Value and challenges of structural monitoring for long-span bridges

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ABSTRACT: Over the coming years, bridges and other physical infrastructure will experience unprecedented demands due to extreme weather and trends in freight. These increasing demands are set against a backdrop of infrastructure deterioration as many assets reach the end of their intended service life. Bridge owners have done a significant amount of work to identify vulnerabilities in their infrastructure but challenges such as budget constraints and environmental complexities limit their ability to adapt. The proper application of technology, however, can help bridge owners safely extend the useful life of their structures. This can be done by gathering information that can be used to optimize lifecycle costs, to better quantify vulnerabilities, and maintain situational awareness to mitigate risk. This is particularly important for long-span bridges which require a disproportionate amount of maintenance expenditures and would cost billions of dollars to replace. However, there are still multiple challenges to deploying a cost-effective structural monitoring system that provides easily understandable and actionable information. This paper will provide an overview of the current practice of managing long-span bridges using structural monitoring (SM), examining both new and existing bridges. The paper will draw on the authors' combined experience working with numerous bridges, each with more than one hundred sensors. The need for new and improved resources for handling the large amounts of data generated by these systems will then be discussed. Finally, a vision for the future of SM for long-span bridges will be presented.

1 INTRODUCTION

Structural health monitoring, or as more commonly called now just structural monitoring (SM), is a process that involves observing and analyzing a structure over time using periodically sampled response measurements. It has been evolving since the earliest applications on bridges in the 1990s as the technologies behind SM have advanced (Brownjohn 2007). It is an ever-emerging tool for structural engineers and asset managers to improve the accuracy associated with structural performance prediction and leads to more rational life-cycle management of bridge systems under uncertainty and can also increase safety.

Physical parameters that can be measured with sensors include strain, displacement, temperature, vibration, rotation or tilt, crack growth, and even acoustic events. At present there are many companies that can provide off the shelf instrumentation equipment for this purpose. The challenge is developing a SM system that provides valuable and actionable information and therefore a favorable return on investment (ROI). This requires technical expertise, experience, and sound engineering judgement.

At its core, the goal of SM is to better understand structures. This is often done to better understand a specific problem or concern. The data captured can also be useful in the future as additional questions arise. SM can range from a full bridge system intended to last the life of the structure or a targeted investigation meant to capture only a few minutes of dynamic data. It is the responsibility of the SM system managers and engineers to provide this data to all stakeholders with the appropriate context and with a full discussion of the limitations inherent with each sensors technology.

Over the last decade there have been significant advances in SM technologies that have continued to make SM more cost effective. For example, low powered wireless sensors eliminate the need for cabling. As the costs for SM continue to drop, and the reliability and accuracy of the systems continues to increase, the value of deploying SM technologies to obtain more accurate, quantifiable, and reliable diagnosis of current condition has become more appealing to bridge owners.

Structural monitoring has been shown to lead to less-expensive interventions, improved prioritization of projects, or both. When there is more uncertainty in information, decisions tend to be more conservative. By having more refined information, the potential savings associated with lower intervention costs by eliminating unnecessary interventions and focusing resources where they are most needed will likely offset the cost of SM implementation (Miceli, et al. 2019).

While SM has been used on bridges of all types and sizes, the return on investment (ROI) has been more easily quantified on long-span bridges. These structures require a disproportionate amount of the owner's maintenance funding. The SM data can be integrated into the structures asset management plan and provide information useful to long-term planning by tracking the degradation of critical components such as joint and bearing movements, fatigue assessment, and wire breaks. This paper will focus on the use of SM for these long-span structures.

2 APPLICATIONS ON NEW AND EXISTING BRIDGES

As discussed above, structural monitoring is an important tool for ensuring the safety and longevity of bridges. However, the application of SM can differ significantly between new and existing bridges.

For new bridges, SM can be integrated into the design and construction process. This allows for the installation of sensors and other monitoring equipment before the bridge is completed. Engineers can then use SM to ensure that the bridge is constructed to the required standards and specifications, and to identify any potential problems or defects before the bridge is put into service. This can include monitoring the stresses and strains within the structure, measuring the deformation of the bridge components, and monitoring the behavior of the bridge under different loading conditions. Additionally, SM can be used to verify the structural integrity of the bridge during construction, allowing for any necessary adjustments to be made to the construction scheme. Establishing a baseline of behavior at the end of construction can lead to more effective and efficient maintenance, as more accurate predictions of the bridge's behavior over time can be determined.

