Smart Bridges Will Solve Our Bridge Crisis

GHAZALEH MOSAFERCHI, JASON TAYLER
and BRIAN WESTCOTT

ABSTRACT

Bridges are a large potential market for Structural Health monitoring (SHM), but SHM has had very little market penetration. Yet at the same time there exists a growing bridge crisis. At the current rate of investment, it will take until 2071 to make all the repairs that are currently necessary, and the additional deterioration over the next 50 years will become overwhelming. The nation needs a systematic performance-based program for bridge preservation, whereby existing deterioration is prioritized, and the focus is on rehabilitation and preventive maintenance. The approach the USA is taking to Bridge Asset Management is not working and needs to change if we are to improve and not degrade our transportation system. The industry needs to innovate to solve the problem resulting in increased productivity or in the case of bridges lower life cycle costs while maintaining full functionality.

Structural Health monitoring (SHM) has been used for many years but has not gained widespread adoption due to it being a partial solution to the bridge asset life cycle management problem and uneconomical to implement. Industry consensus is that Generation 1 SHM alone will not solve the bridge crisis. What is needed is a Smart Bridge using a total solution provided by a digital enterprise bridge performance management platform based on an IoT/cloud architecture that includes: Structural and Operating performance measurement and monitoring, Real-time analytics and alarms, and fact-based decisions for improved bridge life cycle performance and economics.

This paper will present the result of implementing a Smart Bridge strategy on a fleet of bridges by NYSDOT USA and Manitoba Canada. Their success with Smart Bridges has led to a comprehensive bridge lifecycle management strategy aimed at creating 150-year-old bridges through performance measurement and rehabilitation. This strategy is projected to save hundreds of millions of dollars over 20 years.

Smart Bridges are crucial for modern smart cities, integrating digital technologies to optimize bridge performance, reduce congestion, enhance public safety, and support autonomous vehicles. They offer a transformative approach to bridge asset management, supplementing outdated visual inspection methods with advanced IoT technology and data analytics. Both NYSDOT and Manitoba Infrastructure exemplify best practices in innovative bridge asset management, demonstrating the significant benefits of Smart Bridge strategies. These initiatives provide a blueprint for other regions to follow, ensuring the sustainability and reliability of critical bridge infrastructures for future generations.

North America Bridge Management Does Not Work – Time to Innovate

Bridges are a vital component of North America's transportation infrastructure, supporting economic activity, mobility, and community connections. However, the current state of bridge management is insufficient to address the growing challenges. According to the American Society of Civil Engineers' 2021 Report Card, the United States has over 617,000 bridges, with 42% of them at least 50 years old. Among these, 46,154 bridges—7.5%—are structurally deficient and classified as being in poor

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Ghazaleh Mosaferchi, Intelligent Structures Inc., 325 Sharon Park Drive, Suite 317 Menlo Park CA Jason Tayler, Intelligent Structures Inc, 200-135 Innovation Drive Winnipeg, Manitoba, Canada Brian Westcott, Intelligent Structures Inc, 325 Sharon Park Drive, Suite 317 Menlo Park CA 94025

condition and 62,384 bridge are posted for load restrictions. Addressing this crisis requires a significant increase in annual rehabilitation funding from $14.4 billion to $22.7 billion, representing a 58% rise. Without this increase, it could take until 2071 to complete existing repairs, while additional deterioration over the next five decades could further overwhelm resources. A nationwide strategy focused on prioritizing repairs, rehabilitation, and preventive maintenance is essential [1].

The rate of deterioration currently outpaces efforts to repair, rehabilitate, and replace bridges, leading to many being classified as "Fair." These bridges present both a challenge and an opportunity. While they are at risk of being downgraded to "Poor" condition, they can also be preserved at a much lower cost than addressing structurally deficient bridges. Despite the large investments made under the infrastructure bill, since 2021, the number of "Fair" bridges has risen by 8,371, while the number of "Poor" bridges has decreased by 1,506. This trend underscores the shortcomings of the current Bridge Asset Management strategy, which requires reevaluation to enhance rather than degrade the nation's transportation system [1].

To manage bridges more effectively, innovative approaches are needed, including the use of digital performance measurement tools, data-driven decision-making, and life cycle financial analysis as outlined in the Transportation Asset Management Planning process.

