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Structural Monitoring

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Preface

The Joint Subcommittee on Structural Health Monitoring (SHM) is co-sponsored by the Standing Committee on Structures Maintenance (AHD30), the Standing Committee on Testing and Evaluation of Transportation Structures (AFF40), and the Standing Committee on Bridge Management (AHD35). The Joint Subcommittee, whose members include bridge owners, consultants, academicians, and providers of specialty instrumentation for structures, seeks to provide an overview of the current state of the practice for monitoring technologies that support decision-making with regard to transportation structures.

Technology continues to develop at a rapid pace. Bridge owners continue to face challenges on how the evaluate SHM technologies. The focus of the subcommittee is on practical applications of SHM rather than introducing novel monitoring technologies for SHM. The Joint Subcommittee explores potential collaborations between monitoring technology developers, maintenance and preservation decision-makers, asset managers, and other structural engineers. There was recognized need for written guidance on the practical usage of SHM to assist owners in effective operation of highway structures.

The purpose of this Structural Monitoring E-Circular is to help bridge owners understand the different purposes of Structural Health Monitoring. Effective use of SHM can help determine the most cost-effective course of action for resolving some difficult performance or deterioration structural issues. The E-Circular is expected to be useful to those new to the use of Structural Monitoring as well as to those with experience who develop a need for broader application for previously unaddressed performance issues.

PUBLISHER'S NOTE

The views expressed in this publication are those of the committee and do not necessarily reflect the views of the Transportation Research Board or The National Academies of Sciences, Engineering, and Medicine. This publication has not been subjected to the formal TRB peer review process.

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Contents

Introduction

Structural health monitoring (SHM), a term used to describe the deployment of sensing devices on or in certain civil–structural systems, has come to mean different things to different people and organizations. While many have reported on the development of this technology, there are few published reports that document practical, effective use of SHM to support decision-making. This lack of information likely contributes to delaying more widespread implementation of this technology, which has been shown to be an important complement to conventional assessment approaches in certain situations.

While most engineers agree on the definition of a structure, the word “health” has many different connotations. To counter that problem, many practitioners have stopped using the word “health” and simply referred to this technology as structural monitoring (SM) to avoid confusion. This document utilizes that terminology.

The Transportation Research Board Structural Health Monitoring Subcommittee (sponsored by Structures Maintenance Committee, Bridge Management Committee, and Testing and Evaluation of Transportation Structures Committee) agreed to promulgate and utilize the following definition of SM:

Structural Monitoring

A technology-driven automated solution whereby sensing devices are installed and remain in place on or in a structure with the intention of capturing structural data on a continuous basis over a period of time, for the purpose of objectively and accurately assessing structural performance.

Physical parameters that can be measured with sensors include strain, displacement, rotation or tilt, crack width, acceleration, acoustics, and temperature. These sensors are available from a number of manufacturers; however, selecting and integrating these sensors into a turn-key SM solution requires both technical expertise and engineering judgment.

Effective installation of a turn-key SM solution is also a key issue for owners, requiring multidisciplinary experience with field work, safety protocols, and electronics and software. Consideration should also be given to an owner’s procurement protocols (competitive bidding versus sole source) and appropriate insurance coverage.

Data captured by sensors can be stored locally (for manual retrieval) or transmitted by modem using the cellular networks for storage in a secure server or data center. Stored data can then be accessed and presented in a variety of forms, from simple graphs to more-complex 3D diagrams using Internet portals. These options have differences in costs and frequency of data retrieval and additional repercussions when used for an assessment of structural integrity or risk.

Most importantly, the value of SM is generated when the acquired data is processed and interpreted to inform decisions within an asset management context. This process often requires extensive expertise in structural behavior. Data interpretation strategies range from simple (graphical data representations) to complex (calibration and subsequent simulation with finite element models) depending on the complexity of the underlying mechanisms.

SM provides an objective and quantitative perspective on structural performance. As such, SM has the potential to improve decision-making in situations where more conventional assessment methods (e.g., visual inspection) fail to provide a clear explanation for the performance of concern. In these situations, owners have historically opted to stay on the side of conservatism and thus choose traditional, extensive intervention or replacement.

However, given that the costs of SM continue to drop and its reliability continues to improve, many owners are seeing value in deploying SM technologies to obtain a more accurate, quantifiable, and reliable diagnosis of current condition. In cases where conventional approaches provide uncertain assessments, SM has been shown to lead to less-expensive interventions, improved prioritization of projects, or both. When the potential savings associated with lower intervention costs may offset the cost of SM implementation, then SM should be considered an option.

While it is conceivable that the use of SM could indicate that the actual structural condition is worse than revealed through visual inspection, in practice this is extremely rare due to the conservatism that is generally employed. Moreover, discoveries such as these are quite advantageous in that the condition of the structure has been determined more definitively and any remedial action indicated can be more objectively prioritized.

While research continues to improve upon the practice of SM with new sensors and analytical methods, it is important to recognize that current technologies are more than sufficient to underpin successful applications. In fact, successful applications of SM date back many decades and have a record of providing a robust return on investment. Currently, the most common applications of SM technology include

- Identification of the root cause of structural performance problems;
- Estimation of site-specific static and dynamic impacts from live loads;
- Assessment of fatigue failure conditions and its expected progression;
- Preliminary indications of unexpected displacements affecting the substructure;
- Monitoring during extreme events for rapid post-event condition assessment; and
- Verification of repair or rehabilitation project efficacy.

Judicious and targeted use of SM technology can provide significant information, providing both financial and nonfinancial value for owners when costs are weighed against benefits. This E-Circular is intended as a primer to convey an understanding of how SM technology can and should be used most effectively while instilling confidence in its use as situations warrant.

Purpose and Value of Structural Monitoring

The purpose and value of SM will be explained in the following sections with consideration to

- Synergies with visual condition assessment and
- Support for decisions that impact a structure.

SYNERGIES WITH VISUAL CONDITION ASSESSMENT

SM and inspection-based assessments [inclusive of both visual inspection and the use of various nondestructive evaluation (NDE) techniques] are highly synergistic. Their synergy is founded on the complementary nature of their temporal and spatial resolutions as defined by the following:

- Temporal resolution, the number of data collection instances over a specific period of time or the inverse of the time between data collection instances (i.e., frequency of data capture) and
- Spatial resolution, the number of locations data is collected from or the inverse of the distance between data collection locations (i.e., number of sensors deployed).

As illustrated in Figure 1, SM has good temporal resolution, but relatively low spatial resolution. While it can acquire data in a near-continuous manner over extended periods of time, SM is generally deployed as a series of point sensors that provide relatively low spatial coverage. Although this is not an inherent limitation of monitoring, at this stage the available technologies that are mature enough to be deployed reliably and cost-effectively in practice are point sensors. In cases where data is needed from a specific location (e.g., bearing–joint performance or crack opening–propagation) spatial resolution is not a concern.

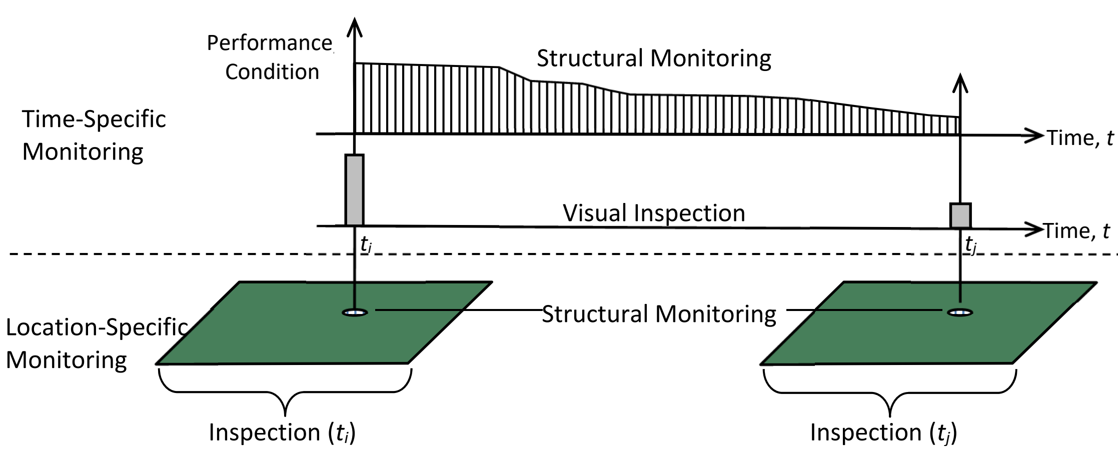

FIGURE 1 Complementary nature of visual inspection assessments and SM.

In contrast to SM, visual inspections provide very good spatial resolution, but relatively low temporal resolution. That is, while they can provide condition and performance data across the entirety of the structure, they are generally applied only once every 2 years. The periodic nature of visual inspection leaves gaps where performances or operational conditions are not being tracked and thus changes go unnoticed. As a result, visual inspection-based assessments have the following industry acknowledged limitations:

- Identification of changes in condition or performance within the inspection cycle frequency;
- Reliable characterization of operational demands and their variability with time;
- Identification of structural characteristics or defects that are not visible; and
- Near-real-time assessment of performance during and in the immediate aftermath of damaging events.

In general, the role of SM (within an integrated, synergistic condition assessment program) is to overcome these shortcomings.

THE ROLE OF STRUCTURAL MONITORING IN DECISION-SUPPORT

Visual Inspection has and continues to serve owners and SM is not intended as a replacement. Rather, when sound engineering reasoning supports its use, SM can be an effective assessment tool. Such situations occur, in general, when visual inspection and other assessment approaches fail to provide sufficient information to identify

- The underlying cause(s) of identified performance problems;
- The impact (in terms of safety–serviceability) of identified performance problems; and
- The rate of change or progression of performance problems.

Without this information, it can be difficult to make objective decisions related to whether an intervention (repair, retrofit, or replacement) is required and can be scoped correctly and cost-effectively. In cases where this uncertainty exists, decisions have historically been necessarily conservative. Although it is difficult to validate, this conservative approach can result in the implementation of unnecessary interventions, which are both costly and may potentially delay other, more-impactful projects.

