Fibre optics for intelligent structural health monitoring: challenges and opportunities

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Outline

- Research background
- Research value proposition
- Case Study
- Approach
    - Development of advanced FO
    - Digital twin model
- Future works

Sustainable infrastructures

Global Alliance for Buildings and Construction

Global Alliance for Buildings and Construction (GlobalABC)

Towards a zero-emission, efficient, and resilient buildings and construction sector.

- A voluntary partnership of national and local governments, inter-governmental organisations, businesses, associations, networks and think tanks

2021 Global Status Report for Buildings and Construction

Statistics

- Built environment represents ~40% of global energy-related greenhouse gas emissions (almost 14 Gt per year) and 50% of global resource extraction.
- To achieve a goal of net-zero emissions by 2050[1]:
  - Direct building CO_2 emissions need to decrease by 50%.
  - Indirect building sector emissions must drop through a reduction of 60% in power generation emissions.

Australian Participating Members in GlobalABC

bcsd australia	LOW CARBON LIVING CRC	GBPN Global Buildings Performance Network
Business Council for Sustainable Development Australia	Cooperative Research Council for Low Carbon Living (CRCLCL)	Global Buildings Performance Network

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[1] *According to International Energy Agency*
https://globalabc.org/resources/publications/2021-global-status-report-buildings-and-construction

#BUILDING TO COP26

#BuildingToCOP26 Coalition

For a Zero Emissions and Resilient Built Environment, Regions & Cities.

- A coalition of 100+ partners to enable widespread access and engagement at COP26 and complemented in-person activities.
- Goal to halve built environment emissions by 2030 through following outcomes:
  - All countries include full building decarbonisation targets, concrete policies and measures and related implementation mechanisms in their Nationally Determined Contributions
  - 1,000 cities and at least 20% of the largest built environment businesses by revenue committed to the UN's Race to Zero.
  - By 2030, 100% of new buildings must be net-zero carbon in operation and embodied carbon must be reduced by at least 40%, and by 2050, all new and existing assets must be net zero across the whole life cycle[2].

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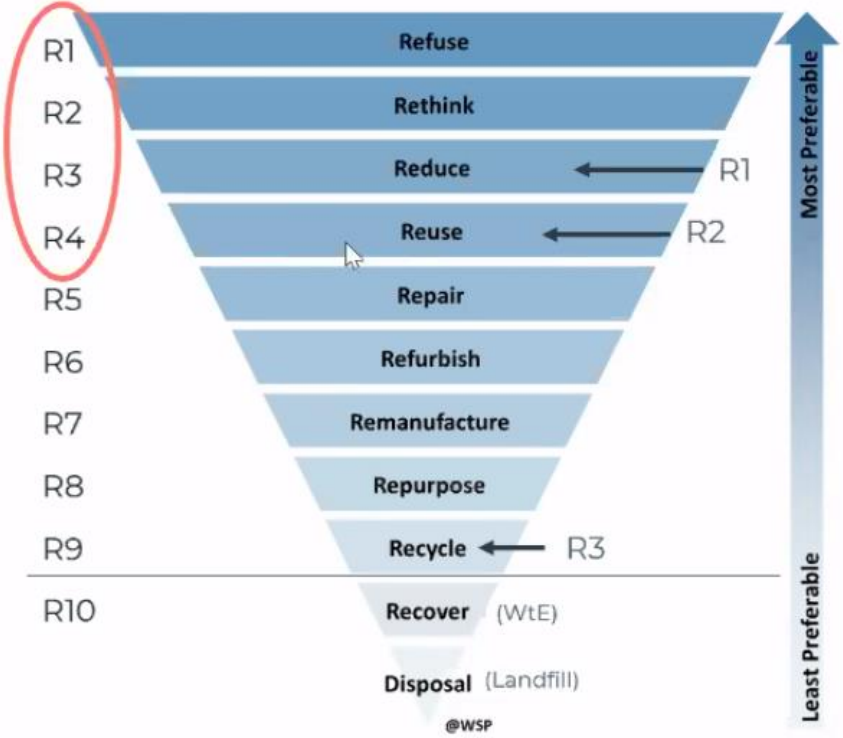
[2] *See UNFCCC Human Settlements Pathway*
https://unfccc.int/climate-action/marrakech-partnership/reporting-tracking/pathways/human-settlements-climate-action-pathway

