CAUSEWAY BRIDGES ACROSS SWAN RIVER, IN PERTH (AUSTRALIA)

Pasarelas Causeway sobre el río Swan, en Perth (Australia)

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ABSTRACT

The Causeway Pedestrian and Cyclist Bridge Project is an opportunity to deliver a landmark active transport connection across the Swan River that responds to the unique cultural and historic significance of the area, integrates with existing landscape and urban design, and provides an attractive link for both tourists and the wider community. Consisting of two cable stayed bridges, the number of river piers is limited to three, acknowledging the spiritual and cultural importance of the Swan River (Derbal Yerrigan) to Perth's first nations peoples. This paper discusses the general design development of the bridges taking architectural input, wind and footfall dynamics as well as construction sequencing into account.

RESUMEN

El Proyecto del Puente Peatonal y Ciclista de Causeway ofrece una conexión emblemática a través del río Swan que responde a la singular importancia cultural e histórica del área, se integra con el diseño paisajístico y urbano existente, y proporciona un enlace atractivo tanto para turistas como para la comunidad en general. Consiste en dos puentes atirantados, con un número de pilas en el río limitado a tres, reconociendo la importancia espiritual y cultural del río Swan (Derbal Yerrigan) para los pueblos originarios de Perth. Este documento aborda el desarrollo general del diseño de los puentes, enfocándose en la aportación arquitectónica, la dinámica del viento y del paso de peatones, y el proceso constructivo.

KEYWORDS: footbridge, cable stayed, footfall dynamics, wind dynamics, construction sequencing.

PALABRAS CLAVE: pasarela, atirantada, vibraciones, análisis viento, secuencia constructiva.

1. Introduction

The existing Causeway Traffic Bridges are one of only four pedestrian and cyclist crossings of the Swan River, being one of the busiest carrying peak hour volumes of over 150 cyclists and 200 pedestrians. The need to improve this connection has been identified for some time as the existing shared path width of 1.8 m, uneven surface conditions and mix of user groups generally presents safety concerns and limits access.

Located about 100 m downstream of the existing Causeway, the new alignment is about one kilometre long, stretching from Point Fraser on the City of Perth side over Heirisson Island to McCallum Park at the Town of Victoria side. The main path comprises a total width of 6 m, where 3.5 m are dedicated to cyclists and e-scooters and 2.5 m are dedicated to pedestrians providing safer access across the Swan River for active transport independent of the road traffic. Consisting of two cable stay bridges, the constructed option limits the number of river piers to just three, acknowledging the spiritual and cultural importance of the Swan River (Derbal Yerrigan) to Perth's first nations peoples.

Based on input from the local indigenous community during the concept design phase, the Point Fraser Bridge comprises a single pylon representing a boomerang. The bridge is asymmetric with a 48 m side span and a 99.7 m main span supported by cables attached to the inner side of the continuously curved bridge deck.

The McCallum Park Bridge comprises two 46 m high pylons representing digging sticks. The bridge is symmetric with 60 m side spans and a 155 m centre span supported by cables attached to the inner side of the S-shaped bridge deck.

2. Design development

2.1 Planning of the alignment

To create an attractive yet functional design, the connections at either end of the bridges were reviewed for their best possible tie into the existing network infrastructure. The existing principal shared path on the Point Fraser side with good access to the secondary path serving the surrounds was a starting point to link with the bus transfer station, the Canning Highway underpass as well as the South Perth to Belmont bike and pedestrian paths on the Victoria Park side. Considerations to minimise the impact on existing trees and to stay clear of environmental and heritage sensitive areas also needed to be considered.

The adoption of an S-shaped alignment was chosen to give the link a more organic shape, responding to the island's natural setting, in response to the bridge structures themselves, and to respect the valuable input from the Noongar Elders. In local history, the 'Wagyl' is a snakelike dreaming creature responsible for the creation of the Swan and Canning rivers and other waterways and landforms provided inspiration for the shape and alignment of the project.

Figure 1. Artist impression of the Wagyl

2.2 Form finding of bridge elements

The reference design had a symmetrical deck cross section. Due to the horizontally curved bridge decks and the single sided cable attachment point the deck cross section was revised to an asymmetric cross section.

