Design and Construction of Seamless Pavement on Westlink M7, Sydney, Australia

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Abstract

In contemporary practice continuously reinforced concrete pavements (CRCP) are terminated and anchored at each bridge approach. An approach slab, jointed at each end, provides the CRCP to bridge abutment link. This transition is not always smooth as the provision of transverse joints can lead to discontinuities in the carriageway profile, particularly if the approach embankment settles. The seamless pavement is an enhancement that eliminates transverse joints and provides a reinforced concrete connection between the CRCP and the bridge deck. This results in improved ride quality for highway users and reduced maintenance costs. Additionally, it eliminates the need for pavement anchors behind each abutment, thereby reducing the pavement cost and minimizing construction activities in an area that is generally on the critical path. The seamless connection between CRCP and bridge deck must accommodate the stresses induced by shrinkage, creep, thermal strain, embankment settlement and traffic loads. Numerical models developed to analyse these parameters compare well with the results of post construction monitoring. This correlation has confirmed the validity of initial design assumptions and has, through further development, resulted in a simplified construction method for the closure pour.

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Introduction

The Westlink M7 (WM7) is a US$1.1 billion privately financed BOOT project connecting the M5 Motorway at Prestons to the M2 Motorway at Baulkham Hills in Sydney, Australia. The 40km long two-lane carriageway has a 10.5m wide continuously reinforced concrete pavement (CRCP) with an asphaltic concrete (AC) wearing surface. These carriageways cross 68 bridges over the length of the project.

CRCP generally allows for the construction of long pavements lengths without transverse joints. Current Australian practice requires that where the road encounters a bridge, the pavement is terminated and a bridge approach slab constructed to link the terminated CRCP to the bridge abutment. Pavement anchors are required together with transverse joints at both ends of the approach slab as indicated in Figure 1.

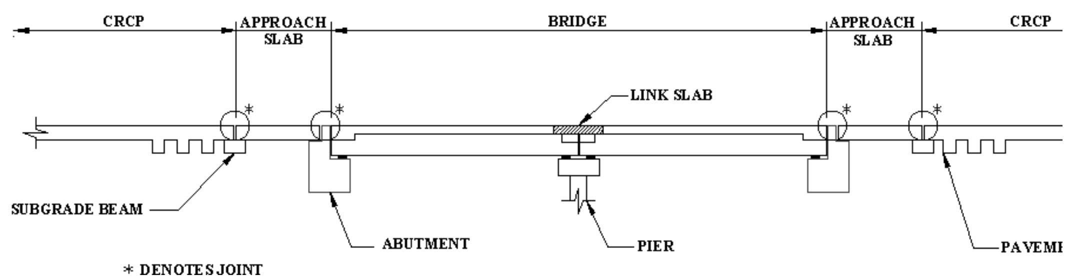

Figure 1: Conventional CRCP/Bridge Interface

There has been a long-term trend in multispan bridge construction to reduce the number of deck joints, which has largely been achieved through the use of link slabs at internal piers. The seamless pavement concept is seen as a natural extension of this concept aimed at minimizing the overall number of joints in the pavement (Figure 2). Continuity is achieved by connecting the CRCP longitudinal reinforcement directly into the bridge decks with additional pavement reinforcement provided in the vicinity of the bridge to resist the induced forces.

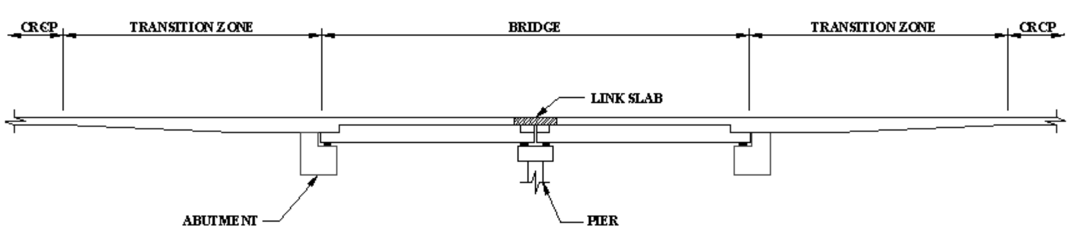

Figure 2: Seamless pavement concept

This elegant yet simple concept requires the bridge and pavement be assessed as a seamless continuum. The bridge, which is stiff compared to the pavement, drags the pavement towards the bridge as it shortens transferring loads to the pavement subgrade in friction. The total movement is taken up in multiple cracks in the CRCP transition zone. The length over which these loads are transferred varies depending upon the imposed strains and the relative stiffness of the bridge and pavement elements. Additional longitudinal reinforcement is provided in this region to ensure that concrete crack widths and reinforcement stresses remain within the code requirements.

The concept is similar to the pavement connection that was trialled on the Irving Lee Street Overpass in 1963 (McCullough and Herber 1966) but addresses the cracking problems that arose in that approach pavement.