With the maturation of SM and other technology-enabled assessment approaches (e.g., NDE) owners that find themselves in this predicament can now invest in more refined SM assessments. SM solutions, when properly selected and implemented, can provide additional information that may prove decisive in developing a cost-effective path forward.

It should be clear from this discussion that SM is not appropriate for every bridge: the vast majority of bridge performance problems can be effectively assessed through visual inspection, engineering heuristics, and physical measurements–standard specifications. However, SM should be viewed as a viable option in cases where a path forward based only on visual inspection or other available assessment data/information is determined to be insufficient.

From an owner's and user's perspective, a bridge given a poor condition assessment has an economic impact. Traditionally, remediating this condition has consisted of only two options, replacement, rehabilitation (or repair). The condition assessment also helps determine the priority in which either of those two options takes place relative to other bridges in the owner inventory. As will be discussed in this document, SM provides more precise and definitive information to help evaluate those decisions, based on more precise, quantitative information over time supporting more objective capital allocation.

When to Consider the Use of Structural Monitoring

The implementation of a SM project is predicated on capturing information that is otherwise unknowable or with inadequate precision in order to make informed engineering decisions about structural integrity and other issues. Consequently, the key question on whether to deploy SM is this:

> "…will the use of SM provide valuable and actionable information that will eliminate unknowns or confirm/improve engineering assumptions at a reasonable cost?"

Similarly, as mentioned in the previous chapter, SM can be thought of as a more definitive diagnostic follow-on to traditional visual inspection. The challenge for owners is to avoid monitoring for the sake of monitoring. SM should be considered when there is a known, deleterious condition and further understanding through the use of SM will lead to a more-informed decision at a reasonable cost. To date, the most powerful financial impact from a SM application is the safe deferral of major repairs or replacement, typically described as bridge preservation.

The most notable SM applications, proven over many years by a broad array of owners and engineers, follow below.

MONITORING TO EVALUATE STRUCTURAL INTEGRITY

Owners of some bridges have justified the use of SM to confirm and track overall structural integrity (generally in the form of validating assumed or simulated load paths), or to extend service life by monitoring the need for preservation or preventative actions over time (e.g., maintenance of movement systems).

The most straightforward application from an engineering perspective is to capture and analyze strain data. Strain is directly related to stress through Hooke's Law and a material's modulus of elasticity. Knowing what stress a member experiences from applied live load is important, but not necessarily definitive, to determine structural integrity. Most bridges are designed using well-understood very-conservative design principles. Knowing the precise response of a bridge to live load can greatly enhance an understanding of its structural condition and performance. By analyzing strain data from key, targeted members, a structural engineer can reach conclusions about load paths and structural response to load that is not generally available from calculations or visual inspection.

Sensors can also capture strain generated by temperature changes as the member expands and contracts. For very short-term testing, thermal effects can usually safely be ignored. However, long-term thermal effects can control structural behavior and greatly affect the structure's integrity. Thus, for any long-term SM evaluation, thermal strain should be de-coupled from live load strain to fully understand the effect of strain on the bridge. Overall, determining actual in situ live load stresses results in a more accurate understanding of structural response. Relevant application examples where strain and temperature data are used for assessment of structural integrity include, but are not limited to the following (in general order of potential impact):

- Evaluating live load response for members of concern, e.g., live load distribution, structural stiffness, response of secondary members and composite action;
- Evaluating thermal strain response, e.g., as it relates to potentially frozen bearings;
- Evaluating fatigue for live load response;
- Evaluating concrete crack propagation as it relates to both live and thermal loads; and
- Validation or understanding of new or unusual designs.

MONITORING FOR MOVEMENTS

The most frequent documented cause of bridge failure is substructure scour. Over the past few decades, the importance of understanding movement of pier foundations subject to scour conditions has come to the attention of engineers. Monitoring methods for determining negative indications, such as tilt, that drive scour behavior and ultimately bridge failure can be critically important.

Fortunately, several SM technologies can be used to track how a substructure is moving over time. For this, tilt meters and accelerometers, in combination with temperature monitoring can be used to evaluate if or how a bridge pier is moving from, for example,

- Applied live loads;
- Unintended member restraint against thermal and braking forces;
- The foundation is losing its ability to support the bridge structure; or
- The foundation movements are impacting moveable bridge span lock misalignment.

With scour, it’s not that critical to know which direction a pier is moving, but if it is moving at all and by how much.

One of the biggest problems generated by scour is it that subtle movement of a structure is not perceptible to visual inspection. To combat this problem, inclinometers can be installed at locations of known scour concerns to track subtle changes in pier geometry. Additionally, when combined with weather data, unexpected movement of the substructure can be correlated with data points such as water levels, rainfall, and other atmospheric conditions.

Importantly, structural failure from scour can be rapid after the onset of sensed structural condition changes. Therefore, owners and engineers should have realistic expectations for the ability of monitoring systems to provide adequate time to react given significant changes.

Conversely, when superstructure movement is expected from thermally induced strain–stress, but is constrained due to situations like frozen bearings, large forces can be generated. This can result in member overloads or in certain cases, out-of-plane bending and buckling (e.g., compression of a tension member), and damage to substructure systems.

Although visual inspection can usually determine the existence of frozen bearings, the impact on the structure may not be apparent. SM has the advantage of tracking both temperature and structural response over time which can capture how the structure reacts to the change in bearing condition.

MONITORING EFFECTS OF EXTREME EVENTS

Visual inspections typically occur on a biennial basis; other inspection frequencies are possible, but are not that common. However, it is recognized that events affecting a structure could occur immediately after an inspection. Thus, consideration should be given to SM when there is an identifiable benefit to knowing how a structure is reacting the moment an extreme event occurs.

Perhaps the most common application of this type of monitoring is related to post-earthquake assessment (e.g., the California Strong-Motion Instrumentation Program). More recently, examples related to capturing the response of bridges during and immediately after impacts have become more commonplace. These include low-clearance bridges that are repeatedly struck by vehicles, important structures over heavily trafficked waterways with the potential for barge impact, or critical infrastructure that could cripple transportation if taken out of service from impact.

Monitoring systems have been installed that can detect when damage takes place via changes in acceleration profiles, then take a photo or video images of the situation and store the images through triggers, indicating relative severity by the combination of accelerometer and tilt meter data, then send text and e-mail alerts to owners and engineers. The challenge here is establishing a workable threshold to eliminate false positives, but still trigger an alarm when a structure is outside normal or expected range of typical structural behavior.

For event response triggers, simple configurations are often better than complex in these situations. In these cases, SM serves as a sentinel to alert more comprehensive assessment when needed. However, the application of engineering expertise is an essential first step to establish a reasonable expectation that the SM solution can track these events.

MONITORING FOR FATIGUE ASSESSMENT

Both concrete and steel are subject to cracking, the former by its nature when subjected to shear and tensile forces, the latter to cyclic fatigue loading. Cracks in both cases are not necessarily bad and are often a natural effect of response to load or deterioration over the life of the structure. However, they can both lead to more critical condition issues that can result in structural failure, so a determination of “cause” is a worthwhile objective for SM.

When by engineering assessment cracks are determined to not be an immediate threat, they can be monitored with sensors to determine the rate of propagation. For example, in the case of fatigue, distortion induced cracks have known to initiate at stress concentrations, but then stop once the connection has sufficiently loosened as the stress concentration is reduced.

For both concrete and steel, the presence of cracks can be serious (fatigue) or propagate slowly enough (surface cracking of concrete) so as not to be an immediate concern. However, sensors can provide extra assurance for tracking the propagation and determination of sudden changes. There are several sensor technologies capable of doing this, allowing an experienced engineer to tailor a monitoring solution.

MONITORING FOR TRACKING TOLERANCES

Although less common, structures such as moveable bridges with critical operational tolerances are typically constructed with control systems in place for operation. Common consideration for SM systems include monitoring tower alignment, pier movement, deck tilt, or other critical components which can greatly assist trouble shooting when the structure does not behave as expected. Overall, these complex structures are beyond the scope of discussion in this document, but serve as an example of how SM can be fully integrated where and when appropriate.

Construction projects can also experience benefits from use of SM:

- The performance of structures under construction (either during initial construction or major rehabilitation), including accelerated bridge construction;
- The performance of structures adjacent to active construction sites; and
- Structures under construction or rehabilitation to assure proper alignment for fit-up.

These applications generally track the evolution of loading to validate design models and construction strategies or monitor engineered tolerances during construction procedures. For structures adjacent to active construction sites, the goal of monitoring is to identify and quantify any significant changes induced by construction activities in a timely manner to verify tolerance limits and mitigate negative consequences.

MONITORING FOR CABLE AND WIRE BREAKAGE AND KEY MEMBER STEEL CRACKING

Post-tensioning or cable stay strands are subjected to the loss of wire, strands and tendons over time and are difficult to access and assess by visual inspection. Acoustic monitoring offers a specific SM solution to continuously “listen” for wire breaks. By filtering out ambient noise, sensors are able to detect the energy released from wire breaks. Properly designed systems can give an indication of the rate of wire breaks on a structure, but not necessarily at a low level, e.g., only a few wire breaks. However, caution is advised as only wire breaks occurring after installation of the system can be recorded and interpretation of acoustic signals require significant experience and expertise. Fatigue cracking of key steel members, e.g., eye bars, has also been effectively demonstrated using acoustic emission technology.

VALIDATING THE EFFECTIVENESS OF INTERVENTIONS

These applications aim to track the performance of an intervention (e.g. connection retrofit, component replacement) to ensure that it is performing as intended. In cases where numerous, repetitive retrofits are required, it is not uncommon for a few competing approaches to be implemented and monitored for a period of time prior to selecting the final approach for long-term monitoring.