Why does Structural Health alone not work?

Structural Health Monitoring (SHM) has been widely recognized as a tool for assessing bridge integrity, yet its limitations hinder its effectiveness as a comprehensive solution. A significant challenge lies in the high costs associated with traditional Generation 1 SHM systems. Installation requires substantial investments in hardware, such as sensors and data acquisition systems, while ongoing maintenance adds to the financial burden. This expense often outweighs perceived benefits, making SHM an impractical choice for large-scale infrastructure networks [2], [3].

In addition to cost concerns, SHM faces challenges in data interpretation. Modern SHM systems generate vast quantities of data, but extracting actionable insights requires advanced analytics and expertise. This process is resource-intensive and time-consuming, often delaying critical maintenance decisions. Studies have also highlighted limitations in differentiating between normal structural responses and damage, further complicating diagnostics [4]

Furthermore, SHM remains reliant on periodic inspections, supplementing rather than replacing manual evaluation methods. This dependency compromises its potential for real-time monitoring, leaving bridges vulnerable to undetected issues between inspection intervals especially for bridges exceeding their design life. Enhanced integration with real-time analytics is essential to address this gap [5]

Finally, Gen 1 SHM technologies often struggle to justify a strong business case due to system design inefficiencies and an inability to demonstrate clear economic advantages. Many systems fail to address stakeholder needs or lifecycle performance metrics, limiting their adoption [6], [7]. This misalignment between SHM capabilities and infrastructure management goals underscores the need for innovative strategies.

In summary, while Gen 1 SHM offers valuable insights into structural performance, its high costs, complexity, reliance on inspections, and weak business case limit its effectiveness. These challenges necessitate advanced approaches such as the Smart Bridge strategy, which integrates IoT-enabled platforms and predictive analytics with autonomous quality control of fleets of bridges to optimize performance and economic outcomes.

Smart Bridge Strategy – Solution to Our Bridge Crisis

Addressing the limitations of traditional bridge management practices and existing Structural Health Monitoring (SHM) systems requires a paradigm shift. The integration of modern monitoring technologies into bridge management systems offers an opportunity to replace conventional inspection methods with innovative, technology-driven approaches. These advancements deliver more reliable diagnostics and enable proactive strategies for structural maintenance, significantly reducing long-term repair and replacement costs. By improving resource efficiency and allocation, such technologies emphasize the importance of adopting modern solutions to enhance the safety, performance, and durability of bridge assets [8].

Building on this foundation, the Smart Bridge Strategy represents the next evolution in bridge management technology, transforming static structures into dynamic, interconnected systems. At its core, a Smart Bridge is a technology-enabled structure that integrates digital elements throughout its lifecycle—encompassing design, operation, and maintenance—to ensure optimal performance. By seamlessly merging the physical and digital realms, Smart Bridges redefine the paradigm of bridge asset management and set new standards for infrastructure sustainability.

One of the defining features of Smart Bridges is the integration of advanced technologies such as networks of sensors, big data analytics, quality control process, alarm system and digital twins. These tools enable continuous monitoring of structural health and performance, not only during everyday usage but also under extreme conditions. A digital twin, a virtual representation of the bridge, predicts critical failures and highlights issues while they are still manageable as minor repairs, ensuring timely interventions and reducing long-term repair costs.

Beyond structural health, Smart Bridges address broader societal and environmental challenges. By leveraging Internet of Things (IoT) technologies, they help alleviate traffic congestion and enhance public safety. Smart Bridges support efficient lifecycle management, offering an integrated solution that prioritizes both functionality and sustainability, thereby transforming critical transportation assets into high-performing, adaptive systems.

The implementation of the Smart Bridge Strategy involves a systematic process, as depicted in Figure 1:

1. Visual inspection for a period until the bridge enters a zone of unknown performance where past practices would warrant the bridge being rebuilt, Figure 2. This is in the late stage of FAIR condition or a condition rating of 5 or the early POOR condition rating of a 4. Also, consideration is given to the age of the bridge and where it is relative to the design life.
2. Once the zone of unknown is established the Smart Bridge calibration stage begins with a preliminary dynamic load testing, determining the bridge natural frequency. The natural frequency provides a first level of sorting of bridges with indications of better structural performance or worse structural performance as that