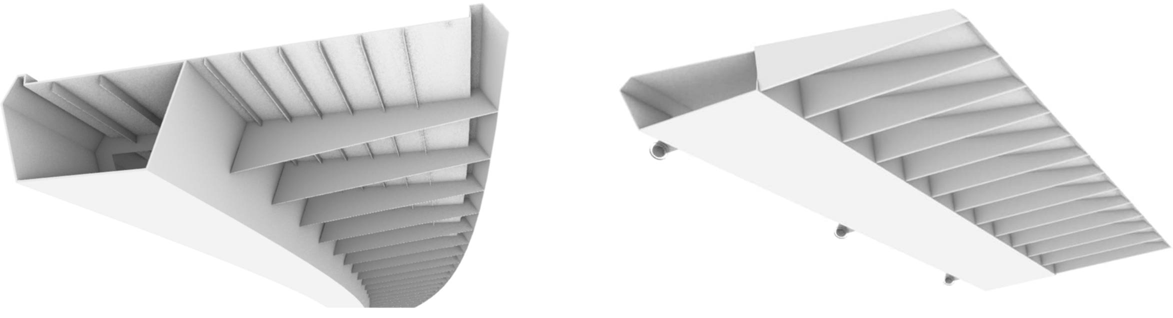

Figure 2. Architectural input – from functional to elegant

A torsional stiff closed steel box transfers the loads to the cables, the pylons and the abutments. It started off with a functional deck cross section driven by structural requirements. With some refinement by the bridge architects the bridge deck got slimmer, and the number of stiffeners was reduced. The cantilevers had to satisfy the aesthetic requirement of being a closed section. By cold forming the outriggers to a V-shape this could be satisfied (refer Figure 2).

The design team eliminated all tie-back cable anchors connecting the pylons to anchor points onshore, as suggested in the reference design, which the client recognized as a major safety improvement. By removing the tie-back cables there was a significant reduction to the number of permanent piles required. In addition, it eliminated the risk of vandalism to a bridge element that had a significant role to the stability of the structures with little redundancy.

Figure 3. Design development – preferred option

The reference design had a dedicated strut to support the bridge deck from the pylon pile caps. This support could be integrated into the pylon providing a moment stiff connection to the bridge deck. As it was a project requirement to provide three pause points facing West, those were positioned at the pylons as well. At the Point Fraser Bridge and the first pylon of McCallum Park Bridge, the pause points feature a wider deck by increasing the cantilever of the pylons. The second pause point at McCallum Park Bridge was wrapped around the pylon which also included the integration of the seating.

The shape of the pylons was refined to respond to the valuable input of the Noongar Elders during the design competition. The pylons of the McCallum Park Bridge are tapered with a smaller 1.5 m diameter at the base, increasing to 1.8 m diameter at the top. The shape of the pylon tip was chosen out of five presented options (refer Figure 4) by the later formed Matagarup Elders Group providing input on cultural heritage to the project. A similar process was used to define the shape of the boomerang forming the pylon of Point Fraser Bridge.

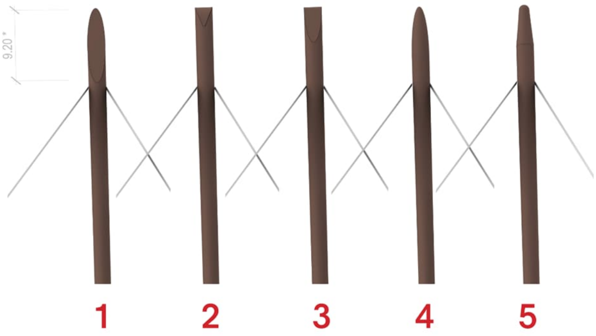

Figure 4. Digging stick top studies

The proposed functional lighting on the bridges was developed to provide a fully integrated and sustainable design solution that caters for the varying needs of the users while achieving safe movement principles. For aesthetical reasons the design team removed light poles from the design and replaced them with lights integrated in the handrail. The bridge handrailing had the further design requirements to provide a light appearance and to restrain crowds, pedestrians and cyclists. The top rail is provided at 1.4 m above the surfacing to comply with [1]. The “smooth deflection rail” for cyclist is at 1.2 m above the surfacing in accordance with [2]. This allows for the handrail lighting to be installed in the deflection rail and spill sufficient lighting onto the bridge deck to comply with [3]. Together with the bridge architects a sleek solution could be achieved using Grade 400 weathering steel stanchions, Grade 316 stainless steel top- and deflection rails and wire rope mesh as well as Grade 2205 stainless steel pipe to support the wire rope mesh. To prevent dissimilar metal corrosion the stainless steel is electrically isolated from the weathering steel. Drainage of the bridge deck is achieved by providing scuppers outside of the navigation channel. For the approach spans on Point Fraser Bridge an integrated drainage channel was designed to collect run-off and reduce the spread width on bridge deck.

