AUSTRALIAN NETWORK OF STRUCTURAL HEALTH MONITORING

Newsletter

Issue 40, June 2024

Contents

President's Message

Tommy Chan

Professor in Civil Engineering, Queensland University of Technology

Dear All,

In the past month, ANSHM Executive Committee members have been working hard to approach potential industry partners (PIPs) inviting them to the proposed ARC "Infrastructure Monitoring for the Future" Research Hub (ITRH)/Training Centre (ITTC) under the ARC Industrial Transformation Research Program (ITRP) using the flyer that we prepared. The snapshot of The flyer of the *Call for Participation from Industry Partners* for the proposed ARC "Infrastructure Monitoring for the Future" ITRH/ITRC is given below.

It is the first fruit that ANSHM EC produced with the help of Dr Ronan Nguyen, ARC DECRA Fellow, and Angela Dahlke, Industry Engagement (Data Sciences) Manager, QUT. For those who are interested in having a print-ready version of the flyer, please email me.

We are also preparing a more detailed document in a booklet form for this proposed “Infrastructure Monitoring for the Future” ARC ITRH/ITTC, summarising the industry challenges to be addressed, partner benefits, and expected contributions of ARC, University Partners & Industry Partners. As members of ANSHM, I show below some of the details (draft) of the booklet for your information and consideration of participating in this proposed ITTC/ITRH.

Industry Challenges to be addressed

Failure to implement appropriate structural health monitoring (SHM) for infrastructure and buildings, for design, construction or maintenance, can be disastrous. Several infamous global and Australian infrastructure failures are featured below. Disastrous consequences included: human fatalities and other serious OH&S incidents; critical structural failures (Queensland’s Callide Power Station, went offline, ~$200M turbine replacement); disruption to utilities, services, businesses, and homes; destruction of property; massive direct and indirect financial costs; and legal liabilities.

Infrastructure Resilience Overestimated

- E.g., 6 transmission towers collapse in Anakie VIC, from high winds. Likely causes: maintenance practices; & operational oversight

Unsafe Infrastructure

- unsafe design
- load capacity design faults

Not Climate Resilient

- high winds
- torrential rain
- cyclones
- earthquakes
- flooding, hail
- fire

Building Defects

- Opal & Mascot Towers
- Buildings evacuated
- ~Opal $24M costs; insufficient defects fund to cover repairs
- Mascot $3bn bill for insurance

Improper Use

- overload
- volume of vehicle traffic
- heavy and overloaded vehicles

Structural Failure

- E.g.: QLD's Callide Power Station structural failure (demand exceeded capacity); unit went offline & power disrupted
- Long delays restoring unit (unit cost ~$200M)

Ageing Infrastructure

- old designs
- not designed for current use / conditions
- issues with repair, monitoring, &/or maintenance

Cumulative Degradation

- less-understood cumulative impacts collisions
- Offshore oil and gas impacted by waves.

(Validate) Innovative New Materials & Reuse (CE)

- structures with new & innovative materials, or reuse, will have different physical-chemical-mechanical properties, to validate and monitor

Collapses from Impacts

- E.g. Collapse of US Francis Scot Key Bridge
- 6 Workers killed & US$1.9bn cost to replace, closure of the port estimated as ~US$1.5M/day

Industry Partners Benefits

Industry & Infrastructure solutions	• Develop and validate state-of-the-art solutions and simulations customised to your infrastructure needs (e.g., custom digital models) or develop/showcase your SHM products and services for real-life applications. • Infrastructure safety, resilience, life-time extension, and cost-effective maintenance, through effective SHM.
Financial Benefits	• Leverage the value of your investment (2-3 times, for Hub/Centre) via the ARC grant funds worth up to $5m (depending on final industry partner contributions).
R&D Benefits	• Access R&D Tax Incentive offsets, where eligible, which are designed to help companies innovate and grow by offsetting some of the costs of eligible research and development (R&D).
Access world-class expertise	• Harness the expertise, extensive industry collaboration experience, networks, and resources, of this critical mass of world-class multi-institutional and multi-disciplinary research team, focused on addressing challenges and supporting innovation to improve infrastructure for your industry.
Grow Human Capital with Training & New Talent	• Participate in regular training events (workshops, conferences) to upskill your team and accelerate the uptake of cutting-edge research results and improve infrastructure management know-how. • Work closely with new industry-immersed research talent and postdoctoral researchers, who will gain industry experience and knowledge in training, contribute new thinking and ideas to help your industry, and contribute to human capital development.
Cutting-edge Testing & Research	• Leverage cutting-edge research infrastructure to support the development of SHM solutions for your infrastructure or your

Infrastructure	products/services - across universities, including Instrumented Living Labs (Vibrational Impacts); SHM Living Labs; World's only Impact Testing Machine (+ other SHM tools, SHM software, sensors and DAQ systems); Computing (including High Performance Computing (AI applications)); and Pilot Plant Precinct.
Innovation, IP, and Commercial Opportunities	• Translate knowledge and outputs to new innovations and improvements, with potential intellectual property. • Leverage support from university technology transfer offices and business development, to support translation and commercialisation of intellectual property from the Training Centre/Research Hub.
Networking, Events, & Brand Promotion	• Enjoy strategic network benefits, participating in a Centre/Hub which brings together the most innovative leaders in infrastructure across multiple sectors. • Enjoy events for brand profiling, to catalyze network connections, knowledge sharing, exploration of synergies, and collaboration.
Strategic Guidance	• Enjoy strategic network benefits, by participating in the Training Centre/Research Hub which brings together the most innovative leaders in infrastructure across multiple sectors.

Expected contributions of ARC, University Partners & Industry Partners

Contributions from grant funding, university partners, and industry partners, both cash and in-kind, enable the Centre's research and training agenda, activities, and operations, to ultimately benefit industry partners.

ARC Grant Funding	Total contributions are relevant to the competitive assessment of the grant application. The level of cash contributions specifically determines the level of investment from the Australian Research Council (ARC). If successful, the ARC provides grant funding of up to $1 million per year, for between 3-5 years, depending on the value of (cash) contributions and research and/or training goals

of the Training Centre/Research Hub.

University Contributions

Universities provide a combination of cash investment, critical in-kind contributions of the academics to enable the research and training (including infrastructure, equipment, software access, and expertise), and several funded HDR (PhD student) scholarships.