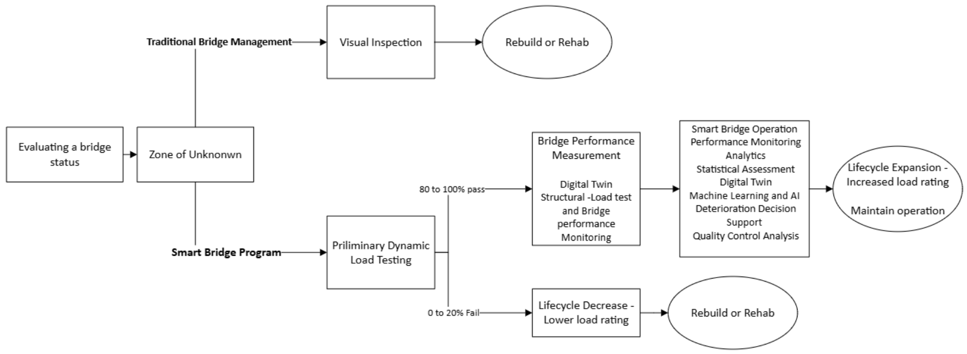

Figure 1. Traditional bridge management comparison with smart bridge program.

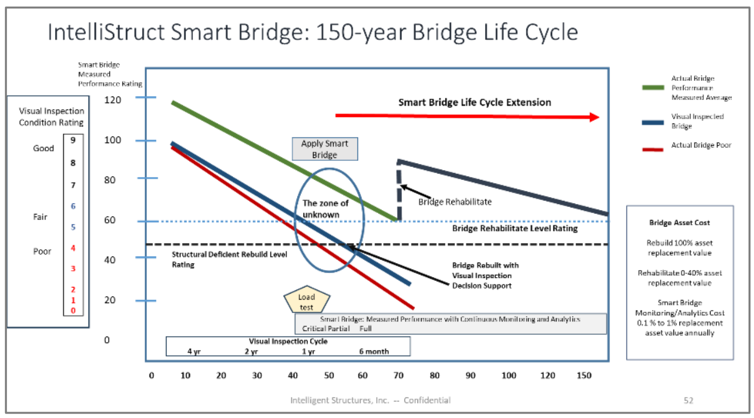

Figure 2. 150-year bridge lifecycle through Smart Bridge Program

predicted by visual inspection. Between 80 to 100% of bridges have a higher natural frequency than expected, indicating a higher performance than predicted by visual inspection. For bridges sorted into the higher performing category, the next step could be the creation of a digital twin, a Finite Element Model (FEM), of the bridge as (new) built, the design of a sensor measurement system related to the bridge's design, material used, issues and level of operational use and environment it operates under. Using the digital twin a set of expected strains are calculated for each of the strain measurement points for the bridge. These strain levels reflect the new condition of the bridge. Under an established set of tests procedures, the bridge will be load tested and continuously monitored using a Smart Bridge Platform.

3. The new performance load rating and condition rating of the bridge will be measured and calculated. The rating will compare the actual strains measured during the various tests to the calculated strains from the digital twin simulated for the same test. A Smart Bridge Performance Factor is calculated based on these relationships. Based on the rating and condition, a fact-based decision on how the bridge should be operated is made: operated as is, rehabilitated, or rebuilt and a schedule for operation. The operating decisions will be reviewed annually based on the measured performance measurements, analytics and quality control system provided by the Smart bridge platform.

4. Bridge managers will then revise budget decisions for the life cycle costs of the Smart Bridge fleet. The results have proven to have significant investment returns for

Bridge owners and should improve bridge condition rating while creating additional budget to spend on other bridge projects.

Smart Bridge Case Study 1: Erie Canal Bridges

New York State Department of Transportation (NYSDOT) is facing the same problem as the United States and identified in ASCE 2021 Bridge Report Card, a bridge crisis. This crisis is the result of aging bridges, insufficient maintenance and rehabilitation and the lack of accurate measured information on real bridge conditions resulting in poor decisions made on bridge asset management. NYSDOT has experienced this problem and despite the increased investment required to meet their Transportation Asset Management Plan (TAMP) has seen an increase in FAIR bridges from 2021 to 2024 of 203 while only reducing POOR by 8.

