STRUCTURAL HEALTH MONITORING IN CIVIL INFRASTRUCTURE APPLICATIONS: NEW PERSPECTIVES

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Structural health monitoring (SHM) has been an active engineering research field since a decade ago. As far as practical implementation is concerned, this field has thus far been dominated with vibration-based technologies that were originally developed for aerospace and mechanical structures. This paper provides a critical review of current structural health monitoring (SHM) technologies for bridge management, proposes a hybrid computational/instrumented simulation framework of a large-scale bridge structure, introduces and characterizes a transformative concept of structural behavior monitoring (SBM), illustrates its attributes with examples, and discusses its potential impacts to ensure structural safety and durability of bridges. The hybrid framework can address both global and local behavior monitoring in an operation-related manner. It consists of a representative substructure that is fully instrumented and the remaining part of the bridge structure that is computationally simulated in great detail. Such a model can take into account the randomness of loads, materials, and environment. The substantial shift from the current SHM to the future SBM concept will create a new paradigm for monitoring and preserving the structural integrity of large-scale civil infrastructure. This advance will generate a surge of new research interests that satisfy both the academic quest for scientific and technological explorations and the pragmatic needs for retrofit design and maintenance solutions in deteriorated bridges and other civil infrastructure such as water systems, dams, and levees. The proposed concept will change engineers' perception from the less favorable SHM to the receptive SBM strategy, thus having significant impact on technological challenges associated with the preservation of the U.S. bridge inventory.

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ABSTRACT: This paper provides a critical review of current structural health monitoring (SHM) technologies for bridge management, proposes a hybrid computational/instrumented simulation framework of a large-scale bridge structure, introduces and characterizes a transformative concept of structural behavior monitoring (SBM), illustrates its attributes with examples, and discusses its potential impacts to ensure structural safety and durability of bridges. The hybrid framework can address both global and local behavior monitoring in an operation-related manner. Such a model can take into account the randomness of loads, materials, and environment. The substantial shift from the current SHM to the future SBM concept will generate a surge of new research interests that satisfy both the academic quest for scientific and technological explorations and the pragmatic needs for retrofit design and maintenance solutions in deteriorated bridges and other civil infrastructure such as water systems, dams, and levees. The proposed concept will change engineers' perception from the less favorable SHM to the receptive SBM strategy, thus having significant impact on technological challenges associated with the preservation of the U.S. bridge inventory.

1 INTRODUCTION

Civil infrastructure includes bridges, roadways, water mains, pipelines, and other distribution systems. The 2009 America Society of Civil Engineers (ASCE) Report Card for America's Infrastructure indicated little change in the overall condition of the nation's infrastructure, and the cost for improvement has increased from $1.6 trillion in 2005 to $2.2 trillion in 2009. Although civil infrastructure is of multi-facet nature, bridges as transportation infrastructure are considered in this paper as an example to review the current applications and illustrate the new applications of various structural health monitoring (SHM) technologies.

On one hand, maintenance of existing bridges is a major undertaking in the years to come for several countries such as the U.S. The U.S. Federal Highway Administration (FHWA) National Bridge Inventory indicated that 26% of approximately 600,000 of the nation's highway bridges are inadequate. Most of them are approaching the end of their

design life of 40~50 years. Their condition must be thoroughly assessed and upgraded (retrofitted or repaired) to ensure the safety of the public, maintain the quality of human welfare, and meet the nation's economic development and military needs. The collapse of the I-35W Bridge over the Mississippi River testified to the urgent need for improved monitoring and assessment methodologies of existing bridges.

On the other hand, construction of new bridges is booming in other countries such as the People's Republic of China. Since the early 1990s, China has constructed a number of long-span bridges annually (Ou et al., 2011). For example, the Sutong cable-stayed bridge has a main span of 1088m, and the Hanzhou Bay Bridge is 36 km in length. Maintaining structural health throughout their lifespan and mitigating potential catastrophes will be a major challenge.

Both maintenance of existing bridges and construction of new bridges present the engineering research community with unique opportunities to develop and apply various SHM technologies. However, SHM technologies applicable to the management of bridge networks are still lacking. The objectives of this study are to provide a critical review of current SHM technologies in terms of bridge management, propose a hybrid (computational/instrumented) simulation framework of a large-scale bridge structure or bridge network, introduce and characterize a transformative concept of structural behavior monitoring (SBM), illustrate its attributes with examples, and discuss its potential impacts to ensure structural safety and durability of bridges. Due attentions will be paid to a complete research and development (R&D) cycle of technology development, practical implementation, and cost-benefit analysis.