Investment Goal and Benefits

The Infrastructure Monitoring for the future Training Centre/ Research Hub aims to attract \$3.75M (\$750K p.a.) total from industry partners, plus up to \$1M p.a. from the ARC, which, together with university contributions, would enable the Training Centre/ Research Hub, and support strategic working groups (including 12-15 HDR students, 3 research fellows, plus field research, research equipment, software, travel costs, workshops, and conferences.

Partner Contributions (Cash and In-Kind)

Partners can contribute valuable cash and in-kind:

- Cash contributions can be leveraged (with grant funding)
    - to support dedicated resources
        - to directly work with and benefit the partner
        - PhD student/s
        - and/or experienced postdoctoral research fellows
        - plus project expenses
    - partnership levels are offered according to cash contributions
    - Bespoke (say, ≥\$50k p.a.) - resourcing and benefits, tailored with your organisation to align with your research, training, and innovation needs/goals
- In-kind contributions, relevant to enabling programs and projects may include:
    - Industry partner expertise relevant to the Training Centre/ Research Hub programs and projects
    - Access to industry infrastructure software, equipment, machines, tools

- Industry training placement, courses, and/or support for the Training Centre/Research Hub members

The above information in the booklet is provided to supplement the *Call for Participation from Industry Partners* flyer for the proposed ARC "Infrastructure Monitoring for the Future" for the industry partners to know better about the ITTC/ITRH, and for the academics to use it when they approach their potential industry partners.

Below are the updates for the month.

ANSHM ARC Industrial Transformation Research Hub (RH)/Training Centre (TC)
As mentioned above, we have started to use the flyer to Approach Industrial Partners. In the first survey we conducted among ANSHM EC members and QUT colleagues, we identified around 40 Potential Industrial Partners (40) with an estimated cash contribution of around $7.65M, which is very encouraging. We understand that it is just an estimated value, and we will be more than happy if we could secure half of the amount. We have already received some positive responses from some of the PIPs we approached and even some have indicated the amounts that they will contribute. According to our working schedule, as stated in the last monthly updates, we will start to collect the corresponding Letters of Support from the confirmed IPs in September. We plan to have our first Workshop to publicise the proposed ITTC/ITRH in July, tentatively at QUT.

Industry News
Please see below the industry updates provided by John Vazy, EngAnalysis, our Industry Liaison Officer.

Industry Vibe
- The number of emergent projects is increasing.
- This is being matched with a general increase in the organisations that are seeking to address these opportunities.
- While there are a collection of ill-conceived projects collecting near-useless data there are several projects exploiting the capability and outcomes of SHM.

Recent Projects
- EngAnalysis have deployed a monitoring system on a Northern Queensland bridge that is a combination of Weigh In Motion, frequency-based response to load, load survey and structural

response. There are a series of complex problems in this where there is an increasingly complex model used to estimate the origin and effect of the observed loading. It could be described as being mighty close to IoT providing a real-time digital twin with cause-and-effect modelling.

- EngAnalysis has instrumented 3 bridges in two states and around 1km of pipeline this month.
- ARTC after three years of load assessment and monitoring are undergoing localised strengthening works and removing the monitoring gear. This is a great conclusion and a smart use of money to solve structural problems in response to observed changes.
- Sixence (owned by Freyssinet) recently deployed a monitoring system on the new Metro Bridge built by Freyssinet in Western Sydney to address a structure-specific vulnerability to lightning and the complex access limitations for inspection.
- Interesting collaborations between EngAnalysis and Rockfield exploiting the capabilities of both organisations in the last two months.
- Many large mining organisations have most of their mobile plat fleet instrumented with some form of structural monitoring. This introduces some problems where the spot-welded sensors may not be the ideal addition to fatigue-sensitive structures and there is definitely "more research required" to verify that spot welding has no detrimental effect and/ or identify a better field deployment solution.

Standards

- ARTC have also released an internal standard for SHM; this document provides an overview of the methods and has a strong focus on the use of accelerometers and frequency-based analysis. Good to see these big organisations developing standards.

Special Issue in Journal of Civil Structural Health Monitoring (CSHM)

So far, A/Prof Xinqun Zhu is handling six papers submitted to this special issue, two of which are under revision and four are under first-round review. It seems that a few papers are handled by the Chief Editor. We are expecting to receive more papers. Please note that if you would like to submit papers to this special issue, please submit your papers via the journal submission system Editorial Manager. During the submission process you will be asked whether you are submitting to a special issue, MAKE SURE TO SELECT "***Recent Developments in Digital Transformation and Intelligent Infrastructure in Australia for Structural Health Monitoring***" from the dropdown menu.

Please also note that as a policy of the Journal, all submissions submitted to JCSHM require either experiments or field instrumentation components. Manuscripts with data analysis alone will not be accepted. Please refer to the aims and scopes of JCSHM on the website:

https://link.springer.com/journal/13349/aims-and-scope.

As mentioned before, although on the website, the deadline stated is 31 October 2024. However, it is the date that the Editor-in-Chief requested us to finalise everything by 31 October 2024. Please also note that all papers must be prepared in accordance with the Instructions for Authors at: https://link.springer.com/journal/13349/submission-guidelines.

16th ANSHM Workshop
As mentioned before, A/Prof Lei Hou is taking the lead to organise the 16th ANSHM Workshop, 21-22 Nov at RMIT. The forming of the Local Organising Committee is progressing well, and they are working on identifying the keynotes and sponsors and finding the best venue at RMIT for the two-day event.

Special Session at IABSE Tokyo 2025
As mentioned before, Dr Fabien Rollet, and Dr David Lo Jacono, Technical Directors at Jacobs are organising a special session at the International Association for Bridge and Structural Engineering (IABSE) is organising their Symposium in Tokyo at Waseda University and Rihga Royal Hotel from 18 to 21 May 2025 (IABSE - Tokyo 2025), and we decided to provide ANSHM support to this special session. The theme of the symposium is Environmentally Friendly Technologies and Structures: Focusing on Sustainable Approaches. The session will be on dynamic bridge assessment and performance that leverages Digital Twin monitoring. Please email me if you are interested in presenting a paper at this special session with the title (less than 50 words) and abstract (less than 300 words) of the paper and the list of its authors with their affiliations.