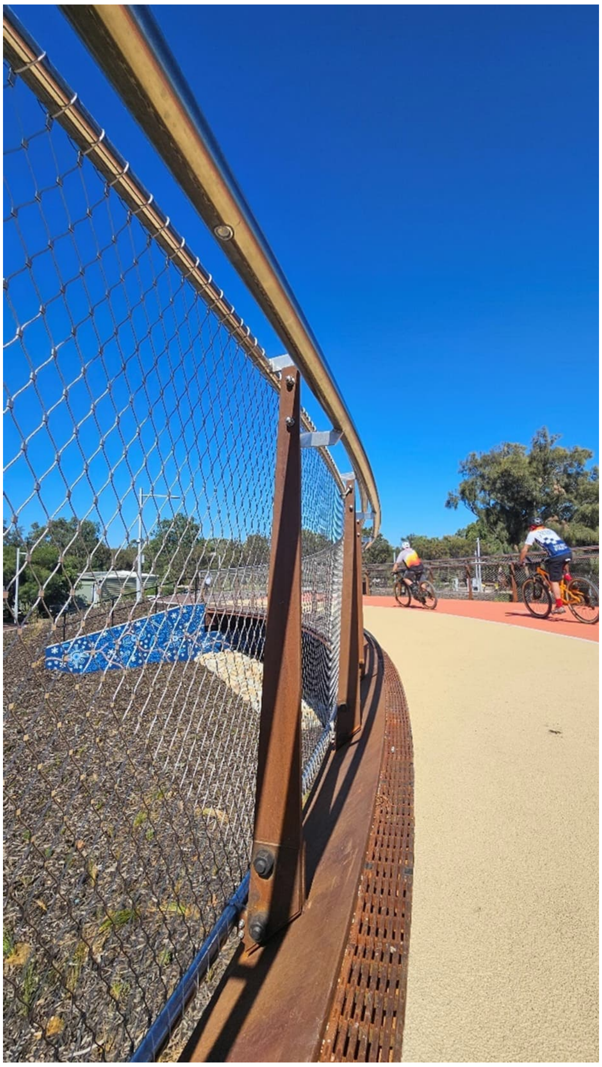

Figure 5. Balustrade with integrated lighting and deck with integrated drainage channel

The abutments are of reinforced concrete cast in-situ construction. They comprise a chamber housing the deck support column and the deck pendulum anchor as well as wingwalls. The chamber is enclosed by the abutment backwall and sidewalls retaining the approach embankments as well as a curved front wall with an access door in it. Curved wingwalls, retaining the side slopes of the approach embankment, extend outward from the abutment front wall. An approach slab is supported by the abutment back wall (refer Figure 6). The spherical bearings and pendulum anchors, which support the steel and provide the required torsional restraint, are concealed within the abutment chamber. Maintenance access is provided through a door in the abutment front face.

