DEVELOPMENT OF LIMIT STATE BASED STRUCTURAL HEALTH MONITORING THRESHOLDS FOR EFFICIENT BRIDGE MANAGEMENT

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ABSTRACT

A common criticism of Structural Health Monitoring (SHM) systems is the inability of the system (or installers/consultants) to provide the translation of raw sensor measurements into actionable information that owners and operators (referred herein as end-users) can use for management decision-making. Reasons why this shortcoming exists include poor anticipation during the system design of how the SHM system was to be used, complexity of the measurements made, and the lack of a comprehensive input-output characterization of the structural system. To address the challenges associated with these limitations, it is important to recognize that the location and specification of sensors does not alone constitute a SHM system design. Instead, the system design must include the definition of performance-based allowable thresholds that directly correlate to structural safety, traffic safety, or operations limit states. This paper presents a framework for performance-based design of SHM systems, from the specification of instrumentation type and location through the requisite analysis needed to properly specify allowable thresholds. The paper will also discuss how such an SHM system design could be integrated into a bridge management system.

An illustrative example will be presented based upon an actual SHM system design and computation of allowable substructure movement thresholds. For this case study, the thresholds were computed based upon superstructure live load strength limit states, substructure serviceability limit states and a kinematic limit state associated with allowable movement at the expansion joints. The thresholds were then used within a live visualization during a critical construction event where the end-user was quickly able to establish the performance of the bridge in real time. The proposed framework is a step forward in addressing the challenge of understanding how SHM systems can be used not only to understand how a structural system responds to a given input, but more importantly to present how that response affects the structure's ability to withstand performance limit states within a bridge management system.

Keywords: Structural Health Monitoring, Bridges, Thresholds, Bridge Management

INTRODUCTION

A common criticism of Structural Health Monitoring (SHM) systems is the inability of the system (or rather the installers/consultants) to provide the translation of raw sensor measurements into actionable information that end-users and operators can use for management decision-making. There are many reasons why this shortcoming exists including but not limited to poor anticipation during the system design of how the SHM system was to be used, complexity of the measurements made, and the lack of a comprehensive input-output characterization of the structural system. However, one of the largest reasons why this shortcoming might exist is the lack of broad design and specification guidelines. The lack of guidance manifests in two types of SHM system failures: 1.) a system that was specified, designed and installed well but lacks integration into the bridge operator's decision making procedures and 2.) a system that was improperly specified or designed leaving the end-users with unrealized expectations.

A design framework for SHM systems was developed to address the shortcomings discussed above. In deriving the framework, emphasis was placed on the end-use of the system and how it integrates into existing decision-making processes. In this light, the framework can be considered a performance-based design approach for SHM.

SHM PERFORMANCE-BASED DESIGN FRAMEWORK

The SHM performance-based design framework was developed after years of experience (personal and industry-wide) in both successful and unsuccessful applications of SHM. All too often, it was heard that SHM requirements were recommended by vendors to the end-users often with little consideration of the end-user's personnel workflow, operations, and experience with SHM. Additionally, vendors did not properly educate the end-user on managing a system that generates large amount of data that does not directly correlate with their metrics of interest (you cannot directly measure remaining service life). This was seen largely after the collapse of I-35 in Minnesota where sensor and SHM vendors flooded the market with potential monitoring systems for avoiding a similar disaster for their customers. The lack of success of the systems installed in this era created a backlash from which the industry is still recovering.

A common theme in the discussion above is the lack of communication with the end-user of the SHM system. It is critically important to understand the needs of the end-user while understanding the limitations with which they operate. These two points will drive how the system is designed and eventually how the system integrates into existing bridge management workflows with minimal or only positive disruptions. Thus, when the framework was developed (shown in Figure 1), engagement with the end-user was appointed both the first and last steps to highlight the fact that the system is borne out of end-user based requirements and ultimately is a tool that the end-user must accept and use. Each of the five steps in the framework will be discussed in further detail in the following sections.