ANSHM Symposium at EASEC-18
As mentioned before we will organise an ANSHM Symposium at the Eighteenth East Asia-Pacific Conference on Structural Engineering and Construction (EASEC-18), 13–15 November 2024 at the Shangri-La Chiang Mai, Thailand, with the topic, Australian Network of Structural Health Monitoring (ANSHM) mini-symposium: Emerging techniques for structural health monitoring of civil infrastructure. The details of the ANSHM Symposium can be obtained via the conference website (https://easec18.org/callforsymposia). Five presentations including 3 full paper submissions and 2 abstract submissions are currently included in this special session. The full paper acceptance deadline is 30 June 2024. ANSHM members if interested are encouraged to submit an abstract for presentation in this special session (abstract submission is fine and a full paper is not mandatory).

In the next sections, we will have two articles from our members. The first article is from Dr Alex Ng and his team from School of Architecture and Civil Engineering, The University of Adelaide, Adelaide, South Australia to introduce an innovative amplitude-modulation vibro-acoustic (AMVA) technique to monitor the progression of thermal damage in pristine graphene (PRG) mortar, addressing limitations related to the emitter's ability to generate low-frequency vibration over a long service time. The second article is from Dr Desiree Nortje, Principal Asset Manager, Civil Structures, Asset Strategy, Transurban, Victoria to introduce their work on monitoring the structural capacity of a 1960s Bridge, which has two unequal spans continuous over the pier and simply supported at both the northern and southern ends.

With kind regards,

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Research profile | **Research publications** | **Google Scholar citations**

A Novel Amplitude-modulation Vibro-acoustic Technique for Thermal Damage Detection in Pristine Graphene Mortar

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Abstract

This study introduces an innovative amplitude-modulation vibro-acoustic (AMVA) technique to monitor the progression of thermal damage in pristine graphene (PRG) mortar, addressing limitations related to the emitter's ability to generate low-frequency vibration over a long service time. The proposed AMVA method employs three distinct amplitude-modulation strategies: pure amplitude-modulated (PAM), suppressive amplitude-modulated (SAM), and transmitted amplitude-modulated (TAM). Theoretical models and experimental validations are presented, with β_{PAM}, β_{SAM}, and β_{TAM} corresponding to the PAM, SAM, and TAM approaches, respectively. These parameters are indicative of material nonlinearity and can effectively quantify various stages of thermal damage. The dynamic elastic modulus E_d, obtained from resonant frequency (RF) tests, serves as comparative linear measurements. The results demonstrate that the AMVA technique is highly sensitive for detecting thermal damage in cement-based materials, compared to the traditional RF methods.

Introduction

Various non-destructive testing (NDT) and structural health monitoring (SHM) techniques have been developed and implemented for damage characterization. Among these, nonlinear acoustic/ultrasonic techniques are highly favored due to their efficiency, cost-effectiveness, and sensitivity to damage.

These nonlinear acoustic/ultrasonic techniques utilize nonlinear features, such as wave-wave interactions, wave-damage interactions[1, 2], internal resonances, and the generation of higher harmonics. In nonlinear wavefields, energy redistribution in the frequency domain results in the emergence of additional waves at various frequencies and wavenumbers [3, 4]. These waves propagate within damaged medium, providing critical information about the damage conditions.

One of the prominent nonlinear features, sidebands, has attracted significant attention over recent decades. They are primarily obtained through vibro-acoustic modulation (VAM) techniques, where a strong low-frequency (LF) pump wave is employed to perturb cracks and a high-frequency (HF) probe wave is used to scan the cracks, as shown in Figure.1. The VAM technique takes advantage of the strong LF pump wave's ability to close cracks due to its powerful energy. Meanwhile, the HF probe wave experiences less attenuation when the crack is in a closed state and is highly sensitive to structural changes due to its short wavelength [5-8].

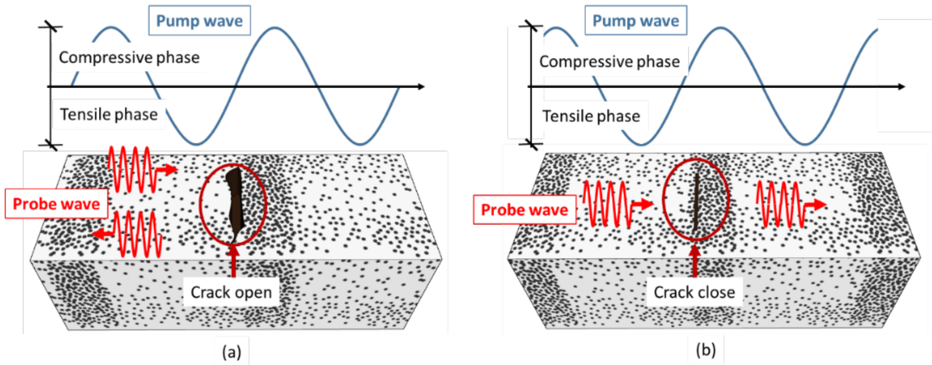

Figure. 1 Schematic of the VAM technique

However, the practical application of the VAM technique is still in its early stages, even the VAM technique offers several advantages for structural analysis [9]. One significant challenge is the requirement for a powerful LF pump wave, requiring large facilities such as electromagnetic shakers. This demand brings operational difficulties for long-term use of the pump wave emitter [10, 11].

To address these limitations, this study proposes an amplitude-modulation vibro-acoustic (AMVA) technique, which utilizes a LF amplitude-modulated pump wave and a HF probe wave. This approach enhances energy efficiency and versatility. The major contributions of this research are:

1. Introduction of the AMVA technique: The AMVA technique employs an amplitude-modulated pump wave instead of the pure monochromatic pump wave used in conventional VAM methods. This study investigates, for the first time, three different amplitude-modulated pump waves: the pure amplitude-modulated (PAM) method, the suppressed amplitude-modulated (SAM) method, and the transmitted amplitude-modulated (TAM) method.

2. Establishment of nonlinear parameters: The nonlinear parameters associated with the PAM, SAM, and TAM methods are theoretically established based on material nonlinearity and are correlated to damage evolution. The reliability and effectiveness of these nonlinear parameters are validated by comparing them with results from conventional resonant frequency (RF) tests.

Schematic of amplitude-modulation vibro-acoustic technique

In the AMVA technique, the LF pump wave is modulated by two frequencies, f_{L1} and f_{L2} ($f_{L1} < f_{L2}$), as illustrated in Figure.2, with the HF probe wave at f_H emitted simultaneously. By changing the amplitude of some peaks, a low frequency f_{L1} is introduced, which can reach a certain displacement to provide powerful energy to perturb cracks. In addition, emitters such as electromagnetic shakers operate at the frequency f_{L2}. This approach allows for the emission of very low frequencies without being limited by the capabilities of the shaker.