Sustainable infrastructures



Corrosion in RC Bridges

- The effects of corrosion contributes 3.5-5.2% of the global gross domestic product (GDP), which equates to around A$78 billion per year being spent on remediating corroded assets in Australia. The Australasian Corrosion Association estimates the annual cost of maintaining Australia's bridges at $8 billion[1].

- Critical infrastructures such as bridges are long term assets and are important in social and economic terms by benefiting communities and facilitating the growth of the national and state economies.

- Corrosion of steel reinforcing bars is one of the most significant and unremitting factors in the process of deterioration of steel reinforced concrete (RC) bridges[2]. If these defects are not detected and repaired, the consequences can be catastrophic, particularly for structures with pre- or post-tensioned reinforcement (e.g. the Ponte Morandi bridge collapse in Genova, Italy in 2018 with 43 fatalities).

Deterioration of RC structures

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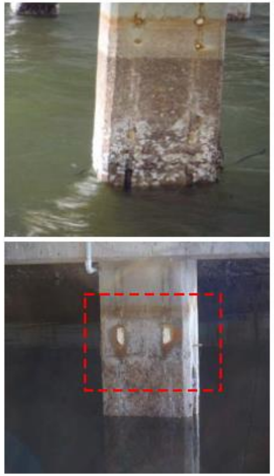
[1] The Australian Corrosion Association, 2021, p. 21.

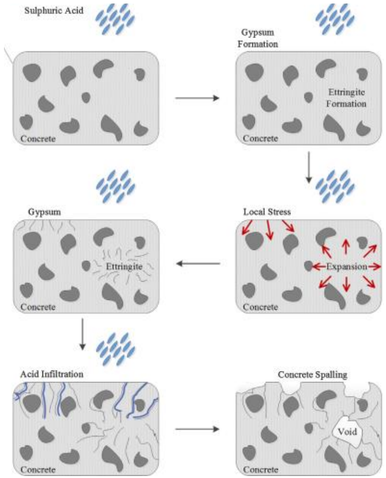
[2] UM Angst, Materials & Structures, 2018; 51(1): 4.

[3] CSIRO and Bureau of Meteorology, Australia, 2015.

Corrosion in RC Bridges



- Corrosion of steel reinforcement occurs as a result of the destabilisation of the oxide layer formed on the steel surface during the hydration process of concrete. When the passivity of the steel is disturbed by chloride contamination of the concrete, reinforcement corrosion starts. The passive layer of the steel surface is gradually consumed, and iron oxide/hydroxide grows on the bar.
- The corrosion products are expansive and reduce the interfacial bond between the steel bar and surrounding concrete, resulting in the significant reduction in load bearing capacity and potentially leading to catastrophic failure of the structure.



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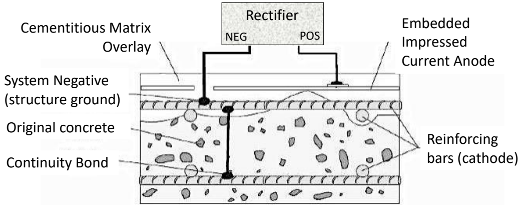
[1] A Hadigheh et al, Construction and Building Materials, 152, 285-303.