For existing bridges, the application of SM can be more challenging. Applying SM systems to existing bridges can be more challenging due to factors such as limited access to the structure, the need to retrofit power and communications, and the application of sensors to aging components. Additionally, the condition of the bridge may be unknown at the time of application, which can make it difficult to interpret the data collected. However, SM can still be effective for existing bridges if deployed to quantify specific behaviors of interest. This is especially if used in conjunction with other inspection and maintenance techniques. By identifying potential issues early, SM can help extend the lifespan of existing bridges and minimize the risk of major failures.

Overall, while the principles of SM are the same for both new and existing bridges, the application and implementation of SM techniques can vary significantly depending on the specific characteristics and conditions of the bridge in question.

3 VALUE OF STRUCTURAL MONITORING

When carried out appropriately, SM can establish a quantitative record of a structure's behavior during the time of monitoring. The in-situ observations of a structure's actual behavior can prove a valuable piece of information for structural engineers and bridge owners alike but must be considered alongside other information sources and not utilized as the sole source of input. The following sections discuss different areas where SM can provide value.

3.1 *Bridge operations*

The operations team for a long-span bridge is responsible for maintaining traffic flow while also prioritizing the safety of the traveling public. Key SM sensors can provide this team with real-time information to make operational decisions. For long-span bridges, one of the most critical data streams will come from the anemometers which provide wind speed and direction.

When a storm or high winds are expected, incoming data can be reviewed to determine if traffic restrictions on the bridge are necessary.

Some structures also utilize temperature sensors that report the roadway temperature. These sensors can help the operations team decide if action is required to mitigate icing of the roadway or warn motorists. Fog sensors are sometimes used to quantify visibility conditions at strategic locations. Depending on the bridge and operational concerns, SM data can also be integrated with other data sources such as weigh in motion (WIM), bridge cameras, and intelligent transportation system (ITS) data to provide greater situational awareness to the operations team.

3.2 *Bridge maintenance*

Bridge maintenance teams perform regular work to preserve the structure and extend its service life. Historically, articulated components are the first elements of a bridge to show wear. For most structures, this means bearings, pin/link assemblies and the expansion joints between different segments of the structure.

Expansion joints on every bridge are subject to infiltration by debris as well as wear over time. Some SM systems include displacement sensors at these expansion joints to measure the opening and track movement. A change in joint behavior can be a signal that debris removal or maintenance is required. Changing behavior could also be an indication of broader structural trends. Following expansion joint maintenance and debris removal it is important to review SM data to verify the previous behavior regime has been reestablished. In the event of a permanent shift in response, a structural engineer should be engaged for a detailed review. Strategically monitored bearings or pin/link assemblies can also provide crucial insights to a bridge owner, especially if wear or lock up is suspected.

In addition to the monitoring of articulating components, corrosion sensors can be added at the time of construction to provide insights into the condition of reinforcement below concrete cover. These sensors serve as a spot check of concrete deterioration and can be supplemented with periodic non-destructive testing when a broader area of investigation is warranted based on the SM data. Information from the SM system should inform bridge life cycle cost estimates and preventative maintenance planning by confirming assumptions on service life and performance degradation of articulated components over time.

3.3 *Extreme events*

Extreme events include, but are not limited to, ship impact, sabotage, hurricanes, and seismic events. After an extreme event, there are two-time scales to consider: instantaneous (during the event) and long-term (after the event). During the event, metrics like peak displacements, tilt and accelerations should be considered. These should be reviewed against design criteria and predicted performance levels to identify potential overstress and other adverse conditions. They can also be compared to the typical operational envelope to give a sense of how much the event impacted the structure. Separately, the high-resolution data during the event should also be reviewed if available and preserved indefinitely to document the event. If necessary, the high-resolution data can be reviewed by an engineer with experience in dynamics by performing analyses in the frequency domain.

The ability to initiate post event forensics with a detailed baseline data set and data from the event itself will likely be very valuable for the bridge engineers investigating. A proactive step for all bridge owners with monitoring system is to routinely review and analyze data sets. There will inevitably be unique characteristics about the structure's behavior and the way the sensors report data. Understanding these unique aspects prior to an extreme event allows a timelier assessment of the what the structure experienced.

In addition to reviewing data from before and during the event, general behavior should be closely monitored for the days and weeks following the event to identify any responses which deviate from typical behavior before the event. If the structure behaves in a consistent manner with baseline behavior, this may provide a quantitative indication that the structure did not experience significant damage. Deviations in post-event responses likely indicate damage was incurred.