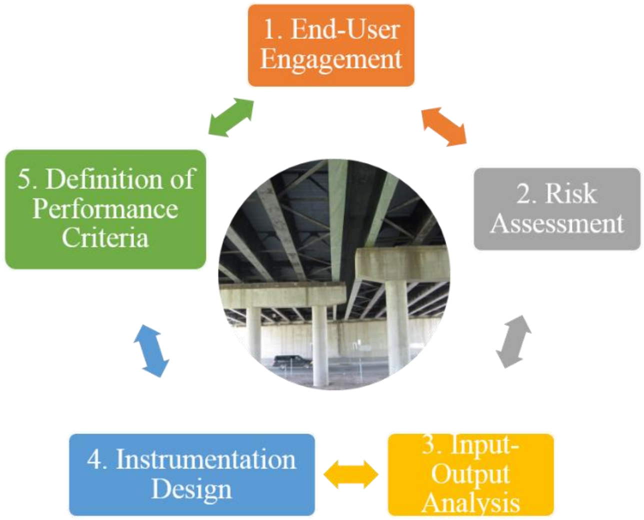

Figure 1: SHM Design Framework

Step 1: End-User Engagement

The first step of any SHM design project is engaging the end-user to understand the motivation of the project, to establish the level of exposure the end-user has had to SHM requirements (installation methods, power and communication, computer hardware, maintenance and operations, software, etc.) and to identify the specific metrics that the end-user wants to monitor. At the end of the initial end-user engagement phase, the feasibility and applicability of SHM to the specific case should be established. Given that SHM is applicable, the end-user should have clear understanding of what the project entails, from installation through long-term operation. The goal of the designer is to have clear performance metrics defined to which the SHM system shall be designed. An example of performance metrics to guide SHM design include but are not limited to expansion bearing performance, critical load path distribution, traffic operations, traffic safety, and movable span operations.

The designer should also have clearly defined threshold parameters from the end-user at this stage as well. In some cases, the thresholds could be directly defined at this stage ("I want a text message when three-minute sustained winds exceed 50mph"). However, most of the thresholds will be defined with respect to other parameters that the end-user is familiar with or could be very high level. For example, the end-user might be interested to know when their movable span is not seated properly. This is a challenging requirement because what is the definition of "proper"? Is it simply traveling a certain distance, or are there other parameters that define a "proper" seating? Usually, there is no direct measure of proper seating, and the engineer must devise an instrumentation program to indirectly assess that measure. Such a threshold would then be defined through engineering analysis as part of the project. However – it is the SHM designer's role to translate measured responses (and the thresholds defined as a function of their values) into metrics that the end-user is familiar with. To continue the example of the movable bridge seating, perhaps an instrumentation approach of measuring distance and strains allows for an engineering calculation of total travel and the seated imbalance of the movable span. Together with the end-user, the SHM designer can then define threshold bounds on these metrics that align with the existing bridge maintenance and operations guidelines for that bridge.

As seen in many new SHM projects, the end-user might be interested in having an SHM system provide support for remaining service life calculations. In this case, the monitoring metrics are very high level and require further analysis to extract monitoring requirements and threshold criteria. Since there is no "remaining life" sensor that we can simply apply, SHM designers are responsible to work directly with the bridge designers or responsible engineers to identify if, and how, a monitoring system can be used as a tool to aid in their engineering assessment of service life.

An additional component to consider in this initial stage is to have understanding of how the SHM system is envisioned to integrate within the existing bridge management platforms. Will the alerts generated out of the SHM system be issued through an existing ITS? Similarly, will a visualization be created for the SHM to be displayed within traffic management centers? These are important questions to consider, as the goal is to minimally disrupt the end-user's management structure and complement the existing maintenance and operations components with the measured performance metrics. Again, the more informed the end-user is at the conception of the project, the more productive and successful the end product will be.

