The Framework for a Comprehensive Bridge Management Platform Using Digital Twin

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Introduction

Critical civil infrastructure, such as bridges, deteriorate with time due to extensive use. For this reason, it is necessary to inspect infrastructure in a reliable way to observe potential damage and the magnitude of deterioration, and then to quantify the health of the examined structures. In many structures, inspectors use sensors to measure displacements and deflections and use the obtained results to determine the serviceability of infrastructure. Still, funds and resources are highly limited, so decisions about repair and maintenance must be cost-efficient.

With these restrictions in mind, the general aim of the approach implemented by Kinemetrics is to develop a bridge management platform using digital twin that will monitor the safety and reliability of bridge infrastructure in a cost-efficient way. In this way, the project will lead to an increase in public safety, and it will also reduce life cycle costs of bridge maintenance. In comparison to other projects of this type, the novelty factor is the observation that the funding that is normally made available for vital infrastructure maintenance is never sufficient, irrespective of whether it comes from federal, state, or local sources. For this reason, this approach pays special attention to asset management that is supported by designated SHM and digital twin technologies.

The Framework

To achieve the intended results, we have divided the framework into four components with the corresponding deliverables, as illustrated in Figure 1 and Table 1.

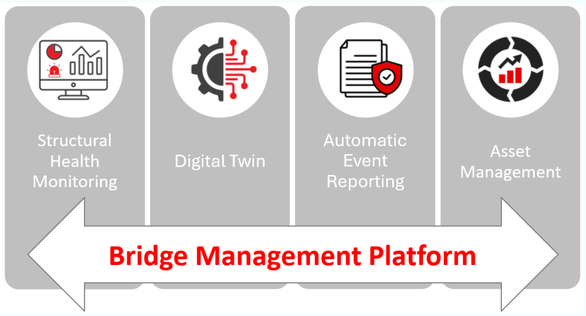

Figure 1. Bridge Management Platform

Table 1. Components, subcomponents and deliverables for the framework

N	Component	Subcomponent	Deliverable
1	Structural Health Monitoring	SHM System design, build, install, and commission, maintenance plan	SHM System
2	Digital Twin	Developing digital twin, damage assessment and prognosis	Updated FEM Model
3	Automatic Event Reporting	Re-evaluation triggers, guidance for SHM	Bridge Evaluation Report
4	Asset Management	Data repository for user access, training material, knowledge transfer workshop	Workshop

Structural Health Monitoring

Structural health monitoring (SHM) relies on various sensors to evaluate bridge conditions (see Figure 2).
Commonly used sensors include:

- Accelerometers: Measure vibrations and dynamic responses to external forces.
- Strain Gauges: Detect strain variations within bridge components.
- Tiltmeters: Monitor angular displacements and inclination changes.

By continuously recording bridge responses, these sensors help engineers assess structural integrity, detect anomalies, and validate theoretical models that guide design and maintenance strategies.

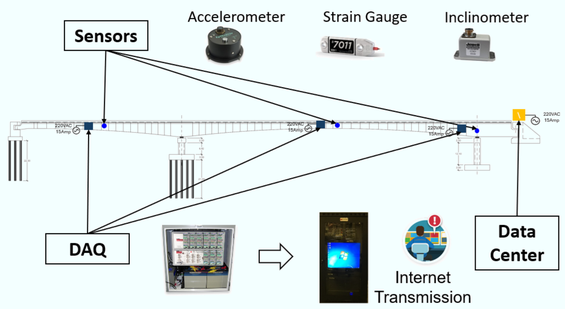

Figure 2. Typical instrumentation in bridge monitoring.

Digital Twin

During this stage, we develop and calibrate an FE model on the basis of the data we collected during SHM. The performed analysis, combined with the interpretation of the digital twin (see Figure 3), help us understand the expected behavior of the bridge under operating conditions and in simulated extreme loads, as well as to recognize vulnerabilities and potential failure mechanisms.

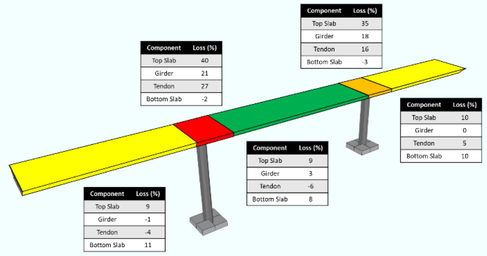

Figure 3. Digital twin of a bridge.

We determine the FE Model scope and detailing by taking into account the condition of the respective bridges. It may happen that some bridges will require additional, extreme event scenario modeling, checks for redundancy, or custom fragility curve development.

A crucial outcome of this stage is the digital twin, which is applied as a valuable baseline to validate identified mode shapes and to determine optimal sensor placement for modest long-term monitoring solutions. The digital twin can be also used as a tool for stakeholders to provide them with rapid, reliable post-event assessment, future assessment and retrofit, asset management, load rating, and even as direct tool for operational monitoring (see Figure 4).

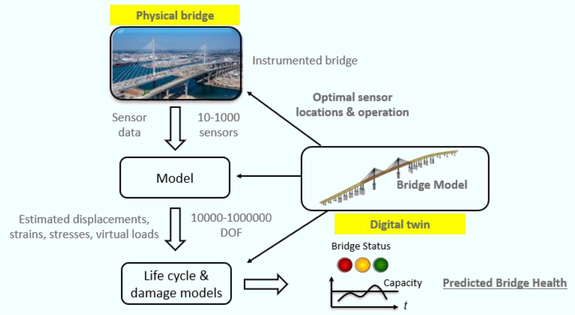

Figure 4. Integration of the digital twin and SHM system.

Automatic Event Reporting

The proposed system integrates sensor technology and automated analysis to provide real-time post-earthquake bridge assessments (see Figure 5). Its primary components include:

- Sensors and Data Acquisition: Accelerometers and other sensors collect bridge response data.
- Data Processing: Raw acceleration data are converted to displacement measurements.
- Threshold Analysis: Predetermined serviceability thresholds identify when structural limits are exceeded.
- Automated Reporting: Once a threshold is exceeded, the system generates an automated report detailing the bridge's condition and recommended actions.

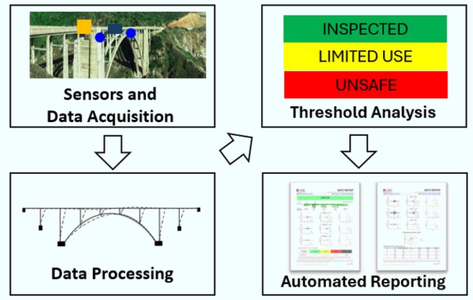

Figure 5. Automatic Rapid Assessment System.

Asset Management

The asset management system takes the form of a secure online data repository for information dissemination and the efforts required to “plugin” each bridge to the SHM system as it is made available online. It is a web-based portal where all data and information retrieved from all project tasks are available and presented in such a way so that it supports maintenance decision-making and priority ranking. We are aware that the previous tasks are unique to each bridge, but the results will be uniform, and we intend to present them in a similar manner.

Conclusions

This poster has presented the workings of a platform developed by Kinemetrics for assessment and management of a large number of bridges. As has been shown, the main aim of the described framework is to develop a platform that will effectively monitor the safety and reliability of bridge infrastructure in big cities, which in general will improve public safety.

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