This paper outlines the design methodology and describes the construction and instrumentation of the seamless WM7 pavement.

Seamless Pavement Advantages

The seamless pavement has the following major advantages over the conventional bridge approach slab and pavement anchor configuration:

Reduced Maintenance. Joints in pavements are a continual source of maintenance. The asphalt placed over isolation joints at the interface between the CRCP and the bridge approach slabs is a point of weakness in the wearing surface. Cracking and long-term failure in this vicinity is significantly greater than for other pavement sections and the passage of water through these joints can result in the deterioration of the approach embankment.

Bridge deck joints also require significant maintenance effort. They are locations where water and other contaminants can concentrate, thereby decreasing durability. Replacement of joint seals and resetting the location of the joint are common maintenance activities.

The seamless pavement eliminates all transverse joints from the bridge and pavement so that maintenance at these locations will be no different from any other CRCP section.

Improved Rideability. The removal of joints allows the wearing course to be installed in a continuous process, minimizing carriageway roughness and providing a running surface similar to any other location on the pavement.

Bridge deck joints result in discontinuities in the pavement running surface which are detected by all road users. Their elimination will improve rider comfort. The seamless approach slab will also assist in minimising the ‘bump’ that is common at the bridge abutments with settling approach embankments. A conventional approach slab results in discontinuities in the pavement profile at each end of the slab. The seamless pavement provides a continuous structural element which will provide a much more effective transition capable of spanning unsupported lengths of approximately 10 m.

Reduced Noise. The noise of vehicle wheels striking pavement and bridge joints is a cause of considerable community protest in urban areas, often resulting in expensive retrofitting of joints and additional treatment of pavement surfaces. The adoption of the seamless pavement eliminates this problem.

Reduced Longitudinal Loads on Bridge Substructure. Bridge structures are designed for the effects of horizontal loads, primarily arising from vehicle braking, centrifugal effects of curved bridges, and impact loads on the superstructure. Traditionally, the horizontal loads have been resisted by load paths through the piers and abutments. By adopting seamless pavement, the horizontal loads applied at deck level can be carried by the pavement well away from the bridge substructure, with a resulting saving in substructure costs.

Elimination of Bridge Deck Drainage. Drainage systems are often provided on relatively short bridge decks to minimise the quantity of water flowing across open deck joints. The elimination of deck joints obviates the need for drainage systems on short bridges.

Simplified Construction. Construction of the conventional triple anchor system is a labour intensive process that interrupts the effective operation of the paving equipment. It also isolates the area adjacent to the bridge abutment thereby affecting construction vehicle access and the timely completion of follow up construction activities.

The elimination of the pavement anchors and the use of a simple connection to the bridge deck means that the approach slab subgrade beam and subsoil drainage systems associated with the beam and pavement anchors are no longer necessary.

Design Criteria

The performance of the seamless pavement under serviceability conditions is the most critical design case since there is significant overload reserve in the continuous pavement system. The performance of the pavement in the post elastic state clearly demonstrates that the potential risks in the overloaded condition are small.

Relevant pavement design loadings are the longitudinal strains and the out-of-plane effects. Longitudinal strains arise from temperature change, concrete shrinkage and creep. Out-of-plane effects arise from traffic wheel loads, the settlement of the approach embankments and the rotational effects from the bridge deck.

The pavement behaviour was assessed by considering reinforcement and concrete stresses under each of the serviceability loading conditions. Pavement crack widths were controlled by ensuring that the design stresses complied with the requirements of AS 5100 (The Australian Bridge Design Code – Standards Australia, 2004).

Design Parameters

The following parameters were adopted for design of the WM7 pavement.

Strains due to Thermal Effects & Concrete Shrinkage/Creep. The seamless pavement design results in a continuum that restrains movements that would otherwise occur in a free-floating system. Strains due to temperature, concrete shrinkage and concrete creep are critical to the behaviour of the overall structure.

Concrete shrinkage, creep and thermal strains were determined from AS5100, The Austroads Pavement Design Guide (Austroads 1996) and from independent research performed by Roads and Traffic Authority (Tinni 2003). The adopted values are tabulated below:

Table 1: Environmental loadings

	Pavement	Bridge
Expansion	100E-6	200E-6
Contraction	300E-6	650E-6

Pavement Restraint. A coefficient of friction between the base and sub-base layers of 0.5 to 1.5 (based on the application of two coats of wax), was assumed. No frictional restraint was assumed under the pavement within 10 m of the bridge to account for the possibility of embankment settlement.

Embankment Settlement. The bridge approach embankments were designed to achieve a long-term settlement of less than 18 mm to minimize the impacts on the motorway pavement. To account for the probable geotechnical and construction variations, however, a more conservative approach embankment settlement of 40 mm was assumed for the seamless pavement design.

