Rectification of Captain Cook Bridge Bearings

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Abstract: Captain Cook Bridge is an iconic bridge crossing the Brisbane River, and is the most trafficked bridge in Queensland, connecting the City's south with the Brisbane Central Business District (CBD).

The suspended spans are supported on sliding knuckle bearings at one end. The original DU Glacier and stainless steel sliding plates, failed and were replaced in 1996-97, with a glass filled PTFE sheet for the sliding material. After 20 years of service, routine inspections in July 2016, identified the extrusion of the PTFE sheet from the bearings on the southern suspended spans. The Department of Transport and Main Roads (TMR), developed unique rectification procedures that were implemented by early February 2017.

This paper discusses, the investigation of the bridge and bearing behaviour utilising in-service instrumentation. The instrumentation measured movements across the PTFE as well as rotations of the bridge and bearing components at the expansion joint, determining the response to a range of traffic scenarios and weather events.

Innovative in-situ modifications were developed to allow the bearings to be rectified within one night. This paper discusses the bearing modifications, including a replacement knuckle with a curved surface aimed to accommodate non-uniform bearing pressures across the new sliding material, *ORKOT TXMM®*. This was the first trial use of *ORKOT TXMM®* in a bridge bearing in Queensland, implemented as this material is not expected to extrude under the immediate substantial increase in traffic loading.

The suspended span was jacked internally to allow the in-situ bearing modifications. A steel lateral restraint brace, restrained the construction stresses and thermal movements during the jacking operation. This brace was also designed to provide the operational lateral restraint, previously provided by the bearings, to allow the most optimal bearing modification design, and accelerate the rectification procedure.

The paper provides important insights into the behaviour of bridge bearings, to meet performance requirements and achieve an acceptable design life to minimise disruptions to the public.

Keywords: Captain Cook Bridge, Bridge Bearings, In-Service Bridge Monitoring, PTFE, ORKOT TXMM®

Introduction

Captain Cook Bridge is an iconic bridge crossing the Brisbane River, connecting the City's south with the Brisbane CBD. The bridge was opened to traffic in 1972, and is currently the most trafficked bridge in Queensland, with an annual average daily traffic of 135,000 vehicles (1).

Captain Cook Bridge contains two separate 550m long bridges, one for each four lane carriageway. The five span, twin cell, variable depth, post-tensioned precast box girder forms the superstructure for each bridge. There are two 34m long suspended spans in each bridge spanning the cantilevers between piers 1 and 2, and piers 3 and 4 respectively (Figure 1). The bridges, each with a kerb-to-kerb width of 13.4m share common substructure foundations.

The suspended spans are supported on three bearings at each end, with fixed hinged knuckle bearings located at one end, and sliding knuckle bearings located at the other end. The original sliding bearings contained a stainless steel plate and a DU-Glacier sliding plate. Inspections discovered that these plates were discharging and were subsequently replaced with thicker stainless steel plates and 4mm thick glass filled polytetrafluoroethylene (PTFE) sliding material in 1996-97 (2). Routine inspections in July 2016, revealed the extrusion of the PTFE sheeting from the sliding bearings of the southern suspended spans, after 20 years of service (Figure 2).

With the frequency of heavy vehicles and hauling expected to increase with the commencement of major construction activities, and high-rise developments in early 2017, immediate action was required to prevent further deterioration of the bearings and potential future structural damage to the bridge.

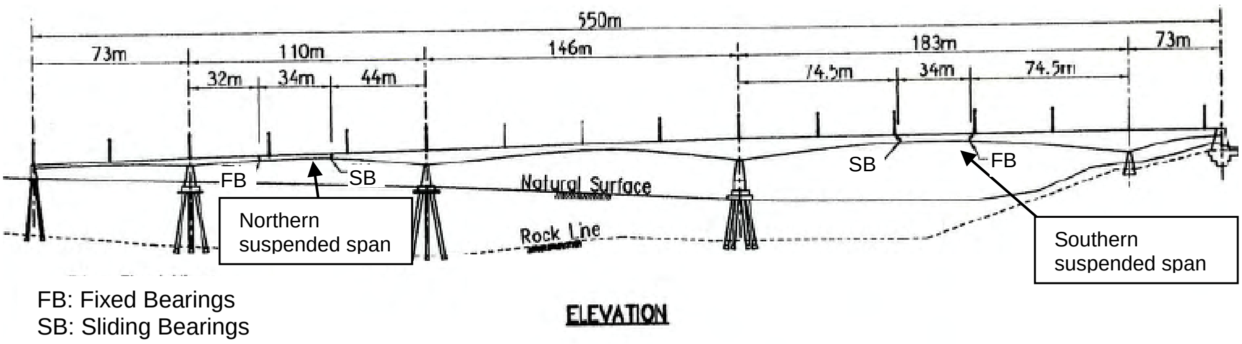

Figure 1: Captain Cook Bridge Details (2)

