Applicability of Structural Health Monitoring of Bridges in Megaprojects

Dinesh Kumar Gupta *
Raghabendra Yadav**

Abstract

Nepal is currently experiencing significant growth in infrastructure development, with numerous bridge construction projects underway. Integrating health monitoring systems into these projects is crucial, aligning with global trends in infrastructure management. Implementing Structural Health Monitoring (SHM) systems using advanced sensors, data acquisition systems, and decision support mechanisms allows engineers to detect minute behavioral changes in critical infrastructure. This early detection capability enables timely interventions, enhancing structural safety and longevity. SHM systems can be tailored to meet specific operator and structural requirements, offering a cost-effective solution. With minimal installation costs, SHM can reduce overall maintenance and operation expenses by up to 98%, while providing invaluable life-saving warnings.

Keywords: Structural Health Monitoring (SHM), components of SHM, design of SHM, SHM data analysis, operation and maintenance of SHM system, sensors for different monitoring item.

Introduction

The Kathmandu -Terai/Madhesh Fast Track [Expressway] Road Project, referred in general as KTFT represents a substantial infrastructure endeavor designated as a "National Pride Project" due to its strategic importance. Considering the scale of the project, KTFT easily qualifies for the category of Megaproject on a global as well as national scale. Oversight of construction management for this initiative was entrusted to the Nepali Army by the Government of Nepal on the 21st of Baisakh, 2074 BS, with formal handover facilitated through the Ministry of Physical Infrastructure and Transportation (MoPIT) on the 27th of Shrawan, 2074 BS. This long-anticipated expressway follows the path initially pioneered by the Nepali Army in 2069 BS. Regarded as an exceptionally demanding endeavor, the Nepali Army views this Mega Project as an opportunity to meet rigorous international standards in civil engineering. Consequently, the Nepali Army aims to construct the Expressway as a benchmark for state-of-the-art civil construction within South Asia. Moreover, the Expressway is anticipated to serve as a catalyst for significant socio-economic development in Nepal. Spanning a length of seventy-one kilometers, the project route traces the Bagmati River corridor, commencing at Sano Khokana and traversing Chhaimale, Gausel, Malta, Budune, and Chhatiwan before culminating at Nijgadh, where it intersects with the East West Mahendra Highway. This initiative is projected to reduce travel distance from Kathmandu to Nijgadh by 193 kilometers and decrease travel time by over four hours. Comprising 89 bridges of varying spans, carriageway widths, and total lengths totaling approximately thirteen kilometers, the project carries an estimated budget of around 214 billion NPR in total, with the bridge component alone anticipated to constitute about 30% of the overall expenditure. Many of the bridges proposed along this Asian Design standard highway represent pioneering ventures within the country and are

* PhD Scholar in Structural Engineering at TU, IOE, Pulchowk Campus. <replydinesh@ioe.edu.np>
** Bridge/Structural Design Engineer, KTFT Road Project, Nepali Army. <raghabendrayadav@gmail.com>

anticipated to serve as prototypes for similar structures in subsequent national projects. While consultants and contractors are tasked with successful design implementation and construction, careful consideration must also be given to strategies for the operation and maintenance of these costly and critical structures. (Nepali Army. (n.d.)).

Over time, all constructions, including vital civil infrastructure like bridges and roads, experience wear and tear. This degradation occurs for several reasons, such as fatigue from repetitive traffic, exposure to environmental elements, and the impact of extreme events like earthquakes. If these damages go unnoticed, it can lead to decreased safety margins or operational issues for the structure. In the end, structural failure is more likely, which could result in property and human casualties. Growing concern over the state of existing structures, particularly after earthquakes, has prompted a number of studies on damage detection using various non-invasive assessment methods. Very few studies have been conducted in Nepal regarding this aspect as one conducted by Pokhrel & Yadav (2019) with the help of smartphones and its applications.