Types of Structural Monitoring Sensor Technologies

There are many different sensor technologies that are routinely used in SM applications to measure dynamic parameters and/or characterize structural response. These are well documented within the industry, easily categorized, and each has advantages and limitations associated with it. Detailed descriptions of typical sensor types follow:

ACCELEROMETER

An accelerometer is a sensing device that measures the rate of change of the velocity of a mass due to the movement of a surface on which it is attached. These sensors generate a signal proportional to the mass rate of movement with time and have been widely used in industry for measuring vibration of structures.

- **Typical Use**: Determining the resonant frequency of a structure for comparison with baseline structural analysis, or determination of structural response during extreme loading events (e.g., earthquake).
- **Pluses**: Relatively easy to install; can be reused, keeping per-use costs low; owners can purchase directly from sensor manufacturers for self-install or incorporate in comprehensive SM solutions.
- **Minuses**: Produces a substantial amount of data; difficult and expensive to reduce the captured data; the responses are global in nature and cannot pinpoint the location of concern on the structure that generated a response.

ACOUSTIC EMISSION

Acoustic emission (AE) is a sensor-based inspection method detecting elastic waves generated by the rapid release of energy from within a test object by mechanisms such as plastic deformation, fatigue or fracture. AE is a term used to describe the sound waves produced when a material undergoes stress (internal change) as a result of rapid change in load distribution. AE technology is designed for monitoring the acoustic emission produced within a structural material as a result of damage development.

- **Typical Use**: Determination of failure from post-tensioned bridge cables or steel structural members when failure is expensive and catastrophic; crack initiation or propagation; seeing increased use in buried pipelines.
- **Pluses**: In commercial use for over 20 years; typically used on steel, high-value structures; technology is well established and there are several suppliers.
- **Minuses**: Literature suggests only 75% to 80% of cable break AEs are captured (secondary system may be desired); background noise to be calibrated and filtered out; sensor placement highly related to actual structural conditions; needs significant power; solution supplier typically conducts first assessment of a signal, which is then relayed to the owner or

engineer; AE analysis is challenging and requires significant knowledge and experience to implement.

CRACK MEASUREMENT–DETECTION SENSORS

A crack measurement–detection sensor is a sensing device used to detect the incipient initiation, presence of, and subsequent growth of cracks in steel and concrete.

Electrochemical Fatigue Sensor

An electrochemical fatigue sensor is a sensing device used to detect the incipient initiation, presence, and propagation of fatigue cracks in metals.

- **Typical Use**: Determination of active crack growth in critical metallic structural members.
- **Pluses**: Can detect the onset of cracking before cracks become visible.
- **Minuses**: Sensor placement crucial for capture of initiation and propagation of cracks.

Displacement-Based Crack Propagation Sensor

A displacement-based crack propagation sensor is a sensor that captures changes in crack width or indicates propagation as determined from changes in electrical voltage driven by displacements.

- **Typical Use**: Highly accurate (<5 microns) sensors are placed over visible cracks to capture width changes with time or temperature, or just ahead of crack tips to capture propagation displacements that signal active crack growth.
- **Pluses**: Can be easily integrated with other sensors in an automatic system or used manually if infrequent data capture is considered acceptable.
- **Minuses**: Size of sensors may prohibit use in tight spaces, in corners, or over uneven surfaces.

INCLINOMETERS (TILTMETERS)

Inclinometers (tiltmeters) are sensing devices used to detect changes in axis orientation of structure to which it is attached; either one axis or two axis. A tiltmeter may also provide a measure of rotation of an element relative to a gravitational reference as well.

- **Typical Use**: In conjunction with a comprehensive SM system for determination of relative rotational movement and structural recovery of a structural element from an event, such as permitted loads on bridges, environmental events (hurricanes or wide temperature swings), or substructure changes due to scour.

- **Pluses**: Relatively inexpensive to add to SM systems; data easy to capture and analyze.
- **Minuses**: Used alone, may not provide sufficient diagnostic information; often used with SM systems that capture and transmit data frequently, since data captured may be critical, especially for scour events. Caution: scour effects can create rapid failure conditions; therefore, engineering judgment is crucial.

LASER-BASED INSTRUMENTS

Laser-based instrumentation (both high and low accuracy measurements) can be used to capture structural displacements, such as deflection. The instruments required can be set up quickly and measure bridge girder deflections under various loading scenarios.

- **Typical Use**: Determination of structural deformities (out-of-plane bending) or unusual deflections.
- **Pluses**: Offered by a number of third-party solution providers.
- **Minuses**: Generally, laser instruments measuring deflection may not be accurate enough to diagnose structural problems; equipment may be too expensive to purchase for owners who don't use it frequently; requires periodic lens cleaning.

DISPLACEMENT SENSORS

Displacement sensors are sensing devices that typically consist of a linearly variable differential transducer in a hollow metallic casing. A shaft, called the core, moves freely back and forth along the axis of measurement. Linear variable differential transformers are used to measure relative deflections or displacements. It is a common type of electromechanical transducer that can convert the rectilinear motion of an object to which it is coupled mechanically into a corresponding electrical signal.

- **Typical Use**: Determination of relative linear movement of a structural element due to a loading event.
- **Pluses**: Direct measurement of movement; highly accurate and precise.
- **Minuses**: Limited scale on the order of inches; requires a fixed point of reference, otherwise movements are relative between points of reference; frequency of data captured should be controlled; consider sensor longevity requirements before utilization.

A subset of displacement sensors is called a "string pot." Some string pots sacrifice precision for scale and thus can capture larger displacements on the order of feet, but with lower resolution as compared to other displacement sensors. However, good quality string pots, when read by modern data acquisition equipment have precision on the order of 0.001 in. which is more than adequate for many SM applications. Consideration of the precision and longevity of this sensor is necessary beforehand, given the data required.

STRAIN SENSOR

Strain sensor is a sensing device used to measure the relative elongation/contraction of a structural material caused by a tensile or compressive force, or pressure applied to a wider surface area.

- **Typical Use**: Widely used to capture the strain response associated with applied loads to a structure, both environmental and live load; probably the most-effective sensor for determining how a structure reacts to its load demand, leading to determination of structural integrity.
- **Pluses**: Easy-to-understand captured data; very accurate; well-known technology in wide use; many suppliers; used by nearly all SM solution providers as a means to characterize structural response.
- **Minuses**: The minuses are dependent upon the frequency of data captured; too much data is expensive to capture, store and reduce; essential that captured total strain data be statistically reduced to eliminate effects of temperature-driven changes; some require periodic calibration.

There are several different types of strain sensors typically used by SM solution providers.

- **Polymer Based**: Sensing element is a polymer encased in a protective housing; long-term stability; can capture peak and current strain over long time periods; no in-use calibration required, sensing element is not temperature-dependent, so no sensor data reduction step required; can also capture compressive and strain reversals; typically installed with epoxy.
- **Electrical Resistance Based**: Sensor is attached to the object by a suitable adhesive, welding, or bolting. As the object is deformed, metallic foil is also deformed, causing its electrical resistance to change. This resistance change, usually measured using a Wheatstone bridge approach, is related to the strain by a quantity known as the gauge factor. Temperature compensation and periodic recalibration are necessary for proper data acquisition. Different methods of attaching resistance sensors are also noted below.
- **Bolted On**: Faster installation than welded or epoxied, however not practical for small components or out-of-plane bending effects.
- **Epoxied**: Sensors are affixed to the structure through use of a specialized adhesive.
- **Weldable**: Small component compatible and high rate of data collection possible versus time intensive installation; less reliable long-term with radio interference; temperature-dependent calibration.
- **Vibrating Wire**: Sensor consists of a vibrating, pretension wire; strain is calculated by measuring the resonant frequency of the wire (an increase in tension increases the resonant frequency). Vibrating wire (VW) strain sensors have the most stable zero over time (meaning less digital drift in the data) and temperature spans when compared to resistance-based sensors. This can be beneficial when measuring long-term environmental responses. Conversely, VW sensors have a lower frequency response than resistance-based sensors and are not usually (currently) sufficient for dynamic response monitoring.

FIBER-OPTIC SENSORS

Fiber-optic sensors are sensor technology based on a specialized polymer fiber with sensing devices embedded or serially installed and integral with the polymer cable. They have been used effectively for over 20 years in a variety of applications, most notably to capture strain and temperature data.

- **Typical Use**: Highly effective when sensors can be installed in a serial, or linear fashion, such as long cable runs (>1 km) in buried pipelines; also effective in high-frequency data capture applications (e.g., >100 Hz).
- **Pluses**: Accuracy to 1 micron or less; less expensive to install in long, linear cables with serial sensors; also effective when used as long gauge length strain sensors on surfaces subject to variability of strain (e.g., older concrete surfaces).
- **Minuses**: Can be more expensive than standard sensors and data acquisition controllers; extra costs can reduce return on investment (ROI), especially when extreme accuracy is not necessary.

TEMPERATURE

Temperature sensors come in two main types. Thermistors are essentially a temperature-sensitive resister, while thermocouples are comprised of two different materials that produce a voltage output proportional to temperature. They are used for both localized (when attached to a member) and ambient temperature measurement.

- **Typical Use**: Used in conjunction with other sensors for thermal compensation and separating captured strain data due to thermal effects.
- **Pluses**: Essential for statistical correlation of temperature change versus captured strain data; inexpensive; highly accurate.
- **Minuses**: Assuming ambient temperatures are desired, sensors should be protected from direct solar radiation or the resulting temperatures will not be representative of ambient conditions.

How to Implement a Structural Monitoring Project

SM is a technology-based data collection process that captures in-service structural performance or condition data to support difficult engineering and asset management decisions. SM has proven to be most effective when used on a structure that has identifiable substandard performance or deterioration, causing uncertainty and possible increasing risks for users and owners.

Used judiciously, SM can reduce or eliminate these uncertainties, making asset management decision-making more effective and providing owners with a ROI. The intent of this section is to help owners make the most efficient and effective decisions on how and when to use SM through discussion of proven practices for planning and implementing an SM project.