NYSDOT identified four historic bridges with undetermined (zone of unknown) operating performance and were subject to load restrictions. One of the bridges was structurally rehabilitated with the other three measured in their operating condition. These bridges were movable Lift Truss bridges built in 1913 and 1914. The goal of this project was to determine and monitor the structural integrity of the bridges during load testing and during their continued daily day to day use.

The bridges' performance was measured and analyzed through the development of a finite element model (Digital Twin) and a calibration of the bridge's performance with a live load test, Figure 3. The Smart bridge measured dynamic characteristics such as load sharing, element coupling, neutral axis, dynamic strain under daily operation, weight of traffic and different environmental conditions which reflect the continuous demands and operation of the bridges.

Once the bridge's real performance was tested, a new load rating was determined. Using a Smart Bridge Program, all the bridges had improved inventory and operating load ratings that were near new conditions and allowed for standard traffic with the load restrictions lifted, demonstrating the effectiveness of the Smart Bridge Program. Bridge A served as a notable example of instrumentation advancements, equipped with 22 strain gauges, 12 accelerometers, 13 temperature sensors, 1 steel temperature sensor, 1 ambient air temperature sensor, and 1 smart frequency module, Figure 4. These monitoring tools provided bridge engineers with crucial performance data for ongoing analysis.

The deployment of Smart Bridge monitoring technologies has revolutionized the way historic structures like these are preserved and maintained. By leveraging real-time analytics, NYSDOT demonstrated the potential to extend the lifecycle of aging bridges, restore functionality, and enhance safety while optimizing costs and improving decision-making in asset management.

Smart Bridge Case Study 2: Manitoba Smart Bridge Fleet

Manitoba, a province that stretches into the Arctic Circle, presents one of the most challenging environments for building and maintaining bridges. Harsh weather conditions and extended exposure to extreme temperatures place immense stress on infrastructure. Recognizing these challenges, Manitoba Infrastructure adopted a Smart

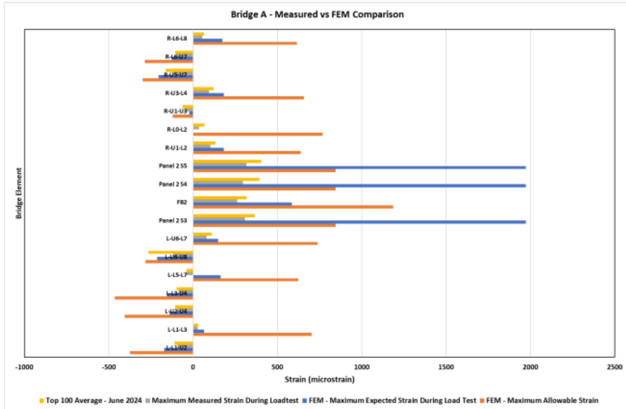

Figure 3. Comparison of maximum recorded strains from Bridge A elements during load testing with maximum expected and allowable strains from FEM predictions, along with the top 100 strain averages representing heavy traffic in June 2024. Results indicate bridge performance surpasses FEM expectations under both conditions.

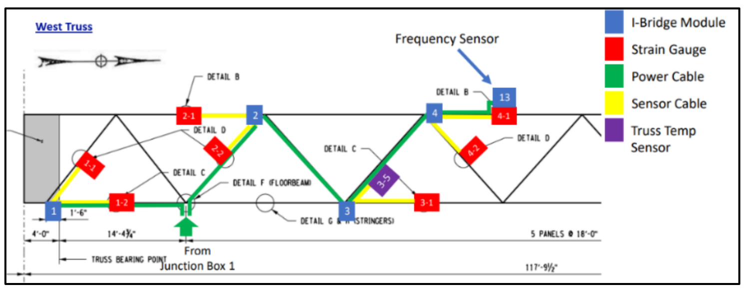

Figure 4. Example schematic view of strain gauges mounted to the West truss superstructure.

Bridge strategy to optimize bridge management, improve mobility, and reduce lifecycle costs. This innovative approach involved implementing a performance platform for a fleet of 20 bridges initially classified as being in an unknown state of performance based on visual inspection. These bridges were originally scheduled for rebuilding.