Overview of Health Monitoring Systems

Bridges serve as the cornerstones of our transportation networks, upon which society relies heavily. As our bridge inventory ages, the tasks of operation and maintenance have become increasingly intricate. Structural Health Monitoring (SHM) has emerged as a crucial component of lifecycle management practices, gaining significance in recent years. To uphold and enhance the superior quality and service standards expected by the public, understanding the lifecycle performance of structures is paramount. This knowledge is essential for ensuring long-term serviceability and durability (Wenzel, 2014).

Applying an approach to identify damage is part of SHM. The procedure comprises periodically taking measurements of a structure, identifying features from these observations, and evaluating the results to determine the structural system's present health. The outcome is periodically updated information about the structure's ability to fulfill its intended function, considering the undeniable aging and degradation from operational conditions (Abdo, 2015). Based on this monitored state, decisions are made regarding appropriate repairs, rehabilitation, and/or strengthening to ensure the continued operation of these structures and extend their lifespan. Civil infrastructure facilities are the foundation of our economy, and monitoring is essential since repairs and maintenance are much less expensive than building new ones. This explains the coordinated efforts of nations such as Japan, the USA, China, New Zealand, and others to install monitoring equipment in bridges, important structures, and dams (Abe, 1998).

While bridges might be monitored periodically to get an overview of the current situation, the SHM we are focusing on now relies on sensors installed permanently to produce continuous data, which is then presented through specialized software featuring intelligent graphics and alert-generating capabilities. This approach is supplemented by occasional spot check inspections, facilitating the analysis of relevant structural data. The main objective of SHM is to preserve infrastructure, extend its operational lifespan, and identify and predict potential faults.

Concurrently, SHM monitors both the structure itself and its surrounding environment, encompassing factors such as usage patterns and weather conditions. This comprehensive monitoring involves integrating a diverse range of measurements, with a significant portion of data collected automatically, including satellite-based measurements. The processed data yields meaningful indicators that operators can rely on to optimize the operation and maintenance of their structures.

SHM market is undergoing a profound transformation, driven by advancements in sensor technologies, data analytics, and the integration of artificial intelligence. As the industry embraces trends such as wireless sensor networks, real-time analytics, and sustainable monitoring solutions, the capabilities of SHM systems continue to evolve. These trends not only enhance the reliability and safety of critical infrastructure but also position SHM as a cornerstone in the sustainable and intelligent development of the built environment.

Given the importance of soundness and longevity of the expensive structures like those proposed in this national pride project, it becomes utmost important to install the monitoring systems during the construction period itself as is the latest trend worldwide. Many existing structures were provided with the monitoring systems during its operation phase whereas the trend to install the systems during construction phase itself is picking up the momentum such as in New I35W Bridge in Minneapolis, USA. Out of 40 bridges considered for case studies, 45 percent of the bridges had the monitoring system installed during the construction phase itself.(Inaudi, 2010)

Millau Viaduct (France), Akashi Kaikyo Bridge (Japan), Queensferry Crossing (Scotland), Golden Gate Bridge (USA), Oresund Bridge (Denmark/ Sweden), The Suez-Canal (Al-Salam) bridge (Egypt) are just to name a few bridges which have permanent sensors installed onto them for monitoring the overall health of the structure These sensors play a crucial role in ensuring the safety and functionality of the bridge.

Components of SHM system Installation

Permanent SHM systems typically consist of several key components working together to continuously assess the condition, performance, and safety of a structure such as a bridge. Here are the main components presented in tabular form:

