed hardware sensors such as strain gauges, extensometers, FO sensors, and accelerometers can be costly, difficult to deploy, require power, and can only be used on one asset. WSNs are not always durable enough to be embedded in the structure, and measurements are limited to a few discrete points. The intrinsic limitations of infrared thermography (IRT) like the thermal emissivity of the structure and external temperature effects reduce the accuracy of measurements. AE monitoring has practical challenges for in-situ investigations and is not suited for many large-scale SBM deployments.

In addition to existing technologies, there are a number of emerging technologies that show potential for future SMB applications, including imaging and computer vision, microelectromechanical systems (MEMS) strain and displacement gauges, and bioinspired sensors (Webb et al., 2015).

Several case studies on in-service bridges were explored to shed light on both existing and emerging SBM technology. The specific cases are listed in Table 1 and are briefly summarized herein. Hoult et al. (2009) investigated the use of four WSNs, drawing conclusions about the advantages and disadvantages of the technology. The study found that significant cost savings could be realized without the cabling and installation required for conventional monitoring systems. However, wireless systems also have drawbacks in terms power consumption (each node must be self-sufficient) and data-transmission bandwidth. All four installations investigated in the literature were successful in providing infrastructure managers with real-time access to previously unavailable data.

Table 1: List of SBM case studies referenced during a literature review

Case Study Name	Location	Sensing Technique	Area(s) of interest	Author(s)
Humber Bridge	UK	WSN	Relative humidity	Hoult et al. (2009)
Ferriby Road Bridge	UK	WSN	Crack width and bearing inclination	Hoult et al. (2010)
Lincoln Street Bridge	MA, USA	UAV	Crack geometry	Reagan et al. (2018)
Plain Street Bridge	MA, USA	UAV	Crack geometry	Reagan et al. (2018)
Streicker Bridge	NJ, USA	GPR	Internal deck features	Morris et al. (2019)
6th Avenue Viaduct	CO, USA	SG	Deflection and stresses	Allen and Rens (2004)
Parkview Bridge	MI, USA	VWSGs	Stresses in deck panels	Abudayyeh et al. (2010)

Note: WSN – wireless sensor network; UAV – unmanned aerial vehicle; SG – strain gauge

Reagan et al. (2018) studied a novel approach to monitor the health of bridges using an unmanned aerial vehicle (UAV) and three-dimensional digital image correlation (3D-DIC). GPS-navigated UAVs with cameras and 3D orthogonal mapping systems, which employed an image-processing algorithm for crack detection proved to be a viable method for SBM. Although this technique could only quantify surface cracks, the approach has the potential to enhance and expedite the bridge inspection process by tracking excessive deformation, monitoring microscopic (less than 10^{-4} m) crack activity, and perform long-term monitoring of areas that are difficult to access. Some notable limitations of this technology include the need to apply an ideal-sized speckle pattern over the areas of interest to create contrast for DIC, and the effects of inconsistent lighting conditions. The authors postulated that further iterations of the UAV-DIC sensor could take measurements at night or with light emitted from the UAV itself to eliminate the lighting variations.

Morris et al. (2019) conducted a high-frequency GPR survey on a reinforced post-tensioned concrete pedestrian bridge with embedded fiber-optic strain and temperature sensors. This study aimed to explore the capabilities of assessing physical and mechanical properties of materials by analyzing GPR attributes. It also validated SBM studies conducted on the bridge and indicated some potential for applying the attribute analysis method to material characterization as an informational tool for SBM. The authors concluded that the study served as a proof of concept and motivation to explore GPR techniques that can estimate material properties directly. Furthermore, they discussed how results and analyses of GPR surveys can be used in SBM projects to verify different deck behaviours, estimate parameters of importance to bridge health (like density or coefficient of thermal expansion), and provide an updated reference configuration of the structure. The authors postulated that a GPR technique could be developed into a robust SBM diagnostic tool with further study of GPR attributes.