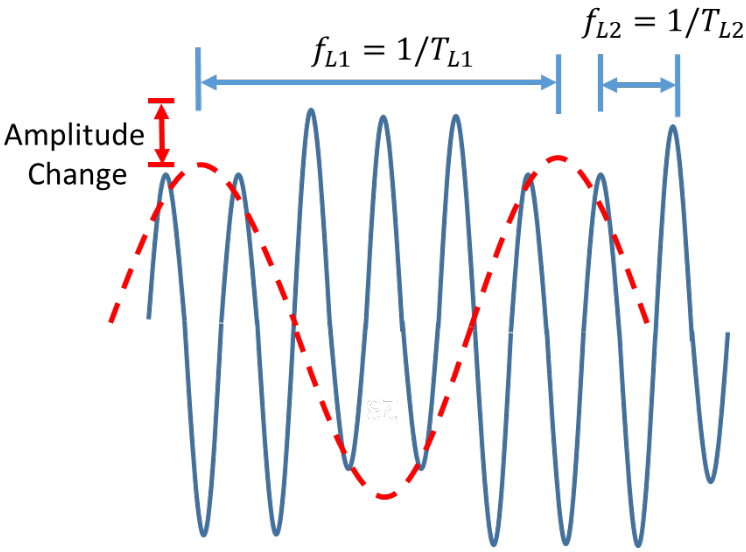

Figure. 2 Schematic of the AMVA technique

Nonlinear parameters of PAM, SAM and TAM methods

Using the Lagrangian coordinate x and time t, the one-dimensional equation of motion for wave propagating in an infinite medium, incorporating the nonlinear parameter β, is expressed as follows,

$$\frac{\partial^2 u}{\partial t^2} - c^2\frac{\partial^2 u}{\partial x^2} = c^2\frac{\partial}{\partial x}\left(\frac{\alpha}{2}\left(\frac{\partial u}{\partial x}\right)^2 + \cdots\right) \tag{1}$$

where c is wave velocity, and u is particle displacement. The incident waves of AMVA technique can be written as,

In the PAM method,

$$u^{PAM} = A_H\cos(\omega_H\tau + \phi_H) + [A_{L1}\cos(\omega_{L1}\tau + \phi_{L1}) + A_{L2}\cos(\omega_{L2}\tau + \phi_{L2})] \tag{2}$$

In the SAM method,

$$u^{SAM} = A_H\cos(\omega_H\tau + \phi_H) + \frac{A_{L1}A_{L2}}{2}[\cos\big((\omega_{L2} - \omega_{L1})\tau + (\phi_{L2} + \phi_{L1})\big)] \tag{3}$$

In the TAM method,

$$\begin{aligned} u^{TAM} &= A_H\cos(\omega_H\tau + \phi_H) + A_{L2}\cos(\omega_{L2}\tau + \phi_{L2}) \\ &\quad + \frac{A_{L1}A_{L2}}{2}[\cos\big((\omega_{L2} - \omega_{L1})\tau + (\phi_{L2} + \phi_{L1})\big)] \end{aligned} \tag{4}$$

where A is the amplitude, ω is the angular frequency, ϕ is the phase, and $\tau = t - x/c$. It should be noted that the subscript H indicates the HF probe wave, and $L1$ and $L2$ denote two LF waves for pre-amplitude-modulation.

Substituting Equation (2), (3), and (4) into Equation (1) and applying perturbation theory of the displacement field, the nonlinear parameter β can be expressed as,

In the PAM method,

$$\beta_{PAM} \sim \frac{\sum A_S}{A_H A_{L1}} \text{ or } \frac{\sum A_S}{A_H A_{L2}} \tag{5}$$

In the SAM and TAM method,

$$\beta_{SAM} \text{ or } \beta_{TAM} \sim \frac{\sum A_S}{A_H A_{L1} A_{L2}} \tag{6}$$

Experiment of inducing thermal damage and AMVA technique

All three specimens are casted into size of 40mm×40mm×180mm, as shown in Figure.4 (b) and (c). The specimens were heated in an electrical muffle furnace at a rate of 5°C/min to target temperatures of 100°C, 250°C, and 360°C for specimens 1, 2, and 3, respectively. Each specimen was held at its target temperature for two hours, and then cooled to ambient conditions until stable. In AMVA tests (Figure.4 (a)), a continuous wave modulated by $f_{L1} = 0.5$ kHz and $f_{L2} = 5.7$ kHz was generated and amplified before being transmitted to an electromagnetic shaker. Pre-modulated pump waves for PAM, SAM, and TAM methods were used according to specified equations. A 3D printed C-shaped clamp efficiently transferred the pump waves from the shaker to the specimens. A continuous probe wave at 50 kHz was generated, amplified, and transmitted into the specimen using a non-metal transducer. The peak-to-peak voltage of the pump wave remained constant, while the probe wave's voltage was steadily increased during the experiment.