Traffic Loads. Assumed live loading on the approach pavement was the SM1600 bridge loading, as defined in AS5100 (Refer Figure 3). The critical design live load was generally the 360 kN tri-axle group, with an impact factor of 1.3.

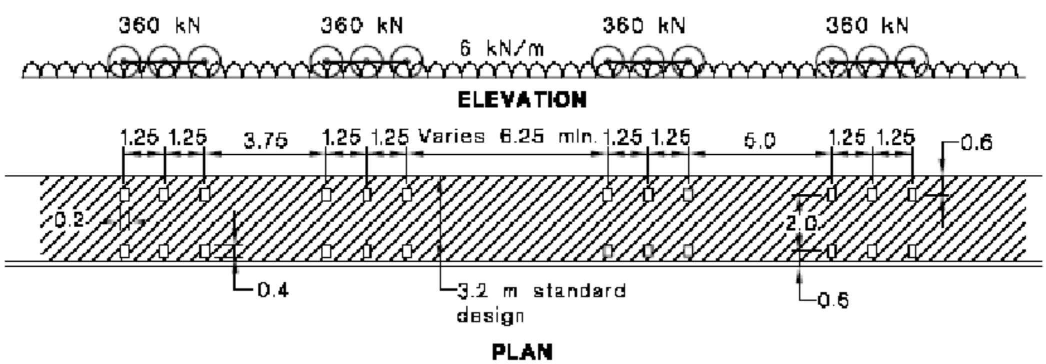

Figure 3 – M1600 Moving Traffic Load

Section Stiffnesses. When a CRCP slab is subjected to tension, cracks form as the concrete tensile strength is exceeded. In the region of the cracks, slip occurs between the reinforcing bars and the concrete, which allows the cracks to widen with the application of further tension. The cracks and the bond slip reduce the longitudinal tensile stiffness below that for the solid slab by allowing additional extension under tensile force (Bridge et al. 2000). The slab stiffness is related to the crack width and spacing which, in turn, is a function of the tensile strength of the concrete, the diameter of the reinforcing bars, the percentage reinforcement, the bond strength between the bars and the concrete strains. The effective stiffness that was used in the longitudinal analysis was developed assuming a linear distribution of bond stress in the slip regions (Bridge and Smith 1982).

Gross composite section properties in compression and tension were adopted for the bridge, as the major structural elements are fully prestressed.

Analysis

Longitudinal Analysis. The pavement can be considered as having three distinct regions as indicated in Figure 4. Region 1 is the normal fully restrained region of the CRCP away from any end effects. Region 2 is that part of the pavement in which the forced movement imposed by the bridge is accommodated. This region is divided into two zones. Friction forces between the pavement and the sub-base are generated in the first, named the Transition Zone. No friction forces are developed in the Approach Zone as the embankment is deemed to have settled, creating a void under the zone. Region 3 is the bridge deck, which is assumed to be unrestrained.

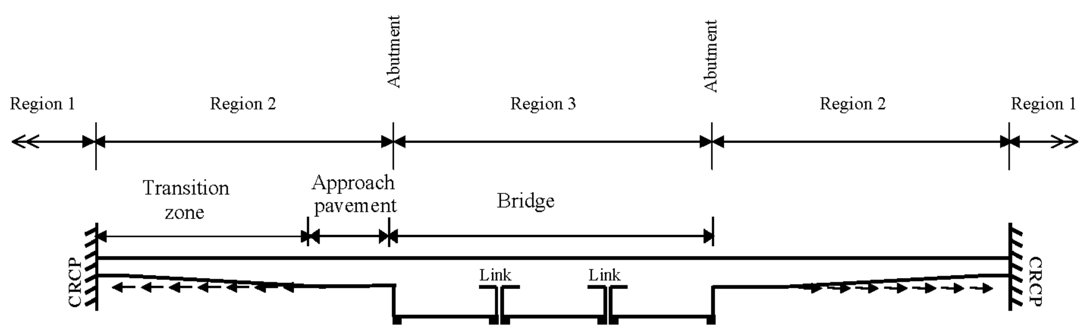

Figure 4: Model for longitudinal analysis

While longitudinal movements can take place at any section within Regions 2 and 3, there can be no movement of the section at the interface between Region 1 and 2 i.e. at the end of the transition zone. Using this fact together with a knowledge of the environmental loadings, the geometrical and material properties of the pavement and bridge elements and the frictional restraint between the pavement and the sub-base, the forces and hence the stresses in the elements can be calculated. For the results shown in this paper, the longitudinal analysis was based on a structural flexibility approach, solved iteratively (Bridge, et al 2005). The results were verified using a non-linear finite element analysis.