Impressed Current Cathodic Protection (ICCP)



Typical ICCP system

- Impressed current cathodic protection (ICCP) is an effective and widely used corrosion protection (CP) method for RC structures located in harsh marine environments[1,2].
- In the ICCP system, the permanent anodes are embedded in the structure and covered by a cementitious matrix (CM) overlay. Impressing an external DC current between the electrodes, results in the steel area becoming cathodic. As a result, the ICCP system extracts the chloride away from the reinforcing bar towards the anode, increasing the alkalinity level around the steel bar which in turn regenerates the protective passive oxide layer around the steel.
- The cost of installation and maintenance of an ICCP system on a bridge varies between A$1-10 M depending on the bridge size, concrete properties, and the primary enablers of chloride ingress (i.e. environmental conditions etc).

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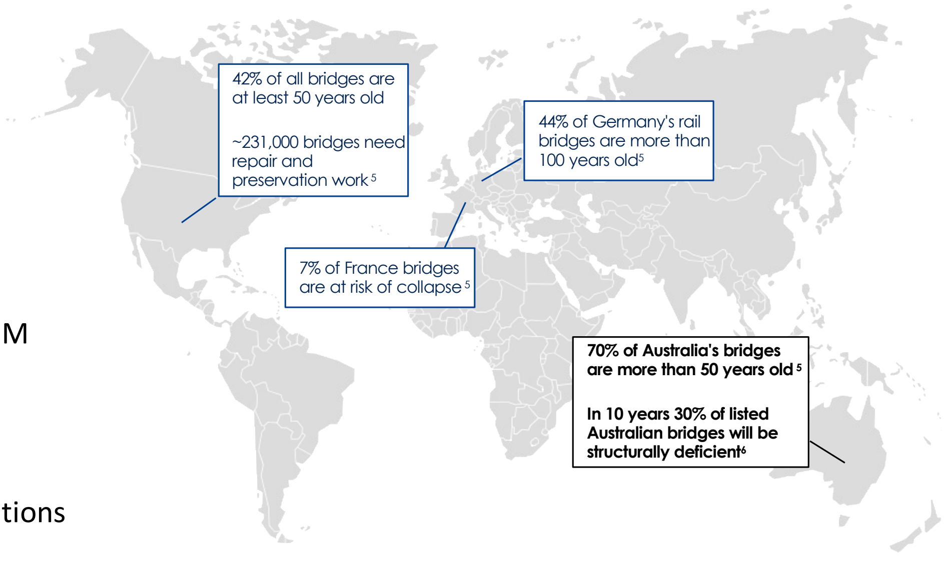
[1] R Barnhart, Federal Highway Administration (FHWA), Washington DC, 1982.

[2] J Hu et al., Construction & Building Materials, 2019; 229: 116869.

Motivation

Structural Health Monitoring and infrastructures

- ☐ SHM is a strategy to effectively monitor and respond to changing conditions in infrastructure assets.
- ☐ The global SHM market was worth $2.8 bn in 2021 and is expected to grow to $6.3 bn by 2029.[2]
- ☐ Routine visual bridge inspections make up 83% of the SHM market.[2] The primary cost of SHM is labour.[3]
- ☐ In a 2001 study of US bridge inspectors, 58% of conditions ratings were incorrectly assigned[4] .



42% of all bridges are at least 50 years old

~231,000 bridges need repair and preservation work [5]

44% of Germany's rail bridges are more than 100 years old[5]

7% of France bridges are at risk of collapse [5]

70% of Australia's bridges are more than 50 years old [5]

In 10 years 30% of listed Australian bridges will be structurally deficient[6]

[1] Mckinsey Institute
[2] Construction dive 21 Feb 2020
[3] Economic Evaluation of Commercial Remote Sensors for Bridge Health Monitoring, Oct 31, 2012
[4]US Dept of Transportation, 2001
[5] American Society of Civil Engineers 2021 Report Card for America's Infrastructure
[6] Monash University, 2018 & Caprani, 2018

Research Value Proposition

Around 5,000 in-service RC bridges in New South Wales (NSW) require continuous inspection, maintenance and rehabilitation.