Step 2: Risk Assessment

The second step of the SHM design process is closely married to the first step. The SHM designer carries out a formal risk assessment of the structure where the hazards and vulnerabilities are clearly defined. Risk can be defined in many different ways depending on the field of application, however in this context the author defines risk as a combination of three components: 1.) Hazard - the likelihood of an event to occur which could potentially induce ill effects, 2.) Vulnerability – the likelihood that, given the occurrence of a hazard, a system will fail, and 3.) Exposure - given the failure of the component, what are the consequences that arise (financial, human life, quality of life, etc.). By looking at the product of these three components of risk, one is able to then prioritize a set of risks. The benefit of doing such an analysis, is that at the end of the prioritization task the analyst is able to develop ways in which to mitigate the specific components so as to reduce the overall risk, relatively compared to the others. For example, a hazard could be the impact to a movable bridge from a ship. The corresponding vulnerability could be the failure of the operating machinery, resulting the bridge not being able to open. The exposure would potentially be the loss of the bridge plus damages to the ship and any human life that might be lost. This risk can be mitigated by reducing the likelihood of the ship impact to occur (decrease likelihood of hazard) or strengthening the bridge against such an impact (reducing vulnerability), or a combination of the two. Note that this could be done procedurally or legislatively and would not require monitoring. For the interested reader, please refer to Moon et al (2007) on a comprehensive study of major risk components faced by bridges and how that can be used in prioritization efforts for a network of bridges. While that paper discusses the applicability of risk assessment to bridge networks, the approach is applicable for one bridge since the interest is to prioritize the set of risks defined for one bridge.

It is most likely required that the SHM designer will need input from the end-user to populate the list of hazards and vulnerabilities, however it is important for the designer to have structural engineering experience to help supplement the list with appropriate items. A role where the end-user plays a crucial role in this step is the prioritization of risks (combination of hazards and vulnerabilities). While in formal risk assessments a third component of risk, exposure, is also computed, in this case it is not required since the owner and engineer will work to prioritize the risks based on heuristics rather than other common exposure metrics (mostly value-driven). The result of the second step is a list of prioritized hazards and vulnerabilities that will drive the design of the SHM system.

Step 3: Input-Output Analysis

The third step in the SHM design framework is the conversion of each of the prioritized risks into a series of measurable inputs and outputs. Inputs are defined as those measured parameters which are independent of the bridge structure (e.g., wind speed, vessel impact, overloads, temperature gradients) while outputs are defined as the response of the structure as a function of material or structural properties (e.g., displacement, strain, surface temperature). As the designer carries out this analysis, the sensing approach to meet the SHM design objectives begins to take shape. Some input/output measurements are fairly straightforward (wind speed) while others still require a degree of indirect measurement to ascertain whether a hazard occurred (ship impact).

Step 4: Instrumentation Design

With a list of specific measurement requirements defined from an end-user driven risk assessment the SHM designer can properly locate and specify the sensors needed to meet the design objectives. This stage may require refined analysis to aid in the process of locating sensors through sensitivity studies as well as computing the magnitudes of response to the desired inputs so that sensor ranges can be properly specified. The end result of this step is the development of SHM contract drawings and specifications which may be bid for construction or used by an SHM integrator for procurement and installation.

Step 5: Definition of Performance Criteria and Thresholds

As part of the SHM design process, each of the prioritized risks is used to specify performance criteria and alerting thresholds to be commissioned upon installation of the system. SHM performance criteria is defined as the metrics used to establish acceptable levels of hazards or vulnerabilities. Some performance criteria are based on institutional or code requirements, such as maximum wind speeds for bridges to remain open to traffic, and often include various levels of satisfactory performance. However, most of the requirements used in SHM system design are based on structural safety performance metrics and require detailed engineering analysis to establish what the acceptable levels of performance, or thresholds, are. It is this step of the SHM design process where it is important to have structural engineering expertise on the SHM design team. A common complaint of SHM systems is that thresholds proposed by SHM vendors are not founded on engineering design metrics of the bridge and are instead focused on anomaly detection or machine learning. It is important for the designer to understand how the response thresholds they are presenting translate to strength and serviceability limit states of the structure.

When the SHM system is fully designed and specified and the performance metrics and corresponding thresholds have been computed, it is critical to receive acceptance of each component of the SHM system design. The end-user must agree on the performance criteria used and on the threshold values presented, for it is their staff whom will be receiving the alerts when thresholds are exceeded and it is important for them to have full understanding of what is entailed in an alert. This stage is critical for the end-user to visualize how the SHM system is going to integrate into their bridge management system.