SM findings should always be reviewed concurrently with post-event visual inspections and other evaluations to ensure consistency of measurements with actual observed conditions. Note that behaviors associated with thermal response (e.g. bearing and joint displacement) may require sufficient change in ambient temperature to fully assess structural response; post-event data review should be extended as required to properly assess these effects.

Because a sensor can only report one type of data (and in the direction it is oriented), the sensors on the bridge may not provide a complete picture of the condition. Sparsely spaced sensors may yield an incomplete view of the behavior. The completeness of the data set should be considered when making critical engineering decisions.

3.4 *Value during inspection*

In the United States, all bridges that are part of the National Bridge Inventory (NBI) are subject to inspection according to federal regulations. The NBI is a database of all bridges on public roads maintained by state and local governments, and it includes more than 600,000 bridges. By default, routine inspection intervals are based on defined cycles and occur at least once every two years. However, some bridges may require more frequent inspections if they are deemed to be in poor condition or if they have a history of structural problems. Bridge inspectors are required to evaluate all elements of the structure within certain guidelines. The presence of an SM system is not intended to replace or otherwise reduce the depth or breadth of this inspection. It can, however, allow a two-way information flow between monitoring data and inspector findings. In addition, SM can help justify extended inspection intervals as outlined in a recent memorandum from FHWA (FHWA 2022) and the implementation guidance found in NCHP Report 782 (Washer, et al. 2014). Because these provisions are relatively new, the implications of technology on improving ROI in regard to extending inspection are yet to be seen.

If structural behavior reported by the monitoring system has identified areas of interest or concern for the bridge owner, they can use this information to request additional in-depth inspection of targeted areas by the bridge inspectors. This would be particularly pertinent for joint movement but could apply to other areas as well. Separately, if new areas of deterioration are identified by inspectors, the SM system may be of use to assess behavior related to this element both in the current time frame and historically if existing instrumentation is present or going forward by adding supplemental instrumentation. The greatest gains can be made when both inspection information and monitoring data are reviewed in tandem.

3.5 *Understanding in-situ wind behavior*

A critical characteristic of long-span bridges is how they respond to wind. This is a key consideration during the design phase and is something bridge owners consider throughout the life of the structure. Even small changes to a main span cross section can have outsized impacts on how a bridge behaves. Luckily, the prediction of wind response, using both computer models and scaled physical models, has advanced significantly in recent decades.

There is still value, however, in quantifying wind speed and direction alongside tilt and acceleration of main span components. By collecting and analyzing this data, long-span bridge owners can confirm previous simulations, quantify behavior under multiple wind speeds and directions, and assess bridge responses, especially if the main span cross section changes.

3.6 *Long-term trends*

Over the service life of a structure, behavior inevitably changes, and deterioration (either minor or major) is experienced. A monitoring system, especially one that has been in place since the end of construction, can provide great value since it allows the comparison of response over time. This will allow engineers to make more informed decisions based on deterioration trends. The baseline data set is the first few months or years after the SM system goes live and serves as a snapshot of the structural behavior at that time. Having this initial data set can prove valuable to bridge engineers in the future. A few example parameters are discussed below.

Settlement of bridge substructure can create numerous issues including forces and deflections not considered during the structure's design. One of the greatest areas of concern is differential settlement where one pier settles more than adjacent piers. This often changes the way load is experienced by the superstructure. GPS units at strategic locations can provide a bridge owner with a better understanding of overall settlement. Long-term settlement can also be tracked by conventional survey or high-resolution 3D survey (LiDAR or other) with comparisons being performed between different surveys. For more immediate settlement concerns (typically 6–24-month timeframe), automated total stations (AMTS) can be utilized to track displacement in 3 dimensions on a frequent basis.

Pier tilt is another important trend to track over time. Typically, pier tilt response is driven by both daily and seasonal thermal cycles, so changes in behavior may not be evident from shorter data windows. However, trends may become evident when data is examined for long-term patterns across years of cyclical behavior. Bearing and joint movement behavior can also be tracked similarly with a thermal perspective since a frozen joint or bearing may contribute to the observed pier tilt.

Dynamic data can be reviewed for variation in characteristics over time. This does, however, require the indefinite storage of data samples. A review of this data from the past compared to the present can indicate changes in structural response. One method would be to look at the frequency, mode shape or damping characteristics of the high-resolution data. A significant change in these metrics could indicate scour or other changes in boundary conditions. Another method would be to compare the range of responses (maximum and minimum) under similar loading conditions from past and present.