Current non-destructive evaluation (NDE) techniques are costly and unable to provide continuous information about the long-term behaviour of the structure. This can result in inaccurate evaluation outcomes, leading to economically impractical maintenance schedules and uninformed resource allocation for asset management.

Reduce Inspections	Optimise Maintenance	Safely Extend Asset Life	Respond to events
Reduce OPEX cost	Condition driven maintenance over scheduled driven maintenance	Monitor & predict fatigue life	Alerts for sudden changes in behaviour
Improve safety for personnel	Understand trends and prevent structural degradation	Target remedial works effectively	Alerts when critical performance limits reached
Fewer shutdowns & disruptions	Clear insights backed by real data	Offset CAPEX costs	Assess damage after natural disasters

Early and autonomous identification of structural damage with an estimation of its scale provides new opportunities for monitoring the structural health of RC bridges, facilitating the interpretation of its behaviour and failure risk management based on comprehensive and reliable measurement data.

Capabilities

- Designing future proof buildings through nanotechnology

Research and prototype foundry (RPF)

- Cleanroom Facility
- Packaging and Soft Lithography Facility
- Fibre Fabrication Facility
- Advanced Fibre Bragg Grating Facility
- Prototyping Facility

Australian Centre for Microscopy & Microanalysis (ACMM)

- Transmission electron microscopy
- Light & laser microscopy
- Scanning electron microscopy
- X-ray microscopy
- Atom probe tomography
- Image visualisation & analysis

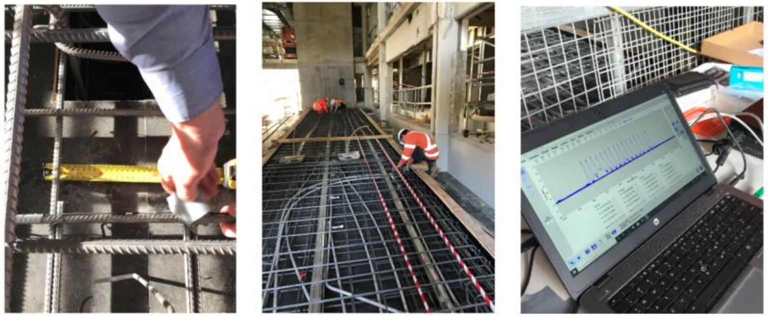
Sydney manufacturing Hub (SMH)

- Additive manufacturing
- Characterisation & post processing
- Heat treatment & melt processing

Research Value Proposition

☐ This project aims to:

produce high performance, low-cost fibre optics and advance their use in health monitoring of infrastructures by carrying out an integrated experimental and field analysis, machine learning modelling and digital twin solution.



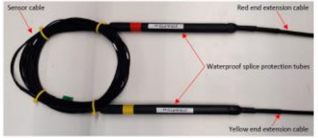
☐ Outcomes of this approach:

provide a holistic, end-to-end fibre optic structural health monitoring strategy that effectively integrates embedded optical sensors, artificial intelligence and computational modelling for real-time remote monitoring of critical infrastructures. Fibre optic sensor enable smart asset management over the life of the asset

This provides significant benefits by digital transformation and expanding application of advanced technologies in a built environment, enhancing resilience and sustainability of infrastructures.

Sensors

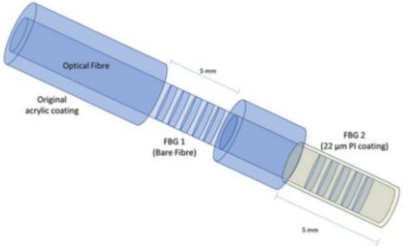
Conventional electrical sensor are prone to degrade due to the corrosive environment and their performance deteriorates within a relatively short period of time, making long term monitoring expensive – or in some cases impossible. Hence, conventional sensors often are unsuccessful in delivering reliable data[1].

