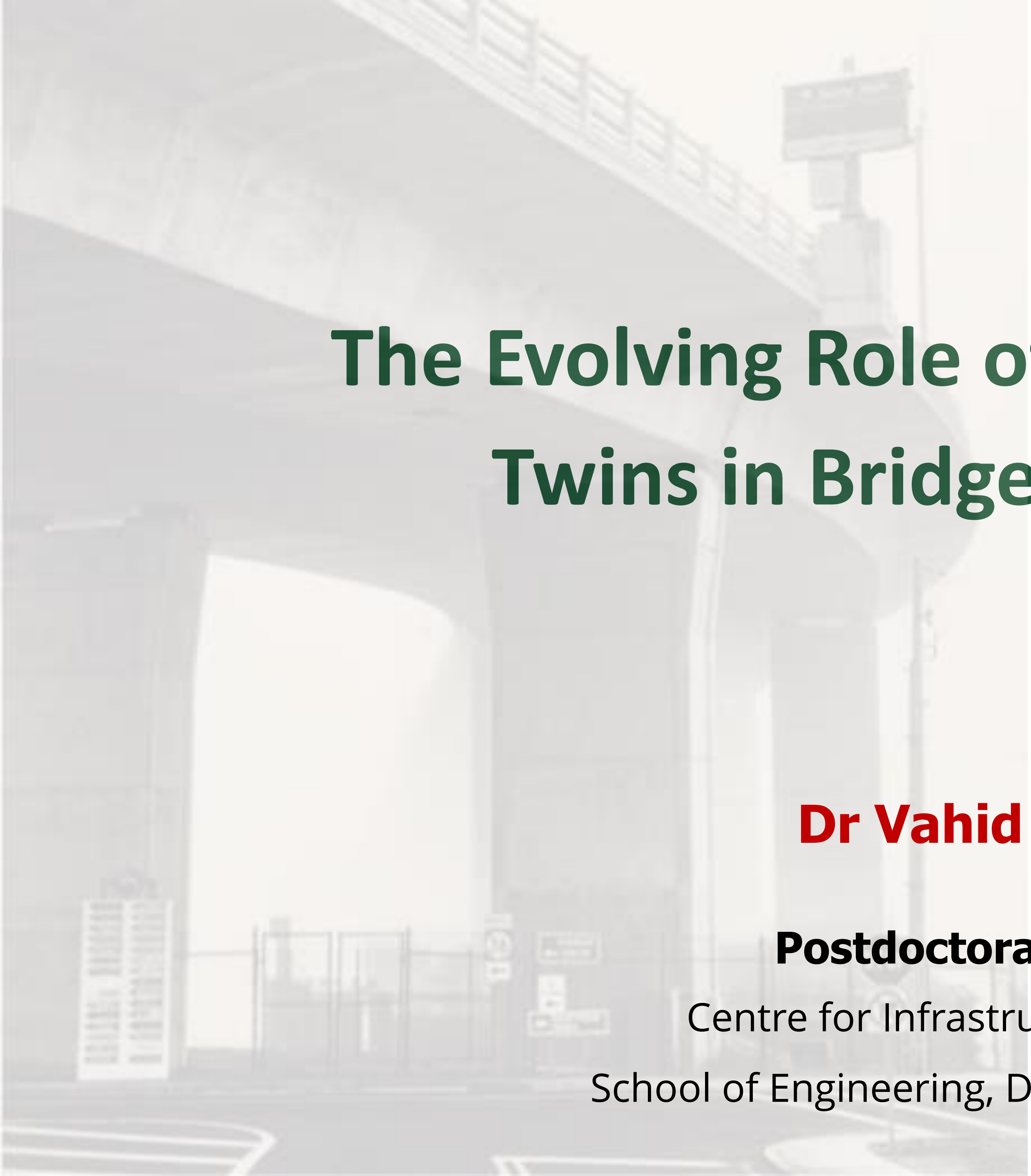

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The Evolving Role of AI-enabled Digital Twins in Bridge Management

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School of Engineering, Design and Built Environment

Overview

- About SAHM Team
- Evolution of Digital Twin in Infrastructure
- Components of a Bridge Digital Twin
- Role of AI in Digital Twin
- Real-time Data Integration and Analysis
- Real time Sensor Technology for Digital Twin
- The Real-time AI-enabled bridge Digital Twin
- Case Study: Real-time Monitoring System

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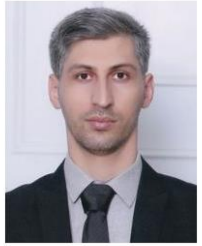
ABOUT SAHM TEAM

SAHM team at Western Sydney University offers specialised engineering consulting and research capabilities aimed at identifying practical solutions to clients' needs.

- ➢ Inspection and Condition assessment
- ➢ Asset digitalisation
- ➢ Structural analysis and health monitoring
- ➢ Heritage preservation
- ➢ Maintenance planning and priority ranking

Liaison for Technical Services

SAHM Team Leader



Team Member

Team Member

MW Engineers · TECHNOCRETE Structural & Durability Consulting Engineers · ARTC · COOTAMUNDRA-GUNDAGAI REGIONAL COUNCIL · GHD · IPWEA INSTITUTE OF PUBLIC WORKS ENGINEERING AUSTRALASIA · QPRC Queanbeyan-Palerang Regional Council · NTRO · CITY OF SYDNEY · NSW GOVERNMENT Transport for NSW · KYOGLE & villages · KYOGLE COUNCIL · CANTERBURY BANKSTOWN · wollongong city of innovation

The Challenges of Ageing in Bridge Infrastructure

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- **In the past two decades, the deficiencies related to ageing bridges have become a common problem throughout the world.**
- **A large number of bridges are constructed over 50 years ago and are subjected to deficiencies due to overloading, harsh weather and limited maintenance.**

USA	**42% of all bridges are at least 50 years old** **7% are structurally deficient**
UK	**A large number of bridges were built in early 1950s** **35% of them are sub-standard**
AUS	**More than 50% of bridges are more than 50 years old**

The Challenges of Ageing in Bridge Infrastructure

- The repair and maintenance of the existing bridges has become the priority to bridge managers.