Figure 2: Extrusion of the PTFE Sheeting from the Previous Sliding Bearings

Captain Cook Bridge Sliding Bearings

Sliding Bearing Behaviour and Design Considerations

The suspended spans are supported on sliding bearings which are 'non-standard' and bespoke (Figure 2). These bearings consist of a stainless steel plate, and a sliding material forming a low friction sliding surface. The sliding material sits in a recess within the top section of a knuckle joint. The fulcrum of the base plate is curved to allow the knuckle to rotate over the base plate. This arrangement accommodates deck rotations and sliding due to live-load induced deflections, and thermal movements. The friction between the sliding material along and stainless steel plate creates an overturning moment, causing a rotation about the transverse axis. The stress is redistributed so that the centroid is at an eccentricity to resist the overturning moment. This results in a non-uniform stress distribution across the knuckle. This bearing behaviour is summarised in Figure 3 and was considered in the design of the new knuckles installed in February 2017.

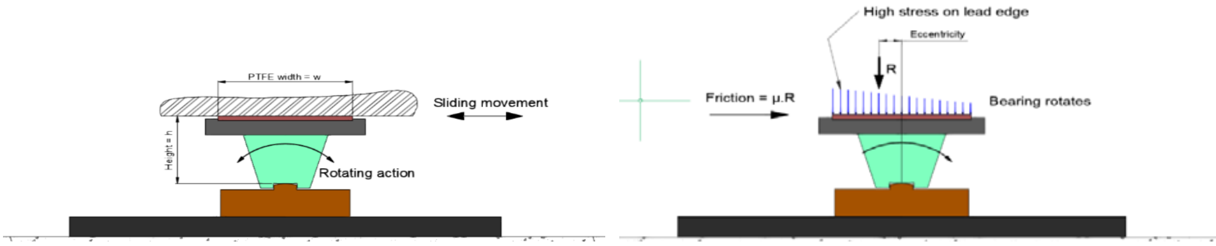

Figure 3: Sliding Knuckle Bearing Behaviour and Design Considerations

The sliding material of the original bearings was a DU-Glacier plate, comprised of a steel backing sheet with a sintered bronze matrix, and PTFE/lead sliding surface layer. These were replaced with 25% glass filled PTFE sheets in 1996-97, when the stainless steel and DU-Glacier plates were discharging from the bearing. Fong, K and Pritchard, R (2) previously concluded that the original bearings failed because of the DU-Glacier plates' inability to tolerate non-uniform bearing.

Extrusion of PTFE Sliding Material (Existing Bearings)

The glass filled PTFE sliding material was found to be extruding from the sliding bearings of the southern suspended spans (Figure 2 and 4). There was no extrusion identified on the sliding bearings of the northern suspended spans. The measured extrusion ranged between 60-85mm, and was protruding from the southern corners.