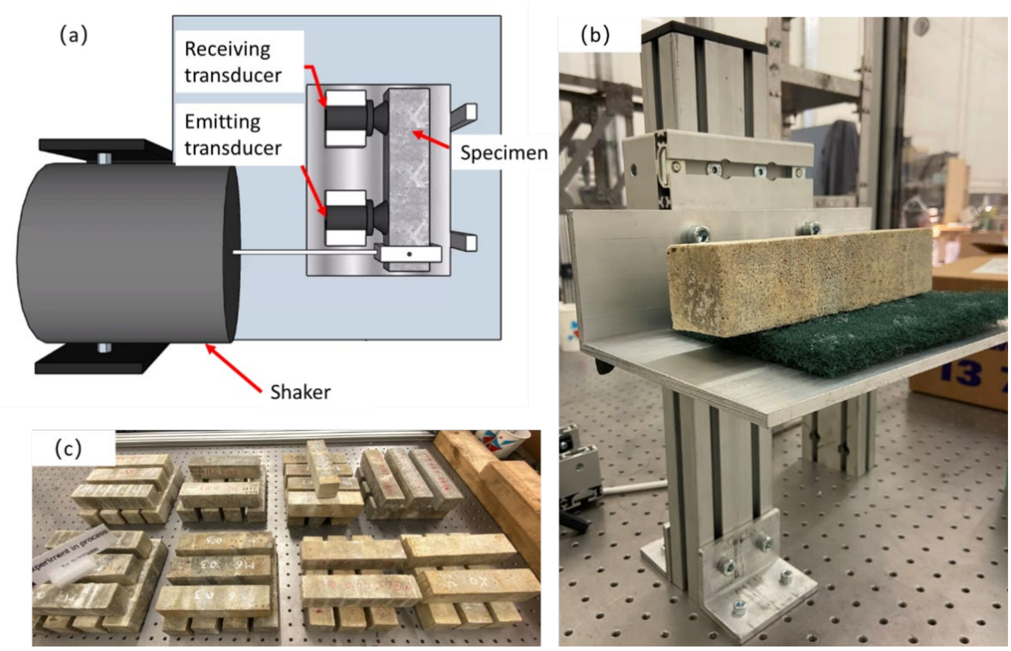

Figure. 4 (a) Experimental set-up, (b) shelf for AMVA test, and (c) pristine graphene mortar

Results compared with conventional measurement E_d and nonlinear parameters β_{PAM}, β_{SAM}, and β_{TAM}

Because the conventional measurement E_d decreases with increasing temperature, whereas the nonlinear parameters, β_{PAM}, β_{SAM}, and β_{TAM}, of the proposed AMVA technique increase. For better comparison, all linear and nonlinear parameters were converted into a dimensionless index I using the following equation,

$$I = \frac{|I' - I_0|}{I_0} \tag{7}$$

where I is the dimension less index, I' is the parameter after thermal treatments (100℃, 250℃ and 360℃), and I_0 is the parameter in the intact state.

Figure. 5 shows the dimensionless index of both conventional and proposed AMVA techniques against increasing temperatures. The dimensionless indexes of the AMVA technique are consistently higher than the conventional parameter after exposure to high temperatures, demonstrating greater sensitivity. Among the AMVA methods, the SAM approach exhibits the highest sensitivity.

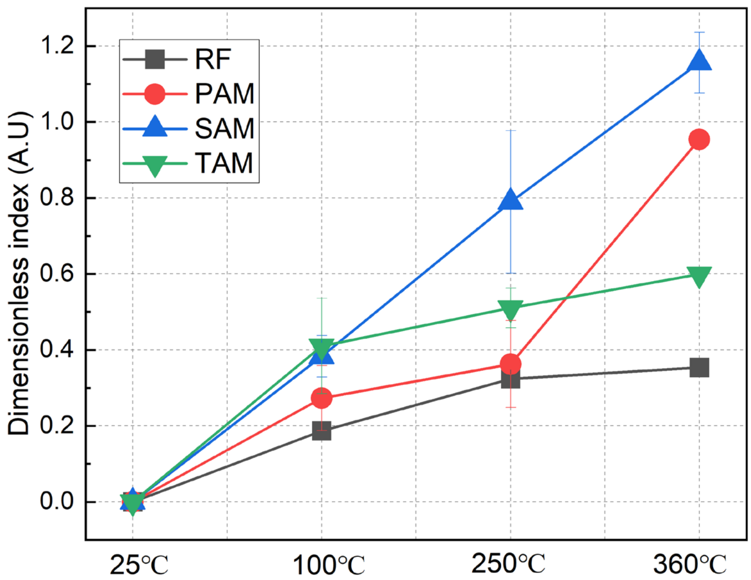

Figure.5 Comparison of dimensionless index of E_d, β_{PAM}, β_{SAM}, and β_{TAM}

The TAM method, while showing a good correlation with the conventional technique, also demonstrates significantly higher sensitivity to thermal damage and the lowest energy consumption. Although the PAM method is sensitive, especially at higher temperatures, its index varies sharply, making damage prediction at elevated temperatures challenging. Thus, the SAM and TAM methods are more feasible and robust for characterizing thermal damage in cement-based materials according to the experimental results.

Conclusions

This study demonstrates the effectiveness of the amplitude-modulation vibro-acoustic (AMVA) technique for characterizing thermal damage in pristine graphene (PRG) mortar. The AMVA technique, utilizing nonlinear parameters, shows superior sensitivity compared to conventional linear methods. Among the proposed methods, the SAM and TAM techniques exhibit the highest sensitivity and feasibility, with the SAM method being the most sensitive and the TAM method offering a good balance between sensitivity and energy efficiency. The results indicate that AMVA techniques, particularly SAM and TAM, provide a robust and sensitive approach for detecting and quantifying thermal damage in cement-based materials, thus offering a significant advancement over traditional linear techniques.

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Monitoring the Structural Capacity of a 1960s Bridge

Desiree Nortje

Principal Asset Manager, Civil Structures and Asset Strategy, Transurban, Victoria

Introduction

Transurban is an Australian-owned company, and we build and operate toll roads in Melbourne, Sydney, and Brisbane, as well as in Greater Washington, United States and Montreal, Canada. In Victoria we own and operate CityLink which was the first toll road built and operated by Transurban. We are also building the West Gate Tunnel which together with Citylink will provide an easy, uninterrupted path between the north, south-east and west Melbourne to keep traffic moving.

Like all road asset owners, we have inherited several bridges on our network which are more than 50 years old and past half their design life. One of these bridges was built in the late 1960s and for the purposes of this article the bridge shall remain nameless. The bridge was designed according to the Highway Bridge Design Specification; however, it is unclear whether this was the 4th edition or the 5th edition [1]. The design vehicle of the 1960s was the MS18 (33 tonne) truck however currently this part of CityLink is gazetted to carry 68.5 tonne B-doubles. This increase in load has caused concerns about the structural capacity of the bridge.

Structural GA

The bridge is a segmental precast, post tensioned box girder consisting of two carriageways connected by a transverse spanning link slab. The bridge has two unequal spans continuous over the pier and simply supported at both the northern and southern ends. The northbound carriageway has two marked traffic lanes, whereas the marked lanes on the southbound carriageway start merging approximately 48 m upstream of the bridge. The link slab was originally designed to carry traffic loads however, at some unknown stage in the past a central barrier was placed on the link slab. The location of the barrier was placed such that the wheels of traffic travelling north are ride on the keyed joint between the link slab and the box girder.

A schematic elevation of the bridge has been shown in Figure 1, and cross sections A and B in Figure 2 and Figure 3, respectively. These sketches have been traced from the original drawings, using shapes and lines in this Word document and consequently are only approximately to scale.