2 A HYBRID COMPUTATIONAL/INSTRUMENTED MODEL FOR STRUCTURAL SYSTEM BEHAVIOR SIMULATIONS OF BRIDGES

Currently implemented SHM systems in bridges (Chen et al., 2007 cable-stayed bridge case study) are relatively few, dominated by vibration-based technologies that were mainly developed for aerospace and mechanical structures. For example, two earliest applications of SHM technologies were in rotating machineries and aircrafts for their process control and fatigue inspections under operational vibratory loads with relatively low stresses (Farrar and Duffey, 1999). In comparison with aerospace and mechanical structures, bridges have unique characteristics such as large scale, unclear boundary, and large uncertainty in external loads and material strengths. They are constructed under harsh conditions and operated in multi-hazard environments, but maintained under tight budget constraints, resulting in accumulated deteriorations and overstress effects. Until recently, bridges have been exclusively designed for structural safety against scour, yielding, fatigue, fracture, local and overall buckling. They are maintained over a long period of time (50 years or much longer in future) for a minimum economic impact to the society and the nation, associated with corrosion, delamination, and crack. In most cases, their deterioration and damage mechanisms (e.g. scour and corrosion) are unrelated to bridge operation and independent of vibration effects. Therefore, the engineers' interest and focus in design and maintenance of bridges completely differ from those in rotating machineries and aircrafts. The introduction of vibration-based technologies is not directly related to the mission of civil infrastructure industries, and often unfavorable to engineers in civil engineering.

Even non-vibration based sensing technologies like optical fiber sensors have thus far been developed mainly in the interest of monitoring the operational process of structures. Most of the sensor research and development have been focused on the measurement of low strain and temperature (Karbari and Ansari, 2009; Ou et al., 2011). To meet the urgent needs for the condition assessment and maintenance of bridges, a new structural monitoring paradigm is needed to collect mission/function-critical data only, apply them for load rating of bridges, and prescribe cost-effective retrofit/repair technologies.

To evaluate the system behavior of a large-scale bridge structure or bridge network with limited sensors, a real-time hybrid (computational/instrumented) model is proposed in this study. The hybrid model includes a representative and strategically important component of the bridge that is fully instrumented to understand its actual behavior and the remaining part of the bridge that is computationally simulated for its predicted behavior. The material properties of the non-instrumented components are updated in real time based on actual measurements of the instrumented component from the SBM concept.

The proposed hybrid model recognizes two practical design factors that a bridge network is typically composed of a number of similar bridges and a bridge often consists of many identical structural components for construction simplicity, architecture pleasing, and cost effectiveness. The strategically important component represents the most overstressed/displaced member of its group so that a full inelastic load-deformation curve or other nonlinear relations can be made available in real time for all non-instrumented components. To this endeavor, large strain or other direct measurements must be taken in various harsh environments. The real-time updating hybrid model can take into account various random factors in terms of materials, loads, and environments, providing a reliable evaluation of structural condition.

As an example, Figure 1 is a computer model of the 1206-meter long Bill Emerson Memorial Cable-stayed Bridge spanning across the Mississippi River (Wang and Chen, 2007). It can be seen from Figure 1 that four reinforced concrete legs in two towers are identical and all cables are similar except for different lengths. The towers, the shortest cables, and the deck element near the towers also represent the most stressed members based on the extensive analyses under various scenario earthquakes (Yan et al., 2010). Therefore, they are fully instrumented and the remaining structural members are computationally simulated in detail, taking advantage of the modern computer technology.