Allen and Rens (2004) conducted a strain gauge study on a highway viaduct following rehabilitation to make the superstructure continuous in 1997-1998. The bridge was fitted with 62 strain gauges and 2 concrete crack gauges to record maximum deflection, stresses, and possible plastic response. The results suggested that the substructure of the viaduct was inadequate for long-term reliability and safety. The study was able to confirm the displacement of the superstructure with temperature changes and high bending stresses in the piers. It also established a relationship between temperature and strain on the piers and identified overstressed conditions in three columns. The authors concluded that additional monitoring and interim repairs were required to ensure short-term safety.

Finally, Abudayyeh et al. (2010) presented the design and implementation of an SBM system for condition assessment of full-depth precast concrete bridge deck panels. A sensor network of 184 VWSGs with built-in thermistors were embedded in the panels to monitor strain and temperature over given increments. While the bridge was new and was not expected to have problems until later in its lifecycle, the authors anticipated that the SBM system would: (1) provide continuous monitoring of the bridge deck to determine its condition, (2) assess impacts from temperature, (3) measure the response to traffic loads and other environmental factors, (4) evaluate the rate of deterioration, (5) enable maintenance and repairs as required, and (6) predict the remaining service life of the bridge. After recording three years of monitoring data, they planned to develop stress envelopes to determine normal bridge deck performance patterns for comparison against design and behavioural limits. A finite element model (FEM) would be constructed using strain data to provide additional information about the performance of the bridge deck.

While the literature review is by no means a comprehensive summary of the state-of-the-art in SBM, it is intended to provide an insight into what is possible using available sensor technologies, and to suggest that SBM systems can provide useful and actionable data to bridge owners.

2 METHOD

An anonymous survey was developed to elicit responses from regional municipalities, industry professionals, and academic experts. The survey was designed to take respondents 10 minutes to complete and posed 19 multiple-choice questions with an optional section for long-form answers. The survey aimed to answer five critical questions:

1. Has the respondent ever used or proposed using SBM to support operation and maintenance on a bridge project? Why or why not?
2. How could current approaches to bridge operation and maintenance be improved?
3. What benefits would an SBM system need to offer for the respondent to consider using it to support bridge operation and maintenance?
4. What components are most important to monitor (i.e. most prone to deterioration) on a bridge, and what information is most useful in assessing the structural integrity of those components?
5. What does the respondent view as the biggest potential drawbacks to implementing an SBM system?

The survey also prompted respondents for anonymous information about their professional experience to qualify responses in the context of respondent expertise.

3 RESULTS

On December 14th, 2020, 39 professionals with backgrounds in structural engineering were invited to complete the anonymous 10-minute SBM survey via email. Responses were accepted until February 1st, 2021, and 26 (66.7%) of the invited professionals chose to participate.

3.1 SBM Survey Results

A total of 19 respondents (73.1%) indicated they had previously used SBM to collect quantitative data about a bridge. Of those respondents, 15 (78.9% of those who had used SBM) had used it on 1-5 bridges. Based on the responses, 78.9% of the SBM deployments were on Canadian bridges, while 15.8% were in the USA. In terms of bridge type, 57.9% of SBM deployments were on beam bridges, 31.6% on cable-stayed, 26.3% on truss, and 21.1% on arch bridges. Of the bridges monitored, 89.5% used reinforced concrete for at least part of the construction and 84.2% used steel. On average, 57.9% of monitored bridges were between 0 and 10 years old, 21.1% were 11 to 30 years old, 26.3% were between 31 and 50 years, and 21.1% were 51 to 70. Only 15.8% of SBM deployments were on bridges older than 71 years.

