TECHNICAL ANALYSIS OF CURVED RAMPS ON THE RIVERSIDE EXPRESSWAY

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Abstract
During the asphalt resurfacing of the thirty-three year old Riverside Expressway, it was found that the curved concrete box ramps had undergone torsional distortion to the extent that an inside support bearing on the Ann Street ramp had lifted clear of its support. After design checks, extensive computer modelling, surveying and instrumentation of the Ann Street ramp, it was concluded that parasitic loss effects, together with differential temperature, was the cause of the ramp rotation. The ramp was found to be performing in a predictable fashion and is considered to be in a safe condition. Further analysis is required to determine what further corrective action is required.

Introduction
The Riverside Expressway (REX) is an elevated concrete multilane roadway along the banks of the Brisbane River. The Coordinator-General’s Department commenced the design of the REX and the Captain Cook Bridge in early 1966. The design methods for the REX are described in the references (7,8).

The construction contract for the REX was let to Messrs. McDougall-Ireland Pty Ltd on 20 August 1969. The greater portion of the expressway deck comprises precast ‘U’ & ‘I’ beams, in situ deck-slab construction, with simply supported spans (Ref 1,2,3,4,5). Six of the curved ramps were post-tensioned concrete box designs, while others were of an ‘I’ beam construction.

The asphalt deck wearing surface on the Captain Cook Bridge and the REX has given thirty-three years of good...
service under high traffic flows, with current flows of 150,000 vehicles per weekday. After thirty-three years of exposure to the elements, the asphalt had become oxidised, which resulted in the surface becoming brittle and large areas had begun to ravel. Based on this and a number of other factors, Main Roads Metropolitan District made the decision to resurface the Captain Cook Bridge and the REX (6).

**Background**

After extensive stakeholder engagement and liaison with major events facilities, a resurfacing schedule was established which would not clash with any major events that could affect traffic flows through Brisbane. The work extended over three weekend time slots for 15 September to 16 October 2006.

The resurfacing contracts progressed ahead of schedule and no significant problems were experienced. However, during the final third segment of the project a major issue arose. On Saturday evening 14 October 2006 during asphalt resurfacing work, it was found that the finger joint at the inside shoulder edge at the river end of the curved Ann Street on-ramp had moved vertically upward in relation to the adjoining ramp. A more detailed inspection revealed a rotational distortion of the ramp of sufficient magnitude to lift it clear of its bearing on the inside of the curve (city side) (Figures 1, 2, 3).

Upon close inspection of the entire ramp, a small crack approximately 0.04mm wide was observed in the web and bottom flange of the box girder, about 3m from the river end on the river side (Figures 4a & b). The curved ramp was constructed of precast reinforced concrete box segments with a 75mm construction joint between each box, and finally post-tensioned with stressing tendons. The crack aligned with one of the vertical construction joints on the outside of the curve and did not extend through the precast reinforced box section. Also, the crack coincided with a terminal stressing strand anchor block which is located inside the concrete box. This crack became the subject of media attention, but was quickly eliminated as a significant structural safety issue.
Later the crack was instrumented with electronic strain gauges; however because of issues associated with the temperature coefficient of the strain gauges relative to the concrete, a number of glass slides were bonded across and around this crack (Figure 5). Thus, if a glass slide broke it would indicate that there was significant movement across the crack. Based on typical properties for glass, a crack widening of approximately 0.05mm would be sufficient to fracture the glass slide. As of the 17 January 2007, none of the glass slides had broken, thus indicating that no significant movement had occurred across the crack.

Because the northbound on-ramp at Alice Street is similar to the Ann Street ramp design (curved post-tensioned concrete box girder), its expansion joint was immediately inspected and found to be exhibiting similar but less severe vertical displacement. The four other box girder ramps exhibited only minor rotations.

At the time of discovery it was not known what created the problem and whether there was a safety issue. To ensure absolute safety for the travelling public, Main Roads made the decision to close various sections of the REX, which prevented traffic driving beneath the Ann and Alice Street ramps.
**REX Closure**

The REX is a major arterial feed into Brisbane’s central business district. The partial closure of the Captain Cook Bridge and the REX required enormous multi-agency teamwork to coordinate the traffic management. Various operational teams addressed a wide range of issues which are broadly summarised below.

1. Traffic management — minimise impact on the motoring public and provide efficient alternate routes.
2. Media/consultation/communication — communicate information to the public about traffic routes and what was happening.
3. Transport — make changes in alternate transport modes, buses and trains, to cater for increased patronage.
4. Inspection — undertake an urgent inspection of all ramps on the REX.
5. Structural — undertake design checks and establish computer models of the ramps.
6. Instrumentation — install and monitor the physical characteristics of the ramps.
7. Survey — survey the ramps and monitor movements and undertake laser terrestrial scanning.