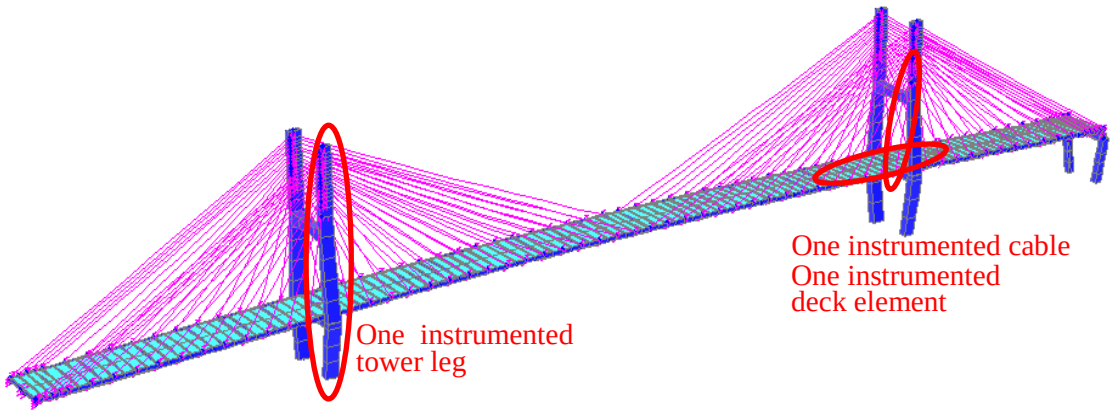

Figure 1. A hybrid computational/instrumented model of a cable-stayed bridge.

3 SBM FOR CRITICAL COMPONENTS AND ITS ATTRIBUTES

Based on common deterioration types as illustrated in Figure 2 and historical collapse statistics in existing bridges between 1966 and 2005 (Briaud and Hunt, 2006), the types of mission critical data or the key parameters for bridge design and maintenance include:

- Scour rate (depth increasing rate) for bridge scour,
- Corrosion rate and mass loss for steel members and steel reinforcing bars,
- Crack width for corrosion or stress-induced cracks,
- Strain range and number of cycles for steel element fatigue,
- Large strain for steel yielding, and
- Delamination in concrete bridge decks or composite structures.

As a problem-driven and technology-based approach, SBM is a process of directly monitoring/assessing structural behaviors, predicting the remaining life of structures, and prescribing retrofit/repair strategies. In simple words, SBM is parallel to clinical monitoring for illness while SHM is parallel to regular checkups for the sound life of man. SBM fundamentally differs from SHM in focus on major failure mechanisms in structural engineering, and use of advanced distributed sensors for behavior-related or mission critical data collection from 'hot spot' areas or the part of a structure that will likely experience damage or significant deterioration. SBM has one or more of the following attributes that are illustrated with the use of coaxial cable sensors for crack detection, fiber optical sensors for corrosion monitoring, and wireless smart rocks for scour monitoring.

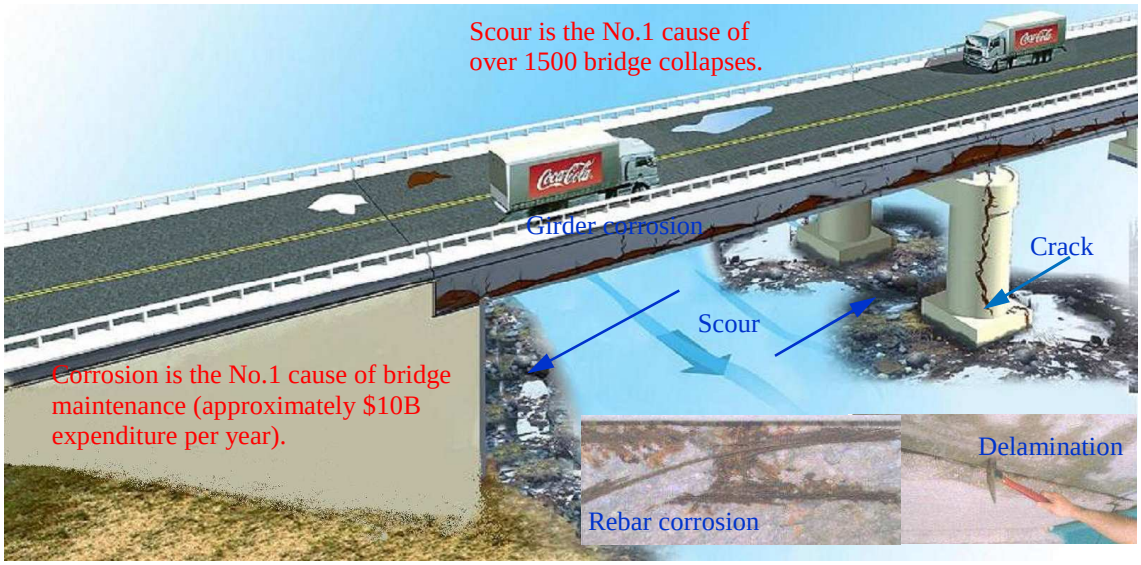

Figure 2. Schematic view of potential failure modes in bridges.