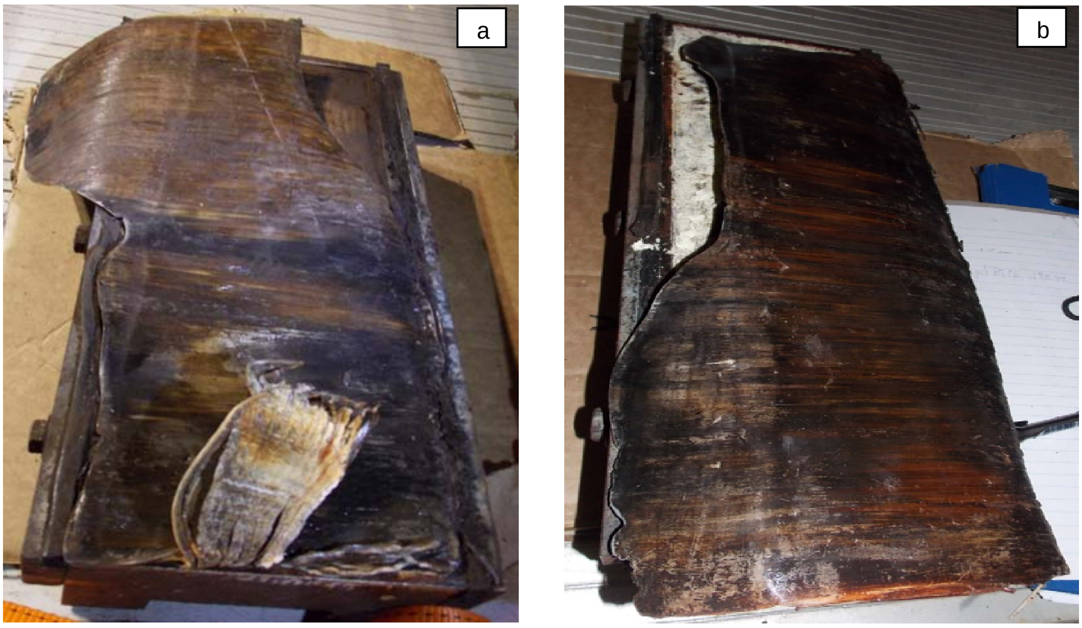

Figure 4: Removed Southbound Bridge Knuckles and PTFE Material (a) Downstream Bearing (b) Central Bearing

There are a number of possible contributing factors to the extrusion of the PFTE from the bearing, including:

- Non-uniform bearing and asymmetrical compressive loading resulting in uneven creep and deformation of the PTFE material, commonly referred to as ratcheting (3).
- Transverse flexure of the concrete diaphragm resulting in non-uniform and concentrated loading.
- Yielding and deformation of base-plate fulcrum restricting rotation of the knuckle leading to non-uniform loading on the PTFE.
- Increased traffic loads increasing the pressure on the PTFE.

Monitoring the Expansion Joint

An instrumentation system was established to understand the behaviour of the bearing and to inform the rectification works. The initial measurements focused on movements – rotations and slip at the expansion joint. Observations include:

- The monitoring revealed the expected daily cycle with cantilever rotating in the opposite direction to the suspended span generating relative rotations across the bearing with a range (maximum – minimum) of approximately 4.5 mm/m during the second week of June 2016 (refer Figure 5). An afternoon of steady winter rain (12.6 mm) after a period of fine weather induced a reversal in the daily pattern and a correction so significant that the range of relative rotations across the joint increased over the next few days to 14 mm/m.

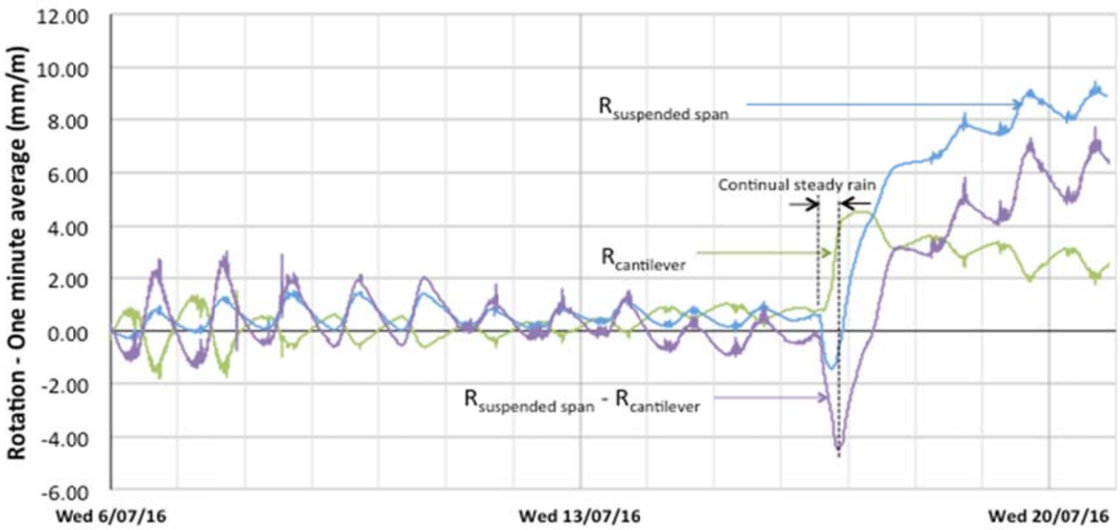

Figure 5: Captain Cook Bridge expansion joint rotations

- The rotations presented in Figure 6 are the average rotations for a one-minute interval and hence respond primarily to environmental effects but the influence of traffic is more evident during the morning and evening peak hour events.
- Figure 6 Illustrates the bridge's response to two "truck and dog" heavy vehicles crossing the bridge, with one overtaking the other on the suspended span. The range of relative rotations is 8 mm/m – much larger than the daily range due to environmental effects. The knuckle rotation does not tightly follow the rotation of the suspended span confirming non-uniform pressure in the PTFE due to traffic loads.
- The range of slip movement due to the two "truck and dogs" across the PTFE was 12 mm. The cumulative displacement across the bearing is approximately 1 m per day, with peaks reaching 1.25 m per day during the weekdays.
- Traffic incidents, and subsequent heavy traffic congestion, induced larger rotations and bearing slip when compared with typical morning and afternoon peak traffic.