If summary data that includes maximum, minimum and mean values is stored indefinitely, the value of the information gathered will only increase over time. Over the years, as issues arise and areas of interest emerge, the bridge owner will have the ability to quickly look back at trends, behavior and changes. Additionally, the effects of concrete creep and shrinkage could be examined.

Bridge owners typically use threshold alerts to automatically identify changes in structural behavior. These pre-set limits are created based on baseline data and can provide early warning of a deviation from past structural responses. While these thresholds can provide value by informing the bridge owner of changes, they can be difficult to set. Thresholds set too narrowly will lead to many alerts while thresholds set too wide may not identify changes in structural behavior. Thresholds are discussed further in the challenges section below.

3.7 *Targeted investigation*

Much of the discussion above is focused on the value SM can provide over a long timeframe, typically as a permanent installation. Targeted, short-term investigations can also provide value when specific questions and concerns arise. By utilizing rapidly deployed monitoring instruments, bridge owners and their consultants can quickly perform investigations. One example would be measuring the acceleration of a stay cable or vertical suspension cables (Li, et al. 2012). A frequency analysis can be performed on this data and an approximation of cable tension can be determined using taut string theory. Separately, bridge element can be evaluated with an accelerometer to better understand the vibration effects of live load and on certain days, wind load. In certain circumstances, the vibration characteristics observed can be utilized to assess that element's fatigue life.

Another example of a targeted investigation would be using inclinometers to track the response of bridge piers or articulating components against daily thermal trends. Reviewing this data can provide insight into issues like bearing lock up, constrained joints or the cause of cracks in a bridge substructure. For owners who oversee multiple long-span bridges or a large inventory of smaller bridges, an investment in a ready deploy kit and staff training can allow quick collection of critical information when needed.

3.8 *During construction activities*

When construction or major rehabilitation takes place adjacent to an existing structure, monitoring can be deployed to confirm that key parameters of the existing structure remain in a range predetermined by engineers. Many owners have standard specifications for vibration and displacement during construction which serve as a starting point for engineers creating a monitoring plan. There is no "one size fits all" for this type of application and the required parameters depend on the project's context and the owner's risk profile, especially for long-span bridges.

3.9 *Structures at end of intended service life*

As structures near the end of their intended service life, owners are faced with challenging decisions. While full replacement may be the superior technical option, minor repairs and deferment of replacement may be more practical based on financial and operational constraints and is often a more sustainable option. When replacement in the near term is not feasible, SM can serve as an important component of a risk mitigation strategy. Tracking key parameters with sensors and utilizing real time alerts can provide bridge owners with situational awareness not achievable, or not practical, by inspection. When compared to a full replacement, the cost of an SM system is negligible, and the return on investment can clearly be demonstrated.

3.10 *Integration with other data sources*

While SM can provide value to bridge owners and structural engineers in multiple ways, it still remains only one tool in the toolbox, not a data source that should be used singularly. The greatest gains can be achieved when data and insights from structural monitoring are combined with other data sources. The preceding paragraphs discussed the value of combining SM data with weather (specifically wind), bridge inspection and bridge operations. This section will briefly touch on the potential value of combining it with Weigh in Motion (WIM) data and non-destructive testing (NDT).

WIM is the process of collecting axle weights and spacing of vehicles at highway speeds. The systems can be either temporary or permanent (higher level of accuracy). Data collected can be used for enforcement of overweight vehicles, freight planning, assessing environmental impacts and determining actual pavement loads. It can also provide significant insights to bridge engineers and bridge owners alike.

The industry currently utilizes a factored design truck and a statistical assumption about truck distribution. Live load demands are not one size fits all and there are bound to be significant variations in both gross vehicle weight and truck distribution between regions. It should be noted that some states and bridge owners have created heavier design trucks to account for local variations, especially if the bridge is near a port or large manufacturing or agricultural base. A WIM system near a bridge site provides the bridge owner with a detailed understanding of the truck weight and spacing. Analyzing this data alongside structural behavior can yield critical insights since both demand and response are quantified.

NDT is a method of testing or evaluating the condition of a bridge without causing damage to the structure. NDT is commonly used on bridges to identify defects, such as cracks, corrosion, or other forms of damage, that may affect the safety and structural integrity of the bridge. NDT techniques can include ground penetrating radar, impact echo, ultrasonic testing, radiography, magnetic particle inspection, and other methods that can detect defects in the bridge materials or structure without causing damage. These techniques are useful in identifying issues that may not be apparent from visual inspections alone and can help engineers and maintenance crews to identify and repair problems before they become more serious.