- Traditional inspection → on-site inspectors

laborious → time-consuming → unsafe → expensive

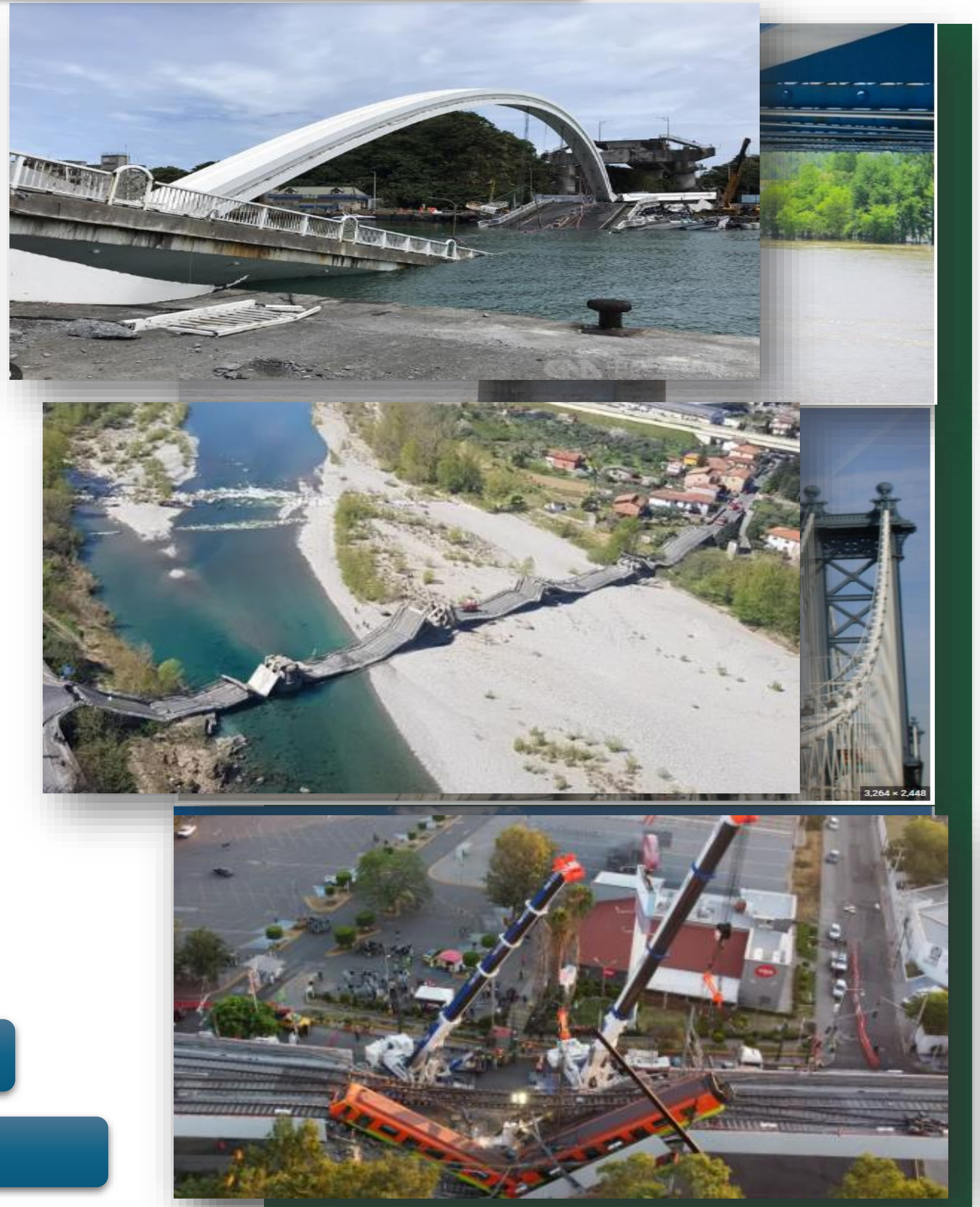
- Bridge Management based on regular inspections have been proven to be ineffective.

- The results of ineffective management would be severe:

Taiwan bridge collapse in 2019

Caprigliola bridge collapse in Italy in 2020

Mexico City railway bridge collapse in 2021

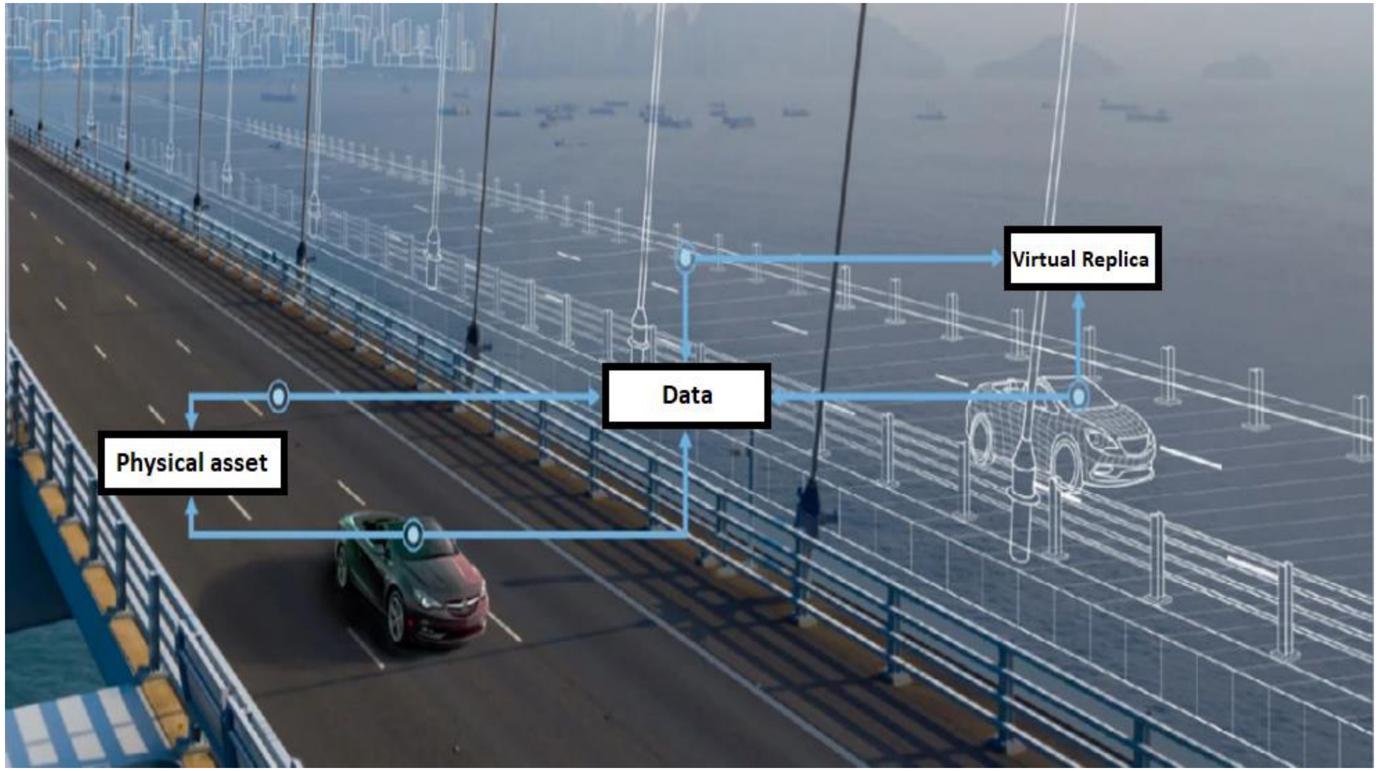


Digital Twins: Transforming the Bridge Maintenance

- Digital Twins have been developed to overcome the limitations of conventional bridge management methods, representing a significant advancement in this field.

- Bridge Digital Twins represents a virtual replica of the physical asset that is employed for monitoring in-operation bridges.