At this stage, it is important to consider that bridge condition, hazards, and vulnerabilities can be time-dependent. That is, it is recommended to re-visit this process periodically to assess not only how the initially defined thresholds are performing, but to re-assess the state of the bridge and its environment to ensure that the monitoring system and the alerting protocols are still appropriate. This suggestion is not uncommon to bridge managers as it is analogous to the protocols followed for updating of live load ratings. When the condition or loading of a structure changes, the load ratings must be updated.

APPLICATION: CASE STUDY ON A STEEL MULTI-GIRDER BRIDGE

The SHM design framework discussed above was carried out on a steel multi-girder bridge in the United States. A brief background of the structure will be presented followed by a discussion of how the framework was implemented for this structure over the next sections. The project is of a confidential nature, and specific details cannot be shared in this paper. However, the general application of the framework is still discussed.

Background

A steel multi-girder bridge in the United States was located on a site where significant construction was occurring nearby as an industrial facility was being built. As part of the construction, heavy loads (large prefabricated components moved on self-propelled modular transporters) were proposed to be hauled underneath the bridge due to limitations in transportation logistics. The owner of the structure was concerned about what impacts the heavy loads would have on the performance of the structure and required the site developer to establish requirements for and install an SHM system for the multi-girder span.

The structural system consists of a two-span continuous steel multi-girder structure supported by expansion bearings on an abutment, fixed bearings on a seventy-foot-tall reinforced concrete pier and a steel plate girder floorbeam which is pin connected to both the steel girders and the supporting 60-foot-tall reinforced concrete columns below. The two reinforced concrete columns supporting the multi-girder span floorbeam also support the expansion bearing of a multi-span continuous steel truss over 1,000’ in length. The steel superstructure is composite with a reinforced concrete deck and supports four lanes of traffic. Further details about the bridge are presented in Warren & Dubbs 2017 for the interested reader, however the aim of this paper is focused on the SHM design process, particularly the definition of performance criteria.

SHM Design

End-User Engagement

The SHM project was initiated by a meeting with the SHM design experts, site developers, and the bridge owners. At this meeting, the performance requirements of the SHM system were specified by the bridge owner as the following:

- Monitor for permanent rigid body translations of the two piers in all three directions
- Monitor for permanent rigid body rotations of the two piers in all three dimensions
- Ensure that any measured rigid body movements do not impact the load rating of the steel multi-girder span with respect to Strength and Serviceability limit states.
- Ensure that any measured rigid body movements do not generate cracking in the reinforced concrete piers.
- Ensure that any measured rigid body movements do not bottom out any of the movement systems.

While the owner laid out the requirements above, it was still required to ensure that additional hazards were not relevant on the site which might also affect structural performance during one of the moves.

Risk Assessment

The project presented herein included an SHM system with a very specific set of performance requirements and a rather narrow set of risks. However, there is a vast amount of literature where risk assessments are used for bridge prioritization (Moon et al 2009) and the interested reader is referred to those resources for more general examples. The main risk for this case study included the hazard of the heavy load passing between the two reinforced concrete piers. The vulnerabilities included overstressing of superstructure components, cracking of the concrete piers, bottoming out of movement systems, and differential settlement of the piers. The main risk defined as the combination of these hazard and vulnerabilities is thus the reduction of load carrying capacity of the existing bridge system due to the heavy load.

Input-Output Analysis

The input-output analysis was carried out to not only determine what sensors were needed to monitor the objectives laid out above, but also to identify what other factors contribute to normal movements of the structural system which would need to be characterized as part of the baseline evaluation of the bridge system. The two main monitoring objectives were focused on tracking rigid body movements (translations and rotations) of the two reinforced concrete piers. Thus, it was important to consider all possible contributing factors to those movements and all possible ways that the piers might deform under service loads. One would not expect rigid body deformation of any kind under service loads, so it was required to provide enough measurements that elastic flexural deformations could be decoupled from any potential rigid body deformation. When considering movement of the substructures, there were two major inputs defined that were of interest to this project: thermal gradients and the heavy moves. The corresponding outputs are of course either the translation or rotation of the piers. The translation of these inputs and outputs to monitoring measurand is shown in Table 1 below.