As discussed above, SM data collected on deteriorated structures near the end of their service life can be crucial to assess remaining structural capacity and validate structural integrity. When this SM data is reviewed alongside NDT findings for critical elements, the bridge owner can better quantify risk and make prudent decisions related to public safety and planning rehabilitations.

3.11 *Partnership with academia*

The real-world data gathered by a SM system will likely be of significant interest to the academic world and may be worth sharing given a suitable partnership. Data potentially valuable to academia would include extreme event (for example seismic) responses and long-term (multi-year) performance data. By reviewing and analyzing SM data sets, the academic community can better advance our industry's understanding of long-span bridges and better position bridge owners and engineers alike to mitigate risk, leverage lessons learned and better manage these assets.

4 OVERCOMING THE CHALLENGES OF STRUCTURAL MONITORING

4.1 *Sheer volume of data*

Receiving data simultaneously from dozens of sensors, especially at a high sample rate, can be overwhelming. Without a knowledgeable and dedicated team, it can be difficult to effectively post process and analyze this information.

Even with qualified staff reviewing the data, determining what is meaningless noise versus valuable signal can be a challenge. Data trends and changes in behavior will inevitably occur throughout the life of the structure and without an in depth review, it can be difficult to determine the significance (or insignificance) of these changes. Having several staff members that are familiar with the system and structure allows multiple sets of eyes to review data.

A prudent first step is to review time series plots of the data. This is an efficient way to assemble an overview of the recorded behaviors. If the system is still in the baselining phase (first several weeks or months), the time frame should be from project start to present. If the system has been in service for multiple years, it may be necessary to limit plots to the most recent year or two of data. When performing this review, the reviewer should be looking for missing data, abrupt changes, clear trends and anomalous values.

Once several weeks or months of data have been collected, that data set can be used as a baseline to compare future behavior. It is assumed that most of the behavior characteristics will be captured in this timeframe although less common events (e.g. high winds or significant changes in temperature) may not be captured during the baseline period. Investing personnel time during these early months to understand the structure and SM system allows the bridge owner to maximize value. This is done by ascertaining a better understanding of the structure but also by being prepared if an extreme or unexpected loading event occurs.

Setting up computer programs (ranging from a simple script to a full software suite) can prove invaluable in handling large data sets efficiently. Python is a free and open-source programming language that has robust data processing and plotting libraries. Scripts can be used to post process data so that it can be reviewed more easily. Examples would be plotting multiple channels on a single graphic, applying a rolling average function or plotting sensor value in a scatter plot against temperature. If the correct tools are used, these reports can be automated which reduces personnel time. If high resolution data is being considered, various signal processing techniques can be applied including shifting the data set into the frequency domain.

4.2 *Threshold alerts*

In addition to a graphical review of the data (in plot format), baseline data can be used to establish threshold alerts. These can be used to monitor structural behavior and automatically receive information on both extreme values and developing trends. These alerts are typically set up at certain level and when the data reported exceed the threshold, an email or text alert is sent. This allows the appropriate stakeholders to stay informed of potential structural changes even if frequent review of data is not feasible. The alerts are also typically logged in the system for future review.

Setting the right thresholds can be a challenge (Tan, Osbourne and Brownjohn 2008). If the threshold ranges are too narrow, a high number of alerts will be received, generating a large queue of reviews for the staff member.

In this scenario, the reviewer may fall behind and time sensitive or critical trend alerts could be missed. The other end of the spectrum would be thresholds that are so wide that a structural behavior change can occur without setting off an alert. Engineers with prior experience developing SM thresholds should be involved in the initial process. Thresholds should be set with a sensitivity to the owner's risk management strategy, including a consideration for the consequences of changes in structural behavior. Some owners also choose to create different alert levels such as minor trend violation and immediate review required.

In addition to alerts about sensor values that exceed specific limits, a best practice is to have notification emails that alert the end user to erroneous values such as all zeros or NaN (not a number) values. Some systems also contain an alerting function when a sensor has not reported data for a certain amount of time.

It is typical for the threshold levels to require adjustment after the initial values are put in place. This could be to account for structural response to annual thermal trends or to incorporate minor shifts in behavior. The decision to modify threshold alerts should be overseen by a qualified engineer and with the consent of all stakeholders. Because some sensors report data more critical to structural integrity and stability, the importance of the sensor and the parameters it reports should be considered.