The primary goal of 52.6% of SBM deployments was to monitor for signs of damage on the structure, while 42.1% were installed to monitor existing damage. Similarly, 42.1% of deployments were used to inform operation and maintenance decisions while 26.3% were deployed for academic purposes (proof of concept) and 15.8% were deployed to test the capabilities, accuracy and/or reliability of sensor technology. Strain sensing was used in 78.9% of the deployed SBM systems and 57.9% recorded ambient temperature and associated expansion/contraction. Similarly, 57.8% of deployments produced deflection data, while 36.8% measured acceleration. Only 21.1% of deployments produced data on crack width and rate of expansion.

Thirteen respondents (68.4%) indicated that individuals were able to make decisions/take actions based on the data produced by the deployed SBM system(s) (see Figure 1). Of the 6 respondents who selected no, the data was not actionable, 3 stated this was because the system had not yet been installed or the bridge had not yet been constructed. One respondent noted that the missing link was moving from understanding/validating structural responses to being able to make actionable decisions regarding operation and maintenance.

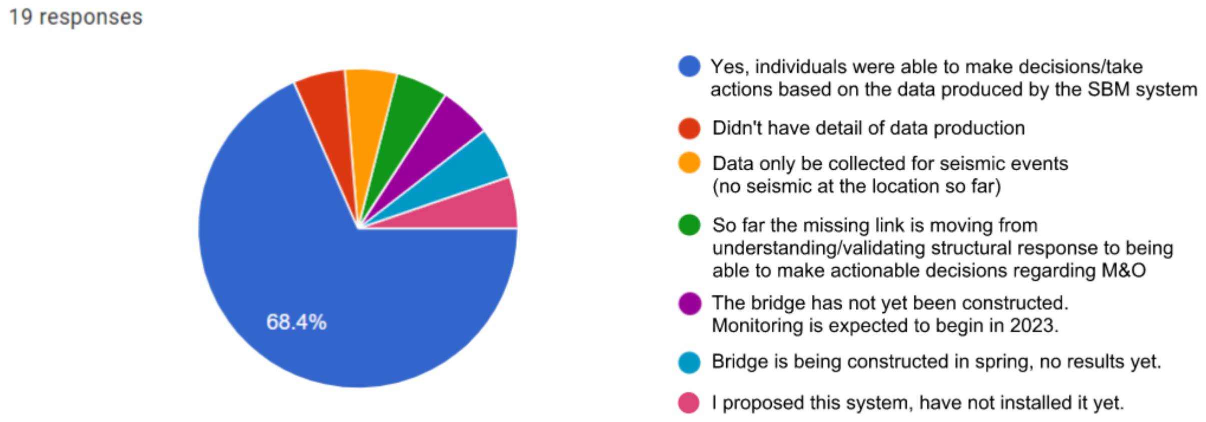

Figure 1: Was the data produced by the SBM system actionable in any way? If not, please elaborate.

Seven respondents (26.9%) had not previously used SBM to collect quantitative data about a bridge. When asked about specific reasons which prevented these respondents from implementing or using an SBM system, lack of knowledge about SBM and lack of requirements for regular bridge operation and maintenance were the most common answers, each at 42.9%.

Six of the 7 respondents (85.7%) indicated that if it could provide more reliable data than visual inspections, including actionable data about bridge behaviour, they would consider using an SBM for asset operation and maintenance (see Figure 2). While one respondent (14.3%) said they would like to use SBM, they noted that client funding for such projects is rare.