Table 1: Input-output analysis

Category	**Performance Metric**	**Measurement Types**	**Sensing Approach**
Input	Thermal Movement	• Ambient temperature • Local temperature • Superstructure strain • Superstructure expansion • Pier rotation	• Weather station • Thermistor • VW strain gage • VW displacement gage • VW tiltmeter
Input	Input from Heavy Moves	• Pore water pressure • Soil inclination • Soil strain	• VW piezometer • VW inclinometer • VW extensometer
Output	Global Rotation of Piers	• Rotation (differential or uniform)	• VW tiltmeter
Output	Global Movement of Piers	• Rotation • Superstructure strain • Superstructure expansion	• VW tiltmeter • VW strain gage • VW displacement gage
*Note: VW = Vibrating Wire type sensing			

Instrumentation Design

The measurands outlined in Table 1 above were used to drive the instrumentation design. The benefit of this systematic framework is that by the time the designer reaches the instrumentation design stage, the efforts can mostly be placed on sensor location and specification instead of attempting to conceptualize the entire design in one step. As mentioned above, Warren & Dubbs (2017) present additional information on the background of the bridge. The paper also presents the final SHM instrumentation plan in detail. Generally, the SHM system utilized eighteen tiltmeters, fifteen strain gages, twelve displacement gages, six piezometers, ten inclinometers, six extensometers and a weather station to meet the measurement requirements. The instrumentation plan is shown below for clarify (Figure 2).