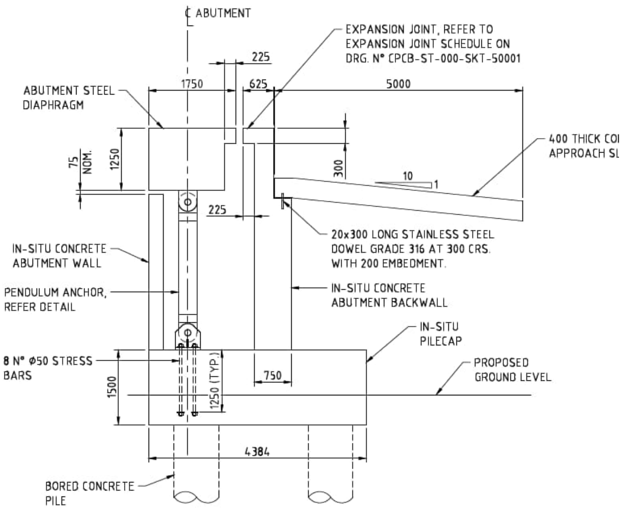

Figure 6. Section through abutment chamber

The original abutment of the Point Fraser Bridge on the Point Fraser side was set back further from the river edge by transitioning the main cable stay bridge deck structure to three short, light weight approach spans. This has significantly reduced the imported embankment fill quantity in this area and created more open space for landscaping. It has minimized intrusive ground improvement requirements by eliminating settlement issues related to fill heights above 2.5 m, as well as settlement issues to the existing Causeway bridge abutment.

The asymmetric stay cable supported bridge deck transitions to a symmetrical design between Pier 2 and Pier 3 for the approach spans. To control cyclist speed and meet the design requirement of a maximum 3% grade, the approach spans incorporate a horizontal curve in the opposite direction from the main stay cable supported spans. This increases the total length of Point Fraser Bridge but was deemed necessary to provide a compliant and save design solution.

Due to the transition of horizontal curves, Pier 3 of the Point Fraser Bridge was designed and detailed to accommodate longitudinal movements from thermal expansion and contraction, provide torsional restraint for the bridge deck, and absorb some anchor forces from the back span cables. The result was a pendulum anchor in the longitudinal direction with a transverse diaphragm in the form of a closed steel box (refer Figure 7).


Figure 7. Pier 3 and Deck Transition of Point Fraser Bridge

3. Wind dynamics

3.1 Sectional models

3.1.1 Deck

Sectional model wind tunnel tests were performed for the Causeway Pedestrian Bridges (refer Figure 8) by RWDI in their Canadian facilities.

Vertical Vortex Induced Oscillation (VIO) was observed for winds approaching the deck cross section from the box side with a full-scale peak amplitude of 80 mm, which exceeds the comfort criterion (5%g acceleration up to 15 m/s wind speed) considering the 1st order vertical modes for both bridges using a structural damping ratio of 0.3% of critical.

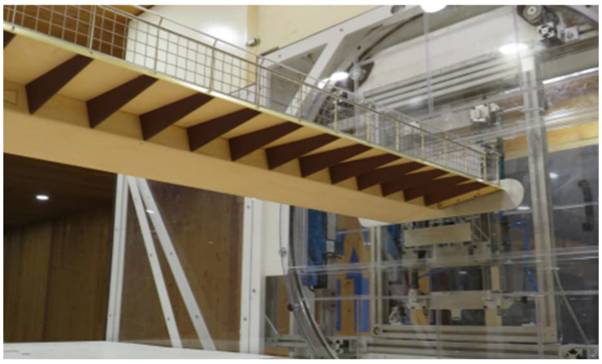
Figure 8. Section model in wind tunnel

No flutter or galloping responses were observed at wind speeds below the stability speed. Several mitigation options were tested in the wind tunnel to eliminate the vertical VIO of the deck. In consultation with the architects, it was decided to implement an option comprising a wind splitter plate (refer Figure 9). This option had completely removed the issue of unsteady aerodynamic loading from vortex shedding.

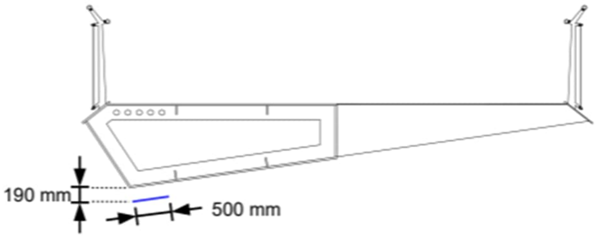

Figure 9. Wind splitter plate to mitigate VIO

3.1.2 Pylons

Individual models of the pylons were built to measure the mean forces and moments acting on the pylons in the wind tunnel. An equivalent distribution of force coefficients was determined from those measurements. For the McCallum Park Bridge pylon, a high Reynolds number simulation was employed to simulate the supercritical regime. The reproduced base forces and moments using the derived force coefficients were found to be in good agreement with the measured values of the wind tunnel testing.