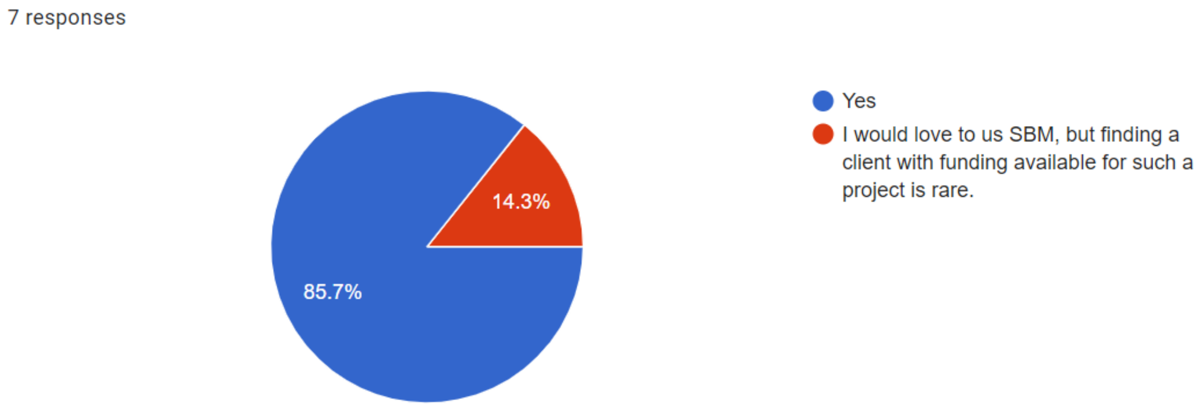

Figure 2: If it could provide more reliable data than visual inspections, including actionable data about bridge behaviour, would you consider using SBM for asset operation and maintenance? If not, please elaborate.

All 26 respondents were asked how current approaches to bridge operation and maintenance could be improved (see Figure 3). The most common answers were to provide more quantifiable and less subjective information at 76.9%, followed by providing more frequent information about bridge deterioration and providing information about deterioration as early as possible, each at 65.4%. Reducing the cost of maintenance was the fourth most selected response at 57.7%, while reducing human error associated with visual inspections was selected 38.5% of the time.

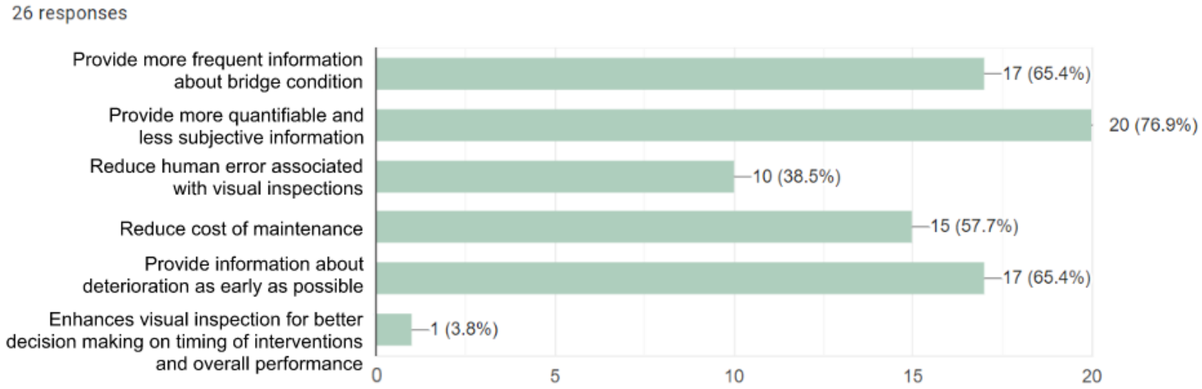

Figure 3: How could current approaches to bridge operation and maintenance be improved? Select all that apply.

When asked what benefits an SBM system would need to offer to be widely used and accepted in practice to support bridge operation and maintenance, 65.4% of respondents selected providing monetary value (see Figure 4). Locating and identifying potential damage indicators was selected at a frequency of 57.7%, while estimating the likely remaining service life of the asset and reducing bridge inspection frequency were selected 53.8% and 46.2% of the time, respectively.