Table 1: Typical components of SHM

1. Sensors	They measure key physical parameters like strain, acceleration, displacement, temperature, corrosion etc. tailored to the bridge's specific monitoring needs.
2. Data Acquisition System	The data acquisition system interfaces with sensors, digitizes readings using components like analog-to-digital converters (ADCs) and signal conditioning modules, and stores data for analysis.
3. Communication Network	A communication network transfers sensor data to a central database for analysis, using wired or wireless technologies like Wi-Fi, cellular, or satellite, chosen based on factors such as distance and reliability.
4. Centralized Monitoring System	The centralized monitoring system is the core of the SHM system, collecting, processing, analyzing, and visualizing sensor data. It includes software, databases, and computing infrastructure for real-time monitoring, storage, analysis, and visualization of structural health parameters
5. Data Analysis and Interpretation Tools	Analysis tools extract insights from sensor data using statistical analysis, signal processing, machine learning, and finite element modeling to identify patterns, anomalies, trends, and potential structural issues
6. Decision Support System	A decision support system offers actionable insights to engineers and bridge operators, aiding in maintenance prioritization, inspection scheduling, structural integrity assessment, and informed decision-making for safety and reliability.
7. Alarm and Alerting Mechanisms	Alarm systems alert stakeholders to abnormal conditions or risks detected by the SHM system via visual alerts, emails, SMS, or automated calls, ensuring prompt response to critical events.
8. Maintenance and Calibration Procedures	Regular maintenance and calibration of sensors, equipment, and software are vital for ensuring the accuracy, reliability, and longevity of the SHM system. These procedures mitigate sensor drift, equipment failures, and other issues that could impact system performance.

By integrating these components into a comprehensive SHM system, bridge owners and operators can continuously monitor the health of their structures, detect early signs of deterioration or damage, and implement timely interventions to ensure the safety, resilience, and longevity of the bridges.

Design of SHM system

The Structural Health Monitoring System (SHMS) encompasses two primary processes: the Structural Health Monitoring Process (SHMP) and the Structural Health Evaluation Process (SHEP). Within the SHMP, continuous monitoring of bridge performance occurs by comparing measured data against design benchmarks, utilizing statistical and numerical analyses. In contrast, the SHEP is dedicated to identifying and predicting potential structural concerns, as well as forecasting future bridge performance. An essential aspect involves correlating measured data with finite element analysis results for structural health assessment, facilitated by relational database management systems to ensure coordinated data processing(Andersen & Vesterinen, 2006).

The effective deployment of SHM systems necessitates thorough planning and precise installation to achieve optimal performance. Owners or operators of structures must carefully determine the specific performance criteria relevant to their particular structure, and subsequently tailor the system installation accordingly. The market offers a variety of sensors, each designed for specific monitoring purposes. Therefore, meticulous attention to the technical specifications of these sensors and their resultant outputs is essential to ensure that the investment in the system is not squandered. Table 2(Wong, 2007), presented below, outlines several available sensors and their corresponding applications, contingent upon the parameters being monitored.