3.1.3 Aeroelastic

An aeroelastic model of the bridge was constructed at a scale of 1:55. The model emulated the physical and dynamic properties of the bridge in service and the stay cables were modelled to match the mass and mean drag of the full-scale cables. Wind tunnel tests confirmed that the bridge deck and pylons are expected to be stable against aerodynamic instabilities such as vortex shedding, galloping and flutter to well beyond the stability criterion wind speed for each bridge. The buffeting responses of the bridge were measured in turbulent flow representative of the expected flow conditions at the site for a number of wind directions around the full compass. Responses were found to be maximum for skewed winds relative to the nominal bridge-normal directions due to exposure differences and the curvature of the bridge deck. The design revision to triple the stay cables on the Point Fraser Bridge, allowing the cables to serve as a canvas for enhanced lighting shows, resulted in generally larger mean and dynamic responses of the bridge due to a significant increase in cable drag. However, no global instability was observed from this design change.

3.1.4 Numerical wind buffeting analysis

The numerical wind buffeting analysis was conducted to validate the results of the aeroelastic wind tunnel test using aerodynamic force coefficients and flutter derivatives obtained from the deck sectional wind tunnel test. Additionally, the analysis was used to calculate displacements, accelerations, and force effects for critical design scenarios not covered by aeroelastic wind tunnel testing.

Since the deck was supported by temporary piers during all phases of construction, it was not subjected to dynamic wind action during this period. Consequently, the buffeting analysis focused on the bridge in its completed state. However, separate desktop analyses were performed to assess the potential for Vortex Induced Oscillations in loose-standing pylons during construction.

The wind parameters provided by the wind consultant (RWDI), including the wind profile, turbulence characteristics, force coefficients, and flutter derivatives, served as inputs for the buffeting analysis. Drag forces, lift forces, and deck moments per unit length were calculated from the force coefficients, while aerodynamic forces induced by deck oscillations were determined using flutter derivatives.

A transient time history analysis was employed to simulate dynamic wind effects. Artificial wind histories were generated, incorporating aerodynamic damping and galloping effects. A typical ULS wind history, representing along- and cross components of the wind at the top of one of the pylons, is shown in Figure 10.

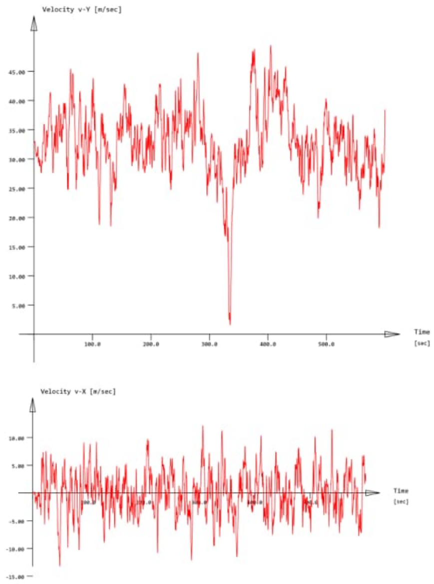

Figure 10. Typical Along and Cross ULS Wind Histories at Top of Pylon

The analysis is based on Unsteady Theory considering the flutter derivatives. To ensure proper aerodynamic interaction, 10-minute runs comprising 12,000 steps (0.05 seconds per step) were performed. For statistically robust results, 11 No. of time history runs were conducted, and the mean of the maximum values was adopted as the maximum response. A routine was developed to automate successive time history analyses for each investigated condition.

Envelopes of displacements, accelerations and force effects were generated which were further used for ULS and SLS design. A close correlation was observed between the aeroelastic wind tunnel test results and the numerical buffeting analysis, validating the methodology.

Dynamic amplification factors were determined by comparing static wind analysis with numerical buffeting analysis. These factors were incorporated into the static loading of the structural analysis model for the final design.

Additionally, deck accelerations under operational wind speeds were evaluated to ensure pedestrian comfort. The calculated mean peak accelerations were well within acceptable limits, confirming that no additional wind damping devices were required to suppress buffeting effects.

4. Footfall dynamics

4.1 Footfall design

Vibration in footbridges primarily raises serviceability concerns related to user comfort. To assess the structure’s performance, dynamic analysis was conducted to simulate the rhythmic loading of groups of pedestrians and joggers. The structural response to harmonically applied load models was evaluated against comfort and stability criteria to determine whether the bridge met performance requirements or required additional measures. The analysis was conducted with reference to the Eurocodes and [4].