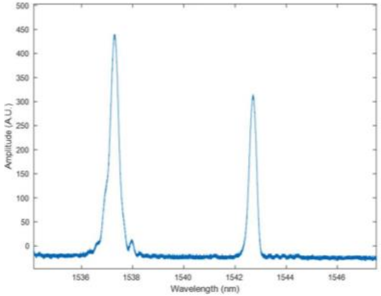


Systems based on fibre Bragg gratings (FBGs) represent an excellent means to acquire data on humidity and temperature reliably and in the long-term[2].

$$T = \frac{1}{C_{T1}}\left(\lambda_1 - \lambda_{1(0)}\right)$$

$$RH = \frac{1}{C_{RH2}}\left(\lambda_2 - \lambda_{2(0)} - C_{T2}T\right)$$





Spectral response of the FBGs written in the fiber, after the PI coating has been applied and schematic of the sensor (FBG 1 is the temperature (only) sensor and provides compensation for FBG 2, the humidity (and temperature) sensor)[1].

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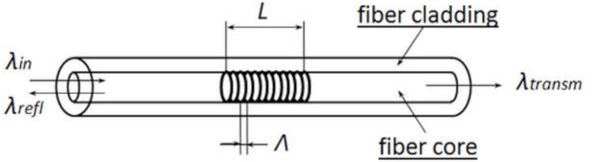
[1] B Rente et al., IEEE Sensors journal, vol. 21, no. 2, January 15, 2021.

[2] B. Rente et al. IEEE Sensors J., vol. 20, no. 6, pp. 2976–2981, Mar. 2020.

Sensors

Fibre Bragg Grating sensors measure the strain and temperature at discrete locations along a bridge based on changes in light intensity in an optical fibre. This is represented by the Bragg wavelength equation

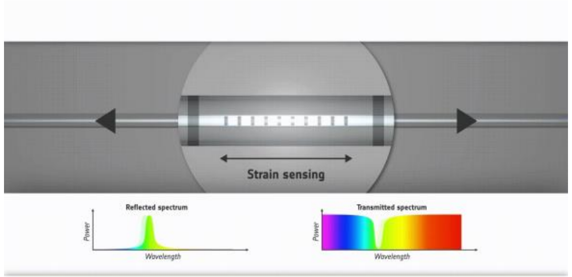
$$\lambda_b = 2n_{eff}\Lambda$$



As the cable is elongated, the intensity of the wavelength is shifted. This Bragg wavelength shift is used to quantify changes in strain and temperature. Note that:

- FBG sensors are sensitive to thermal, chemical and mechanical effects and so temperature compensation is required
- Output is total strain ($\varepsilon_{total} = \varepsilon_{mechanical} + \varepsilon_{thermal}$)

$$\frac{\Delta\lambda_{\mathrm{B}}}{\lambda_{\mathrm{B}}} = (1 - p_e)\underset{\substack{\uparrow \\ \text{Total Strain}}}{\varepsilon} + \left(\alpha_f + \xi\right)\Delta T$$



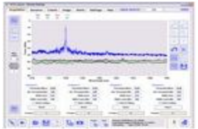
Bragg wavelength shift induced by mechanical and/or thermal effects

Digital Twin Concept

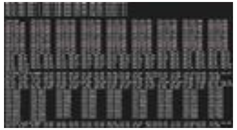
- Develop a novel data architecture workflow for the deployment of a machine learning based digital twin using fibre Bragg grating optical sensors
- Apply data analytical processes to successfully convert sensors information into meaningful structural insights

Si255 Interrogator

Embedded FBG Sensors



ENLIGHT Software

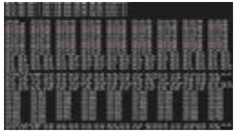


Strain Files Processed Locally

Local Storage on Edge Computer

CURRENT STORAGE MECHANISM

- Synthesise the structural analytics into a unified and parametric digital twin to assist site engineers and asset managers