4.3 *Evaluating unexpected data*

Anomalous data is defined as clearly erroneous values, missing or NaN values or data unexpected based on previous observations. When an anomaly is observed, there are several causes to consider alongside the possibility of a change in structural behavior. First, software errors should be investigated since this can be done without deploying personnel into the field. Depending on the type of system, this may be a simple or complex task. Typically, the staff or subconsultant directly managing the data hardware can review data at the local level (data acquisition unit on structure) as well as via the remote web interface. If post processing scripts are being used, these should be checked to confirm they are not causing the anomaly due to unanticipated edge case behavior. Sensor hardware issues can also result in an anomalous data due to conditions such as a failed sensor, loose or shifted sensor mountings, frayed, or exposed wiring and power or signal faults at the data acquisition unit level.

Separate from hardware and software issues, activity on structure can also lead to anomalous results. This includes the vibration from nearby construction activities and interaction by field personnel or vandals. Operational changes such as partial roadway closures or trains traveling on different tracks or at different speeds can also lead to unexpected results. Assessing the significance of anomalous data can be a challenge. The steps above, including evaluation of hardware, software, on structure operations and nearby activity are a good start. Reviewing the history of the sensor, looking at behavior of adjacent sensors and an in person visit to the sensor and data acquisition unit can also be prudent. One of the main causes of trends is the response of the structure to temperature.

4.4 *Avoiding a false sense of security*

When a monitoring system is installed on a deteriorated structure or because of concerning behavior, it is important to avoid a false sense of security. The monitoring team must consider the limitations of the sensors. This means not only understanding the shortcomings of specific monitoring technology but also the fact that individual sensors can only report one type of data and at the location they are installed. This can be like looking at the world through a straw. If there is a high sensor density, a fuller picture of bridge behavior will come into view.

The team designing the monitoring should also consider the expected and possible failure modes of the structure. If the purpose of the system is to provide early warnings of these failure modes, the team should assess whether the sensors installed will capture these failure modes and if the threshold alerts will be exceeded prior to an adverse event occurring.

4.5 *Long-term personnel involvement*

Structural monitoring is not immune to the personnel issues found in many public agencies. Due to staff shortages, it can be hard to commit personnel time as this will come at the cost of other areas not being covered. While a new structural monitoring system may garner significant attention in the beginning, once a pattern of structural behavior is reached, interest tends to reduce. Other pressing matters will inevitably arise, but it is important to keep at a minimum level of review so that issues with the system or structure do not go unnoticed.

The transfer of institutional knowledge, while not unique to SM, can also present a challenge. Using a system for multiple years will inevitably lead to multiple lessons learned and insights about structure and system. As personnel inevitably move on to other roles, transferring this knowledge can be difficult. Besides overlapping of staff to allow knowledge transfer, overview documents explaining the system and lessons learned are important. Keeping a log of sensor issues, hardware replacements and structural events of note can also help staff avoid performing duplicative investigations or analysis in the future.

4.6 *Sensor Outages*

Bridges and other physical infrastructure often present a harsh environment for high precision electronics. Besides exposure to the elements, there can be maintenance and construction activities and even exposure from nearby saltwater. Maintaining the sensors and their associated hardware in this environment can be difficult. By utilizing robust components that meet the proper Ingress Protection Code (for instance IP67 rating), much of the potential damage is avoided. Utilizing modular components that are widely replaceable and broadly compatible also allows the damaged portion to be identified and quickly replaced. Finally, utilizing a monitoring consultant with a proven track record of success on similar projects is important.

4.7 *Ongoing maintenance costs*

When constructing a new bridge, the addition of monitoring technology may be a minor change in cost, the proverbial drop in the bucket. Because conventional maintenance costs are typically low in the early years of a structure, the upkeep of the monitoring system may prove a significant portion of the budget. This is largely because monitoring technology tends to have a service life far shorter than other bridge components. Additionally, the continued advancement of technology may render a system obsolete over the lifetime of a structure. While this should not discourage owners from leveraging monitoring technology to provide value, it should be a consideration during the planning phase when the monitoring system scope is determined.

5 THE PATH FORWARD

The topic of big data has been discussed a dozen times over. Any attempt to restate the basics in this text feels unwarranted. The past decade has seen many claims about how big data would change our lives, and many have come true, at least in part while others have fallen flat. The field of data technology has reached a certain level of maturity and because of the prevalence in our everyday lives, and a cursory recounting of the recent years seems unnecessary. With that said, perhaps two metaphors will help to frame the discussion.