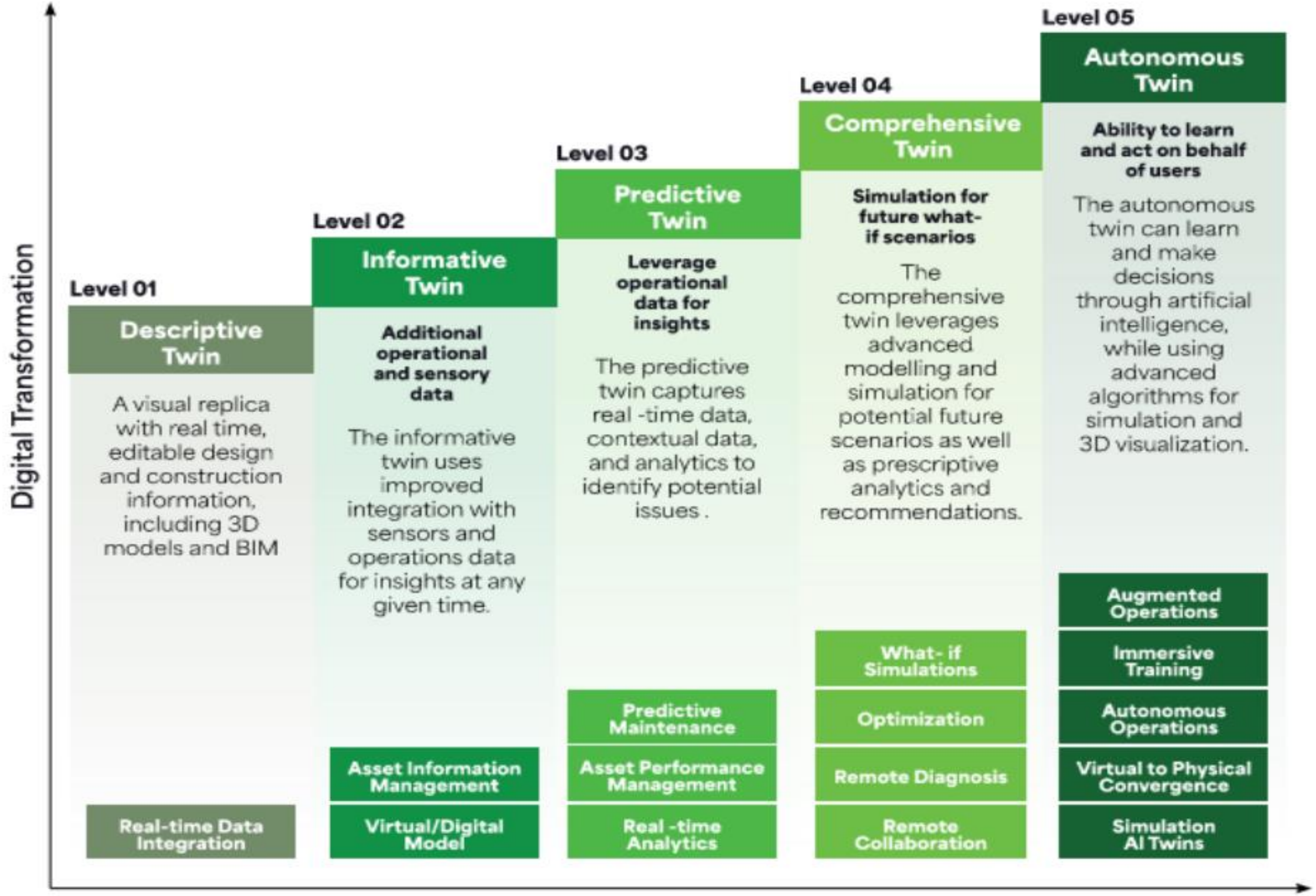
- Enables Monitoring:
  - Condition
  - Performance
  - Behaviour
  - Real time- near real time



Digital Twins: Transforming the Bridge Maintenance

- **Digital Twins** Maturity Model

To make the most of Digital Twins Development of Digital Twin should move along maturity levels



Source: Inspired by the Verdantix's five-level maturity model

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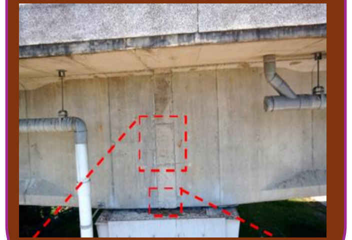
Digital Twins Components

Digital Twin Data collection methods

- **Effective data collection play a vital role in Digital twins development.**
- **They provide valuable information about different aspects of the physical object's performance.**
- **Different methods can be used to collect data for bridge Digital twins:**

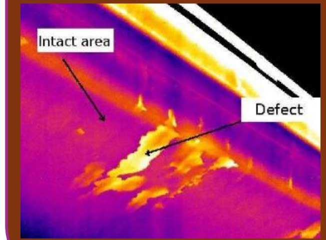
RGB Image



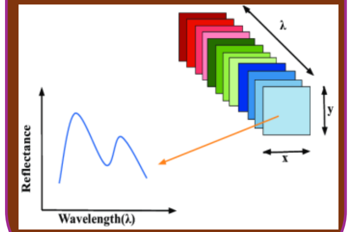
Ground Penetrating Radar

Point cloud

Infrared thermography



Hyperspectral Imaging



Contact sensors

Digital Twins Components

Digital Twin virtual models

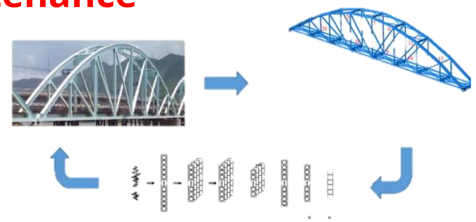
- The generation of the virtual models for the bridge, serves as the main skeleton of the Digital Twin.
- Virtual models can be categorized into four groups based on their components and functionalities:

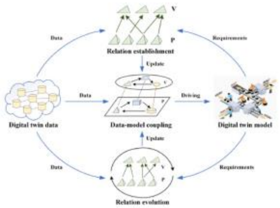
Geometric-based Models

Functions
- Determining bridge geometry changes
- Defect detection

Data-driven Models

Functions
- Real time Monitoring
- Predictive Maintenance



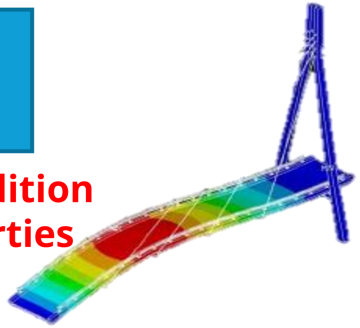


Information Models

Functions
- Life-cycle maintenance data storage
- Analysis of historical data

FEM-based Models

Functions
- Structural condition
- Physical properties



Role of AI in Digital twin

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- **AI-Enabled Digital Twin offer numerous capabilities and benefits in infrastructure management and maintenance.**