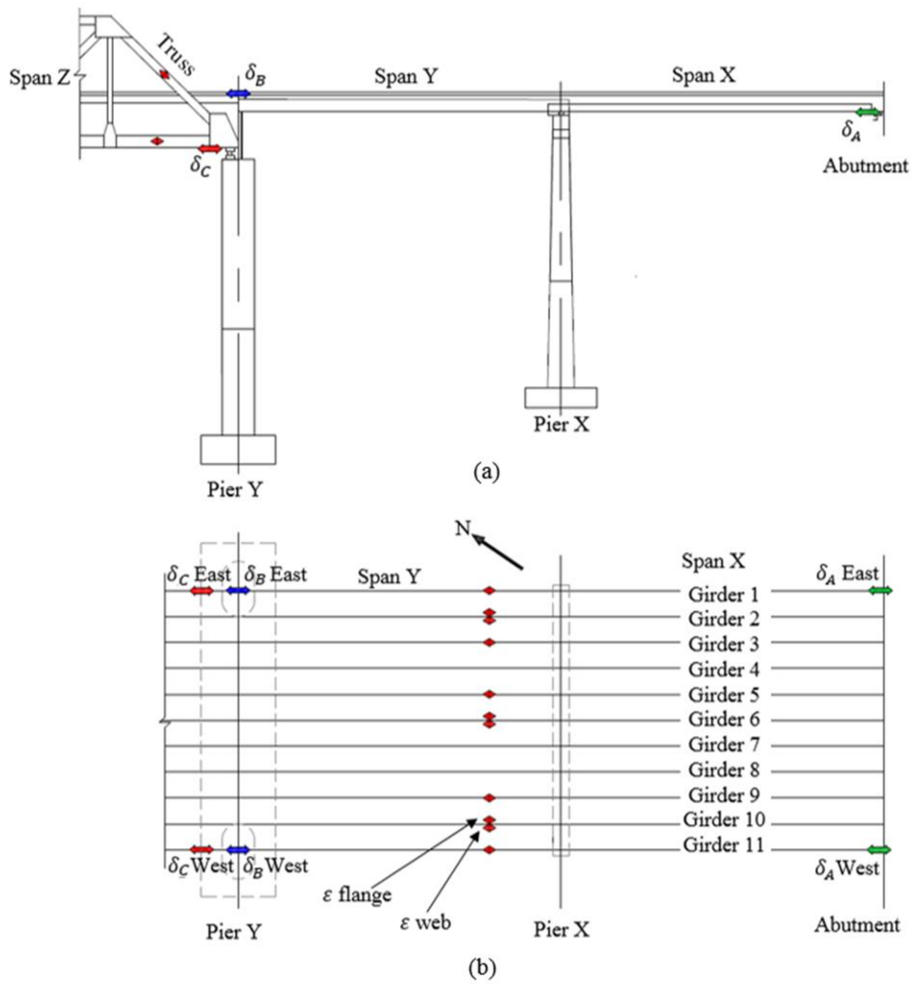

Figure 2: Instrumentation Plan for the SHM System (Warren & Dubbs, 2017)

Definition of Performance Criteria

The challenging part of this project was the definition of acceptable performance criteria. Once the system design was prepared, the bridge owner was re-engaged to present the design and to discuss performance criteria and alerting thresholds. The last three SHM performance requirements listed above heavily drove what analysis was needed to support the computation of monitoring thresholds:

- Ensure that any measured rigid body movements do not impact the load rating of the steel multi-girder span
- Ensure that any measured rigid body movements do not generate cracking in the reinforced concrete piers
- Ensure that any measured rigid body movements do not bottom out any of the movement systems

Note that none of these performance requirements are readily measured by a single sensor. There is no measure for remaining live load capacity or allowable additional stress until onset of cracking is initiated. Sure, one could measure strain in the piers – but what magnitude of response is of concern? In order to develop quantitative thresholds associated with these performance limit states, the following analyses were carried out:

1. **Superstructure live load rating**. A 3D finite element (FE) model was used to develop the refined rating of the superstructure in its current configuration. The preliminary live load rating factors were all well above 1.0, suggesting that there was sufficient capacity to accommodate demands from substructure movements. The extent to which the substructures could move before unsatisfactory live load rating factors were observed was computed by incrementally applying rigid body movements to the substructure elements in the FE model and re-generating the superstructure live load rating factors until a value of 1.0 was reached. The amount of movement needed to generate this "break-even" rating factor was then defined as the threshold for this performance limit state.
2. **Substructure cracking**. It was hypothesized that the piers would potentially crack under tensile stresses due to p-delta effects associated with their rotation and the dead load of the multi-girder span above, resulting in a failure of a serviceability performance state. A geometric nonlinear analysis of the same FE model described in the first analysis above was used to establish at what extent of rotation tensile stresses in the extreme fiber of the piers reached cracking magnitudes associated with the material properties of concrete.
3. **Kinematic analysis**. The final performance limit state analyzed was a kinematic assessment of the allowable movement of the expansion mechanisms. If either pier rotated or moved longitudinally, the movement systems could potentially either be closed or opened too far, either case presenting a performance failure for the bridge owner. The kinematics of all movement mechanisms were analyzed and the net allowable movement at each joint (factoring in the space needed for normal expansion and contraction of the structure) was computed. The corresponding translations and rotations of the substructure that generated these movements in the mechanisms was then computed and reported as the allowable thresholds for this analysis case.

Following the three analyses described above, the governing limit state per each of the response metrics of interest of the bridge was computed are shown in Table 2 below. A schematic of the bridge showing the various directions of movement for the two piers is also shown in Figure 3 below.