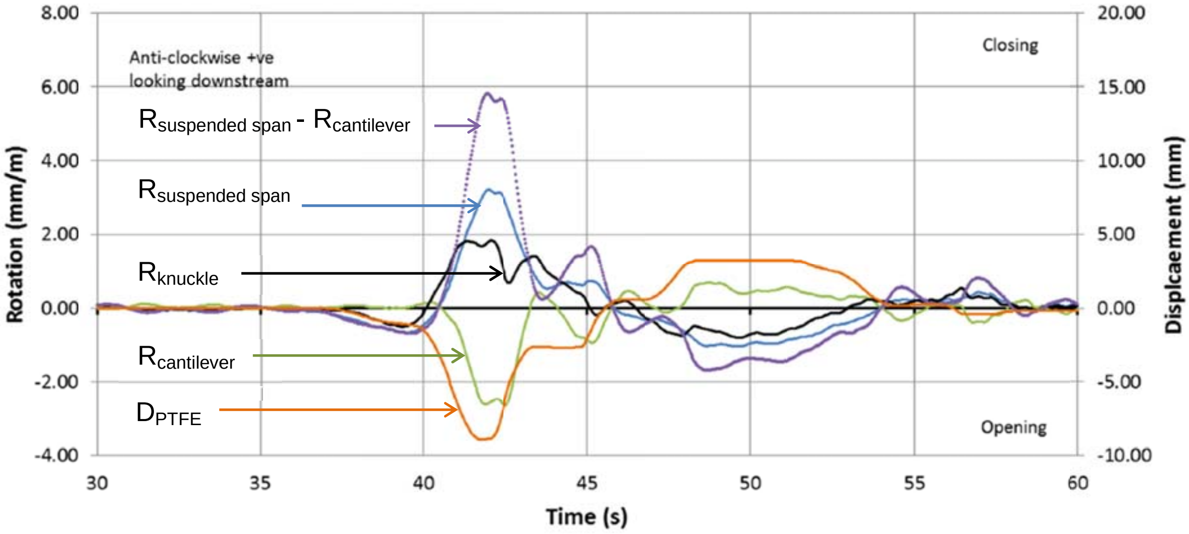

Figure 6: Captain Cook Bridge expansion joint: Response to two “truck and dog” heavy vehicles crossing the bridge

Bearing Rectification Design

Bridge and Bearing Load Analysis

The combined dead and superimposed dead load of the suspended span was calculated to be approximately 800 tonnes. A 50.5 tonne truck and dog was adopted for the live load assessment, along with a 12 kN/m uniform distributed load to account for general traffic (T44 Lane Loading).

The suspended spans are supported on cantilever spans of varying length, girder depth, web thickness, and flange thickness along the span length, resulting in a variation of stiffness and flexibility along the structure. The distribution of the loads across the three bearings per girder is a function of the relative lateral and torsional stiffness of the suspended span with the adjacent cantilever span. This relationship is complex and difficult to model accurately. Therefore, a finite element analysis was undertaken to determine bearing loads estimates for the following support conditions:

1. The suspended span modelled as plate elements supported on equal spring stiffness at each bearing location.
2. The suspended span modelled as plate elements supported on rigid pin supports at each bearing location. These supports were modelled as rigid in vertical displacement and released rotationally.
3. The suspended span modelled as plate elements supported on the cantilever spans modelled as plate elements.

The above approach produced upper and lower bound estimates for the girder load distribution:

- The rigid pin support condition replicates rigid flexural and torsion stiffness in the cantilever span. Under these assumptions the external bearings attract more load due to the cantilever flange.
- The spring support condition assumes a relatively soft cantilever torsion stiffness. This resulted in a more even distribution of load across the bearings.
- The cantilever plate model was considered to be the best representation of the relative flexural and torsion stiffness between the suspended span and the cantilever spans. The results of this model are within the bounds of the rigid and spring support results, with the results tending to align more closely to the results of the spring support assumptions.

Table 1, tabulates the Serviceability Limit State (SLS) and Ultimate Limit State (ULS) vertical bearing load ranges estimated from the modelling undertaken. The horizontal bearing loads were calculated from the vertical load estimates using a static fiction coefficient of the sliding material.