Strain Files Processed Online

Cloud Based Storage

PREFERRED STORAGE MECHANISM

Data Flow Chart

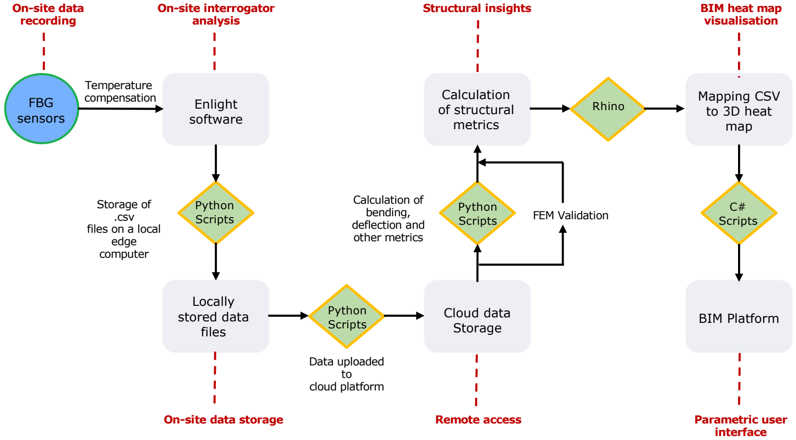
Step 1
- Data origination

Step 2
- Data conversion

Step 3
- Data storage

Step 4
- Processing

Step 5
- Visualisation



On-site data recording

On-site interrogator analysis

Structural insights

BIM heat map visualisation

FBG sensors

Temperature compensation

Enlight software

Calculation of structural metrics

Rhino

Mapping CSV to 3D heat map

Storage of .csv files on a local edge computer

Python Scripts

Calculation of bending, deflection and other metrics

Python Scripts

FEM Validation

C# Scripts

Locally stored data files

Python Scripts

Cloud data Storage

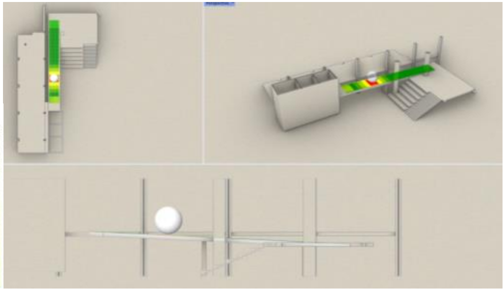
BIM Platform

Data uploaded to cloud platform

On-site data storage

Remote access

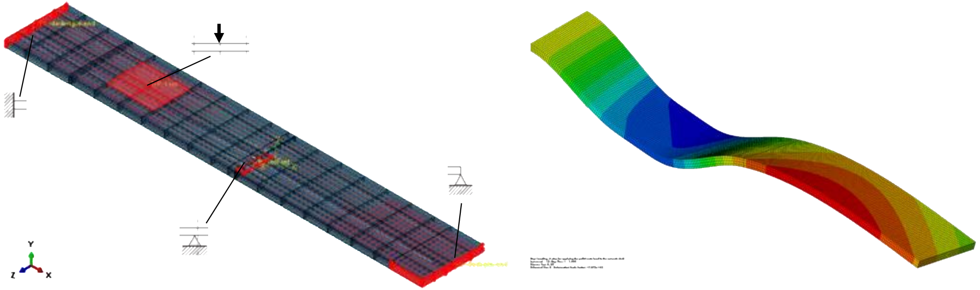
Parametric user interface



Digital twin live update of a bridge with embedded fibre optic sensors

FE Analysis & Parametric Heatmap

Part	Deck	Reinforcement	Stirrup	P/T duct
Element	3D solid brick	Wire	Wire	Wire
Dimensions (mm)	15200 × 280 × 2600 2700 × 300 × 2600	⌀10, ⌀12, ⌀16	⌀16	49.1 × 10
Mesh seed size (mm)	70	70	70	70
Mesh method	C3D8R	B31	B31	B31