Eight years after the adoption of the Smart Bridge program, Manitoba's fleet continues to demonstrate the value of technology-driven lifecycle management. At the outset, all 20 bridges were found to be in better condition than predicted by visual inspections. Through the use of continuous monitoring and real-time analytics, the bridges remained operational, avoiding immediate rebuilding, Figure 5. Over time, changes in measurements and analytics have identified the need for rehabilitation or rebuilding for only 4 of the 20 bridges, while the remaining 16 continue to operate at full capacity. This fact-based analytic approach equips engineers with decision-support tools to proactively manage deterioration and allocate resources effectively.

Manitoba's success illustrates the transformative potential of Smart Bridge strategies for a fleet of bridges in extending infrastructure lifespan, reducing costs, and adapting to extreme environmental conditions. By leveraging advanced monitoring technologies, the program not only preserves critical infrastructure but also sets a benchmark for innovative bridge management practices in challenging climates.

Figure 3. Left: Manitoba Smart Bridge Fleet real-time alarms. Center: Single measurement data from one of the Smart Bridges in Manitoba. Right: Smart Bridge Quality Dashboard

Smart Bridge Economics

The implementation of Smart Bridge strategies demonstrates the substantial economic and societal benefits of advanced infrastructure management practices. Within the Erie Canal Lift Bridge Fleet, New York State Department of Transportation (NYSDOT) leveraged cutting-edge monitoring technologies and predictive analytics to improve bridge performance while optimizing budget allocation. This initiative successfully complied with New York State's Transportation Asset Management Plan (TAMP) laws, ensuring adherence to rigorous infrastructure management standards. Beyond the measurable financial returns, the program enhanced mobility, resiliency, and safety for residents, showcasing its multifaceted value.

Economically, the application of the Smart Bridge Strategy to four bridges resulted in a net present value (NPV) of $3,200,000 and an internal rate of return (IRR) of 62%. These impressive figures highlight the long-term cost savings and operational efficiency achieved through proactive maintenance and data-driven decision-making. This approach underscores the transformative potential of Smart Bridge programs in addressing infrastructure challenges while delivering significant public safety benefits.

Similarly, Manitoba's Smart Bridge strategy has proven its economic viability across a fleet of 20 bridges with an asset replacement cost exceeding $500 million. By deferring capital expenses, the province achieved annual savings of $35 million, while maintaining operational expenses of less than $500,000. This remarkable return on investment reflects a responsible and efficient asset management strategy, aligned with the TAMP framework. The implementation of Smart Bridge technologies has optimized lifecycle costs and demonstrated the province’s commitment to infrastructure sustainability.

Building on the success of Smart Bridge fleet management, Manitoba Infrastructure has developed a comprehensive lifecycle management strategy aimed at creating "150-year bridges" through performance-driven assessments and targeted rehabilitation. Once fully implemented, Manitoba’s Smart Bridge strategy is projected to deliver tens of millions of dollars in annual savings. Economic modeling estimates budget savings ranging between $300 million and $400 million over a 20-year period, emphasizing the strategy’s transformative financial impact and scalability.

Conclusion

The Smart Bridge Strategy offers a transformative solution to the urgent challenges of bridge infrastructure management. By transitioning from static, inspection-dependent systems to dynamic, technology-enabled structures, this innovative approach enhances safety, resiliency, and sustainability. Through the integration twins, and predictive analytics, Smart Bridges empower proactive real-time diagnostics, and fact-based decision-making, fundamentally redefining the lifecycle management of critical transportation assets.

The successful implementation of Smart Bridge programs by NYSDOT in the USA and Manitoba in Canada demonstrates the significant economic and societal benefits of this approach. From improving bridge performance and complying with regulatory frameworks to achieving measurable financial returns—including a $3,200,000 net present value and a 62% internal rate of return for NYSDOT and projected savings of $300 to $400 million for Manitoba over 20 years—Smart Bridges illustrate the power of innovation in infrastructure management. Beyond financial outcomes, these programs contribute to public safety, reduce traffic congestion, improve environmental quality, and support modern urban mobility, making them invaluable to communities.

As infrastructure systems continue to age and face increasing demand, the Smart Bridge Strategy provides a scalable and sustainable pathway toward efficient and resilient bridge management. Its adoption will not only mitigate current challenges but also lay the foundation for smarter, future-ready infrastructure that serves both economic and societal needs. By embracing this approach, governments and organizations can ensure the reliability and sustainability of essential transportation systems for generations to come.

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