Table 1. Vertical Bearing Load Estimates

Load Case	SLS (kN) DLA = 0.4, LLF = 1.0, DLF = 1.0, SDLF = 1.3		ULS (kN) DLA = 0.4, LLF = 2.0, DLF = 1.2, SDLF = 2.0	
	External Bearings	Internal Bearing	External Bearings	Internal Bearing
DL + SDL	1320 – 1450	1130 – 1390	1690 – 1870	1390 – 1730
DL + SDL + LL	2260 – 2500	1670 – 1930	3520 – 3960	2470 – 2800

DLA: Dynamic Load Allowance, LLF: Live Load Factor, DLF: Dead Load Factor, SDLF: Superimposed Dead Load Factor

Constraints and Bearing Rectification Strategy

The bearing rectification strategy had to be developed to allow the works to be completed in an 8 hour traffic closure of each carriageway. This was paramount to minimising distribution to the public and the traffic network – a key objective for the project. In addition to the limited working time, the following constraints were also recognised in the preliminary stages of the design development:

- The top sole plate, and base plate, along with the anchor bolts were unable to be removed due to the confined space, and time constraints.
- Replacement components, had to be designed and detailed to the existing bearing geometry.

With consideration of the constraints, outlined above, the following strategy was adopted to modify the bearings, and is illustrated in Figure 7:

- The upper steel mounting plate, and base plates along with the anchor bolts would remain.
- The steel spacer plate could not be replaced and was lengthened with bolt-on plates.
- The stainless steel sliding surface would be replaced, with a plate containing a harder wearing surface and lower frictional resistance.
- The knuckle would be replaced and modified to include a larger bearing area and improved geometry.
- The replacement sliding material would be sufficient for a 50-year design life.

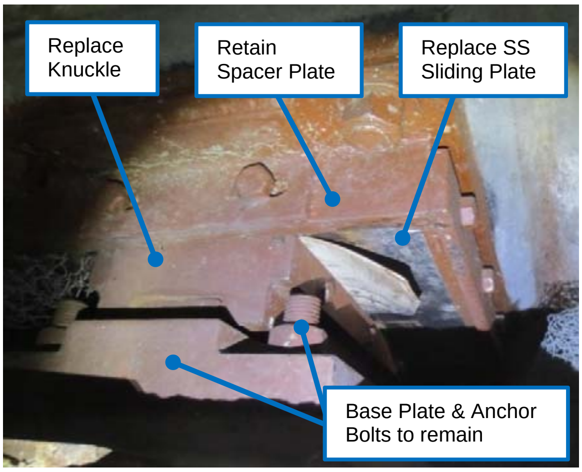

Figure 7: Bearing Rectification Strategy

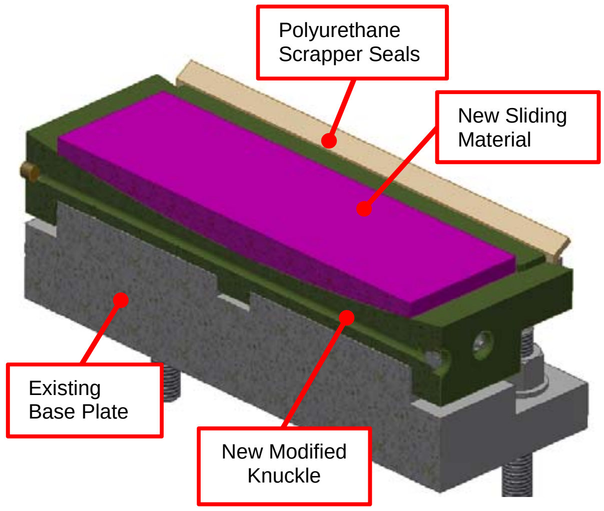

Figure 8: Modified Bearing Details (Section View)

Bearing Rectification Design

New Modified Knuckle

The existing top and base steel plates, illustrated in Figure 7, were retained and incorporated into the bearing rectification design, as illustrated in Figure 8. The size of the modified bearing knuckle was increased to provide a greater bearing area, from 408x140 mm to 408x160 mm.

The design of the existing sliding bearings only provided rotation about the transverse axis of the knuckle, and did not facilitate rotations about the longitudinal axis. This could have contributed to the accelerated wear, and extrusion of the PTFE sliding material as a result of thermal effects, concrete creep, and initial misalignment of the plates during the bridge construction. The modified knuckle design (and sliding material) included a curved surface to allow the bearing to rotate about the longitudinal axis during operation and the thermal expansion of the structure. This was also implemented to improve the uniformity of the bearing pressures across the knuckle.

The modified knuckle includes scrapper seals, manufactured from polyurethane E93A, to prevent dust and foreign material from entering the bearing, and accumulating on the sliding surface

Sliding Plate

A K1042 steel plate coated with electroless nickel was adopted for the bearing sliding plate. The plate is ground, polished and coated with 50 µm of electroless nickel followed by 15µm combination of electroless nickel and PTFE. The plate is then heat treated to achieve a surface hardness of at least 60 Rockwell C. The sliding plate hardness was increased to account for the high frequency of dynamic movements over a daily cycle and be scratch resistant to abrasive fine debris.