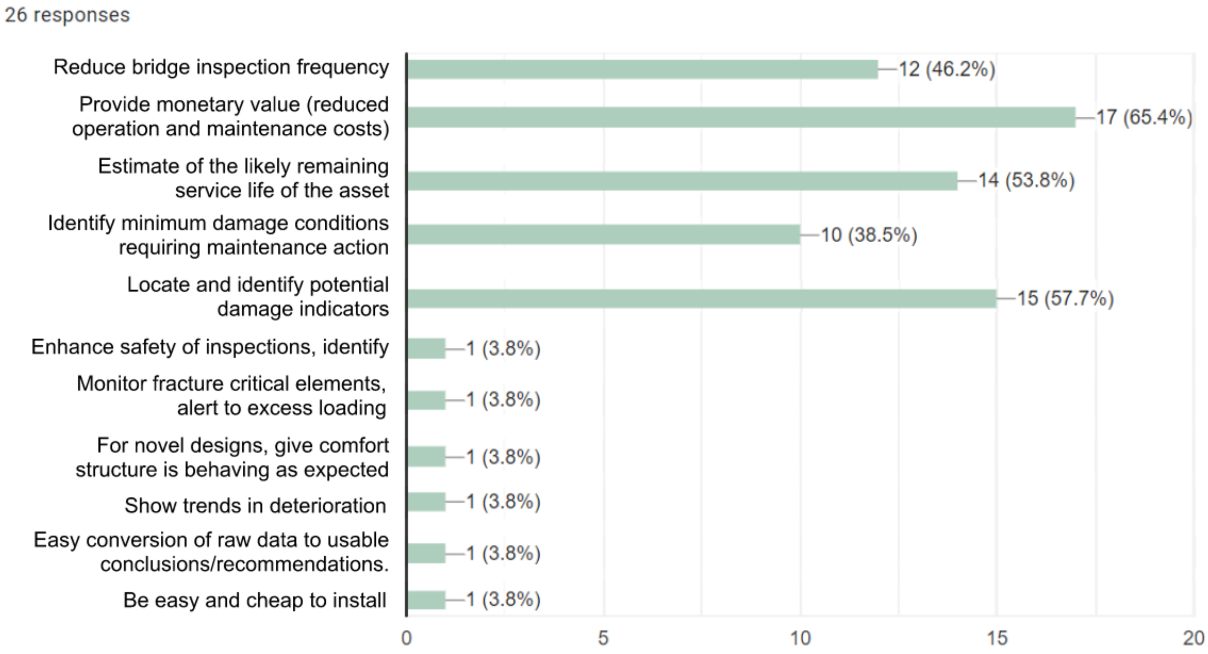

Figure 4: In your opinion, what benefits would an SBM system need to offer for it to be widely used and accepted in practice to support bridge operation and maintenance? Select all that apply.

Respondents selected cables as the most important bridge component to monitor 69.2% of the time. Girders and bearings were the second-most popular responses, with each option being selected 65.4% of the time. The deck, expansion joints and piers were selected 53.8%, 38.5% and 30.8% of the time, respectively.

Seven respondents chose to fill out the optional long-answer question: “Do you have any other comments or concerns regarding the implementation of a sensor-based monitoring system for bridges?”. In long form, some respondents expressed concerns about how SBM data is collected and made available, the resilience and operability of sensors, and the cost of installing and analyzing sensor information. Other respondents indicated that SBM data collection and storage should be considered from the outset and aimed at providing practical, reliable, and actionable information to bridge owners regarding the structural safety and operability of the bridge. Respondents also commented on the need to know more about successful SBM applications and noted that the value for money of bridge monitoring must be articulated to owners in regions where visual inspections are a blanket requirement. One respondent indicated that SBM systems are of no value unless the asset manager is able to continue monitoring the system over the lifetime the bridge without simply losing track of the data.

For the next series of questions, respondents were provided with some information about a sample bridge structure with prestressed concrete girders and a steel arch supporting the main span. When asked to identify the most important components of the bridge to monitor, respondents selected the steel arch 69.2% of the time. The bearings and deck were selected at 53.8% and 50% of the time, whereas the concrete girders, expansion joints and piers were selected 46.2%, 42.3% and 38.5% of the time, respectively.