As noted in previous sections, it is important to identify the specific parameters SM intends to capture. Crucial to implementing an effective project, owners should focus on key objectives for a given structure or group of structures, for example,

- Determination of baseline performance;
- Safe extension of operating life;
- Enhanced user safety;
- Confirmation of the need for rehabilitation or replacement;
- Confirmation of the efficacy of a repair; or
- Any combination of these objectives.

PROGRESSIVE DIAGNOSTIC APPROACH

Much like a medical doctor starts with simple diagnostic tools like a blood pressure cuff, then progresses to more definitive diagnostic tools, structure owners–engineers should also utilize the most technically appropriate and cost-effective SM solution at the right time to support optimal management decisions. Effective implementation of this concept in the context of SM can be termed "progressive diagnostics."

The SM spectrum of complexity and costs range from short-term, sparse, localized monitoring to long-term, dense, global monitoring of a presumed deficient structure to characterize its response to both live and environmental load demands. Four distinct SM quadrants are illustrated below with relative cost notations (Figure 2).

Results from any initial monitoring scheme will help determine subsequent steps along the four quadrants, if and when necessary. These steps may include immediate repair or replacement if the assessment indicates a serious issue, or initial monitoring may indicate that periodic visual inspection is sufficient. Using this approach, condition knowledge is developed in a progressive manner at typically increasing costs, however, this is done with the intent to gain sufficient information in the initial stages and possibly forego the more expensive options.

Past experience has shown that an engineer, owner and an instrumentation team are generally able to pinpoint what key data needs to be captured, at what frequency, and for what duration. Following this logic, it is considered good practice to start small. For example, if there

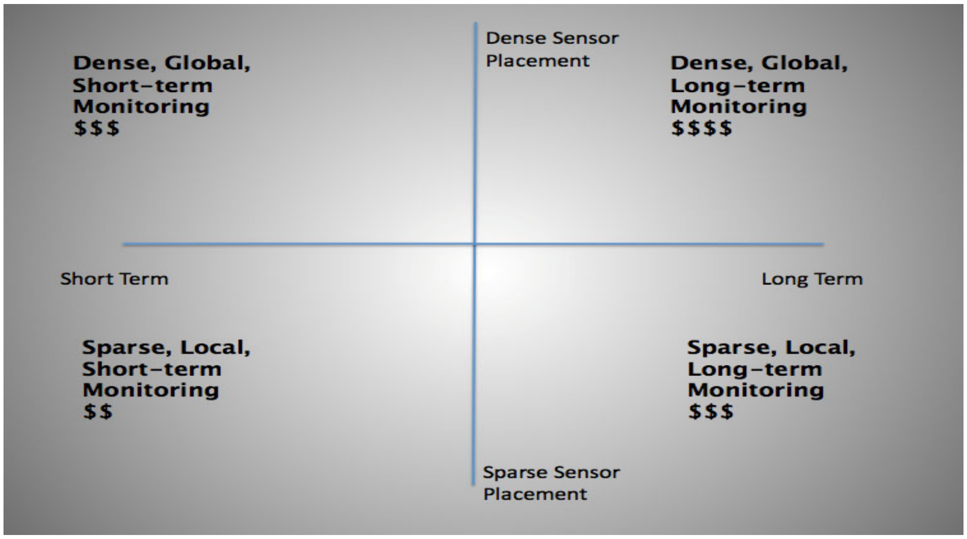

FIGURE 2 Progressive diagnostic quadrants for SM and cost implications.

is a detail that is thought to be an issue and it is systemic throughout several spans (e.g. a viaduct), it may be most useful to install SM on one or two of those details in the location(s) of greatest concern to validate if there is a problem, rather than "sensorizing" the entire bridge at substantial cost.

Results generated at each step will help determine if more comprehensive SM is necessary, if and when remediation or replacement should be implemented, or a combination of both. Keeping to these progressive steps can lead to improved SM ROI, especially if it is able to prove no action is necessary, or when the results indicate extending operating life can be done safely.

By utilizing SM as a component of an asset management or risk assessment/mitigation application, the engineer and owner should first develop a decision tree unique to the structure itself. Although there is no defined order or methodology for testing or condition assessment, it must be done in an organized manner and be tailored to each individual structure. This plan is dependent on issues such as current condition, results from previous assessments, and the costs for SM.

Depending on the data and information obtained in the process, it may be necessary to iterate the process with additional testing and/or monitoring to pinpoint the root cause of the deterioration before remediation or replacement actions are taken. In general, the prudent methodology is to start with the least expensive and least comprehensive monitoring that still enables the owner to meet objective(s) for the structure in the most cost-effective manner.

Returning to the medical analogy, when implementing a treatment plan, doctors typically monitor patient progress by comparing current physical data to that collected during initial examination. Similarly, extended periods of SM provide owners with assurance that the initial diagnosis and subsequent asset management decisions were correct and are effective.

STEPS TO PLAN AND IMPLEMENT A STRUCTURAL MONITORING PROJECT

Initial Information Gathering: Visual and Nondestructive Testing

SM supports and enhances bridge management, but in no way does it replace federally mandated visual inspection, which routinely occurs on all bridges in the United States. Typically, inspections occur every 2 years, but inspection frequencies can vary between 6 to 48 months, depending upon observed condition [and Federal Highway Administration (FHWA) approval for extended frequencies]. Results from prior visual inspection reports can be used to help form the scope of a nondestructive testing (NDT) or SM project by indicating deterioration trends that may deserve attention.

Visual inspection provides a condition state on a structure, indicating type, location, and severity of visible deterioration. This has proven to be a reasonably effective method to determine if structural integrity has been compromised. However, the FHWA and most state departments of transportation (DOTs) acknowledge that visual inspection for the purposes of condition assessment can be subjective with a wide range of results varying from inspector to inspector, or can vary depending on the time of year the structure is inspected.

NDT can also be used to augment visual inspection when appropriate. NDT is becoming more commonplace to further clarify structural deterioration and remains an effective set of tools to possibly implement prior to SM. Documenting damage locations and the likely extent of damage are the primary goals of NDT methods, such as ultrasonic testing or impact-echo testing. To most effectively use SM, visual inspection and NDT damage assessment results are interpreted with engineering knowledge and judgment, and ultimately considered against funding and other owner constraints. The information gathered from visual inspection and NDT is invaluable to determine if SM can provide actionable data and a suitable ROI.

Essential Considerations and Due Diligence

Formulating any SM project should give proper consideration to each owner's unique structure management program with differences in budget, personnel, policy, environmental conditions, and the type of structures in their inventory. To capture meaningful and actionable data from a SM project, systematic planning is essential. This approach starts by posing key questions and critically thinking through each aspect of the project before implementation.

Recommended questions to answer before starting a SM project include the following:

- What is the ultimate asset management objective(s) we want to achieve?
  - Enhanced user safety;
  - Development of repair options versus replacement;
  - Safely extending asset life;
  - Reducing life-cycle costs; and
  - Verification of design, as-built, and/or confirm baseline structural performance.
- Given what we know from visual inspection and NDT testing:
  - What is the extent of deterioration and how does that affect use and risk?
  - Can we define the current financial impact on users, e.g., detours, and costs for potential repair or replacement actions?

  - What SM scope will provide the data we need to achieve the ultimate asset management objective(s)?
  - What is the preferred schedule to implement?
- Can we define the potential for a ROI from SM?
  - Initial and ongoing monitoring costs; potential for long-term SM.
  - Development of less-expensive rehabilitation options versus replacement.
  - Value derived from a better understanding of structural condition, e.g., deferral of a replacement project.
- Do we have sufficient in-house knowledge or do we need to hire specific expertise?
  - To understand the various technologies and how they are used.
  - To understand which sensors to use and to efficiently locate them for to capture usable data.
  - To understand how often to capture data (frequency), store data, and its impact on analysis costs.
  - To analyze the captured data and recommend asset management decisions.

In addition, owners should conduct due diligence on various SM technologies, solution providers, and monitoring approaches to develop the most cost-effective monitoring plan and acquisition strategy. Soliciting differing monitoring approaches can be valuable, but they must be carefully evaluated in terms of owner-defined SM objectives for a given structure. Things to consider for due diligence activity include

- Previously demonstrated efficacy of the planned SM technology;
- Experience of SM technology–solution providers, reputation, and prior use recommendations;
- Demonstrated reliability of the hardware, power, and software stability;
- Demonstrated reliability of the data steam, from structure to storage to Internet access;
- Presentation of the data via an Internet portal, embedded analytics;
- Acquisition of technology–solutions using a detailed bid scope (low price) or unique performance specifications (best value proposal), or sole source/proprietary;
- Evaluation methods for unique proposals; valuing solutions; contracting expertise; and
- Impact of proprietary or sole-source technologies.

Location, Type, and Severity of Anomaly or Deterioration

Deterioration and/or anomalous behavior, its location, type and severity to be monitored is a crucial factor to evaluate. Examples most suitable for SM include superstructure section loss, fatigue prone areas, out-of-plane bending, cracking, stress redistribution (e.g. settlement, frozen bearings), and alignment issues of the substructure.

For example, where superstructure corrosion and associated section loss is a concern, an appropriate monitoring objective would be to monitor strain near the most corroded areas or whole-member tensile strain under various live load and thermal loads to determine whether areas of concern experience excessively high strain levels.

If the deterioration is not severe, then monitoring may not be worthwhile (when balanced against other determining factors) and can be revisited at a later date. If the deterioration is very severe, the answer may also be "no" because the condition may warrant immediate repair or replacement. Monitoring is typically warranted when deterioration is significant and structural risk is of concern, but uncertainty still exists regarding the immediate need for a repair or replacement decision.

Criticality of the Structure

Determining the criticality of a structure considered for SM is important and is often determined based on parameters like average daily traffic and the average daily truck traffic (ADTT), as well as emergency routing and detour lengths. It is also important for SM planning since it affects both perceived risk and potential ROI.