Prototype Nodes

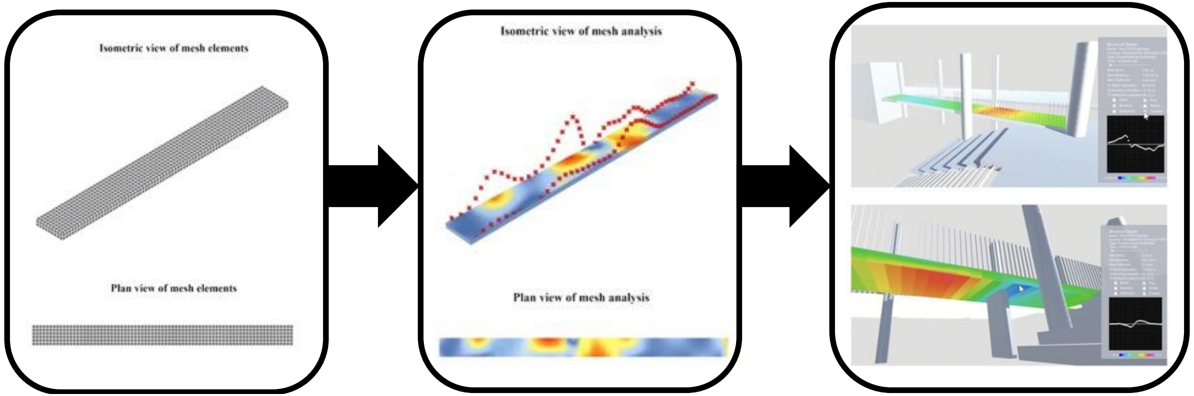
Rhinoceros + grasshopper

Prototype Heatmap

Rhinoceros + grasshopper

Digital Twin Visualisation

unity



Conclusions & Remarks

The project will create smart technologies and operational capabilities to effectively improve the resilience and durability of critical infrastructures. This provides sustainable solutions for extending the service life of bridges, reducing the impact of climate change on infrastructure, and minimising cost and energy consumption related to replacing deteriorated structures.

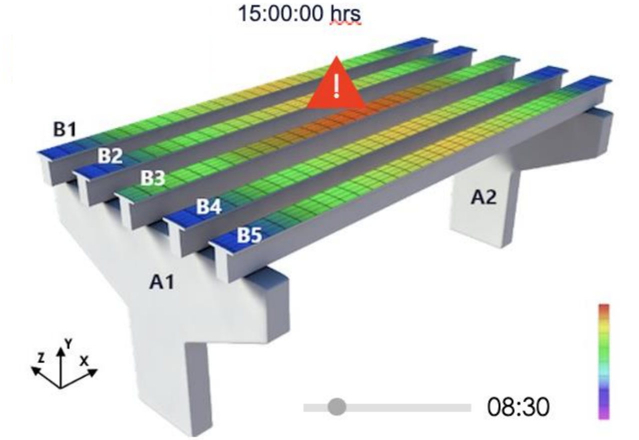
Hence, the project is actively addressing the UN sustainable development goals, including industry, innovation and infrastructure (G9), sustainable cities (G11), responsible consumption and production (G12), and climate action (G13). It also contributes to Australian National Research Priorities in Advanced Manufacturing, Environmental Change, and Transport.

Digital twins developed from fibre optic sensors can measure the detailed performance of a structure in real time and assist asset management through

- Programmed alert messages
- Providing actionable insights

Preliminary digital twin concepts for SHM show promise for asset management but still limited due to

- Lack of effective damage detection capabilities
- High upfront FBG sensor and interrogator costs



WARNING! Element B4 is not performing as expected. Location of abnormality: Span 7.5m between member A1 - A2.

Acknowledgments

Thank you!

NSSN
NSW Smart Sensing Network

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