Real-time Data Analysis and Processing

Predictive Analytics and Maintenance

Enhanced Simulation Capabilities

Improved User Interaction and Experience

An Evolved AI-enabled Digital Twin Framework

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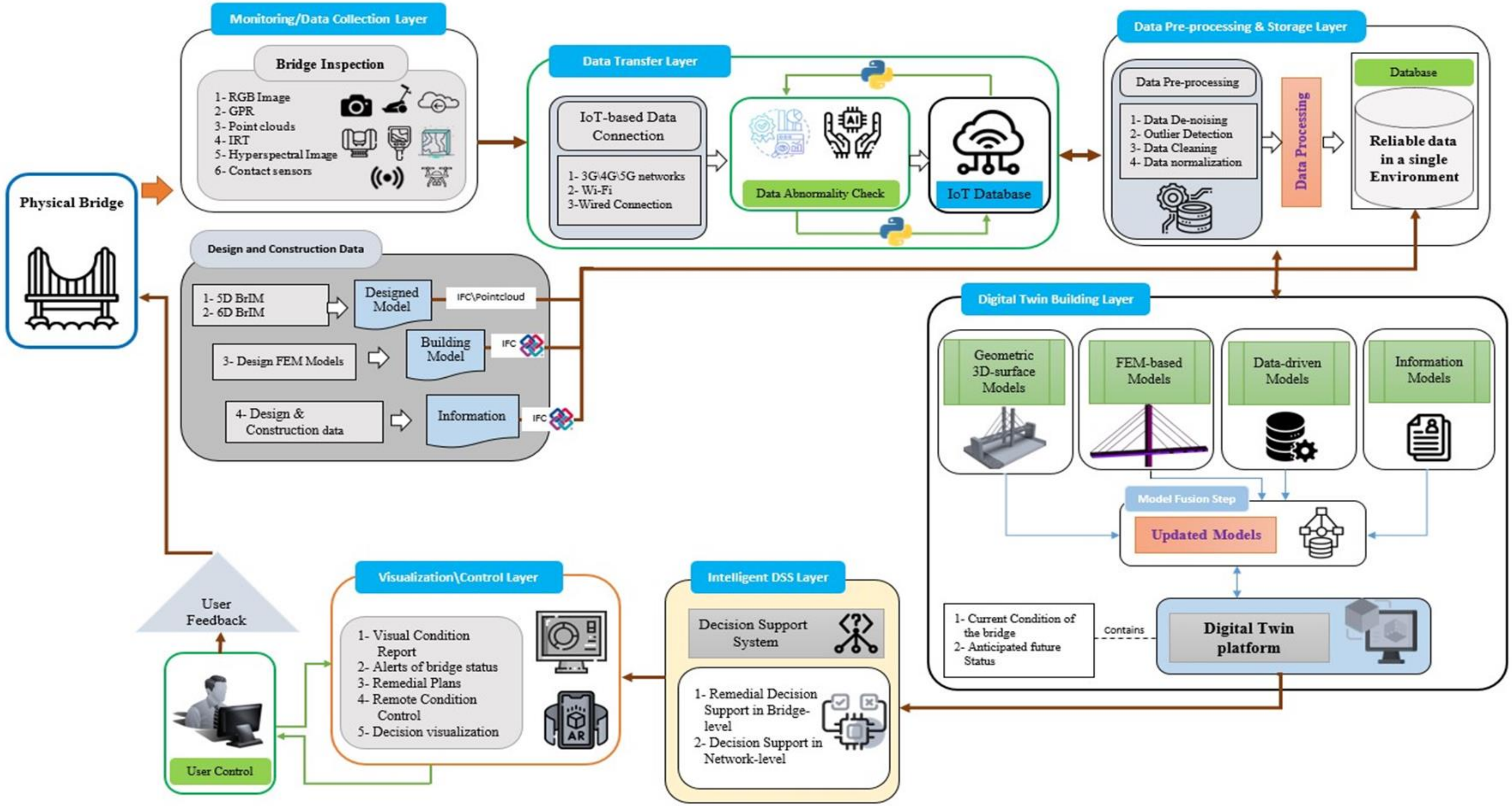
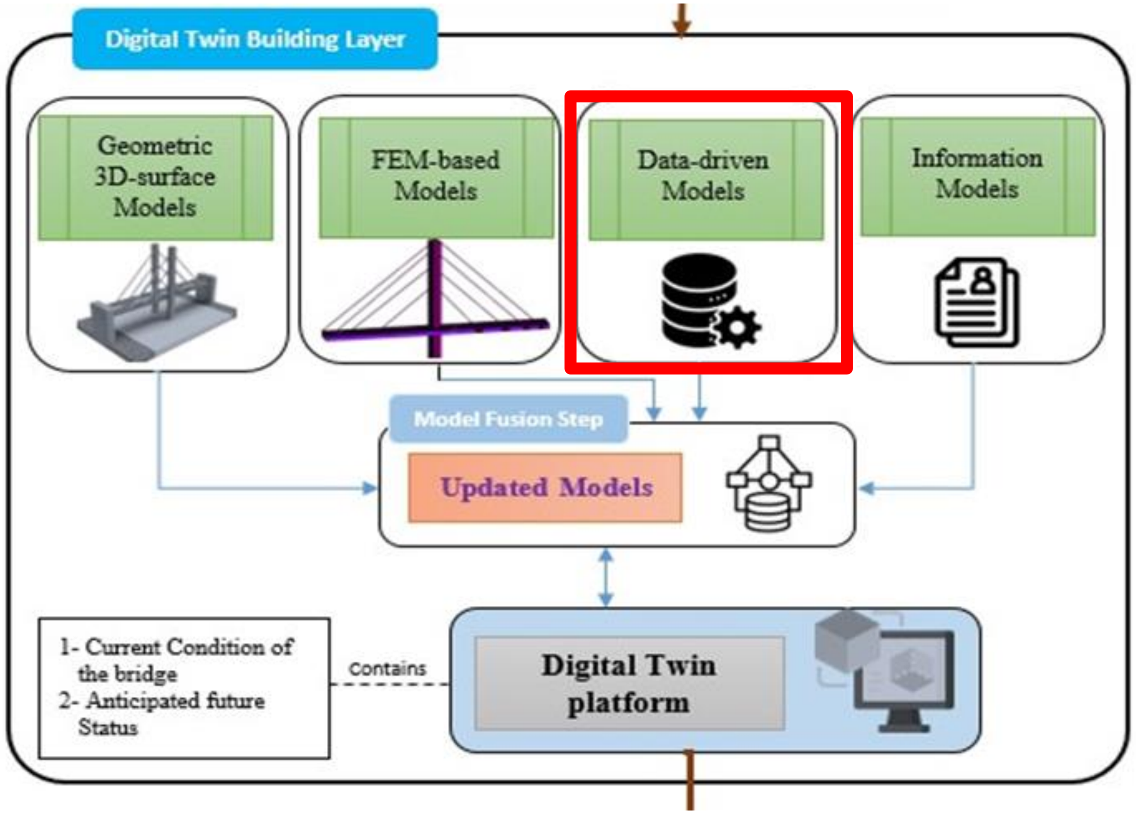


Role of AI in Evolved Digital twin

Data-driven models are computed through AI-based mathematical models that approximate the behaviour of the bridge based on exploration of the relationship between data.