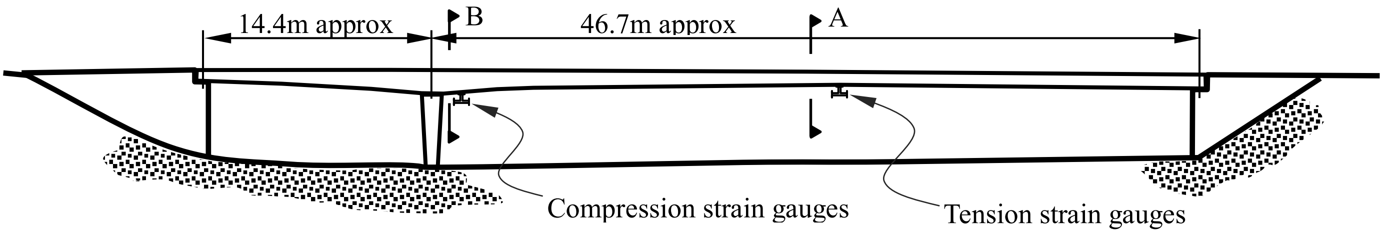


Figure 1: Bridge elevation

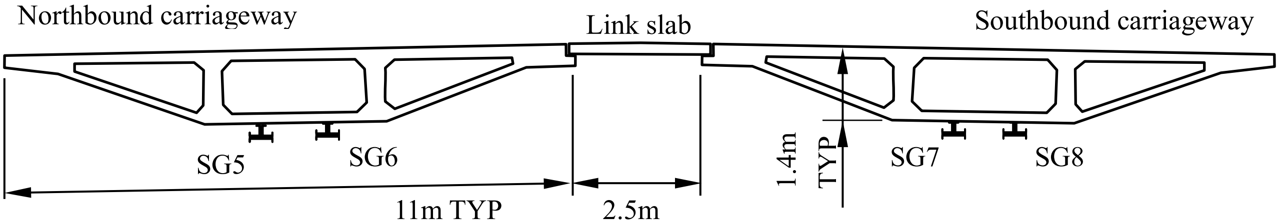


Figure 2: Bridge Cross-section A-A showing tension strain gauges on the soffit of segment 15

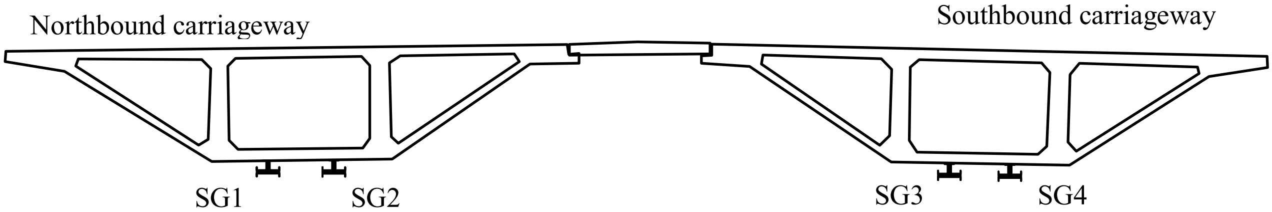


Figure 3: Bridge Cross-section B-B showing the compression gauges on the soffit of segment 6

Strain Gauges

Vibrating wire strain gauges were installed on 12-16 June 2023 and are Geokon gauges, model VW4150/VW4000 with a measuring range of ±3000**με** and a resolution of 0.4**με**. The active gauge length is 51mm and has a measuring rate of 100Hz during vehicle crossings and a 1-minute interval outside of vehicles crossings [2].

The gauges have been mounted to the bridge using Devcon plastic steel putty resin. The strain gauges are mounted on the soffit of the box girders at one third spacings of the width of the soffit, as shown in Figure 2 and Figure 3. Gauges 1 to 4 are the compression gauges in segment six adjacent to the pier, and gauges 5 to 7 are the tension gauges fixed to the soffit of segment 15. A photo of the gauges has been given in Figure 4, source; Rockfield report [2].

Figure 4: Photo of a typical strain gauge mounted on the Bridge

Power to the strain gauges was supplied by Transurban's maintenance and engineering teams from the power box at the abutment of the bridge.

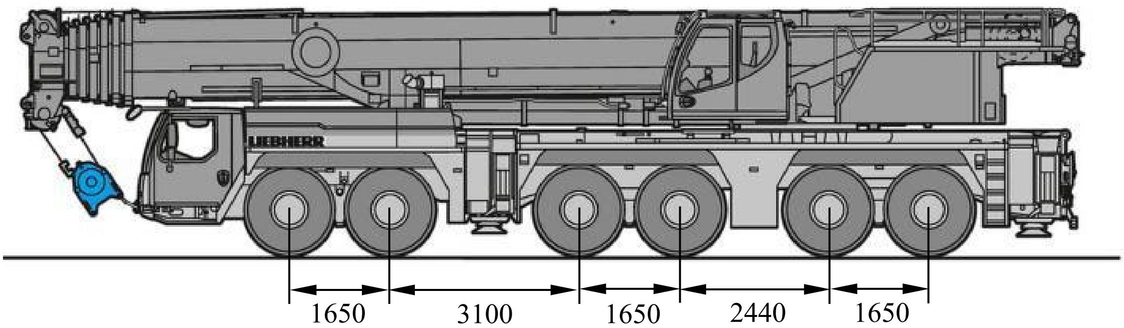
The USA supplier of the gauges issued a certificate of quality, conformity and calibration for the strain gauges. The certificate states that the gauges comply with the requirements of EN 61326-1:2013 'Electrical Equipment for measurement, control and laboratory use'.

Control Load Tests

Once the strain gauges were installed, a series of control load tests were conducted using a 44-tonne truck (T44) and a 72-tonne crane. The vehicles, drivers and axle loads were supplied by Transurban's maintenance contractor. The T44 and 72t crane geometry and axle loads have been given in Figure 5 and Figure 6, respectively.

Axle loads 6.32t 16.22t 21.62t

Figure 5: T44 axle spacing and loads as supplied for the June load test



Axle Loads 12t 12t 12t 12t 12t 12t

Figure 6: 72t Crane (Model LTM 1300-6.2) axle spacing and loads as supplied for the June load tests; Source Liebherr web page

Static tests as well as dynamic tests were conducted on both the northbound and southbound carriageways in the design lanes of both carriageways, not the marked lanes. The location of strain gauges 5, 6, 7 and 8, relative to the northern expansion joint were marked on the asphalt on the top of bridge using top hats.