If a structural limitation (load restrictions or complete closure) is likely and the structure's ADTT notes a significant amount of truck traffic may be forced onto local streets and other structures, the monitoring justification becomes much easier. Other issues to consider are whether the structure is classified as fracture critical or scour critical, leading to increased risk. The more critical the structure is to the owner's system, the easier it is to justify a SM investment.

Need for Extended Service Life

Another factor to consider is how long the structure must stay in service without a major repair or replacement action. If the owner's capital plan is already oversubscribed, an investment in SM for critical structures with moderate to severe deterioration may be advisable to lower structure and overall system risk.

If the structure is currently scheduled for longer-term replacement, SM may still be justified to avoid unnecessary restrictions on loads or to assure user safety without immediate spending for extensive repairs, rehabilitation, or higher-frequency inspections.

Safely extending the asset life of a bridge presumed deficient generates the highest ROI for SM. Also, extending service life has been American Association of State Highway and Transportation Officials (AASHTO)'s highest priority for years and is reflective of long-term infrastructure funding challenges.

Existing Regulatory–Testing Requirements

While the National Bridge Inspection Standards (NBIS) protocol is federally mandated for bridge condition assessment, there are various references to monitoring within NBIS documents. For example, FHWA requires a plan of action for scour critical structures, before remedial action, that can be satisfied with scour monitoring, which includes SM. In this context, SM may be required instead of optional.

Owner's Funding Constraints

Transportation legislation requires owners to implement data-driven, risk-adjusted asset management plans. SM technology and solutions can play a significant role in meeting this mandate.

It is also important for SM solution providers to keep funding constraints in mind and work with owners to find the most appropriate technology/solution that fits both owner needs and means. Additionally, a number of state DOTs have successfully demonstrated that deploying SM solutions at the right time leads to a higher ROI for its taxpayers.

Access and Installation Considerations

Access to the structure for SM installation affects the cost of a monitoring system. As access becomes more difficult, installation costs increase. Access costs typically include traffic control, work platforms, and whether installation is conducted during daytime or nighttime hours.

It is frequently more cost-effective for owners to employ their own equipment and operators for both under bridge access (platform or bucket truck) and traffic control. These services are much more costly for a technology–solution provider to obtain than an owner to provide.

Installation services can be provided either by in-house personnel, technology–solution provider staff or a qualified third party (installation subcontractor). Demonstrated experience is crucial to conduct this scope; not only for adhering to technical details related to system installation, but the ability to work around traffic on bucket trucks or platforms and installation personnel safety. Any entity conducting an SM system installation should have a documented safety program, adequate and periodic safety training and sufficient liability insurance. Moreover, an experienced installer can more-effectively troubleshoot and resolve field issues during the installation.

Access to power is also important. While access to AC line power is often best, monitoring systems can also be battery operated with solar panels for battery recharge. However, care must be taken to ensure battery-powered monitoring systems work under demanding environmental conditions, e.g., very cold temperatures or long periods of time with minimal sunshine (autonomy). Isolation of the power source from lightning strikes is also important.

Durability and Reliability of SM Hardware and Software

The cost of an SM system is often a function of its reliability and durability. Since data capture, relay and storage are the primary functions of any SM system, higher levels of durability and reliability are typically worth the added investment. Due diligence from another owner's experience is highly recommended to evaluate potential differences in SM solution provider pricing.

For example, a wired SM system (sensor to system controller) will likely be initially more expensive than a wireless system, especially if conduit is included. However, a wireless system depends on battery power at the sensor to relay data from node to node, then to the controller. Replacing a small, sensor-mounted battery under a large structure (with traffic control and an access vehicle) can be very expensive and disruptive compared to a system that doesn't require repeated access. Moreover, wireless systems can be subject to transmitter interference and data loss.

Some SM systems require periodic maintenance or recalibration while others don't. The costs for these actions should be considered in initial planning and acquisition strategies. Costs for periodic maintenance and/or recalibration actions may be minimal, but similar to sensor-mounted battery replacements, the costs and disruption during access could be substantial.

Finally, the reliability of system software is also a critical issue that must be taken into account. Due diligence references from previous installations are recommended, but when the captured data is stored and accessed via the Internet, this adds to the ultimate costs of SM systems. When SM software needs upgrading, determine if that is done remotely or requires access to the controller on the structure.

Data Management, Analysis, and Recommended Actions

If captured data is stored locally (on the bridge) it requires periodic access to the system controller for retrieval, whereas transmission of the data to an off-site server using a cell network does not require such access. However, the data storage location can be a significant determinant of data reliability, e.g., a "server in an office closet" has different reliability characteristics than a professional data center staffed 24/7/365 with redundant servers.

Owners must also take into account the costs and personnel requirements for data review and analysis. Many owners rely on third-party consultants for this scope, which has proven to be effective, but can cost more. Other owners use in-house engineers for this purpose. Key issues to consider for data review and analysis planning include the following:

- Amount of data captured (number of sensors and capture frequency);
- Will the captured data and subsequent analysis be "actionable;"
- Structural experience and expertise for analysis, developing in-house expertise;
- Liability for analysis and recommendations;
- Personnel availability (who gets "data alerts" on the weekend);
- Costs of in-house analysis versus third-party consultants; and
- Data management—what organization is responsible for storing and maintaining the data?

Procurement, Owner Contract, and Long-Term Funding Mechanisms

Procurement of SM technology–solutions requires careful planning to execute in a manner that meets regulatory and practical constraints. For example, owners may consider competitive bidding, provider prequalification, or sole-source negotiation as distinct alternatives.

Competitive bidding requires a comprehensive and detailed scope (technology, sensor selection and placement, data capture, etc.) which may be extremely difficult and problematic if owner's staff is not intimately familiar with the technology or the firms providing solutions. Provider prequalification is an effective way to ensure proposals are only submitted by firms that have demonstrated experience and expertise. Sole-source procurement can be very effective (and acceptable) if an owner needs a certain unique technology or is convinced the provider is highly competent and will propose a unique technology–solution at a competitive price.

Owners may also have procurement challenges with long-term SM system contracts. If consultants are providing data management and analysis, this may be an issue if long-term funding is not dedicated to maintaining that contract. Structuring a contract so that the owner, after the initial SM term, can analyze the data in-house may be a more cost-effective alternative however; issues of expertise and liability then come into question.

Transforming Structural Monitoring Data into Knowledge

Obtaining objective, actionable structural performance data is the purpose of SM. Monitoring data alone rarely delivers actionable information unless proper engineering analysis is performed before developing the SM plan.

Once the appropriate structural performance parameters to be monitored have been identified following the guidance in previous sections, sensors installed to capture the in place structural responses, data collected and transferred to a central computer server, it then becomes available for engineering analysis. It's important to have this important information be easy to access, manipulate, and display.

There are many ways to store, retrieve, manipulate and display captured data, both with off-the-shelf software, or customized solutions for complex applications. For simple applications, SM data analysis can use spreadsheet applications to support adequate analysis, but are quickly restrained by data limitations.

As data requirements increase and larger amounts of data are collected by multiple SM systems, a cloud-based database is often utilized as the most-effective approach to facilitate utilization of captured data. Software programs specific to data display are typically used and can be tailored depending on the nature of the data.

The complexity and nature of the data captured, plus the desired analysis protocols will drive how an engineer or owner wants the data reported. It is important to work with the SM providers to devise a plan in which the captured data is presented in a format which supports the engineering analysis necessary for actionable decision-making.

TREND PLOTS

Trend plots are the backbone of structural evaluation, using time as the X axis, or abscissa. Trends can be established using a variety of data for the types of monitoring mentioned in previous sections, such as

- Plots of strain over a period of time,
- Pier movement (tilt) over time, and
- Crack growth over time.

These plots can be used to quickly visualize and evaluate maximums, minimums, anomalies and trends. For example, the data presented below in Figure 3 shows how a tie girder on an arch structure reacted to an overnight thermal cycle. In this particular example, it was desired to know the effect of thermal cycling constraint-induced strain to assess the fatigue life of welded details. If we expand this overnight cycle over several months, we can see how rain flow stress cycle counting (or an alternate method) could be used to determine the trend of how the strain behavior changes with respect to seasonality.

Depending on the needs of the monitoring, most global short-term SM benefits from data capture frequency of 10 Hz or less. The Nyquist criteria would suggest the system needs to sample data at a minimum of 20 Hz; 100 Hz would be a better choice if significant noise rejection (i.e., filtering) is needed.

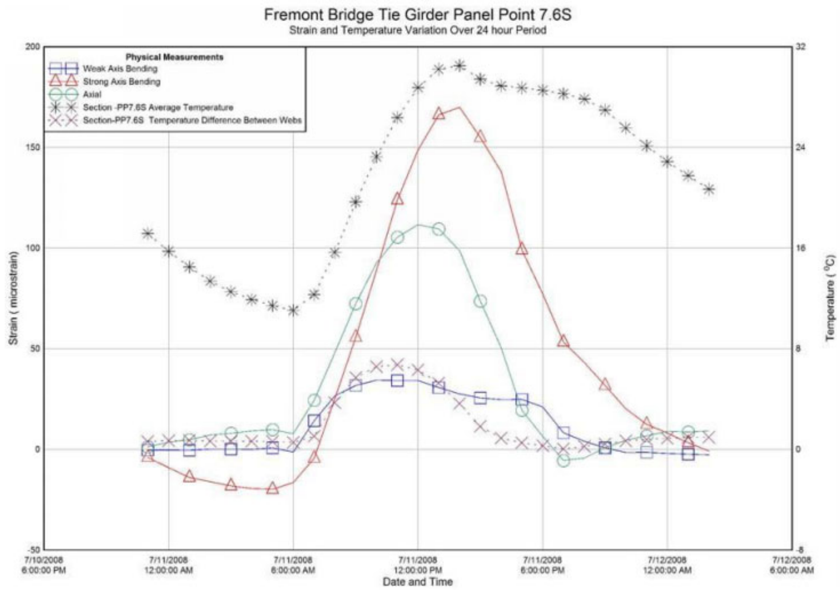

FIGURE 3 Example of thermal strain time history, showing one overnight thermal cycle, from a tie girder from the Freemont Bridge crossing the Willamette River. (Figure courtesy of Oregon DOT.)