The first is a car missing one of its tires. The idea of a car driving into town missing a wheel has been proposed as an analogy to proceeding in our current times without technology. This example is perhaps more pertinent than even the original creator understood. Technology and data are unquestionably essential in attempting to tackle the coming infrastructure challenges. But there are other elements that are equally essential. These include solving problems from with multi-disciplinary input (breaking out of our expertise silos), engaging all stakeholders including underserved and disadvantaged communities, and preserving institutional knowledge in a meaningful way. Data and technology are critically important but relying on them solely is like trying to drive a car into town with three wheels missing.

The second metaphor is the idea of data as a flashlight. Just like data, a flashlight does not change the physical world around us, but it can be used to determine the best path forward and to avoid pitfalls along the way. Considering data and technology in these terms helps to frame their value both within the engineering community and with non-technical stakeholders.

In the beginning, there were no sensors. Engineers and scientists were forced to rely on theory and first principles. Several decades ago, the infrastructure industry began utilizing sensors both in the lab and in situ. As time went on, the sensor reliability increased, cost of implementation went down, and they became more common place. Over the past 5 to ten years, the number of monitoring sensors (and in general, Internet of Things) has proliferated to near ubiquity. At the same time, computation and data storage prices continue to fall. With this abundance of information, current best practices include using automated post processing, in depth data security, and visualization to allow those without deep technical backgrounds to assess and even interact with the data. If this is the current best practice, the inevitable question is, what comes next.

5.1 *Digital twins*

Much of the current focus at the intersection of infrastructure and technology is on digital twins. Definitions vary by company and organization but essentially, a digital twin is a virtual representation of real-world entities and processes, synchronized at a specified frequency and fidelity. Essentially a computer-based model of a physical asset. Digital twins are already providing value to owners and the level of model and data complexity will surely increase. While multiple industries are becoming increasingly engaged with this idea, in civil infrastructure, a digital twin tends to be a virtual 3D representation of an asset with data (either static or real time) added in for specific components.

On the upper end of digital twin complexity, the sky is the limit (they are literally used for commercial aviation) but there does not appear to be a lower bound definition for digital twins. Because the term can apply just as readily to a jet liner as to a single sensor feeding into a simple CAD model, diligence must be used in assessing the capabilities and limitations of digital twins. For instance, many digital twins in the civil infrastructure industry do not include finite element model connectivity so no predictive takeaways related to structural behavior are possible.

As with any other data intensive exercise, digital twins are limited by the amount of data, the type of data, and the quality of data they receive as input. Integrating data sources in a meaningful way can also be challenging and labor intensive during the initial phases. Earlier in the paper, the value of post processing and visualizing data was discussed. Some of the most immediate value from a digital twin involves combining and visualizing disparate data sets on a user-friendly dashboard, especially when the user can tie the data to a specific element of the model and interact with the data over a range of time. Currently, the greatest gains are related to human analysis of the combined and post processed data sets. Initial predictive functions have been implemented, and their breadth and depth are expected to increase in the coming years. A special caution should be applied when automated prediction functions are used in matters of public safety or in high consequence decision making.

Predictive analytics is a term sometimes used in the context of digital twins, and it can range significantly in both meaning and implication. Two hypothetical situations will be given to illustrate this point. The first situation relates to a degradation curve. If a digital twin includes multiple years of data on pavement condition and its deterioration, it may be able to leverage that data along with other input parameters to predict when portions of pavement will require rehabilitation work to maintain a state of good repair. It should be noted that an erroneous prediction would likely have minimal impact on public safety.

The second situation relates to hazard curves, where a hazard is defined as a low probability and high consequence adverse event. If a large amount of SM data has been collected, engineers may attempt to use predictive analytics to identify significant structural issues up to and including failure. While the use of structural monitoring data to identify structural anomalies (discussed above) and the use of algorithms to assist in review is prudent, the concern arises in trusting the predictive analytics of a digital twin to identify potential issues without the direct participation of an engineer.

The detection of a structural issue has clear public safety implications and would also be related to edge case behavior which goes beyond the capabilities of a predictive algorithm trained on typical behavior. In leveraging predictive analytics, the type of curve being used (degradation or hazard), and the implications of an erroneous prediction should be considered.

No two complex bridges are quite the same (the one exception being parallel twin bridges). While a digital twin may yield insights on a given bridge structure, there will likely be minimal value in translating lessons learned to a different complex bridge. Of course, general takeaways can be passed between complex structures in the data analysis sphere like how subject matter experts leverage lessons learned from one structure to another. For structure types that are all very similar, wind turbines for instance, the ROI of a high-resolution digital twin which is created once but used many times is more evident.