The bridges were assessed under various loading conditions, including pedestrian crowd loading and jogger loading for marathon events. Traffic scenarios were evaluated against agreed comfort classes based on horizontal and vertical acceleration limits. The load model presented in [4] was adopted for pedestrian footfall analysis. While [4] provides a load model for a single runner, it lacks guidance for larger groups of joggers. Some National Annexes to the Eurocode provide load models for small groups of joggers, e.g. [5] for a group of four. Larger groups are generally avoided on pedestrian bridges by restricting large marathon events. For this project, jogger streams were statistically analysed to determine the equivalent perfectly synchronized joggers for densities of up to 0.5 joggers/m^2.

In addition to vertical and horizontal vibrations, the bridges were checked for stability against lateral lock-in. Lateral lock-in is the phenomena where pedestrians try to compensate for lateral vibration by adjusting their centre of gravity and swaying with the bridge. Groups of pedestrians tend to synchronize their steps at twice the bridge's horizontal frequency, which can excite low-damped bridges to large vibrations. [4] provides two alternative approaches to prevent the triggering of lateral lock-in. The first is based on the method of Dallard et al. that was developed from the Millennium footbridge tests. In this method the triggering number of pedestrians are determined by an expression which is a function of the structural damping ratio, the modal mass, the natural frequency and a bridge specific constant. The second approach uses a triggering acceleration in the range of 0.1–0.15 m/s². The method of Dallard predicts a substantially higher damping requirement than that of the second acceleration triggering method. Given the potentially catastrophic consequences of lateral lock-in, the more conservative Dallard method was adopted for this project.

Substantial damping was required for both bridges to meet walker and jogger comfort limits and to ensure stability against lateral lock-in. Tuned Mass Dampers (TMDs) were selected for this purpose due to their effectiveness in reducing vibrations. However, TMDs have a narrow effective frequency bandwidth, requiring separate dampers for walkers and joggers due to their differing critical frequency ranges. A total of 11 TMDs were installed on McCallum Park Bridge and 6 on Point Fraser Bridge. To minimize mass and optimize efficiency, vertical and horizontal dampers were combined wherever possible.

Table 1. Vertical natural frequencies

TMD Type	Design natural frequ. vert. (Hz)	Measured natural frequ. (Hz)	Tuning frequ. (Hz)
1	1.75	1.88	1.82
2	1.97	1.88	1.84
3	2.41	2.34	2.15
4	1.5	1.47	1.45
5	3.0	2.88	2.85
6	3.17	3.4	3.35

4.2 Dynamic testing and commissioning of the TMDs

Both bridges were tested in accordance with the suggestions of [4], using a group of 15 people. The determined relevant natural frequencies were in good agreement with the theoretical predicted values from the design models, allowing the tunning of the TMDs to be within the provided range (refer Table 1).

After engaging the TMDs the same tests were performed to measure the effectiveness of the TMDs. The measured accelerations were mathematical extrapolated to find the number of perfectly synchronised people required to exceed the design comfort criteria and to trigger lateral lock-in instability.

5. Construction sequencing

The adopted construction scheme involved erecting prefabricated deck modules, each up to 45 m long, on temporary pier supports. The deck segments were spliced at the temporary support positions, initially using bolted splices to ensure rapid progress, followed by permanent weld splices. Stabbing guides have been used to allow simple and quick alignment of the deck segments (refer Figure 11).

Figure 11. Stabbing guides to align deck segments

The complete deck was assembled together with the pylon, after which the cables were installed and stressed in a two-stage process. In the first stage, the cables were stressed to 10–15% below the final force levels. The temporary supports were then lowered, allowing the forces in the cables to be evaluated for adjustments to the second final stressing stage. This approach ensured the required target forces and displacements were achieved during final stressing.

To ensure the structural behaviour during construction aligned with the design intent, detailed construction stage analysis was undertaken. This analysis accurately determined the force buildup during each construction stage and the eventual final force distribution in the structure. Cable force finding was integrated with the construction stage analysis using an iterative solver to meet target forces in the deck and pylon. The analysis accounted for geometric non-linearity including second-order effects and cable sag. Moderate pre-cambering of the deck elements was necessary to achieve the final deck profile, but pre-cambering of the pylons was not required, as their final deflections were relatively small.