Long-term monitoring of environmental and live load effects typically utilizes data sampled hourly or less frequently. Higher sample rates can be used over finite time spans and averaged to a single value which can provide effective noise rejection. Regardless, the frequency of response is an important parameter depending on the condition being monitored.

Live load data can sometimes benefit from capture at higher frequencies. Here, converting strain time histories into strain frequency, e.g., rain flow cycle counting, is one of the most useful forms of data analysis for fatigue studies. It offers the opportunity to convert thousands of hours of data into a single scalar quantity, the root-mean-cube (RMC), or “effective stress range.” Knowledge of the operating effective stress range can be used for simple evaluations by comparing it to the fatigue endurance limit of the details in question and determining if fatigue is expected to occur and predicting remaining life if the endurance limit is exceeded. Several widely available publications provide thorough examples of this process with rain flow cycle counting going back to 1975 and RMC to 1976.

Note that sensors can only capture data related to the change in structural behavior from the time that they were installed. There is no proven method yet to calculate structural condition or residual stress data prior to sensor installation, although research in this area is ongoing at the time of this publication.

TRIGGERING EVENTS

SM makes it possible to determine what levels of response are satisfactory and, if exceeded, suggests damage or a potential for imminent structural failure. A properly calibrated triggering program can be set to continuously scan for key data. Common events include, but are not limited to

- Structural strike,
- Earthquake,
- Overloads,
- Superstructure member displacement,
- Substructure misalignment or foundation settlement, and
- Scour or undermining causing substructure movement.

Also, unique triggers can also be established for a variety of data mentioned earlier:

- Anomalous strain data or rapid changes in strain behavior,
- Rapid change in pier tilt,
- Wire strand breaks,
- Rapid or sudden change in crack growth, and
- Exceeding predetermined safety related tolerances.

Using event triggers, structural knowledge to be verified is built into the monitoring system. For example, the engineer can determine what activity or trigger limit they know will negatively affect the structure and the SM system set up to capture it. It is important to note that, depending on the type of trigger limit being used, a balance must be struck between triggering false positives with too conservative a trigger or missing possible damaging events with a trigger that is not sufficiently conservative.

Additionally, if the trigger is for a wait-and-see event, environmental considerations should be incorporated (e.g., separation of the thermal response from live load). An example of an important trigger is to monitor bridges getting hit by over-height vehicles. Figure 4 is an image of a horizontal acceleration with clearly definable trigger limits reported with visual evidence when the bridge was hit. Thus, the owner and engineer had near-real–time images if the bridge needed prompt inspection to determine the severity of impact damage.

FIGURE 4 Triggered impact image. (Photo courtesy of Purdue University.)

In addition to images, triggers can be set to capture a predetermined amount of data prior to and after an event. Duration and volume of data can be predetermined based on informational needs and capacity of the monitoring system. For bridge strikes (pictured above), often only a few seconds of data are needed to capture the level of energy imparted on the structure.

Triggered events should be calibrated with respect to "normal" structural behavior in order for the data to be usable for structural decisions. For example, it is hard to tell if the strain reported on a sensor corresponds to an overload when the strain generated from normal truck traffic is not known. Thus, when setting up a triggered system, it is common to run a load test with a vehicle of a known axle weight and spacing to serve as a point of comparison.

In another example from Oregon DOT, truck loads were estimated using a calibrated model to set triggers that captured a record of the truck crossing. Plotting these values readily shows the outliers and the estimated truck weight (Figure 5). The engineer can then use this data to evaluate if certain weights are likely to damage the structure, allowing the owner to make more-informed decisions about the need for weight enforcement. Triggers are also a convenient way to capture a burst of dense, short-term data for analysis during a long-term SM application without overwhelming the data storage system with high-frequency data capture.

Continuous SM can be a convenient support for making operational decisions. Also, the use of geographic information systems (GISs) and graphical user interfaces (GUIs) can enhance continuous visual reference concerning structural response.

Continuous SM can be useful with various types of data, such as

- Visualization of near-real–time strain:
  - Overload tracking for permit (overweight) loads,
  - Effects of certain construction loads on structural response, and
  - Extreme weather conditions, including thermal responses;
- Pier tilt or bridge accelerations due to scour or unexpected impacts;
- Wire strand breakage;
- Potential fatigue damage at problematic locations or repair/retrofit locations; and
- Any of the trigger responses noted above could also be tied into a GIS system.

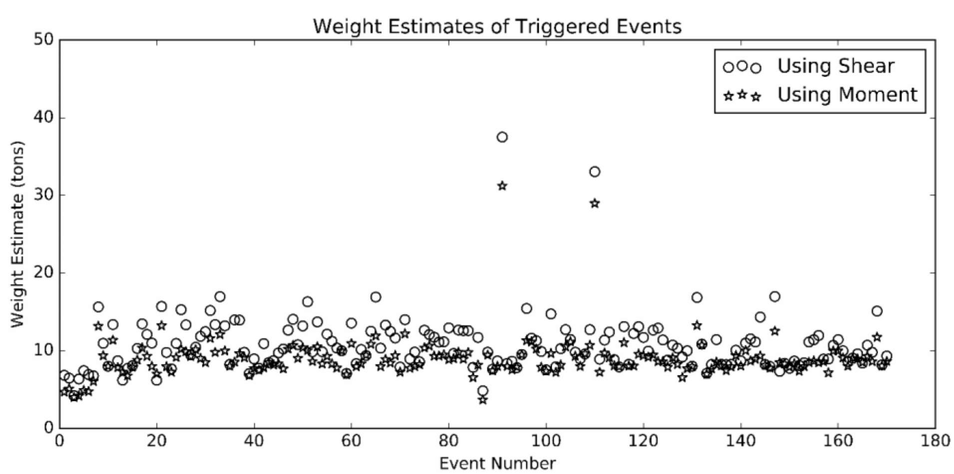

FIGURE 5 Weight estimate of triggered events on a bridge. (Figure courtesy of Oregon DOT.)

CONTINUOUS MONITORING

Like triggers, structural response knowledge that is derived from GIS–GUI monitoring is predetermined by the engineer. Yet, for most SM applications, the desired structural response knowledge is focused on ensuring safe operation, and can be likened to gauges on automobiles that indicate when fuel is low or when maintenance is needed.

The example shown below in Figure 6, containing sample data, is representative of a structure with sensors at various locations. The engineer worked with the owner to determine what thresholds trigger a warning that should be investigated (yellow), or something more critical that requires immediate service (red). This type of application is helpful in that it provides a quick visual indication of what issues need immediate attention and what issues can be addressed later.

Monitoring solutions that incorporate customized trigger events or GIS monitoring with customized GUIs can be expensive, complex, and should be evaluated to establish a ROI before agreements are reached between the owner, engineer, and SM provider. However, a useful approach to data presentation is shown in Figure 6. As a minimum, starting with simple, easy-to-understand data capture and presentation offers most SM users what is required to take appropriate actions.

Similar to trigger events, a baseline of normal behavior must first be established. This baseline must determine the normal behavior of the structure which can be surprisingly varied. A well-established baseline decreases the chance of false positives and increases the chance of capturing anomalies. Since each condition and each structure, as well as the target of measured response can vary substantially, this baseline observation period can be a few days or may require up to a year to sufficiently capture thermal cycles, which can be statistically separated before final analysis of how live loads are affecting structural response.

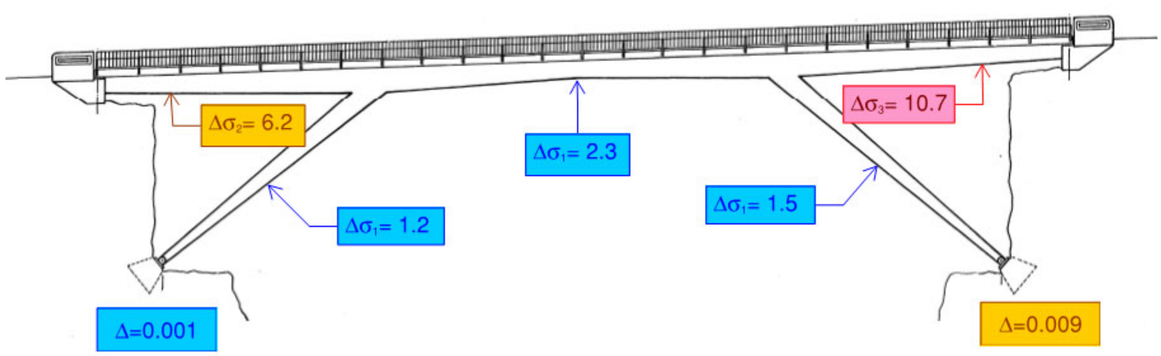

FIGURE 6 Example GUI for continuous SM.

COMBINATIONS OF DATA AND PRESENTATIONS

As should be obvious, each of the previously described types of data presentations and analytics can be and are often combined. Simple examples from previous descriptions follow:

- The truck overload trend plot can be used to both evaluate truck traffic trends as well as alerts coming from triggered events.
- GIS monitoring data can certainly be captured in addition to the visual cues and be used for trend plotting or triggered response. For example, it may be worth evaluating if a particular location trends to problematic as a seasonal effect, or results from a live loading effect; or if a recurring event triggers an indication of instability at a particular location.

In summary, SM can have substantial value in providing objective, precise and informed knowledge on how a structure is actually performing over time and with applied loads (both live and thermal), supporting more-informed asset management decision-making.

Ensuring a Financial Return from a Structural Monitoring Project

SM is another tool in the asset management tool belt, but not without cost. Owners should carefully evaluate the type and number of sensors installed, the amount and type of data captured, system maintenance, the time it takes to analyze the data, and the combined cost of each. In the context of SM, ROI or value can be generated several different ways:

- Increased safety by lowering risk for structure users and lowering liability exposure for owners and engineers who work with problematic structures (especially when difficult to objectively quantify);
- A finding that the structure being monitored is in better to much better structural condition than previously presumed from visual inspection followed by conventional analysis, allowing the owner to safely defer a major repair or replacement project;
- Development of lower cost rehab options, such as repair versus replacement; and
- Removing or reducing the impact of restrictive load postings.