This article will focus on the initial construction of the ramps and the last three items — structural, instrumentation and survey. For information on the other points refer to an article in the March 07 edition of Queensland Roads (6).

**Original construction**

The original design and construction of the ramps will be briefly revisited to give a better understanding of the design issues. The REX design occurred in late 1960s and although mainframe computers existed, the analysis software was limited in capability. The ramps are extremely complex in shape, with most of the following geometric features varying — horizontal and vertical curves, superelevation and lane width. Hence the majority of box shapes are dimensionally unique. Even by today’s standards these are complex structures and they are a credit to the original designers. The philosophy of the design of both the Captain Cook Bridge and the REX was one of elegance with smooth clean lines, providing aesthetically pleasing structures in harmony with the Brisbane River and adjacent Victoria Bridge. A typical cross-section and end view are shown in Figure 6 & 7.
The expressway headstocks are recessed into the girders, necessitating the use of halving joints (Figure 8). While this technique is an accepted practice in bridge construction, the downside is increased complexity of design to compensate for the stress concentrations at the halving joints. As the headstocks are recessed, inspection and servicing of the bearings is made more difficult. Additionally to provide a more aesthetically pleasing structure, the open spaces around the bearings have cover plates fitted; hence quick and simple bearing inspections are not possible. Because the ramp support bearings must be contained within the profile of the box, they provide less torsional restraint than if located on a full width headstock. Hence, in the design process there are tensions between aesthetic appeal, maintainability and the structural requirements.

The ramps were constructed by assembling the precast reinforced concrete box girder segments onto temporary falsework. An indicative arrangement is shown in Figure 9. Construction is managed in stages around supporting abutments and piers. Once the box girders were assembled onto the falsework, the post-tensioning tendons were installed but not tensioned, the gaps between boxes were grouted and finally that stage of construction was post-tensioned from within the inside of the box at the end. Successive stages are then added with the post-tensioning tendons overlapping each other as indicated in Figure 10.

The Ann Street ramp is 155m long and is comprised of 91 segments. The city end of the ramp provides both lateral and horizontal restraint via a vertical pin and two support bearings. The river end is supported on twin sliding pot bearings and a separate lateral restraint allowing free longitudinal movement to allow for expansion. At the intermediate piers, a single support bearing was provided. This bearing provides only vertical support with no torsional restraint. The reasons behind this design choice are:

- limited space on the top of column
- restraint would only slightly increase torsion and bending moments
- restraint would induce unwanted loadings to the already high columns.
Figure 9. Construction method

Figure 10. Typical stressing strand pattern in the centre web

Figure 11. Instrumentation of bridges
Bridge inspection
Survey
Load tests
Comparison of design, check and input data. Technical discussion
Solution

Figure 11.
Structural analysis

It became apparent from early in the investigation that the differential temperature effects were causing the ramps to warp. The high temperature from asphalt caused an increased rotation of the end of the box ramp due to its heating of the top surface of the box. It is believed that this heating exaggerated a pre-existing condition. Laying asphalt at night further increased the temperature differential between the top and bottom faces of the box. The warping resulted in the transfer of load from a two-bearing support to a single bearing, which was witnessed by the finger joint displacement on the deck. This load transfer then placed increased loading on the single bearing and the adjacent halving joint.

To ensure a low probability of error in the structural analysis, a rigorous review process was initiated. This review process is shown in Figure 11. Main Roads staff performed the design review while external consultants independently checked the designs. Different computer software packages were used throughout the process to ensure that any idiosyncrasies in software packages did not skew the results.

The review commenced at the lowest, simplest, fastest and least accurate tier then through to the highly tiers requiring more complex analysis for critical sections. The analysis was comprised of a line model, a 3D dimensional model, finite element model and thermodynamic model. The response and accuracy of the models was verified and calibrated by surveying, instrumentation and load tests with a fully laden water truck and semi-trailer.

During the modelling of the structure, a number of factors and scenarios were considered. An allowance had to be made for creep and shrinkage in the concrete and relaxation of tension in the post-stressed tendons. For the Ann Street ramp, the combined effects of these losses totalled 40.9%. Each bearing was packed up separately to model the effects of repositioning/replacing the bearings and for packing up the inner bearing at each end to balance the torsion effects from post-tensioning losses and differential temperature.