5.2 *Machine learning*

Machine learning (ML) has become a buzzword both in our industry and in broader society. It is sometimes more generally referred to as artificial intelligence (AI). While order of magnitude jumps have been made in other sectors such as autonomous vehicles or facial recognition, ML is only now starting to take root in the field of civil infrastructure. Entire textbooks have been written about subfields of ML and so the brief discussion here is meant to serve as an overview of ML and its application to the bridge industry. As caveat, this discussion attempts to look under the hood on ML to discuss what it is and potential pitfalls in applying it.

In simplest terms, ML is the exercise of applying statistical principles to a data set and making predictions. While the simplest algorithms rely only on linear regression, more complex applications utilize neural networks which mimic the human brain, with hundreds of simulated neurons connected in various layers (Eltouny and Liang 2021). These complex networks can take incredibly complex data and create predictions based on trends not apparent to even the most astute humans (Li, Yi and Rahman 2019). With the proliferation of data, (Li, Yi and Rahman 2019) storage and computing power, the ability to engage ML in both simple and complex arenas is now at the fingertips of anyone willing to learn. The greatest gains appear to be in collaboration between humans and this technology, not algorithms alone.

Software packages for applying ML are often free and supported by a large user community that not only address bugs but also provides helpful discussion via searchable message boards. At the simple end would be Python's sci-kit learn package and at the upper end of complexity would be programs like TensorFlow with a Keras interface.

One approach with ML would be to process the data without expectation and see what trends emerge. A more productive way, particularly for those just beginning, would be to approach the data with a question in mind or problem to be solved. As the adage goes, "if you don't know what you are looking for, you probably won't find it". ML and the data manipulation techniques of the associated software can significantly augment the ability of engineers. In the same way that excel spreadsheets transformed engineering calculations 30 years ago, ML is poised to do the same with our data today. Just like SM, however, it is only a tool in the toolbox to be used alongside various others.

The advantages of ML must also be balanced alongside the challenges and pitfalls. One challenge is simply obtaining a clean enough data set to work with. Real world data can be messy with gaps in the data, inconsistent time stamps, erroneous values, and NaN (not a number) values. This will require manual input from the person performing the analysis. Something else that must be considered is the significance of the error rate. A prediction algorithm with an accuracy of 95% may be considered a success by someone in the data science field but this may not be sufficient for engineering applications. There are many aspects of engineering and design that must be 100% verified to protect public safety. Reconciling these mentalities is the responsibility of the engineers who choose to use ML.

Edge cases are another pitfall of ML and are sometimes called black swans. Edge cases are scenarios or data points that fall outside the typical range of the data set. This means that the trained algorithm will not be able to adequately make predictions for these cases. At this point accuracy will be reduced. Increasing the size of the data set and incorporating a wider variety of data is one a way to mitigate this pitfall.

Like the discussion on digital twins above, the uniqueness of complex structure creates a challenge when attempting to utilize data and analysis from one structure to predict the behavior of another. Finally, complex algorithms can have unclear inner workings where data is input, and a solution or prediction is returned with little human understanding of what occurred in between. Complex neural networks use the terminology “hidden layer”. This is a similar problem to complex finite element models utilized by structural engineers which sometimes lend few clues as to how results were determined (Yarnold, Moon and Aktan 2015). Ultimately with complex ML, the results should be checked by common sense, by simple hand checks and with the oversight of a senior engineer to confirm validity. The real-world consequences of an incorrect prediction must be weighed against what is known about data quality and prediction accuracy.

6 CONCLUSIONS

Structural Monitoring is a crucial technology used to detect damage or deterioration on bridges. Using sensors, SM systems can measure various parameters, such as strain, displacement, and vibration, to provide real-time information on the condition of a structure. One of the most important conclusions about SM is that it can significantly improve the safety and reliability of structures, especially those subjected to harsh environments or extreme loads. Additionally, SM systems can help reduce maintenance costs, extend the lifespan of structures, and enhance their overall performance. As technology continues to advance, the potential applications of SM will continue to grow, making it an indispensable tool for modern infrastructure management. The use of new data analysis tools such as artificial intelligence, machine learning, and digital twins are revolutionizing the field of structural monitoring. AI and ML algorithms can analyze vast amounts of data generated by SM sensors, identify patterns, and make predictions about the health of a structure. This can help engineers and maintenance teams to detect damage and deterioration early on, prioritize repairs, and reduce downtime. Digital twins, which are virtual replicas of physical structures, can also be used to simulate the behavior of a structure under different conditions, and optimize maintenance schedules. As these technologies progress, they will transform the way we monitor and manage the condition of critical infrastructure, making it safer, more reliable, and more efficient to manage long-span bridges.

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