One challenge encountered was the large locked-in sagging moments that were developed as a result of splicing the girders at the temporary support positions. To counteract these moments, the far end of the deck, away from the splice, was installed in a higher temporary position. After temporary bolt splicing, the deck segment was lowered, reducing the sagging moments and introducing a hogging moment, which balanced the forces more effectively.

The adopted construction scheme, combined with detailed analysis, ensured an efficient and accurate assembly process, achieving the required structural performance for the completed bridge.

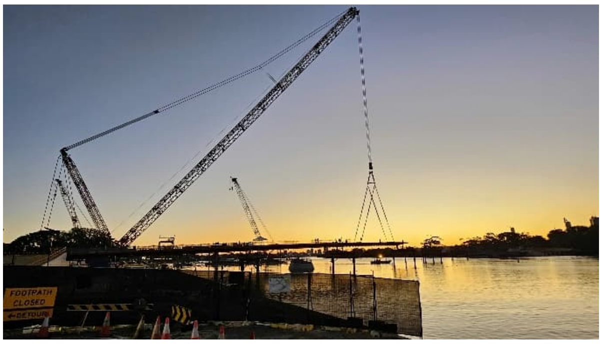

Figure 12. 1600-ton crawler crane installing module 5 of McCallum Park Bridge

It was planned to use barge mounted cranes for the installation of bridge modules. However, due to the Swan River being influenced by tidal fluctuation the water depth required for the crane and barge size was insufficient. The construction team had to revise their installation process using land-based crawler cranes. The largest crawler crane Australia has to offer was employed on the project, enabling the installation of 120 t segments with a reach of over 130 m.

6. Summary

Bridge designs that recognise important cultural icons were achieved which included integration of pylons reflecting a boomerang on one bridge and digging sticks on the second bridge.

The two bridges were jointly named the ‘Boorloo Bridge’ which is the indigenous word for Perth. The bridges were opened to the public on December 22nd, 2024, with 530 marathon runners crossing the bridges. This first official event on the bridges was a good test to confirm through user experience that the comfort criteria is met and the dynamic analysis for both wind and pedestrian induced vibrations were confirmed to be withing the predicted range. The additional cables to serve as a lighting canvas for the Point Fraser Bridge have been a design challenge. However, being able to display images with an integrated stay cable lighting system has added another attraction to the City of Lights.

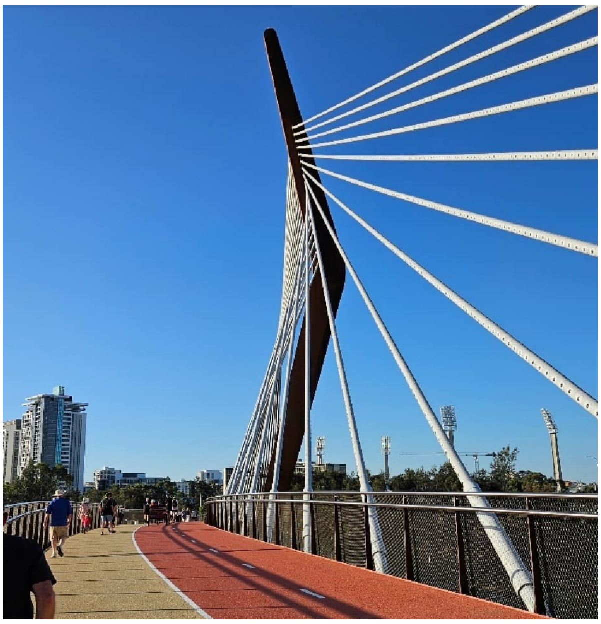

Figure 13. Point Fraser Bridge

Figure 14. McCallum Park Bridge

7. Acknowledgements

The Causeway Link Alliance consisting of CIVMEC, Seymour Whyte and WSP won the competitive tender to deliver this project under an Alliance Agreement with Main Roads Western Australia. The project is jointly funded by the Australian and Western Australian Governments as part of the Perth City Deals.

The Matagarup Elders Group was involved from the early stages of concept development and shared their valuable stories which have added depth and character to the design and the project delivery process. We hope we have listened.

Figure 15. Point Fraser Bridge at night

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