Surveying

A 3D laser terrestrial scan was completed of both the Ann and Alice St ramps. This scan covered the substructure and the top and bottom of the superstructure, along with the surrounding terrain. The objective of this survey was to provide a 3D map of the structure and surrounding terrain which could then be further processed to provide a three-dimensional computer model of the structure (Figures 12 & 13). The accuracy of the model is approximately ± 20 to 30mm as the scan was taken over several hours. This model was accustomed determining normal daily changes in displacements and rotations.
Measurements were taken using a digital level and a total station survey unit. Because the ramp was a moving target, speed of measurement was essential. Absolute movements were measured by fastening a number of prisms to points of interest on the structure (Figures 14 & 15). To ensure a high accuracy of measurement, the total station was mounted to rigid steel posts. The data collected from the total station is considered accurate to ±2 to 4 mm, depending on the distances of the targets away from the station.

**Instrumentation**

The ramps were instrumented to record:

- temperature at strategic points in the structure
- deflections and differential movements between the ramps and headstocks
- inclinometers to measure the rotation of piers
- strain measurements.

The some typical instrumentation set-ups are shown in Figure 16.
Figure 16. Typical instrumentation set-ups
Findings
A review of the original design (7,8) did not describe fully the structural behaviour at either the city end or river end for the designed support conditions. In particular, the paper did not mention the structural response to the possible lifting off of any end bearings.

The Ann Street box girder ramp was heavily post-tensioned with 68 tendons in lengths from 17m – 117m. The paper indicates that the final concrete compressive stresses are low. This coincides with the review results which indicate the compressive stress level under dead load and post-stress ranging from 2.2MPa in shortest span to 5.8MPa in longest span. The implication here is that the concrete creep would not be an issue for this girder. The parasitic effect of the post-stressed tendons was analysed. The paper indicated that the parasitic torsion moments had slightly exceeded the opposite dead load torsion moment at the river end bearing. However, the paper and thesis failed to predict what reaction would happen at the twin end bearings.

A 17°C (30°F) temperature differential between the top and bottom faces of the deck slab was analysed by the ramp designers. Later research indicated that this temperature differential figure was acceptable (9). The analysis determined that a differential temperature would increase both bending and torsion stresses throughout the structure using a load combination of 1.5DL+2.5LL+1.0DT. The original design checked for ultimate bending moments although differential temperature was applied to a cross-section, ity did not consider the torsional effects.

These design loadings were not applied to the ramp to check for differential temperature torsional effects.

The paper mentioned that horizontal movements of the structure are controlled by the lateral restraints. Any change in length due to temperature, shrinkage, axial shortening due to post-stressing tendons and creep causes rotation about vertical axes and longitudinal movement along the centre line. It appears that the uplift issue at the end bearings as a consequence of these factors was not addressed in the paper.

In summary, it appears that the potential uplift at a bearing was expected in the original design. However, the effects of the uplift on the structural behaviour, in particular the ‘nib’ capacity at the halving joint were not fully addressed. A possible reason behind this might be that the uplift was classified as a stability issue rather than a structural issue.

Analysis of the instrumentation and surveying results for the ramps over an extended period revealed that the Ann Street ramp movement was cyclic and was based on the environmental temperatures and conditions on any particular day. There was reasonable correlation between the asphalt/deck temperature and ramp rotation. The small time lag between the deflection and temperature was because of the time it took for heat to diffuse through the structure. Figure 17 shows relative displacement and temperature data for Ann St at the inner bearing on the river end.

![Figure 17. Displacement & temperature data.](image)
The above understanding was obtained only after intensive analysis of the ramps in Structures Division. Before the start of this project, there were many views about the cause of the uplift at the inside bearing at the river end of the Ann Street ramp. It has been understood that only differential strain can induce a twist in a curved closed section curved ramp. As concrete creep and shrinkage occur uniformly throughout the structure, no uplift reaction would be expected. Any unbalanced reaction may be attributed to the restraint of post-stressing tendons to the concrete.

The factors that needed to be considered included creep and shrinkage, relaxation of stressing strand, temporary high temperature on the top flange due to the asphalting, differential temperature between top flange and the remainder of the section. By recognising that these effects could only occur non-uniformly or in part of the structure, three-dimensional modelling was an automatic requirement. How to correctly reflect the function of the post-tensioned tendons was a challenge. The intention was to use minimal assumptions and to use advanced tools and methodologies so that the true structural performance could be revealed. The 3D model could also be used to calibrate line models.

A 3D model can be a general finite element analysis (FEA) model. However, it was found that there was a practical difficulty to incorporate the post-tensioned tendons in a conventional FEA model. Therefore a 3D frame model was initiated.

The 3D frame model was based in principle on the widely used 2D bridge design grillage model. The advantage of a frame model is that moment and torsion can be directly transmitted from a member to its adjacent members without any assumptions in comparison to a truss model. According to FEA principles, as long as the material and member properties are known, the overall structural performance can be infinitely approached if the division of the structure parts is sufficiently small.