SM solutions can range from relatively inexpensive to very expensive, so the judicious application of this technology is essential for owners to generate an ROI. Owners are urged to conduct due diligence on various SM technologies and solution providers, including key reference checks, before deployment to ensure they are purchasing only what they need and no more.

In particular, this includes an evaluation of how many sensors are necessary to meet monitoring objectives, how much data is captured and at what frequency, who conducts the analysis, and so forth. By balancing minimal data needs and analysis scope with expected costs, owners will avoid dissatisfaction with both the technology and the SM solution provider.

ALWAYS ASK: DO THE DATA HELP ME MAKE A MORE-INFORMED DECISION?

The actual ROI will only be confirmed after the project is complete and all costs and financial returns have been properly identified and accounted for. Yet it is important to plan for an ROI before an SM project is implemented. In the following paragraphs, we offer some guidance on how to make an owner's ROI both highly likely and financially robust. Achieving both outcomes is about picking the right structures for the right reasons and deploying the SM technology with qualified firms most likely to produce the desired results.

CANDIDATE STRUCTURES

The best candidate structures to ensure an ROI will typically be structures that are expensive to repair or replace, or are critical to the community in terms of indirect costs. This is due to the heightened probability of determining that a structure is in better condition than visual inspection indicated, meaning a major repair (but particularly an expensive replacement) can be safely deferred. For example, the ability to safely defer a $25 million replacement project, even using a nominal 5% interest rate, is worth $1.25 million per year. If an SM solution costs $250,000, the owner will experience a first-year gain of $1 million by reducing life-cycle costs. A more comprehensive financial analysis, including discounted future replacements cost, is worth consideration by the owner to pinpoint financial value.

DEFINING THE STRUCTURAL MONITORING OBJECTIVE(S)

A tight definition of SM objectives is crucial because it reduces or avoids spending more than necessary to capture the essential data. Over the past decade, strain, tilt, acceleration, and temperature have proven to be the most-effective sensor types, but there are a number of other sensor types that fill specialized needs, and others yet being developed. Data capture frequency is also crucial; less captured data drives lower data analysis costs and is often sufficient to meet project objectives.

FINDING THE BEST TECHNOLOGY–SOLUTION PROVIDERS

Demonstrated experience and structural knowledge of the solution provider have proven to be important elements of a successful monitoring project. Talking with previous owners who have used an SM solutions firm is often helpful to match issues with the available technology.

MINIMIZING THE COSTS OF STRUCTURAL MONITORING

The major costs associated with turn-key SM solutions include both hardware (data acquisition controller, sensors, power) and installation (cabling, access equipment, traffic control). Sensors and ongoing monitoring fees to store and present the data over the Internet are minor in comparison. Owners should always favor a solution that meets the following criteria to keep long-term (especially unexpected) costs to a minimum:

- Proven reliability of the technology supplier hardware (including power system) and software (long-term stability with remote updates as necessary);
- Proven ability of the installation team to minimize time on the structure during installation, minimizing owner costs for traffic control and user disruption; and
- Proven ability to reliably transmit captured data to a high-reliability data storage center and then to present the data over the Internet on-demand with triggering features as desired.

MAXIMIZING OUTCOMES FROM STRUCTURAL MONITORING

Simply put, an optimal outcome (meeting all SM objectives) from the use of SM solutions requires a minimized system (hardware and software) with proven high reliability, installed correctly the first time with minimal owner involvement, capturing minimal data, operating only as long as necessary to capture essential structural performance data, then allowing hardware redeployment (redeployment that lowers per-use costs) when the current project is complete.

The use of discounted cash flow is a reasonable method for calculating an ROI. Cash expenditures are input; costs avoided or positive cash flow are outputs; both are discounted year to year by using the time value of money concept. Discount rates are considered the cost of capital for a private firm (blend of debt and equity, e.g., cost of capital), but can be much less for public agencies that are funded by taxes. The use of a 5% discount rate is recommended as an easy-to-utilize ballpark first estimate.

Frequently Asked Questions About Implementation of Structural Monitoring Technology

SM is a technology-driven automated solution where sensing devices are installed and remain in place on or in a structure with the intention of capturing structural data on a continuous basis over a period of time for the purpose of quantitatively assessing structural performance. It is also the use of appropriate instrumentation for targeted evaluation a specific issue or issues on a bridge, such as refined load capacity, diagnosing unexpected movement, validating an unusual or new design method, or assessing cracking or other unusual performance. Twenty frequently asked questions about SM and their answers follow.

1. Is SM technology considered proven and commercially available?

- Many SM projects have been successfully planned and implemented by states and other bridge owners over the past decade. Well over 20 state DOTs have already used the technology in one form or another to meet their specific needs. These systems have been planned appropriately, designed to provide the proper data to answer specific questions, collect data efficiently, installed by qualified and knowledgeable personnel, and configured for the needed time frame.
- SM technology has been available for more than 20 years. With a variety of vendors, it is considered commercially viable and has proven its capability to provide ROIs with appropriate planning and analysis before implementation.
- Off-the-shelf SM technology is one of many complimentary NDT technologies that are available to help assess the condition of bridges and other structures.

2. Is SM technology widely available?

- There are multiple consulting firms that are familiar with SM implementation. There is also a wide array of different technologies and solution providers who have substantial experience deploying SM on transportation structures.
- The technology is flexible enough so that different systems can be customized to target the type of SM required. Industry experts are typically available to discuss alternative solution approaches before procurement.

3. Should we prequalify SM solution provider firms?

- Similar to all consultant related services, prequalification is a reasonable step to ensure SM providers are properly vetted prior to bidding on a project or to provide proposals.
- Conversely, prequalification could exclude new technologies or limit options for open bidding where a certain SM solution or provider is desired. In those cases, sole-source procurement may be implemented if warranted.

4. Can we use standard procurement methods to purchase these solutions, or does every bridge require a unique solution, suggesting the use of performance specs?

- Standard procurement methods have been successfully used by several DOTs and other structure owners. Understanding proper scoping and terms of service, however, are critical so as to maintain appropriate expectations for installation, data transference, and system maintenance. Additionally, the objective for a given structure may dictate procurement of specific technologies with unique capabilities which should be considered when preparing a scope of work. The type of performance being monitored can also affect the procurement process.
- Typical procurement methods, containing detailed specifications and drawings, can be used once an owner gains sufficient experience with specific monitoring systems. If SM is new to the owner, it may be difficult to prepare a detailed design or scope of work. This presents difficulties for procuring SM technology, simply because there are a variety of sensors, controllers (data acquisition units), and approaches that typically cannot be combined into a single document. In this case, use of a consultant firm with significant SM experience may be the most-effective procurement alternative.
- If there are three to four prequalified firms, a performance specification with drawings should be acceptable to conduct a "technical approach and value" procurement.
- If there are only two prequalified firms, consider negotiating with both, then selecting the highest-value proposal.

5. How can we work with patented and/or proprietary technology?

- SM technologies are sufficiently commercialized so that patented technologies are required less often. However, there is always the potential for a sole-source procurement, depending upon specific performance requirements, which can be more important than the need to implement competitive bidding. This situation can be addressed using existing procurement methods. Additionally, if the owner can accurately specify performance capabilities, there may be other technology options available which are not commonly known. This approach provides owners with access to a wider range of feasible technologies.
- The FHWA recently published a notice of proposed rulemaking that suggests sole-source procurement of patented and proprietary technologies may be both appropriate and acceptable in certain situations. FHWA also has a policy that allows sole-source procurement with stipulated justification.
- The use of patented or proprietary technologies should be driven by defined need as part of the SM solution and should not be dismissed as inappropriate if the need is established.

6. What existing structural conditions suggest the use of SM technology?

- SM technology is typically focused on collecting data to support structural assessment of the superstructure. For example, if severe section loss was noted on prior inspections, it may make sense to determine, using SM technology, if key members have sufficient remaining structural capacity. Owners can't necessarily reach that conclusion by relying solely on visual inspection findings.

- SM technology is also useful for monitoring the performance of specific elements or components of a bridge to verify the progression or effects of visible defects, e.g., cracks in steel or concrete, out-of-plane bending, or the proper operation of bearings.
- SM technology can also be useful for monitoring substructure movements, but keep in mind that substructure failures can be brittle (rapid) in nature. It may not be judicious to rely solely on SM technology to provide timely alerts in cases where scour or a related foundation failure can cause collapse.
- Small movements, such as those causing moveable bridge span locks to engage, have been successfully monitored and diagnosed with SM.

7. For what reasons do structure owners utilize SM technology?

- Primary reason: to provide objective, repeatable, precise, and timely global performance-based data, supporting difficult and expensive decisions related to structure repair, replacement, risk assessment, and safety enhancement.
- Secondary reasons: to more accurately determine safe load ratings or to monitor known defects, e.g., steel or concrete cracking or out-of-plane bending to determine impact of these defects, how quickly they are progressing, and when to schedule rehab actions, as warranted.
- Other reasons include: to verify or reject findings from visual inspections that relate to maximum permitted load capacities, load demand, proper bearing operation, pier rotation, or related structural anomalies.

8. Can we use FHWA funds as part of the NBIS bridge inspection program to pay for SM technology–solutions?

- Yes; certain federal funding can be used for inspection, evaluation, and monitoring.
- Another option to make funds available for SM is to extend the routine NBIS inspection intervals for bridges in very good condition (must be approved by FHWA), then applying the saved funds for supporting SM projects or a long-term program.