These models can be used to predict the bridge's response under different conditions without the need for extended and time-consuming simulations or physical testing



Real-time Data Analysis in Digital Twin

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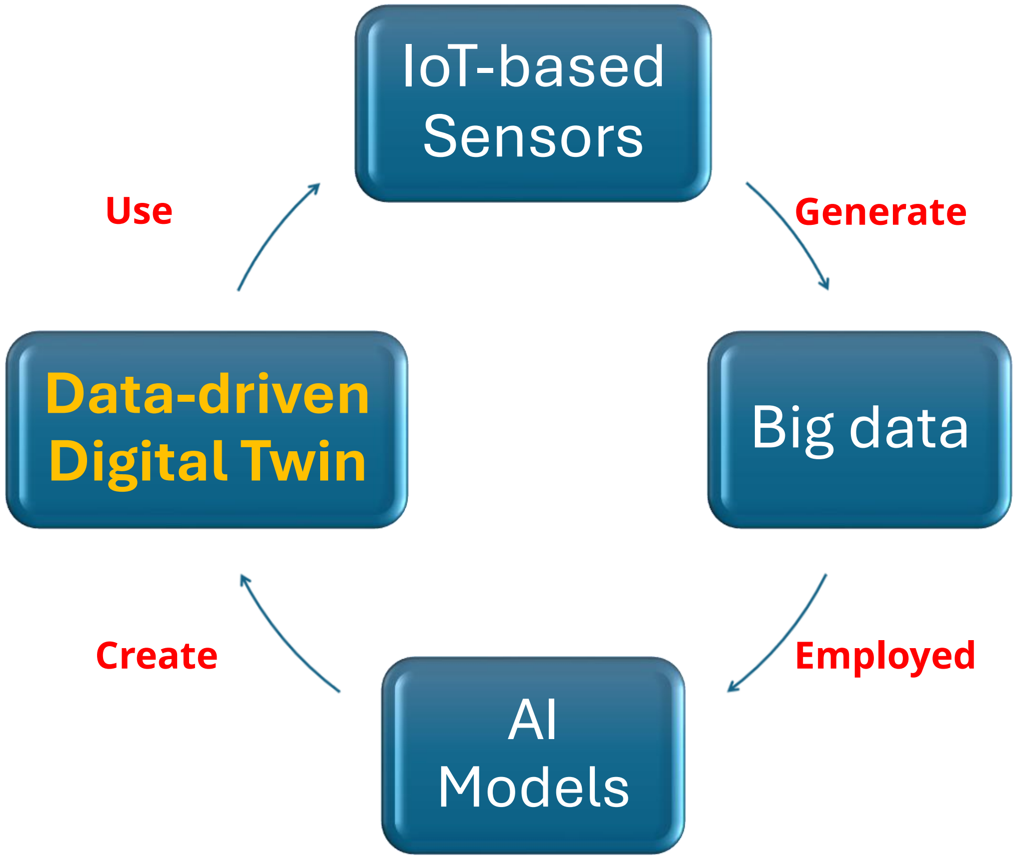
- **Real-time data analysis enable predictive maintenance and early fault detection.**
- **Enhances the Digital Twin's fidelity and responsiveness to actual bridge conditions.**
- **Supports automated alerts and decision-making systems.**



Real-time Sensor Technology for Digital Twin

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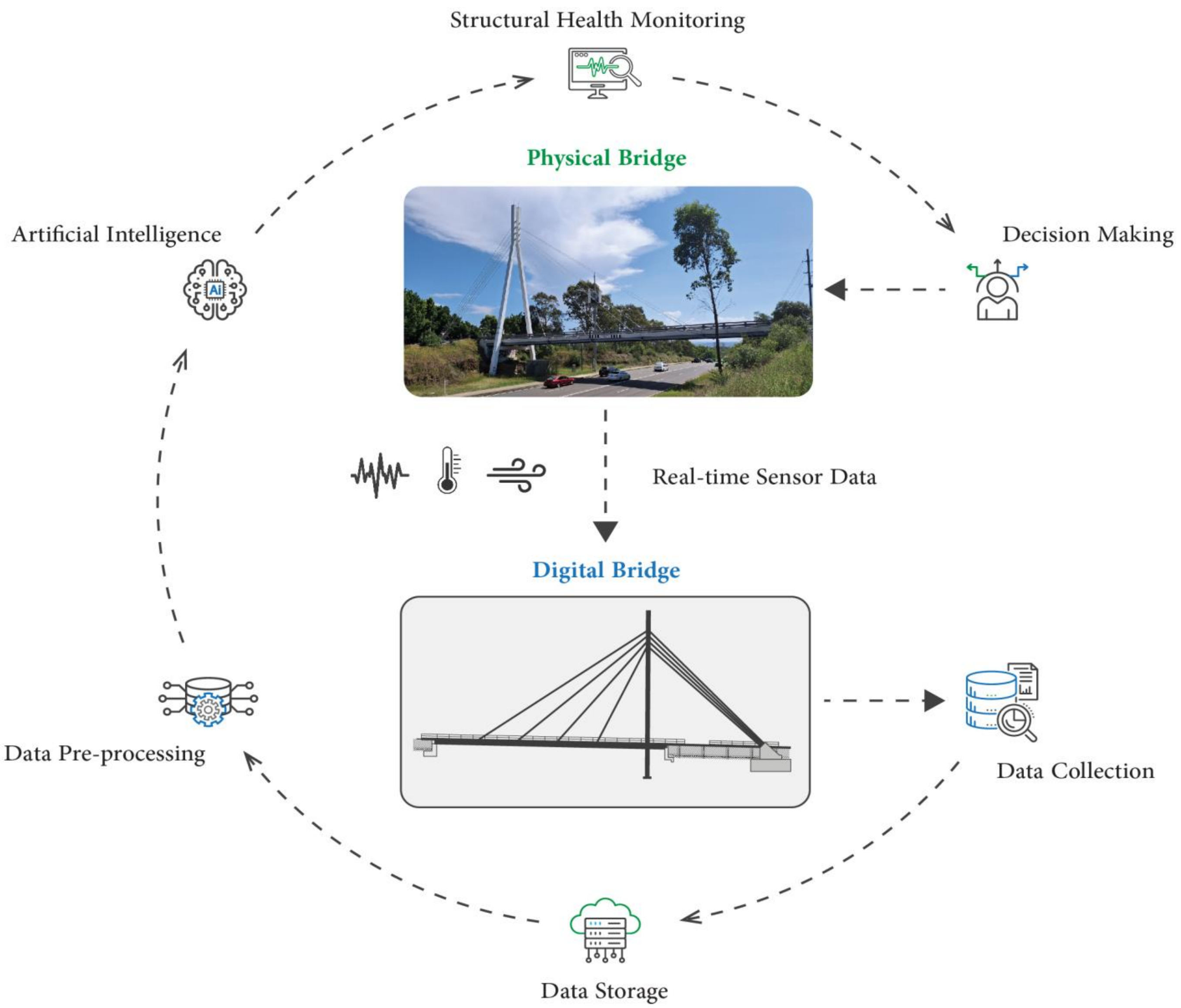
- ❑ Strain Gauges
- ❑ Accelerometers
- ❑ Displacement Sensors
- ❑ GPS Sensors
- ❑ Fibre Optic Sensors

The Real-time AI-enabled bridge Digital Twin

- ❑ A layered architecture for efficient data analytics in bridge Digital twins.
- ❑ Data-driven digital twin framework facilitates proactive maintenance and operational efficiency.