Table 2: Computation of Allowable SHM Thresholds with Governing Performance Case

	Movement	Allowable	Governing Case
Pier 1	+ Ry (°)	0.15	Pier Serviceability - Differential Rotation
	- Ry (°)	0.06	Kinematic - Abutment 1 Expansion Joint
	+ Dx (in)	2.2	Pier Serviceability - Differential Longitudinal Movement
	- Dx (in)	0.91	Kinematic - Abutment 1 Expansion Joint
	+ Dy (in)	0.35	Pier Serviceability - Differential Transverse Movement
	- Dy (in)	0.55	Pier Serviceability - Differential Transverse Movement
	+ Dz (in)	0.2	Pier Serviceability - Differential Settlement
	- Dz (in)	0.3	Pier Serviceability - Differential Settlement
Pier 2	+ Ry (°)	0.3	Kinematic - Span 3 Rocker Bearing
	- Ry (°)	0.09	Kinematic - Span 3 Rocker Bearing
	+ Dx (in)	4.34	Kinematic - Span 3 Rocker Bearing
	- Dx (in)	1.32	Kinematic - Span 3 Rocker Bearing
	+ Dy (in)	0.75	Pier Serviceability - Transverse Movement
	- Dy (in)	0.55	Pier Serviceability - Transverse Movement
	+ Dz (in)	6.2	Superstructure Rating - Negative Bending Interior Girder
	- Dz (in)	6.2	Superstructure Rating - Negative Bending Interior Girder

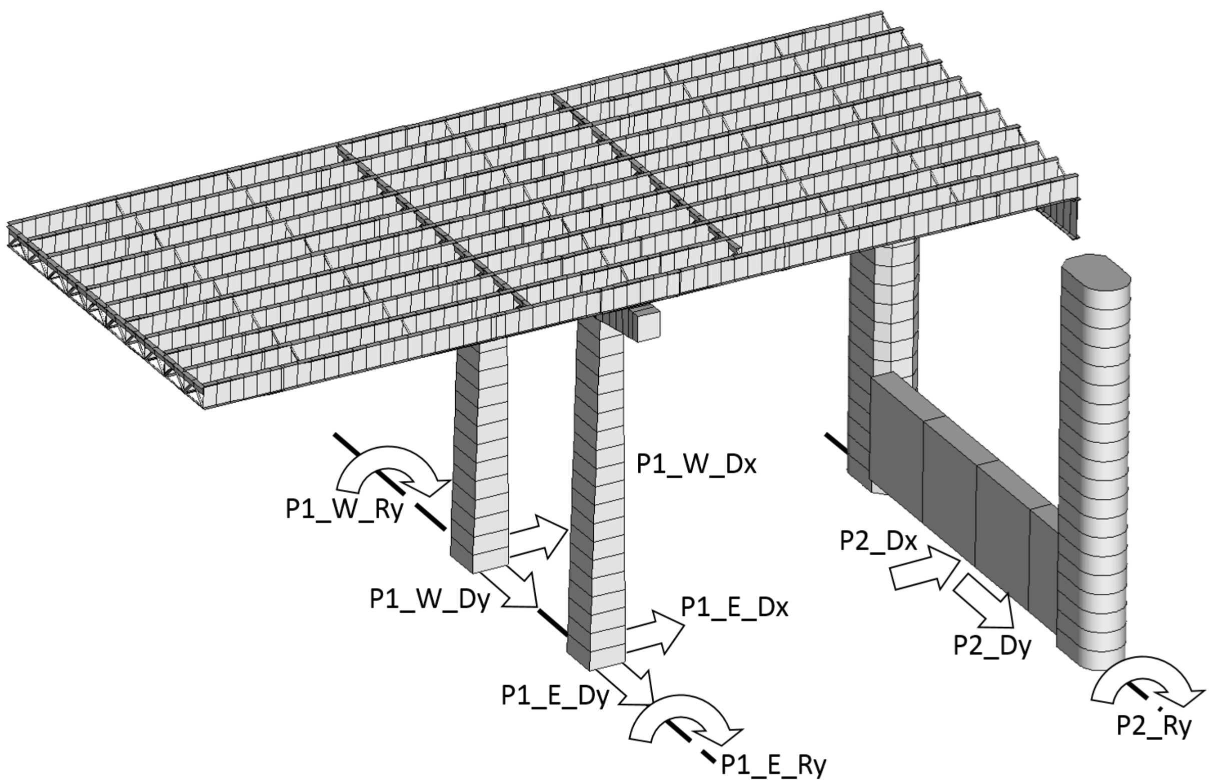

Figure 3: Schematic showing movement sign convention for the two piers

Implementation

A report was prepared documenting the allowable movements for the piers during a heavy move operation and accepted by the bridge owner. It should be noted that the analysis carried out herein focused on the superstructure performance alone and did not consider the geotechnical capacities or forces generated on piles. Those analyses were completed by a separate consultant.