For the static tests the drivers slowly approached the bridge and stopped with their front axle in line with the top hats while the strain readings were recorded. This procedure was repeated for each axle, after which the truck slowly left the bridge. An example of a strain gauge reading for the different axle positions for the December 2023 tests, is shown in Figure 7. For the dynamic tests the drivers travelled over the bridge as fast as possible noting that their run up was short due to traffic control constraints for the bridge closure. The maximum speed the vehicles could reach was 50km/h. The purpose of the load tests was to correlate the readings from the strain gauges with the weight of the vehicles travelling over the bridge.

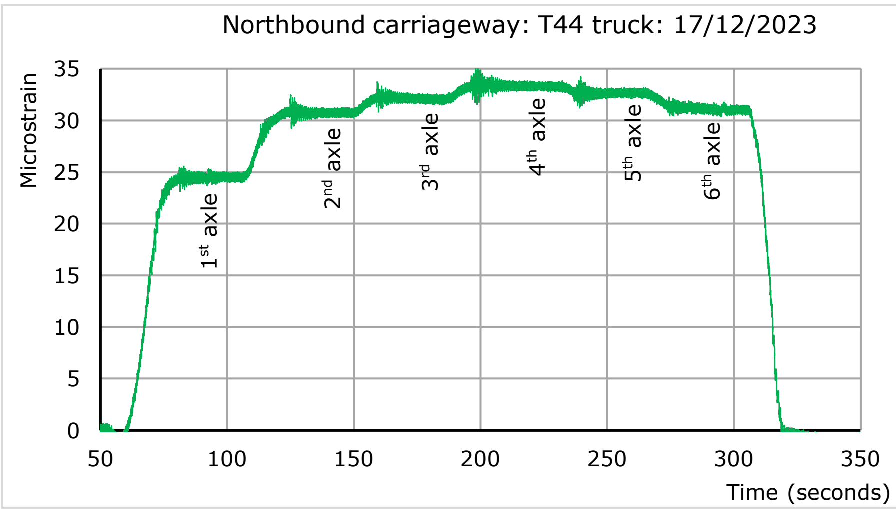


Figure 7: T44 static test strain gauge readings: Outer lane of the northbound carriageway

Bridge Structural Performance

A trigger level in the strain readings was set which corresponds to an acceptable level of structural response of the bridge. When this trigger level is exceeded Transurban receives an automatic email alert showing which gauges show higher than acceptable readings. These alerts have assisted Transurban in understanding the traffic flow and compliance on our structure.

As discussed previously the bridge was designed for 33 tonne trucks. The concern for the bridge is the structural capacity to carry two B-doubles side-by-side, which occurs frequently on this bridge, as shown in Figure 8aFigure 8 below. Similarly, vehicles regularly travel on the bridge that are significantly heavier than the gazette load, such as the 90 tonne GCM (gross combined mass) vehicle shown in Figure 8b.

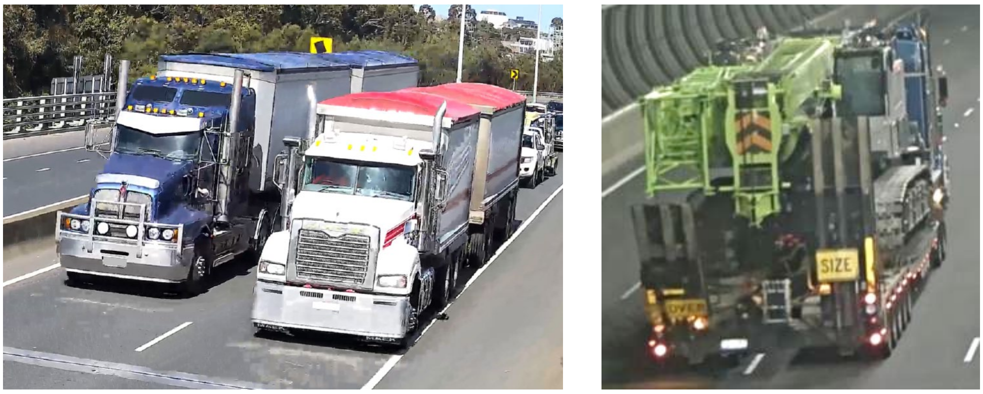


Figure 8: (a) Two B-Doubles; (b) approx 90 tonne GCM travelling over the bridge

To assess the risk of the structural capacity of the bridge, Transurban assessed the strain gauge data looking for signs of plasticity of the tendons. The expectation was that if the tendons are becoming plastic then the strain readings would be increasing over time for the same loads.

The background raw data from the strain gauges should show an increase in the readings if the bridge was starting to go plastic. However, nothing showed up that would indicate a concern of plasticity starting to develop since the readings remained constant.

Despite this, it became clear that there was an increasing difference in the values of SG5 and SG6 for the same load, as shown in Figure 9. For the same strain reading from SG5 the graph shows a high variation in the reading from SG6, and this difference increases with increasing load.

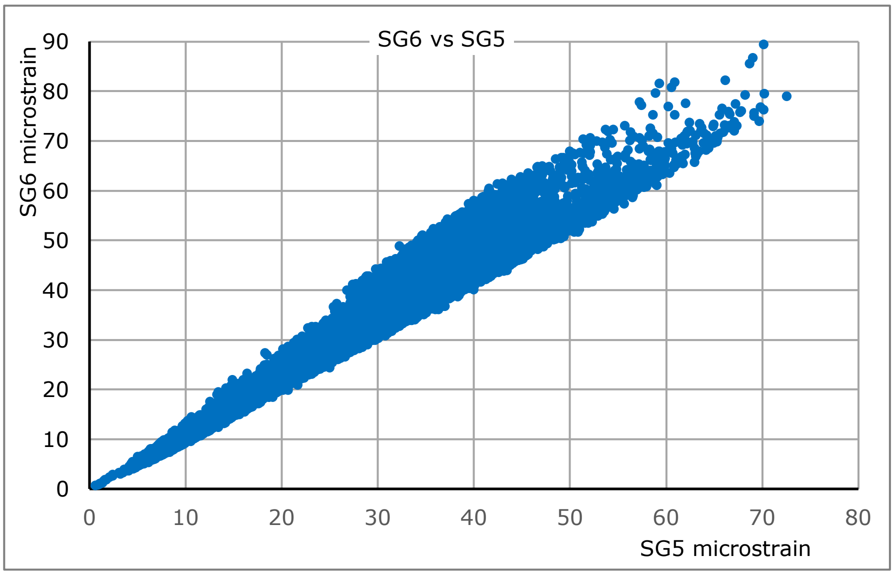


Figure 9: SG6 data vs SG5 readings from June 2023 to December 2023

The assumption was that SG5 was stable and SG6 was either drifting, unstable, or alternatively the bridge was starting to go plastic in one half of the box girder. The latter suggestion was not considered likely, and hence Transurban conducted additional load tests in December to determine which strain gauge was stable. On comparison of the results from the December load tests with those of June, the conclusion was that SG5 was stable and SG6 was giving higher readings for the same load.