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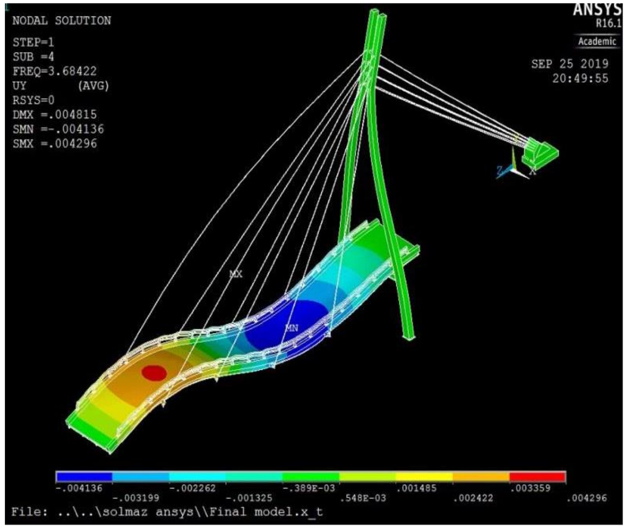
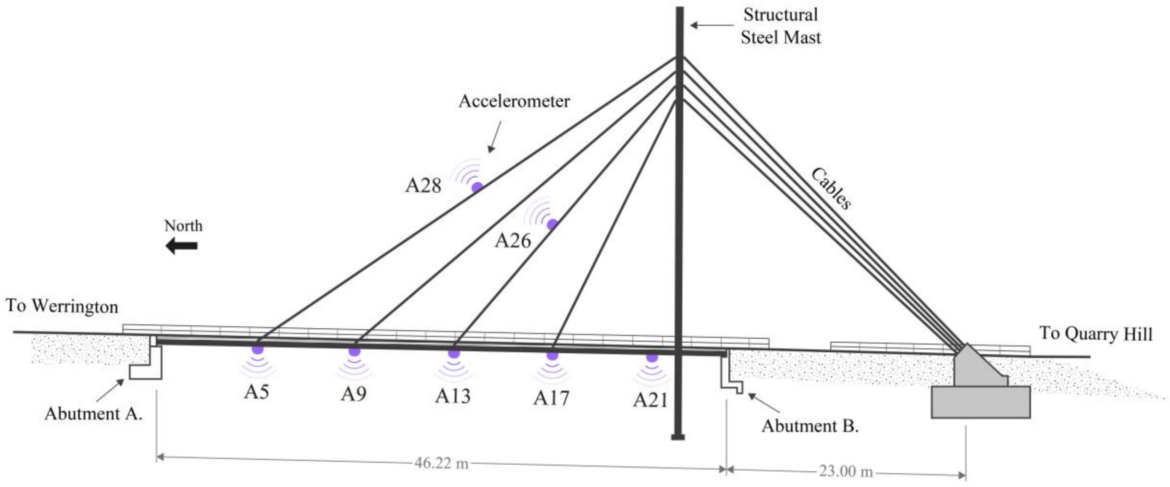
Case Study: Werrington Bridge





Case Study: Werrington Bridge

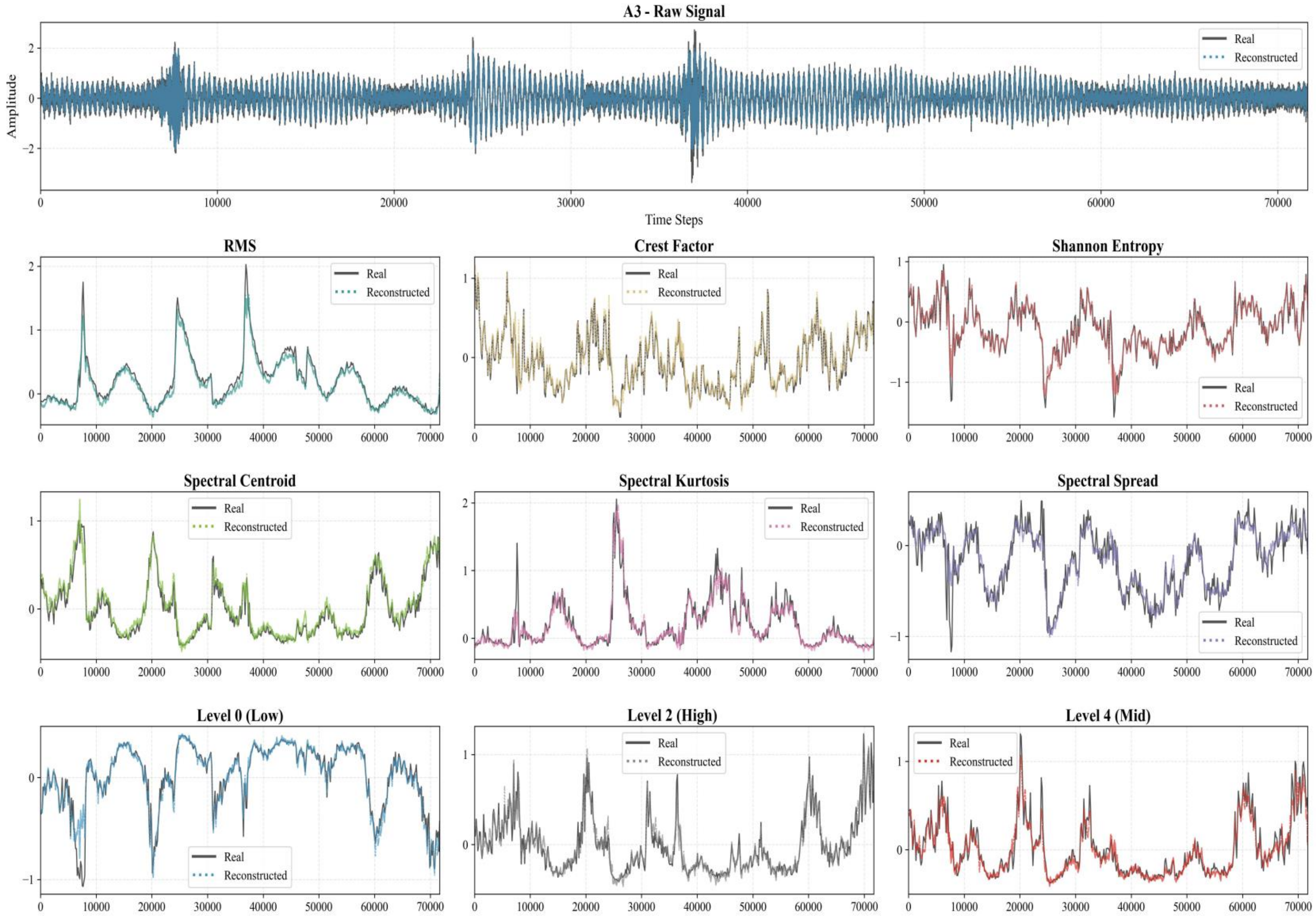
Signal Processing and Extracted features:

- **Pre-processed acceleration signals and their corresponding extracted features**
- These extracted features formed the foundation for training the AI model, providing a comprehensive representation of bridge's dynamic behaviour under normal operating conditions.