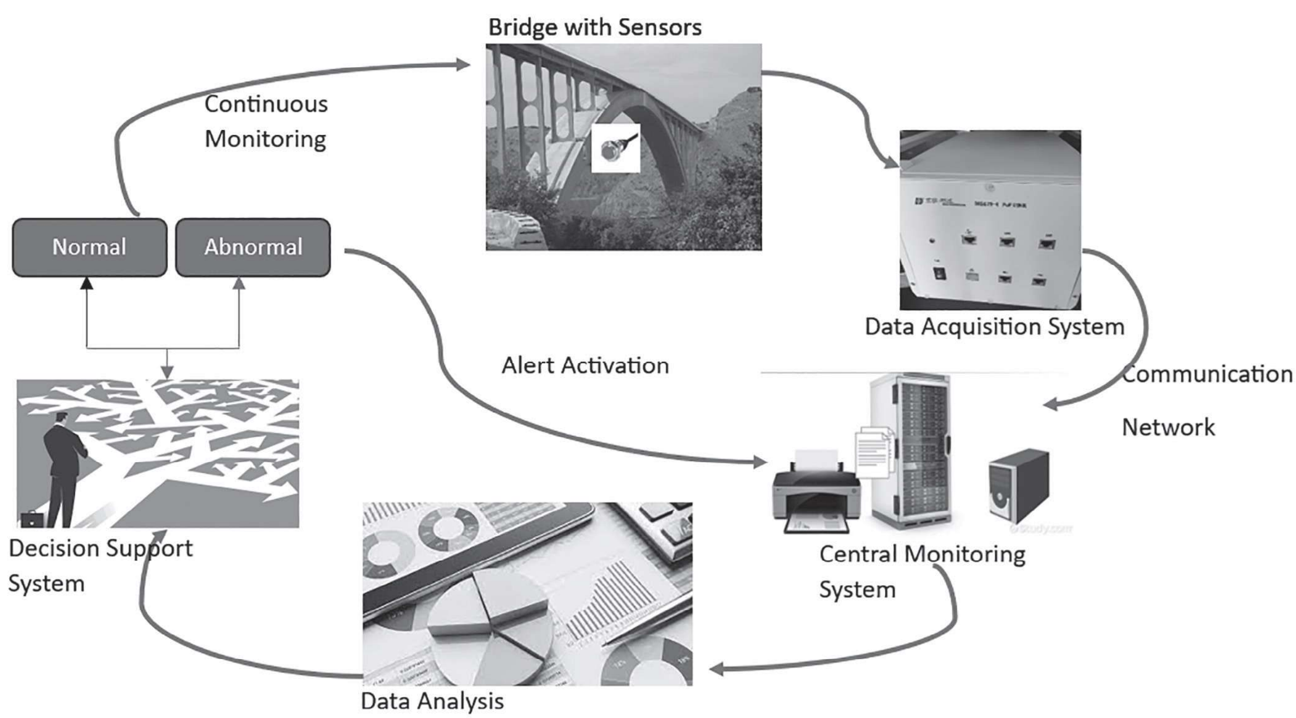

Figure 1: SHM in Function

Table 2: Major items for Design of SHM systems

Category for Monitoring	Items for Monitoring	Sensor Type	Probable Parameters
Loads and Environments	Wind Loading	Anemometers, Barometers	Wind speed and Direction, Air pressure
	Temperature Loading	Thermistors, Thermocouples, Infrared Sensors	Temperature gradient in different parts, air temperature
	Highway Loading	Load Cells, Accelerometers, Weigh-in-motion sensors	Traffic Load and Patterns, Bridge Deflections, Vibrations
	Seismic Loading	Accelerometers, Seismometers,	Bridge vibration, ground motion.
	Corrosion Status	Electrochemical sensors, Corrosion Probes, Impedance Spectroscopy	Corrosion status of Rebars, Rate of Corrosion.
Bridge characteristics	Static Influence Line Characteristics	Strain gauges, Displacement Sensors, Load Cells	Influence Lines, Influence Surfaces.
	Dynamic Influence Line Characteristics	Accelerometers, Data Acquisition Systems	Mode shapes, Modal Frequencies, Damping Ratios
Bridge Responses	Geometric Configuration	GPS, Level Sensing Stations, Inclinometers	Bridge coordinates, Tilt of structure members, Deck and water level.
	Strain-Stress Characteristics	Static Strain gauges	Strain and stresses in various structural components, Bearings.
	Fatigue Characteristics	Dynamic Strain gauges	Stress cycle, fatigue levels and dynamic strain

Supervisory Control and Data Analysis

The preceding section, which concentrated on the SHM process, underscores the commensurate significance of the structural health evaluation process. The meticulous assessment of data gathered from diverse sensors affixed to the structure is imperative, both to ascertain data quality and to ensure the structural system's proper operation. Prompt notification to experts is essential upon detecting any anomalies in the data. Depending on the anomaly's characteristics and severity, corrective measures may involve verifying and ensuring the proper functioning of the transmitting sensors or subjecting the structure, particularly the suspected component, to continuous scrutiny. The ensuing table provides a comprehensive overview of the monitoring system infrastructure requisite for maintaining the structural integrity and optimal performance of the sensor network.

Table 3: Different components in Monitoring infrastructure and their purposes

Monitoring component	Purpose
Establishing Data bases	The data received from the sensor arrangement as well as visual inspection are to be logged based on the type of sensors, date of visit or receipt etc.
Data Acquisition and Transmission	The acquisition of data shall be planned carefully and should be stored in temporary devises shall the permanent servers be unavailable for a short period of time.
Data Storage	All the data received shall be stored permanently on dedicated servers unless reviewed to be deleted by a panel of experts.
Data Processing	The data received shall undergo a pre-processing and any unusual signal shall be immediately reported to the panel of experts where the data shall be checked for any possible defects in the structure and their possible remedies.
Data Access	The stored shall be accessible to concerned stakeholders such as designers, builders, operators as their interest in data is fueled by their specific interests.