SBM advocates for need-based measurements. Real time monitoring can automatically report the onset of an abnormality in a bridge system. The engineer can choose when to economize or when there is a strong need to understand the underlying physics of a measured parameter and a sufficient time to use the real time data. This requirement

depends on the time scale within which a behavior is developed. Table 1 summarizes the need for various structural behaviors. Real time (continuous) monitoring is necessary for yielding and scouring processes only.

Table 1 Time Scale versus Real Time Monitoring (RTM) of Major Behaviors

Behavior	**Time Scale**	**Need for RTM**	**Data Usefulness**	**Monitoring**
Buckling	Seconds	High	Low	Periodic
Crack	Seconds	High	Low	Periodic
Yielding	Minutes	High	High	Continuous
Scour	Hours	High	High	Continuous
Fatigue	Years	Low	High	Periodic
Corrosion	Years	Low	High	Periodic

3.1 Direct Monitoring and Assessment of Structural Behaviors

The first and foremost SBM attribute is a direct monitoring and assessment of structural behaviors so that only mission critical data are collected for a cost-effective prediction of the remaining life of structures and for a credible life-cycle cost analysis. To this end, advanced sensors must be developed with a well-defined mechanism to experience the extension of any structural damage or deterioration. As a result, these sensors are subjected to a significant change in their topology and thus referred to as ‘sacrificing’ devices. Due to its permanent nature, this change allows engineers to retrieve the most severe damage or deterioration that a structure has ever experienced during its life span. Therefore, ‘sacrificial’ sensors give reliable data with a dual measurement process: during and after an event (Chen et al., 2005).

The concept of ‘sacrificial’ sensors was first proposed in 2002 at Missouri University of Science and Technology to develop crack sensors with coaxial cables. To date, a fundamentally new, topology-based cable sensor design has been developed and recently patented by Chen et al. (2004, 2005, 2008). Cable sensors are basically communication coaxial cables with an innovative design of their outer conductor, spirally wrapped around dielectric or Teflon as illustrated in Figure 3. The prototype sensor has an inner core made of 10 gauge wires and a Teflon dielectric coating. The outer conductor is made up of a stainless steel spiral material. The edges of the spirals are in close contact to ensure electrical continuity while mechanically separate. To ensure continuity and keep the spirals from separating prematurely, a thin solder coating was applied over the entire surface of the outer conductor. The outer conductor is capable of sliding along the smooth surface of the Teflon coating when a crack occurs across the sensor. The solder layer will break locally in the event of cracking.

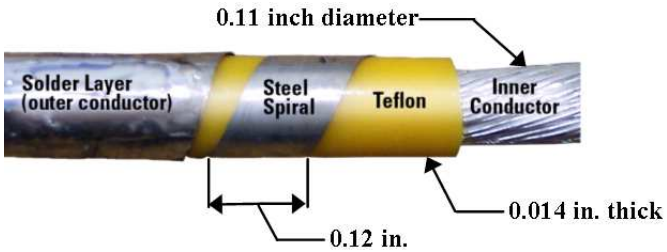

Figure 3. Cut-away sample of a coaxial cable sensor.

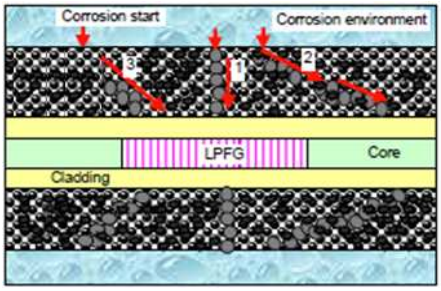

Figure 4. Schematic of a corrosion sensor.