Case Study: Werrington Bridge

Training Performance:

- Comparison of the actual and reconstructed signals for a sample accelerometer
- The close alignment between the real and reconstructed signals across all domains indicates that the model successfully captured the underlying patterns associated



Case Study: Werrington Bridge

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Evaluation Strategy:

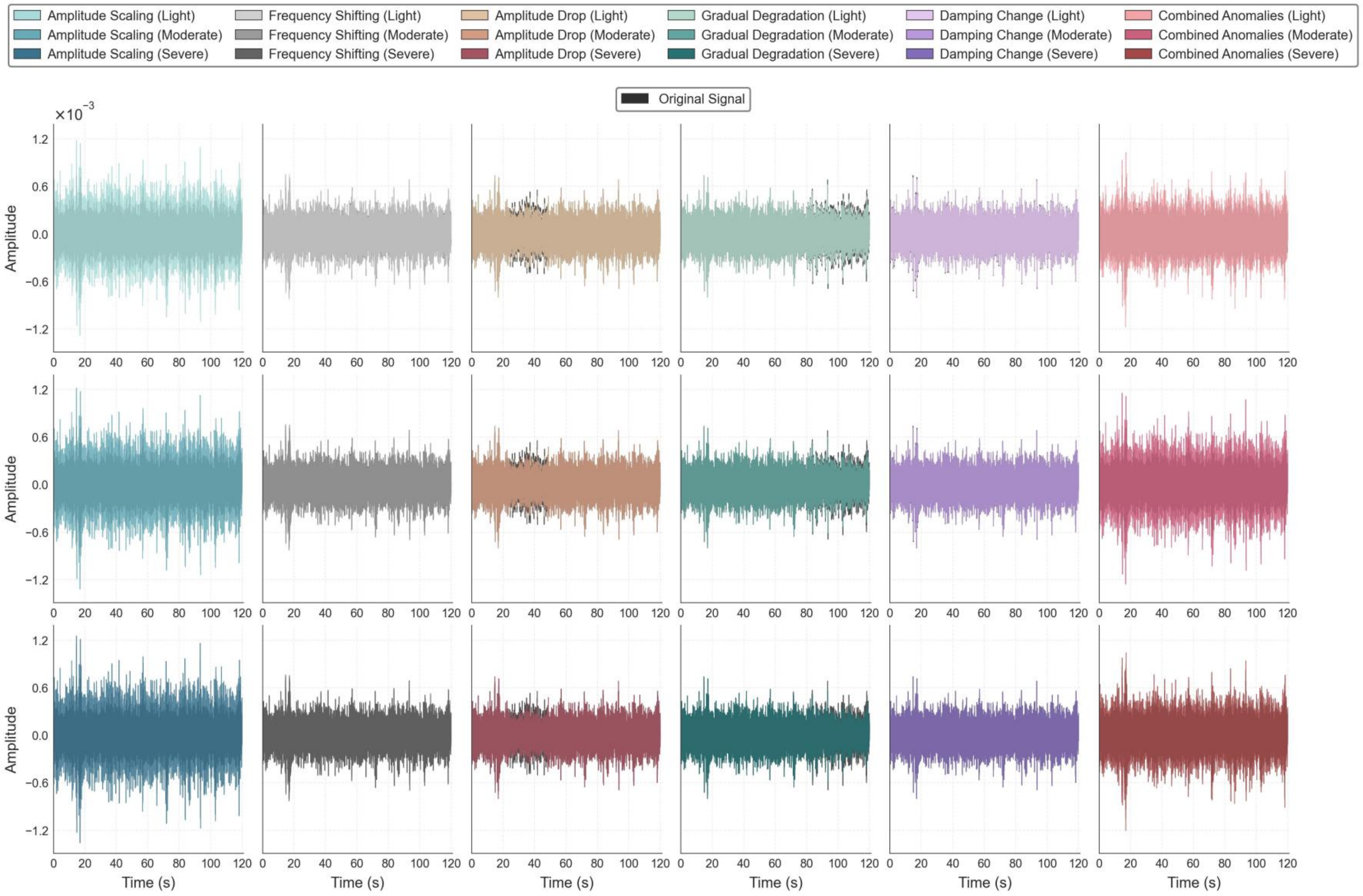
- The capabilities of the Digital Twin framework were evaluated by introducing a series of synthetic anomalies into the normal-condition data generated for accelerometer signal.

Anomaly Simulation

Anomaly Type	Severity	Magnitude of Change	Description
Amplitude Scaling	Light	+10% increase	Uniform scaling of acceleration amplitude
	Moderate	+15% increase	
	Severe	+20% increase	
Frequency Shifting	Light	0.2 Hz shift	Changes in natural frequencies or modal shift
	Moderate	0.15 Hz shift	
	Severe	0.1 Hz shift	
Amplitude Drop	Light	15% reduction	Sudden localized amplitude reductions
	Moderate	20% reduction	
	Severe	25% reduction	
Gradual Degradation	Light	15% reduction	Gradual deterioration of structural response
	Moderate	20% reduction	
	Severe	25% reduction	
Damping Change	Light	30% redistribution	Modification of damping around the primary modal frequency
	Moderate	20% redistribution	
	Severe	10% redistribution	
Combined Anomalies	Light	+5% amplitude, 0.14 Hz shift, 10% damping change	Combined amplitude, frequency, and damping modifications
	Moderate	+7.5% amplitude, 0.1 Hz shift, 6% damping change	
	Severe	+12.5% amplitude, 0.06 Hz shift, 1% damping change	