Respondents selected strain readings and locations at a frequency of 73.1% as the most useful information for assessing the condition of the component selected in the previous question. Expansion and contraction measurements at expansion joints were selected 65.4% of the time, and the following three items were each selected 53.8% of the time: crack location, width and rate of expansion, image of damage with location, and visual inspection with report on findings.

When asked what respondents viewed as the biggest potential drawbacks to implementing an SBM system on the sample bridge, the most popular response was that expert analysis would be required to make decisions with SBM data at 57.7%. The second most common response was that information provided by the SBM system would not provide value to operation and maintenance at 46.2%, followed by the system being too costly to install and operate at 38.5%. Other concerns included system reliability, accuracy, durability and usefulness.

4 DISCUSSION

The next section discusses the key findings of the survey as well as suggesting ways forward for the use of SBM systems on bridges.

4.1 SBM Survey Key Findings

Several important findings can be drawn from the survey results. SBM systems have generally been deployed on reinforced concrete beam bridges to monitor for signs of damage, monitor existing damage and/or to inform operation and maintenance decisions by collecting strain readings, expansion/contraction (along with ambient temperature) and acceleration data. Most respondents who had previously used SBM reported that the data produced by the system was actionable, implying these types of deployments have been successful in the past. It is therefore reasonable to conclude that using sensors to monitor strain, expansion/contraction and acceleration reading could provide actionable data if installed on bridges in the future.

The 26.9% of respondents who had not previously used or implemented an SBM system cited lack of knowledge about SBM and lack of requirements for regular bridge operation and maintenance as the primary reasons (see Figure 5).

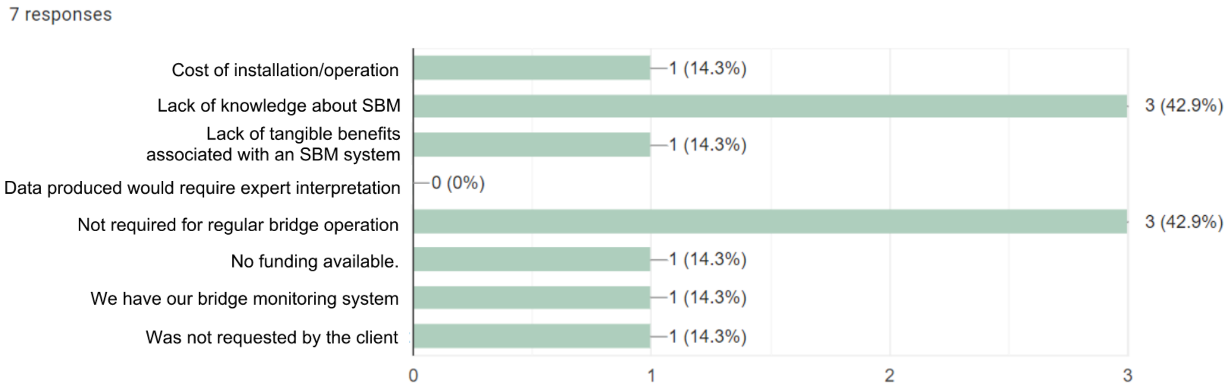

Figure 5: Are there specific reasons that prevented you from implementing or using an SBM system? Select all that apply.

Given that 85.7% of these respondents would consider using SBM for asset operation and maintenance if it could provide more reliable data than visual inspections and actionable data about bridge behaviour, the motivation for this publication and the importance of further SBM research is clear.

It is of interest to note that 53.8% of respondents had more than 21 years of work experience, with 69.2% hailing from industry, and yet 78.9% had only used SBM on 1-5 bridges. Furthermore, 57.9% of SBM deployments were on bridges between 0-10 years of age. This highlights the relative infancy of SBM systems in the private sector, as there are generally few instances of using SBMs, and they are being deployed by experienced professionals on relatively new assets. It can be concluded that further SBM systems must be proposed and deployed to bring widespread awareness of the potential benefits to private industry.