In conventional FEA modelling for an elastic structural analysis, the reinforcement in concrete is usually neglected. Though the effect of tendons should not be omitted, it is difficult to add tendons into a conventional FEA model. However, it is relatively easy to incorporate tendons into a 3D frame model as this type of model essentially consists of beam elements.

When the ramp was test loaded with a fully laden tri-axle semi trailer, the measured deflection was 6.5mm at the river end, while the predicted deflection of the 3D model was 6.9mm. Previous research (10) showed that high dynamic loadings are associated with vehicles which are not fully laden. This research was considered. However, the ramp needed to be checked under the highest loading condition. As the test vehicle was fully laden, the design was checked using the dynamic load factors of the Bridge Code (11).

At this stage, it was proven that the 3D frame model predicted with reasonable accuracy the structural performance for non-thermal loadings without any pre-assumptions. The validation of the 3D frame model for differential temperature predicted a deflection at the river end of 18.2mm, while site survey was 17.7mm. This validation shows that the 3D frame model can predict the differential temperature effects with a good accuracy.

An analysis of the structure without considering parasitic losses indicates fairly balanced end bearing reactions at the river end of 483kN to 484kN, and 530kN to 616kN at the city end. However, it was found that the effect of parasitic losses was significant. The bearing reactions with losses at the river end are 89kN (inside) to 1015kN, and 241kN to 951kN at city end. The inside bearing at the river end is only lightly loaded, hence it is expected that this bearing could lift off if sufficient additional torsion was added — for example through differential temperature.
It may be concluded that significant parasitic effects together with differential temperature, were the causes of the ramp rotation resulting in the inside river end bearing lifting clear of its support.

Relocating the internal pier bearings radially outward was modelled. After modelling the load combination of DL+PS+DT/15°C, it was found that shifting bearing R4 would not be necessary while outwardly shifting of bearings R1, R2, R3 would improve the loading and result in only a small uplift (approx 2mm) at the inside bearing of the river end. This meant that the inside end bearing would be in contact under most differential temperature loadings. This analysis indicated that relocating three pier bearings radially outward would enhance the performance of the ramp.

The effect of increasing the distance between the Ann Street ramp river end bearings was modelled. The results indicate that the uplift issue could be effectively solved, even with a 15°C temperature differential. The moment, shear and torsion distribution along the ramp were also calculated. The analysis indicated that this proposal would not significantly change the moment or shear throughout the ramp under the load combination of DL+PS+DT/0°C and DL+PS+DT/15°C. Under these loading conditions, a differential temperature of 0°C would not change the torsional load; however a differential temperature of 15°C significantly increased the torsional load at both ends of the ramp.

This analysis indicates that the uplift issue would not be a concern if the end bearings had been widely spaced. However, the box girder, headstock and pier would need to undergo significant dimensional and structural changes to accommodate the larger torsional forces at ends.

A simpler consideration was to raise the lower support of the inside end bearing. Modelling various load combinations indicated that raising the inside end bearing level would provide reasonable results.

Conclusions

A review of the technical papers by the ramp designers revealed that the uplift at the end bearings caused by differential temperature and loss of post-stress in the tendons was not fully addressed in the design.

Computer models of the Ann Street ramp were calibrated with load tests. The deflections observed during the load tests correlated closely with the deflections predicted by the models. The instrumentation, survey and modelling demonstrated that the ramp is performing in a predictable manner. The modelling reveals that the creep and shrinkage of the concrete did not play a direct role in lifting of the inner river bearing as the creep and shrinkage strains in the ramp appear to be small and uniform. It has been determined that uniformly distributed strains do not induce torsional moments. Their indirect adverse contribution to the rotation issue was a small reduction in post-stressing force.

Parasitic losses were predominately comprised of relaxation of tension in the post-stressed tendons, together with a small amount of creep and shrinkage in the concrete. These losses caused the inside bearing at the river end to be only lightly loaded. Additional torsion, occurring through differential temperature between the top of the box section and the lower parts of the box, caused a ramp rotation, resulting in the inside river end bearing lifting clear of its support.

The curved concrete box ramps on the REX are structurally sound; however Structure Division is currently examining a range of options to ensure the longevity and serviceability of the ramps. One aspect of the investigation will be the strengthening of the halving joint nib at the outer bearing location on the river end of the Ann Street ramp.

1 15°C differential temperature
All previous condition assessments of the REX have been at night time to minimise disruption to traffic. In the cool of the night, a heat-distorted ramp would settle back into position onto its bearings, hence the inspection crew had not witnessed the distortion. The inspection methodology for these curved ramps will be changed to compensate for this phenomenon.

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Abbreviations
- REX: Riverside expressway
- DL: Dead load
- LL: Live load
- DT: Differential temperature
- PS: Post stress
- FEA: Finite element analysis

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