The SHM system was installed by agency contractors in October of 2015 and is in operation as of publication of this paper. The planned monitoring period is five years in total, which was necessary to capture all the planned heavy moves on site. For this project, the main monitoring effort focuses on system performance during the heavy moves. As such, detailed reports will be prepared after those moves documenting not only the SHM results but also findings of pre- and post-move bridge visual inspections.

As part of the implementation process, the bridge owner requested a load test to verify SHM system performance and to understand the performance of the geotechnical instrumentation installed as part of the geotechnical consultant's scope of work. The load test utilized a 200-ton Caterpillar 777D truck fully loaded with stone. The vehicle made several passes under the multi-girder span at varying spacing between the two piers. It was noted that the superstructure sensing did not deviate at all from their normal performance and were instead responding to the live loads passing on top of the bridge. The geotechnical sensors did, however, respond to the load and the data was used by the geotechnical engineers to validate sub-surface assumptions and soil parameter recovery times.

INTEGRATION OF SHM DATA INTO A BRIDGE MANAGEMENT FRAMEWORK

The specific case study was not incorporated into a bridge management framework since it was a single application of a fixed duration construction monitoring project. However, the framework followed and the products that were developed from the project do lend themselves to a bridge management application. As previously mentioned, a major challenge in the SHM industry has been the translation of raw sensor measurements to actionable information that end-users can readily understand. The case study presented herein was able to translate raw measures of sensor data into a single dashboard that indicated the performance of the bridge based on a series of engineering calculations and analyses. At any point in time, but most likely during a heavy move, the bridge owner can open the dashboard and immediately see what effect, if any, the operation is having on their bridge and what specific performance limit state is most vulnerable.

For a general bridge management application, the author does not envision that a bridge owner needs active involvement with the SHM system. Conversely, a properly designed SHM system should take on the active role of analyzing and interpreting the data and alerting key personnel of performance issues (including SHM system performance) immediately as they occur and then providing a means of quickly and effectively disseminating the system measurements so that the personnel can either confirm or deny the relevance and importance of the issued alert. It is envisioned that integration within Bridge Management software would be straightforward given properly designed alerting thresholds. The bridge manager would need to identify ways in which third party applications can interface directly for automated integration, or at the very least could set up a manual integration process where SHM-issued alerts are first received, reviewed, and manually entered into bridge management applications.

CONCLUSIONS

The study discussed herein presents a framework that can be used to approach the development of performance-based thresholds for SHM systems. The acceptance of such a framework provides the opportunity for direct integration with bridge owners' current bridge management frameworks by translating raw sensor measurements into information that the owner can readily understand and, most importantly, that the owner can act upon. The framework is systematic in that it forces the designer to begin the design process with high level requirements laid out by the end-user of the system and then end the design process by translating the raw sensor measurements into actionable information by deriving response thresholds founded on structural engineering analysis. The benefits of such an approach lie in the need of the SHM design to explicitly plan how the responses from each sensor are going to be used in a management framework by informing the end-users of a specific performance limit state exceedance.

A case study was presented where the framework was utilized to design an SHM system that not only used targeted instrumentation but also used structural engineering analysis to compute quantitative thresholds founded on end-user prescribed acceptable performance requirements. Since the end-user did not have experience with SHM, it was the responsibility of the SHM designer to provide a system that can translate raw sensor output into a quantitative indicator of structural performance.

REFERENCES

Moon, F.L. J. Laning, D.S. Lowdermilk, S. Chase, J. Hooks, and A.E, Aktan (2009) "A Pragmatic, Risk-based Approach to Prioritizing Bridges," Smart Structures and Materials & Nondestructive Evaluation and Health Monitoring, SPIE, San Diego, CA.

Warren, M. and Dubbs, N.C. (2017), "Periodic Temperature-Based Bearing Assessment of a Steel Multi-Girder Bridge," 96th Annual Meeting of the Transportation Research Board (TRB), Washington, D.C.