From the responses, it is clear that an opportunity exists to improve current bridge asset management practices using SBM. When all respondents were asked how current approaches to bridge operation and maintenance could be improved, they identified: (1) a greater degree of quantifiable information, (2) increased frequency of data collection, (3) providing early information about damage, (4) reduced cost of maintenance, and (5) reduced human error. Respondents also identified the specific benefits they felt an SBM system would need to offer to be widely used and accepted in practice to support bridge operation and maintenance. Responses included: (1) providing monetary value in the form of reduced operation and maintenance costs, (2) locating and identifying potential damage indicators, (3) estimating the likely remaining service life of the asset, and (4) reducing bridge inspection frequency.

The survey also highlighted strain readings from primary structural members as a common area of interest for SBM deployments. Respondents identified cables, girders, and bearings as the three most important general bridge components to monitor, followed by the deck, expansion joints and piers. When provided with sample information about a bridge structure, they identified the main steel arch as the most important component to monitor, followed by the bearings, deck, concrete girders, expansion joints, and piers. Strain readings with locations were further identified as the most useful information for assessing the condition of those components, followed by expansion/contraction measurements at the expansion joints.

Another conclusion which can be drawn from the survey results is that data from any SBM system must provide value to operation and maintenance personnel and minimize the amount of analysis required by a bridge engineer or similarly qualified expert to make decisions. These were identified by respondents as the two biggest drawbacks to implementing an SBM system on the provided sample structure. This conclusion underscores the importance of SBM data being accessible and actionable by all parties involved with asset operation and maintenance, not just those with a background in structural engineering.

4.2 **Next Steps**

Based on the survey results, a useful SBM system should provide value to asset operators with minimal engineering analysis required for decision making. Furthermore, asset operators should be able to quantify the accuracy of the information provided by an SBM system since they are ultimately responsible for invoking maintenance action. Sensor limitations and assumptions about SBM data could be quantified to develop confidence intervals for output data to further assist with decision-making. The potential for applying a mathematical framework to support decision-making related to operation and maintenance, such as the one proposed by Neves et al. (2019), is worth exploring in future research. Similarly, the value of applying a reliability-based framework of analysis to SBM should be explored.

The large datasets produced by SBM systems over the life cycle of a bridge could lend themselves well to the application of artificial intelligence and machine learning algorithms to recognize trends and is worth exploring in future research. Given the amount of time needed to capture these datasets and observe changes in bridge performance, the effect of prolonged environmental exposure on sensor networks also merits further investigation.

To gain buy-in from asset owners, a cost benefit analysis should be performed to determine the financial viability of proposed SBM packages over the life cycle of the asset. The installation and operation costs of the system should be compared against potential savings on operation and maintenance, and traditional bridge inspection costs. An SBM system designed to collect data from several different bridge components could be deployed in phases using a cost benefit analysis to determine the optimal order and timing of installation for each sensing option.

5 CONCLUSIONS

An anonymous survey circulated among industry professionals and academic experts to get their insights into the current state of the use of sensors for monitoring bridge infrastructure received 26 responses. Respondents identified lack of knowledge about SBM and lack of requirements for regular bridge operation and maintenance as the primary reasons they had not previously used or implemented an SBM system.

Respondents also felt that to be widely used and accepted in practice to support bridge operation and maintenance, an SBM system would need to offer the following benefits: (1) provide monetary value in the form of reduced operation and maintenance costs, (2) locate and identify potential damage indicators, (3) estimate the likely remaining service life of the asset, and (4) reduce the bridge inspection frequency.

Perhaps the most notable conclusion from the survey was the seemingly widespread interest in SBM for bridges, even among structural engineering professionals without prior experience using SBM. A total of 73.1% of survey respondents reported having previously used SBM, and 85.7% of those who had not expressed an interest in using it for asset operation and maintenance if it could provide more reliable data than visual inspections. These conclusions validate the importance of SBM research and the need for continued investigation to easily interpret data and to quantify financial benefits.

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