Another example is the use of nano iron particles coated on a long period fiber grating (LPFG) sensor as illustrated in Figure 4. Black circles represented the nano iron particles and white spaces represented the filled-in nano silica particles. After the polyurethane was burnt away, a string of nano iron particles were in close contact as indicated by arrows in Figure 2, providing several corrosion paths from the environment to the optical fiber. When placed in a corrosive environment, the embedded nano iron particles are corroded away, resulting in a refractive index change of the coating that can be monitored by measuring the LPFG resonance wavelength shift. In applications, the optical fiber sensor is deployed near steel rebar so that the corrosion process of the steel is calibrated with that of the iron particles. Monitoring the corrosion process of iron particles in a well-controlled environment has much higher quality than monitoring the steel rebar directly.

Sensor placement in SBM is less an issue than that of vibration-based SHM (Soon et al., 2003). It can be determined from a pre-installation structural analysis for damage related monitoring or from maintenance experience for deterioration monitoring. For example, a uniform simply-supported reinforced concrete (RC) girder bridge is always subjected to the maximum design moment at mid span under service loads. The mid-span area shall be instrumented for cracking. On the contrary, if the 2nd natural frequency of the bridge is used in SHM, the quarter point is the optimal location for accelerometer deployment. This mathematically optimum location in SHM does not correspond to the most susceptible damage location in SBM since natural frequency is an indirect measurement of cracking.

3.2 Coupled Local and Distributed Measurements

The second attribute is a simultaneous measurement of local and distributed parameters. While the local measurement leads to high resolution observations of ‘hotspot’ areas, the distributed nature of the measurement gives critical spatial information about a structural behavior. Coupled measurements are generally unavailable with vibration-based technologies. Optical fibers and coaxial cables can be used as both sensors and signal transmitters to detect dominant structural behaviors: scour, corrosion, fatigue, and cracking/yielding. With coupled measurements, the mission critical parameters are measured twice at ‘hot spot’ areas. This dual measurement further enhances the reliability in measurements.

An electric time domain reflectometry (ETDR) sampling head launches a series of low-amplitude and fast-rising step pulses onto a coaxial cable and samples the reflected

signal caused by a topology change along the cable after the spirals are separated ('sacrificial' nature) due to local crack effects. This process results in a detour of current flow path along the outer conductor as illustrated in Figure 5. The cable as a sensor continues to function until the spirals are broken, which only occurs after a structural element collapse. The intensity and the arrival time of the reflected signal represent the size of a crack and the distance from the point of monitoring to the crack, respectively, realizing a coupled distributed and local measurement.

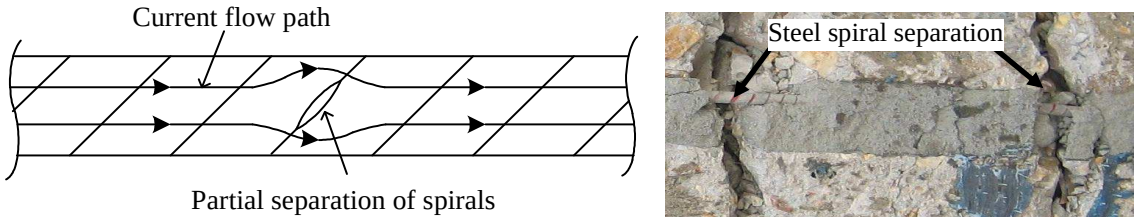

Figure 5. Work mechanism and realization of topology-based coaxial cable sensors.

3.3 Integrated Monitoring and Mitigation Strategy

Once identified from monitoring and assessment, problems can be mitigated with multifunctional materials. As an example, wireless smart rocks with embedded electronics can be used to monitor the process of bridge scour as illustrated in Figure 6. Furthermore, rocks are used to mitigate scour as a rip-rap measure. As such, smart rocks can combine the monitoring and mitigation functions. Figure 6 involves smart rocks and natural rocks placed in an existing scour hole around a pier so that the effectiveness of the scour countermeasure can be evaluated. As it moves, a smart rock or its group with other smart rocks changes its position. By tracing the position of smart rocks, the scour process is monitored effectively. Two wireless communication modes can be considered for underwater/air transmission of signals: acoustic and magneto-inductive.