Case Study: Werrington Bridge

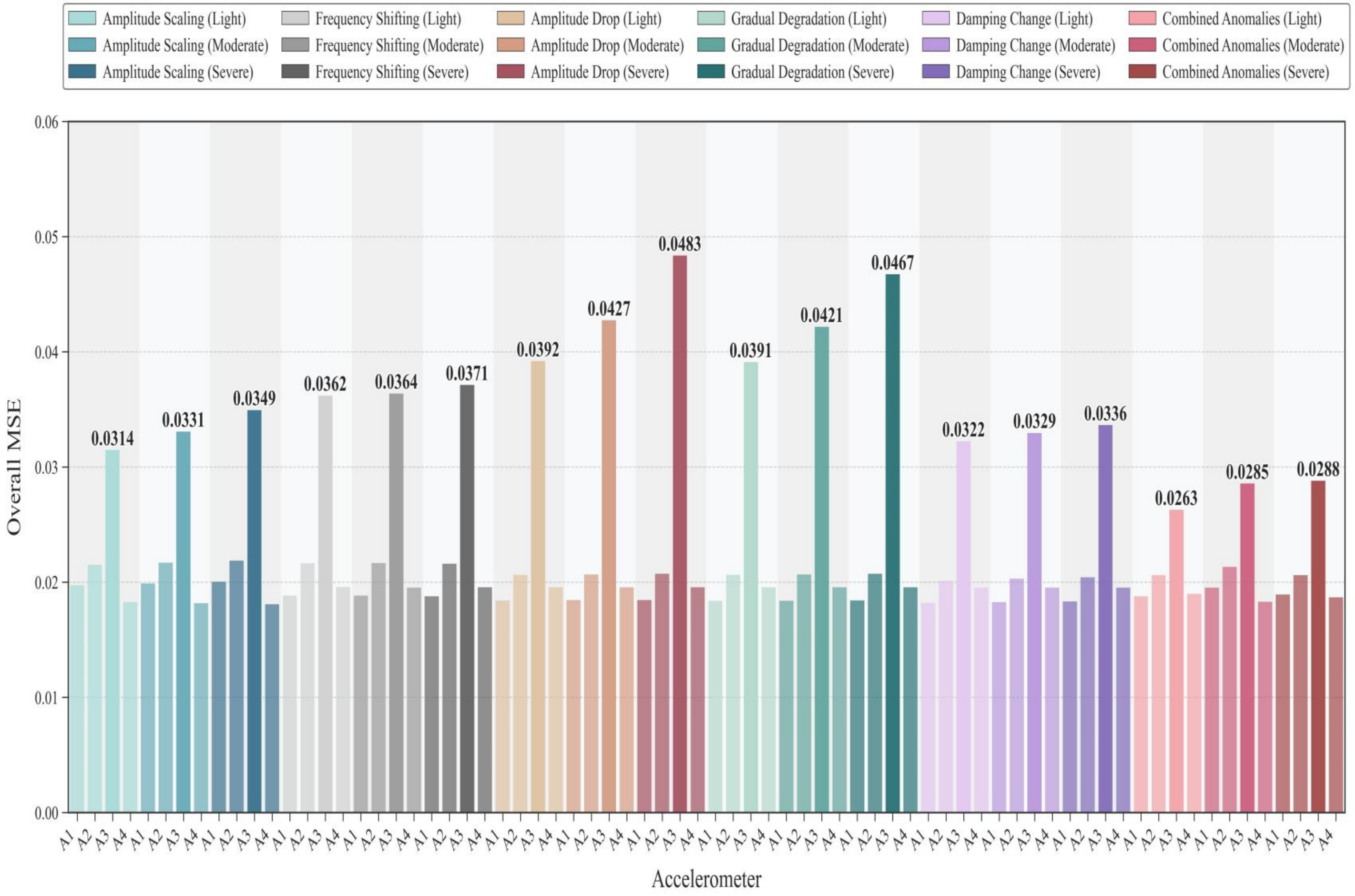
- Simulated anomalies in acceleration signals in three levels for a sample accelerometer



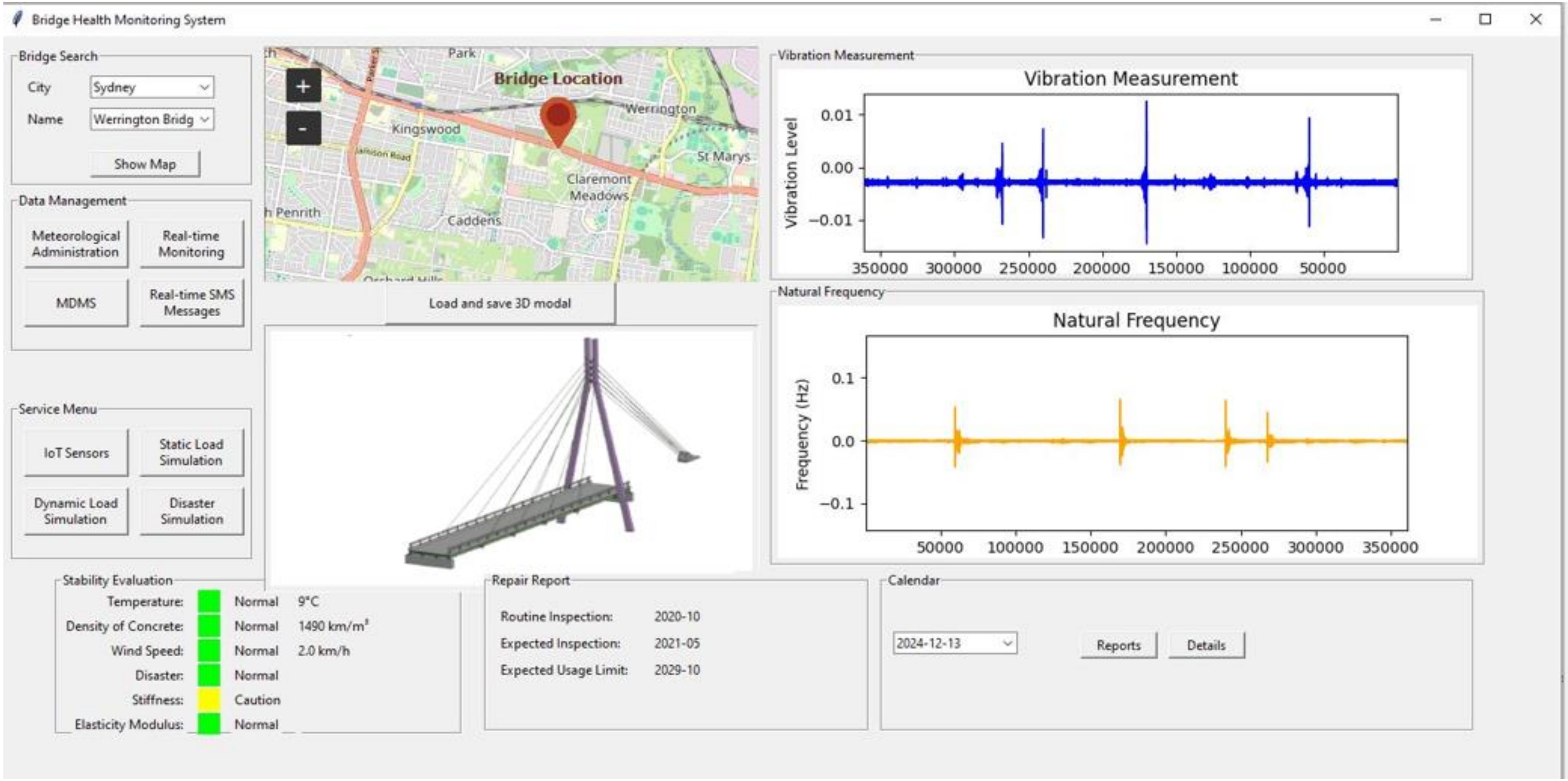
Case Study: Werrington Bridge

- The Mean Squared Error (MSE) values of all accelerometers for each anomaly scenario and severity level

- The MSE values at A3 consistently show elevated levels compared to other accelerometers, demonstrating the model's sensitivity to localized structural changes.



The final Digital Twin



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Thank you for your Attention

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