9. Is it likely we will get a ROI from use of SM technology?

- From project inception, you should plan to get a ROI.
- Bridge preservation (extending service life) is probably the most financially powerful objective and the simplest ROI to calculate when using SM.
- Improving load ratings is an easy-to-confirm financial impact, for which an ROI can be easily quantified by valuing the reduction in truck detour lengths.
- Subsequent to verifying the efficacy of repair and retrofit prototypes, prior to widespread implementation across a state, should be a relatively easy financial measure to quantify.
- Other objectives, such as risk assessment, monitoring defects, or proper operation of bearings are more difficult to quantify, but viable nonetheless.

10. What project or program objectives typically support the most-effective use of SM technology?

- Some large signature bridges have justified the use of SM technology for global or targeted structural performance assessment using the objective of extending service life (e.g., bridge preservation or verification of design assumptions and initial performance baselines for new signature bridges). The downside of large, complex monitoring systems is their cost and the large amount of data collected that requires sophisticated storage and analysis protocols to be meaningful and actionable. Some of these systems have been shut down after a few years based on the realization that very little actionable data was being collected.
- A second, often more-effective use is to develop bridge preservation options other than full-scale replacement. For example, it may be more cost-effective to rehab an old bridge rather than replace it, but in order to reach that conclusion; owners need to determine if the remaining members or structural components are in sufficiently good condition to support a rehab option. It is also likely to take no action if it can be determined the bridge is performing better than expected, when compared to the findings from visual inspection.
- A third use that has proven effective is to reduce structural and user risk by monitoring the progression of visual defects, such as cracking, out-of-plane bending, or proper bearing operation.
- A fourth use that has proven effective is to provide data for the objective determination of safe load capacity using the AASHTO *Manual for Bridge Evaluation* Chapter 8 alternative load rating protocol or a variation thereof.
- A fifth use is to determine load demand by leaving the sensors in place for some time (months) to ascertain the strains–stresses caused by traffic using the structure. This use provides useful data to manage structural risk or support load-enforcement actions.
- Importantly, new applications and innovative SM project objectives are being developed every year, both by SM technology suppliers and owners.

11. What type of sensor should we consider using for various structural issues?

- Accelerometers are typically used to determine a global structural modal response, or "signature" (most often for large, expensive, new structures) that can be compared to subsequent modal response "signatures" to ascertain if significant structural changes have occurred. These sensors capture a substantial amount of data, which can be difficult and expensive to analyze, and have limitations in pinpointing the location of structural anomalies after modal changes occur.
- Strain sensors are the most versatile and cost-effective sensor type for determining the performance of individual structural members or the entire superstructure. There are a variety of strain sensors on the market, with varying degrees of accuracy and cost. Some can be used for a variety of applications; others for capturing only tensile strain. Some are reusable.
- Inclinometers are highly useful for determining minute substructure movements, such as tilting or proper bearing operation. These sensors are relatively inexpensive, but they are highly accurate and can be reused as warranted.
- AE technology is generally a stand-alone application that captures and processes noise from new or propagating steel cracks, posttensioned cable breaks on box beams, or other structural anomalies.

- Displacement sensors (strain, cracks, and crack detection) can be used to determine if bridge bearings are operating properly, the travel of expansion joints, concrete or steel crack-width monitoring, crack propagation, or out-of-plane bending. See the section on Types of Structural Monitoring Sensor Technologies for more-detailed descriptions.
- Temperature sensors are critically important to include in any monitoring scheme, allowing statistical correlation with captured displacement–strain sensor data to determine the impact of changes in temperature (delta T) on observed strain data. The ability to statistically separate the impact of temperature induced displacement–strain data from live load data is essential for determining the impact of controllable factors (live load) from uncontrollable factors (weather) when considering structural member capacity and overall structural integrity.
- Laser-based instruments technology is used to capture significant structural displacements, normally from a ground position, such as deflection.
- Fiber-optic sensors typically captures both strain and temperature on one fiber cable. Particularly useful for long structures where one cable can carry a substantial number of individual sensors.

12. Does the precision of commercially available displacement–strain sensors make a difference for decision-making?

- Within reason, generally not, but it's always good to understand the sensor limitations, so that engineering judgment (always important) can be used with increased confidence.
- You will typically pay more for hyper-accurate sensors (~1 microstrain), but you should determine if that level of accuracy will result in a different decision based on that level of accuracy. Realism and engineering judgment should always be used in the selection of sensors.
- Most applications work effectively with displacement sensors that are accurate to ~5 microns (average human hair is 80 microns in diameter) or strain sensors that are accurate to ~20 to 30 microstrain (~1 ksi). Given the significant impact of temperature changes on captured displacement–strain data and the ability to statistically separate this impact, engineering judgment is still a very essential element of data analysis.

13. How much data should we expect to capture?

- That depends upon the owner's needs and preference, the SM technology provider's efficiency, the need for future data analysis, and overall project objectives. Generally speaking, capture what's needed and no more.
- Capturing data at 1,000+ Hz, will quickly overload data storage and make future analysis difficult and expensive. On the other hand, accelerometer data must have high-frequency data capture to be meaningful.
- Capturing data at much lower frequencies will lower costs and reduce the time and complexity for future analysis. A preferred approach is to reverse engineer the monitoring system by starting with your project objectives, determining data need and then have the system configured to capture the data needed at a desired frequency for future analysis.
- Another key consideration for data capture is sensor "polling," or interrogation frequency, particularly when owners want out-of-tolerance (trigger) alerts to be sent to responsible parties. That situation may require sensor polling every minute, but data retention at lower frequencies.

14. Where will the data be stored and will the data be secure?

- This is a critically important consideration and must be discussed and evaluated before a project is designed and procured.
- Data can be captured locally (on the bridge) in self-contained data acquisition controllers, for download by the user at a later time.
- More often, after capture by a local on-bridge controller, data are transmitted via a wireless communication system (cell towers) to a secure remote server for on-demand display in an Internet-enabled application.
- Data reliability is crucial, especially if the monitored structure has significant defects or is structurally problematic. Having the data stored in a server that is not attended 24/7/365 will have lower overall data reliability when compared to data housed in a commercial data center that is attended continuously, has back-up, or mirroring capability, and measured proof of its on-line availability. There is no reason why a highly reliable data stream (e.g., .9999) can't be assured by the SM technology–solution provider.
- When using a commercial data center, data security is of utmost concern and should be confirmed by the data center operator and SM solution provider.
- Data reliability should be fully addressed and considered for evaluation of solution providers as the part of a monitoring system configuration.

15. Who is best suited to conduct the analysis on the captured data?

- That depends on the amount of data captured, the experience and capacity of an owners' organization, and what is needed to meet project objectives.
- For simple SM projects, such as load rating short-span bridges, DOT in-house personnel may be fully capable of conducting the necessary analysis.
- For complex SM projects, such as conducting the structural assessment of a large or complex bridge, the necessary analysis may include development of a calibrated finite element model (FEM). Some state DOT personnel may have the experience and capability to conduct an FEM analysis, but do not do it routinely and therefore decide to outsource that scope.
- Third-party analysis is reasonable if the owner expects to transfer some liability to the consultant conducting the analysis. This is a key consideration for owners.

16. Will the hardware we purchase be reusable on different bridges? Should we consider renting or leasing equipment?

- That will depend upon your procurement objectives, the SM technology provider's business methods, and the robustness of the hardware. Data collection and storage devices are commonly reused, but many sensor types are not manufactured for reuse.
- Reuse will significantly reduce the per-use cost of SM technology, especially if the owner expects to deploy systems on other structures over time.
- Reuse will typically require re-engagement of the SM technology provider, since the skills and experience to develop a customized SM solution with various components and secondary suppliers (e.g., cell system vendors) is only done by a few state DOTs.
- Renting or leasing equipment may make sense for short-term monitoring and some equipment providers may offer this option. As with everything else, the choice to rent, lease, or

purchase is a matter of cost with respect to the overall project objectives and long-term asset management plan.

17. Who will install SM systems for us? What qualifications should they have?

- Experience matters and that should be thoroughly vetted before project award.
- The owner should ask for and be satisfied with the installers' safety program and insurance experience factors (workman's compensation data).
- Some SM technology providers conduct installation using their own personnel. That can be beneficial since they know how the system is configured and should be installed, but may be more expensive if those personnel are engineers. Other providers (universities) may use graduate students with limited insurance coverage or safety training. In either case, adequate insurance coverage and safety training–procedures must be confirmed before project award.
- Some SM technology providers use qualified electrical contractors who have the requisite experience installing control systems. One important consideration is the ability to safely tap into line power (240/120 V) on the bridge or install a battery–solar power system which connects to the controller. Power connections must be done with utmost care.
- A highly qualified SM technology provider will support the installation company with a project manual that explains and guides every step of the installation, reducing the probability of errors or loss of critical data.

18. Should we expect a warranty on system operation?

- Yes. A 1-year commercial warranty is reasonable and will help ensure a quality installation that operates as expected. Be sure to understand the terms of the warranty and ensure the data collection system is completely covered. Understand any contingencies and the potential cost of lost time and data.

19. Are there any general guidelines for what we should avoid when adopting SM technology?

- Avoid using unqualified SM providers with minimal experience, lack of installation expertise, that are uninsured, or do not have adequate safety practices.
- Avoid over-sensoring for the sake of collecting data. Use good engineering judgment when determining the number of sensors.
- Avoid excessive data capture frequency, as that will increase costs and data analysis complexity.

20. What is considered the best way to start the process of SM technology adoption and what could it possibly lead to?

- Consider beginning with a pilot project; maybe one to three structures with different SM applications such as
  - Load rating a short-span bridge;
  - Defect monitoring—cracks, bearing operation, out-of-plane bending; or
  - Global performance assessment of a larger, expensive-to-replace structure.

- Next, move to a comprehensive SM project, including third-party FEM analysis, to extend the life span of a major bridge.
- When you are comfortable with all aspects of this process, consider a long-term, multistructure program to significantly reduce the number of deficient bridges in your inventory by using objective, precise, and timely structural response data to ascertain structural performance. You may then want to consider developing a guide within your state for when the use of SM is appropriate and useful given your inventory, weather conditions, and procurement practices.

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