On reviewing the data from mid-June 2023 to end May 2024, another influencing factor has been identified. Figure 10 is the plot of SG6 for all occasions that SG5 registered a 35microstrain reading, as a function of time. The values from the compression strain gauge SG1 have also been shown.

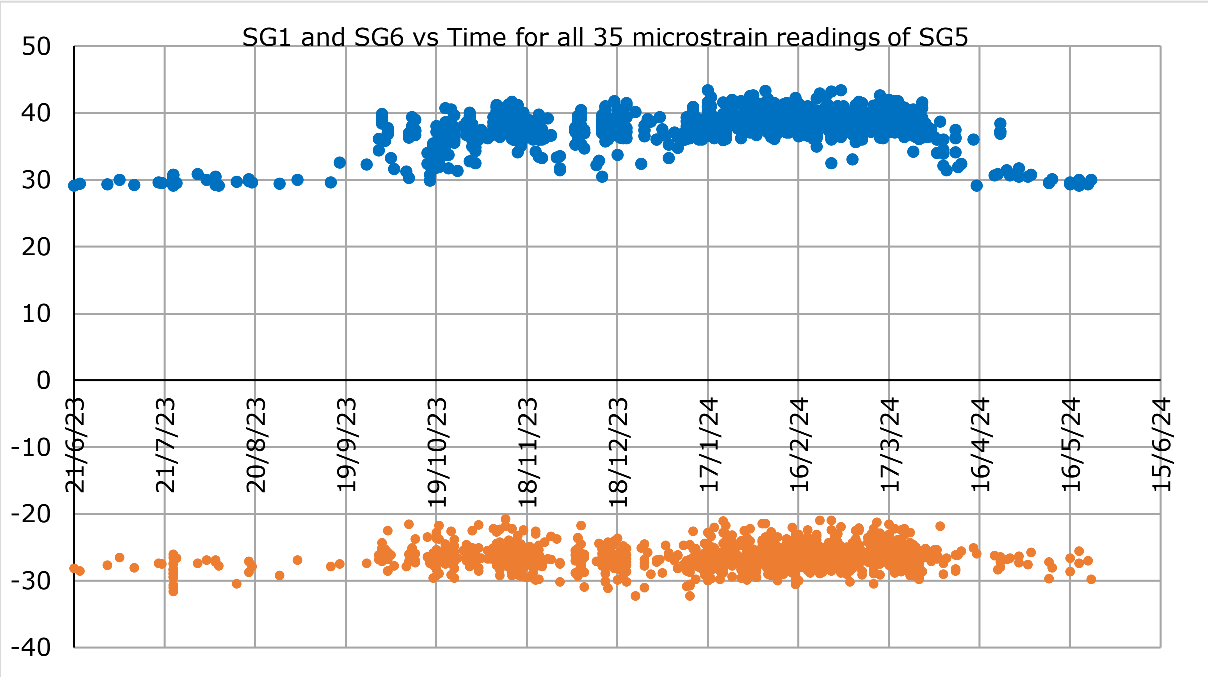


Figure 10: SG1 and SG6 vs Time for all values of 35 macrostrain for SG5

As can be seen there appears to be a reduction in the variation of SG1 and SG6 values for the same value of SG5. This reduction has occurred over the past two months and appears to show a trend towards more constant values. The likely reasoning for this is the weather has become cooler and in the month of May we have experienced several low overnight temperatures. Consequently, the acceptance that SG5 is 'stable' needs to be revised, as it will also have been affected by the temperature of the bridge.

Conclusion

The purpose of putting strain gauges on the bridge was to provide real data in connection with how the bridge response to loads. This data was then to be used to build a finite element model that represents the actual response of the bridge. Transurban then considered the option of retaining the strain gauges in place and monitoring the behaviour of the bridge with time.

Initially there was an attempt to correlate the strain readings directly with the loads travelling over the bridge. In this case there is no simple direct correlation due to other influencing factors. One factor is the ambient temperature causing expansion and contraction of the bridge. Although the December 2023 load tests appeared to verify that SG5 is stable and SG6 unreliable, the question of temperature effect was not considered at that time. Hence adjustments need to be made for the values from all strain gauges prior to comparing the results of the load tests conducted in June and December. While temperature will affect the bridge, Transurban believes this effect should be consistent for strain gauges in the same location on the bridge. This will be assessed in further work Transurban is undertaking on the bridge.

References

1. The Conference of State Road Authorities (COSRA) existed between 1934 and 1959 and published the first four editions of the specification. COSRA was renamed NAASRA, the National Association of Australian State Road Authorities, in 1959 and published six editions between 1965 and 1975.
2. Rockfield, 'The Bridge As-built Instrumentation', June 2023, Works commissioned by Transurban, and embedded in Transurban reports.

Conference News

- ANSHM minim-symposium "Emerging techniques for structural health monitoring of civil infrastructure" in the 18th East Asia-Pacific Conference on Structural Engineering & Construction (EASEC-18), 13-15 November 2024, Chiang Mai, Thailand. Organized by Prof Jun Li, Prof Hong Guan and Prof Tommy Chan. https://easec18.org/
- The 11th European Workshop on Structural Health Monitoring, 10-13 June 2024, Potsdam, Germany. http://www.ewshm2024.com/
- The 1st International Conference on Engineering Structures, 8-10 November 2024 Guangzhou, China. https://www.ices2024.cn/
- Tokyo Symposium of the International Association for Bridge and Structural Engineering (IABSE), 18 to 21 May 2025, Waseda University and Rihga Royal Hotel, Tokyo, Japan. https://iabse.org/Tokyo2025

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