ORKOT TXMM® Sliding Material

Considering, the previous PTFE sliding material failed after 20 years of service, a new sliding material was trialled for the bearings. *ORKOT TXMM®*, manufactured by Trelleborg, was selected based on the material properties showing that it was unlikely to extrude under the expected immediate substantial increase to traffic loading across the bridge, and the performance of the material could be easily monitored from inside the Bridge.

ORKOT TXMM® is manufactured from medium weave fabrics, with a unique low friction surface incorporating molybdenum disulphide and PTFE (4). Table 2, outlines the material properties of *ORKOT TXMM®* compared with PTFE. The compressive strength of the *ORKOT TXMM®* is 280MPa, and far exceeds the calculated maximum ultimate limit state (ULS) bearing load of 60.5 MPa (DL+SDL+LL Load case), utilising the modified design bearing area of 408x160mm.

The instrumentation monitoring of the expansion joint revealed the accumulated movement of the bearing can peak at 1.25m per day during weekday traffic conditions. The calculated wear for the sliding material is 1-2mm, based on the following considerations:

- *ORKOT TXMM®* wear rate of 2.15×10^{-15} m^3/Nm (4).
- Bearing loads of 60.5 MPa (ULS) and 38.8 MPa (SLS) accounting for dead load, superimposed dead load and live load.
- Accumulated movement over a 50-year design life of 30 km, to account for traffic increases.
- A 5 mm wear allowance adopted for the bearing design.

Table 2. Comparison of ORKOT TXMM and Characteristic PTFE Material Properties

Property	**ORKOT TXMM**	**PTFE**
Compressive Strength	280 MPa	10-15 MPa
Tensile Strength	55 MPa	10-43 MPa
Shear Strength	80 MPa	5 MPa
Coefficient of Friction	0.05-0.1	0.1
Elastic Modulus (Tensile)	3.2 GPa	0.4-1.8GPa
Elastic Modulus (Flexural)	1.8 GPa	0.5-0.7GPa

In-Service Load Monitoring

The new bearing knuckles were strain gauged and calibrated prior to undertaking the knuckle replacement and bearing rectification works. The instrumentation allowed the bearing loads to be monitored during the installation works, and has enabled the in-service bearing loads to be monitored in real-time. The system records the bridge movements due to environmental effects and traffic loads over time. The bridge in-service performance data provides the opportunity to develop bridge-specific load models and risk strategies to be included in the Structure Management Plan for the Captain Cook Bridge.

Lateral Restraint Design

The lateral restraint for the suspended spans was previously provided by the existing bridge bearings with the following mechanisms (Figure 9):

- A shear-key and key-way guides in the knuckle and base plate.
- The sole-plate 'caps' the knuckle, restricting lateral movement. This is a steel-on-steel interface.

The lateral restraint mechanisms were removed from the bearing to enable the most efficient and optimal bearing rectification design, including the modified knuckle, increased thickness of sliding material and sliding plate. Therefore, the lateral restraint brace developed for the jacking works was also designed for permanent in-service operation. The lateral restraint brace controls lateral movements from inbuilt stresses, and thermal expansion and retraction.

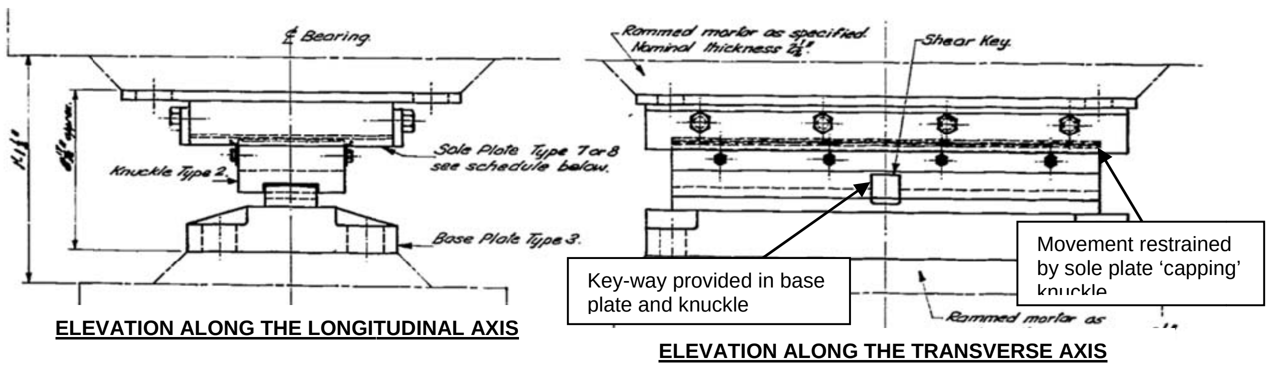

Figure 9: Existing Bearing Providing the Lateral Restraint

Lateral Restraint Brace

Lateral restraint brace, illustrated in Figure 10, incorporates the following features:

- The brace is held in position on the cantilever span using M30 Chemical Anchors.
- Stainless steel pistons are pushed against the webs of the suspended span box girder, using horizontal hydraulic jacks. Once the span is in the correct position, tension rods are locked off to provide lateral restraint for both jacking and in-service operations. The hydraulic jacks are then removed.
- The lateral position can be altered and managed using horizontal hydraulic jacks, and tension rods, throughout the jacking and in-service operations.
- The stainless steel plate, mounted to the box girder web, and *ORKOT TXMM®* sliding material provides a low friction sliding surface to account for longitudinal movements from deflections, and thermal expansion and retraction. This sliding surface also accommodates the vertical movements during the jacking operations.
- The lateral restraint brace’s constructed position accounts for the differences in alignment (and confirmed by survey) between the suspended span and cantilever span, inherent from the bridge’s original construction, with the *ORKOT TXMM®* sliding material tolerant to non-uniform bearing, and ability to adjust the stainless steel bearing plates on the webs.

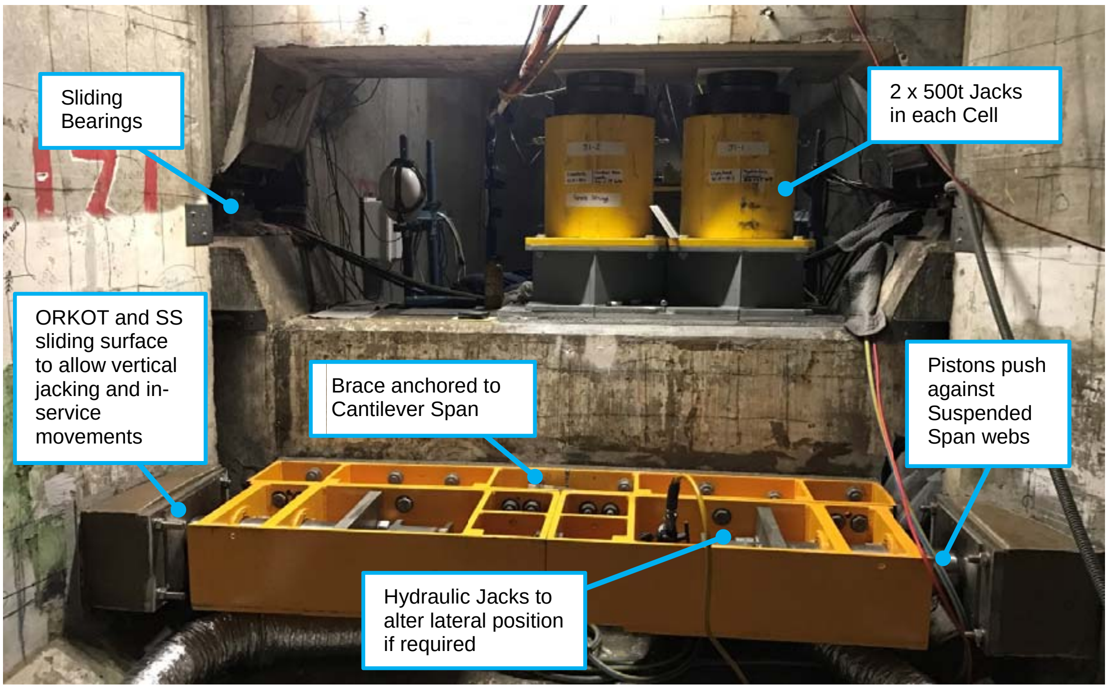

Figure 10: Lateral Restraint Brace Details

Design Considerations

The minimum transverse design load of 500 kN, outlined in AS5100-2004 (5), was adopted for the design of the lateral brace. Lateral loads accounting for differential thermal movements, and possible stressing and post-tensioning methodologies were not analysed due to the time constraints of the project. The 500 kN load assumed for the design exceeded the lateral loaded determined as part of the previous jacking operation and bearing replacement. The lateral loads measured during the lateral load transfer from the bearing to the lateral brace, prior to installation of the modified bearings, were less than the assumed ultimate limit state design load.