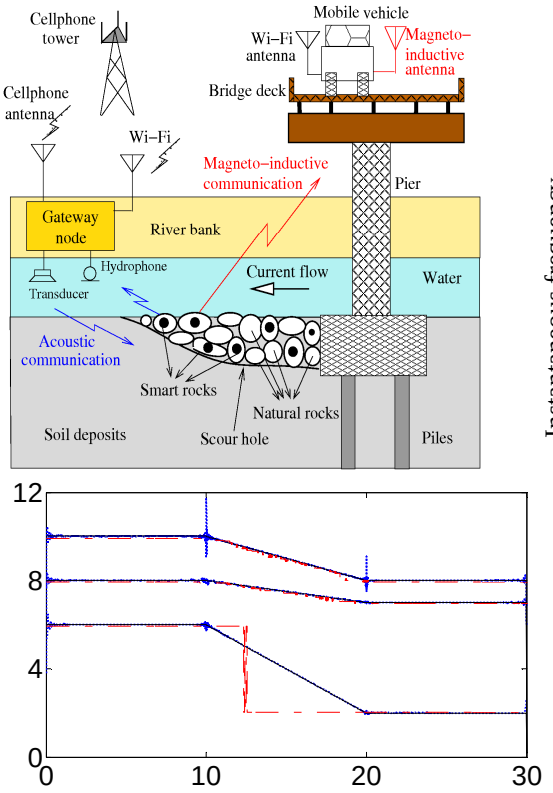

Figure 6. Smart Rocks for Scour Monitoring/Mitigation.

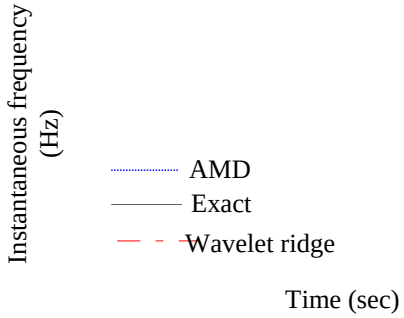

Figure 7. Instantaneous Frequencies.

3.4 Decomposition of Non-Stationary Signals for Nonlinear Systems

When vibration-based technologies are supplemented to the SBM strategy, the measured structural response of a bridge may be highly non-stationary corresponding to its nonlinear behavior, including multiple instantaneous frequencies. In this case, adaptive signal analysis is needed to extract useful engineering data such as instantaneous frequencies. To decompose such a signal, analytical mode decomposition (AMD) based on a new theorem (Chen and Wang, 2011) was developed. For example, a non-stationary signal with three frequency components that varies from 10 to 20 sec. as illustrated by "Exact" values in Figure 7 was studied by Wang and Chen (2011). As shown in Figure 7, the three instantaneous frequencies identified from AMD are in excellent agreement with those exact values. They are significantly more accurate than those by the wavelet analysis. Figure 8 shows the stationary time series in the first and last 10 sec. of the signal and the non-stationary time series in the middle 10 sec.

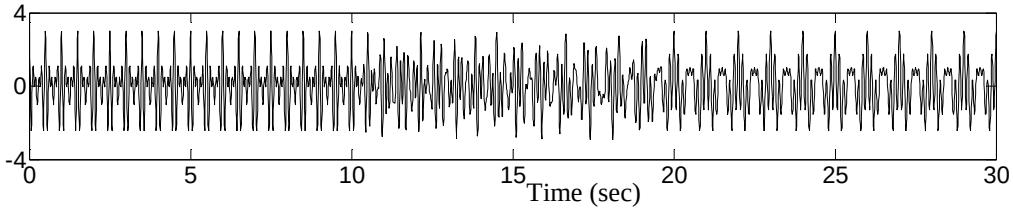

Figure 8. The non-stationary signal with three frequency components.

4 CONCLUDING REMARKS

A hybrid instrumented/computational model of a bridge with the SBM concept provides a practical framework that can address both global and local behavior monitoring in an operation-related manner. It consists of a representative substructure that is fully instrumented and the remaining part of the bridge structure that is computationally simulated in great detail. Such a model can take into account the randomness of loads, materials, and environment. The substantial shift from the current SHM to the future SBM concept will create a new paradigm for monitoring and preserving the structural integrity of large-scale civil infrastructure. This advance will generate a surge of new research interests that satisfy both the academic quest for scientific and technological explorations and the pragmatic needs for retrofit design and maintenance solutions in deteriorated bridges and other civil infrastructure such as water systems, dams, and levees. The proposed concept will change engineers' perception from the unfavorable SHM to the receptive SBM strategy, thus having significant impact on technological challenges associated with the preservation of the U.S. bridge inventory.

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