Structural Health Monitoring (SHM) systems have demonstrated their effectiveness in providing early warnings of potential bridge failures, thereby allowing for preventative measures to be taken before catastrophic events occur. SHM systems utilize an array of sensors and data analytics to continuously monitor the structural integrity of bridges, detecting stress, wear, and other critical indicators.

A significant case highlighting the potential of SHM systems is the I-35W Mississippi River bridge in Minneapolis, Minnesota. Despite the absence of a fully integrated SHM system prior to its collapse in 2007, this incident underscored the critical need for such technologies, subsequently leading to their broader implementation (Lai et al., 2009).

Furthermore, the Queensferry Crossing in Scotland is equipped with an advanced SHM system, which monitors various structural parameters in real-time and has been successful in providing early warnings for maintenance interventions (Brownjohn et al., 2018). Another pertinent example is the Sutong Yangtze River Bridge in China, where the SHM system has successfully detected cable slippage and other structural issues, enabling timely maintenance and repair actions (Ni et al., 2011).

Operation and Maintenance of SHM system

In addition to above mentioned infrastructure, the monitoring systems shall be designed to make the system to normally run unmanned and to be operated by non-technical staff(Andersen & Vesterinen, 2006). There are various key considerations to ensure the installed system is robust and functioning as per the expectations. A few of them being listed below:

1. **Regular calibration:** Ensure the calibration of the instruments is done before installation and is done periodically as well.
2. **Data quality:** Ensure the data received is of desired resolution that can be processed to something meaningful.
3. **Continuous monitoring:** Ensure the devices are working round the clock or for desired duration, if not a quick check on devices is advised.
4. **Remote accessibility:** Desired end users shall be able to access the data remotely as visiting the site might be costly or time taking affair.
5. **Regular maintenance:** Routine inspection, servicing, upkeep of sensors is advised on a regular basis.
6. **Cybersecurity Measures:** Encryption, authentication and intrusion detection system while accessing the data is advised for the security of the data.
7. **Adaptability and scalability:** The monitoring system shall be adaptable to future expansion or partial replacement of the sensor systems.

Conclusions

The KTFT, a significant infrastructure project managed by the Nepali Army, is labeled a "National Pride Project" for its strategic importance. To ensure long-term safety and durability, it's crucial to integrate SHM systems during construction. SHM involves continuous monitoring via sensors that measure key physical parameters like acceleration, displacement, strain, temperature, and corrosion etc. These sensors, part of a comprehensive data acquisition and analysis network, detect damage and degradation over time, enabling timely maintenance and repairs.

SHM systems comprise sensors, data acquisition systems, communication networks, centralized monitoring systems, data analysis tools, decision support systems, alarm mechanisms, and maintenance procedures. These components work together to provide real-time data and alerts on the expressway's structural integrity, aiding in extending its lifespan. Advanced SHM systems utilize wireless sensor networks, real-time analytics, and AI, enhancing infrastructure reliability and safety.

The design of SHM involves the SHMP and the SHEP, using statistical and numerical analyses to assess and predict structural health. Careful planning and sensor selection tailored to specific performance criteria are essential. Ongoing supervisory control and data analysis ensure data quality and prompt detection of anomalies.

Effective operation and maintenance of SHM systems encompass several crucial practices: regular calibration, continuous monitoring, remote accessibility, routine maintenance, cybersecurity measures, and adaptability for future expansions. These practices ensure that the SHM system remains robust and reliable, providing essential data for the safe and efficient management of infrastructure like the expressway. Regarding the cost of installation, Torti et al. (2022) found that SHM systems are economically viable, with a payback period of less than 50 years, averaging between 13 to 18 years. Additionally, compared to regular inspections, event-based inspections triggered by sensor alarms result in approximately 98% cost savings (Zulfiqar et al., 2015). These findings underscore the financial and operational benefits of implementing SHM systems in infrastructure projects, especially megaprojects.

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