The lateral restraint system transfers lateral loads into the box girder webs. The structural assessment of the webs and diaphragm of the halving joint was undertaken using a combination of 2D finite element modelling and strut-and-tie analysis. The analysis results showed that the 500 kN design lateral load did not exceed the ultimate web bending capacity of the suspended span, but marginally exceeded the cracking capacity of the web. Considering the modelling was conservative in its approach, and load distribution assumptions, it was deemed acceptable in the structural assessment of the design.

Construction Considerations

The design of the lateral brace accounted for the following construction constraints and considerations:

- The lateral restraint brace was modularised to minimise the weight of components, and ensure they would fit through the small accesses in the box girder diaphragms.
- The assembly of each fabricated module negated in-situ hot-works, and associated risks.
- The lateral restraint brace included a mounted checker plate and was positioned close to the floor of the box girder. This was implemented to ensure access for the bearing rectification works and future inspections was not impeded.

Bridge Jacking and Analysis

The suspended span is supported on the adjacent cantilever span by a ‘halving joint’ with the cantilever span providing the bottom diaphragm and the suspended span containing the top diaphragm. Four 500 tonne high pressure hydraulic jacks, positioned on the cantilever diaphragm, were used to jack the suspended span by approximately 27 mm, to enable the bearing rectification works. Two jacks in each cell were paired together, controlling the load and displacements during the jacking operations. Each jack included a lock rings on the main piston to ensure the bridge would remain supported in the unlikely event of a jack failure. The suspended span rested on these lock rings during the bearing rectification works.

Bridge Jacking Design Considerations

A number of design scenarios were considered during the analysis and design development of the jacking system, including the following:

1. Determining whether load restrictions were required when the bridge is supported on jacks. Allowing a level of reduced traffic operation over the bridge during the rectification works would significantly reduce the distribution to the public and the network – a key project objective and requirement.
2. Determining the jack positions and associated jacking loads, considering jack lead and lag tolerances, and contingency scenarios such as, jack failure and replacement.

Jacking Analysis and Assessment

A combination of strut-and-tie modelling and finite element analysis was used to assess the box girders and diaphragms of the suspended and cantilever spans, for a range of supporting jack locations.

Allowable Traffic Loads

The analysis and assessment determined that normal operated loads (50.5 tonne GML Truck and Dogs) were permitted to travel across the bridge under the following traffic management conditions:

- Traffic travelling in the two internal lanes only, at a restricted speed of 40km/h
- Jacks located in the positions outlined below.

- Completion of jacking and bridge and jack lock rings are engaged.

The structural capacity of the diaphragms was determined to be sufficient with a reduced ultimate live load factor of 1.6, for the 50.5 tonne GML Truck and Dog loading regime. This was considered acceptable based on the following:

- Stringent traffic management conditions would be in place, including 40 km/h speed restrictions.
- Certainty of the operational load and a low probability of an overloaded truck crossing the bridge.

Although the structural capacity would not be compromised, heavy vehicles were diverted during the works for safety reasons deemed by the Contractor.

Jack Positions

Each cell contained two jacks hydraulically linked and located as close as practically possible to each external web of the box girder (Figure 10). This was determined to be the optimal jack configuration for design loading regime. The centroid of the jacks were located approximately 1310 mm and 1810 mm from the outside face of each external web of the box girder. The design allowed for a jack lead and lag tolerance of 1 mm, and assessed the structural capacity of the diaphragms if a jack had to be replaced.

Conclusions

Captain Cook Bridge is an iconic bridge crossing the Brisbane River, and is the most trafficked bridge in Queensland. Routine inspections in July 2016 identified the extrusion of the PTFE sheeting from the sliding bearings on the southern suspended spans. A prompt resolution and strategy was required to minimise the risk of further bearing deterioration. As a result, within 6 months innovative and unique procedures were designed, developed, and implemented to rectify the bearings. These included in-situ bearing rectification works, the trial of a new sliding material, new replacement knuckles, and new sliding plates. A steel lateral restraint brace was designed to restrain the construction stresses and thermal movements during the jacking operation. This brace was designed to be the in-service operational lateral restraint, previously provided by the bearings. This approach allowed the most optimal bearing modification design and accelerated the rectification procedure to be completed within an 8 hour timeframe.

Strain gauges were installed onto the new knuckles to allow the real-time, in-service monitoring of traffic and environmental loads. This is the first time in-service monitoring of bearing loads has been implemented in Queensland, and will be analysed in the future to gain a better understanding of the Captain Cook Bridge behaviour.

Within one night, the bridge was jacked and bearing rectification works completed under live traffic. This resulted in minimal distribution to the public and State’s transport network.

The bearing rectification works were successfully completed on both suspended spans by early February 2017, and regular inspections of the bearings will be undertaken in the future to monitor their performance.

Acknowledgement

The authors would like to acknowledge the collective efforts of numerous colleagues across the project team.

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