The results of the in-plane pavement analysis for a typical 120m long bridge, including forces, reinforcement stresses and longitudinal movement are shown in Figure 5 for the contraction load case. The maximum tension force induced by linking the bridge and CRCP varies depending upon the length of the bridge and the pavement to sub-base coefficient of friction. The maximum tension force associated with a 120 m long bridge is 1200 kN/m and impacts on the pavement for approximately 120 m on either side of the bridge. This load decreases to 800 kN/m for a 40 m long bridge with the impacts on the pavement extending 60 m from the bridge abutments.

The results for the expansion load case are shown in Figure 6. For a value of μ = 0.5 the maximum compressive force is close to 1200 kN/m at the abutment and impacts on the pavement for approximately 180 m on either side of the bridge. For a value of μ = 1.5, the compressive force increases to 1600 kN/m but the impact on the adjacent pavement is reduced to a length of approximately 100 metres.

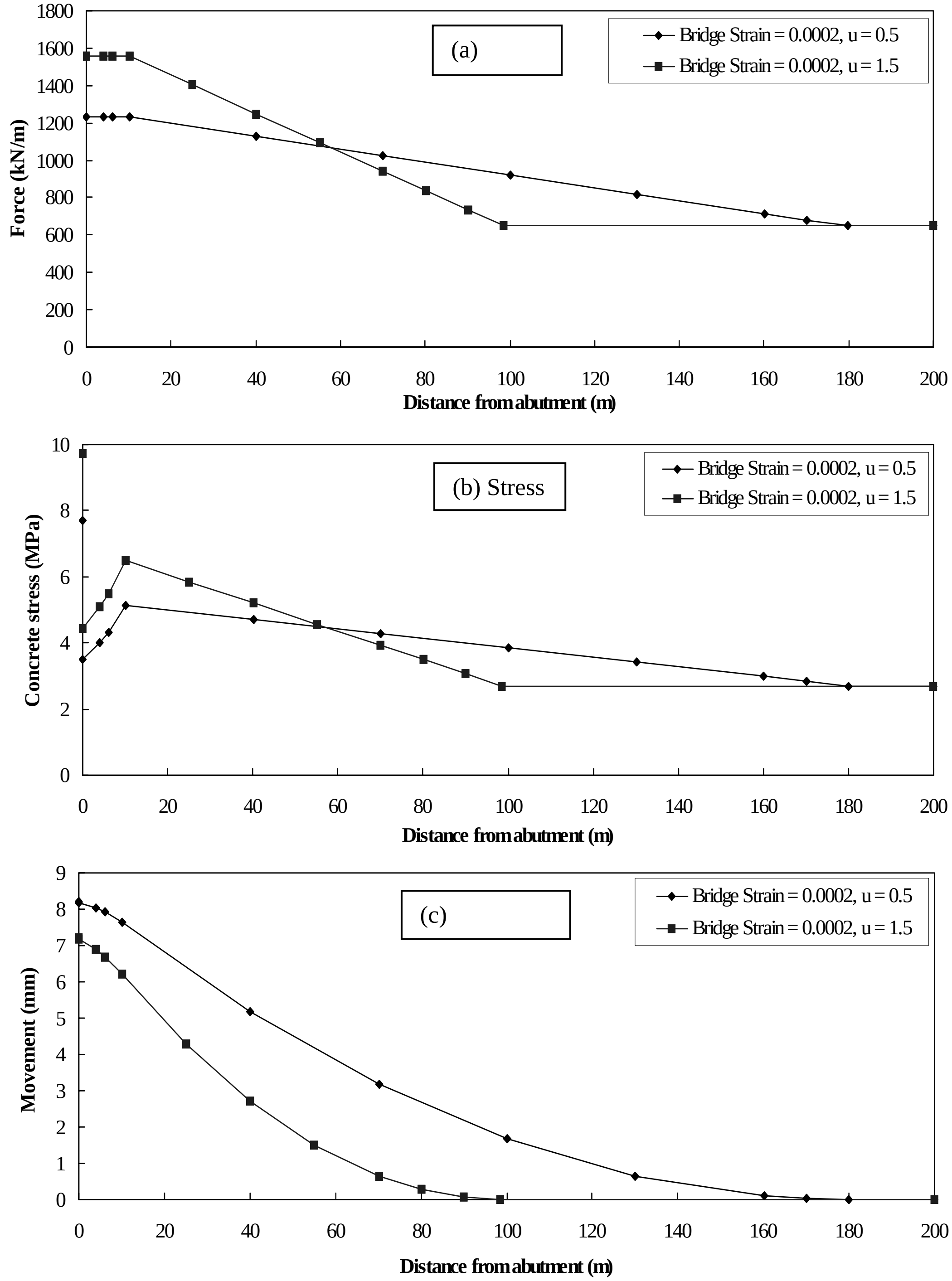

Figure 5: Force, stress and movement in pavement for contraction loading, 120m long bridge

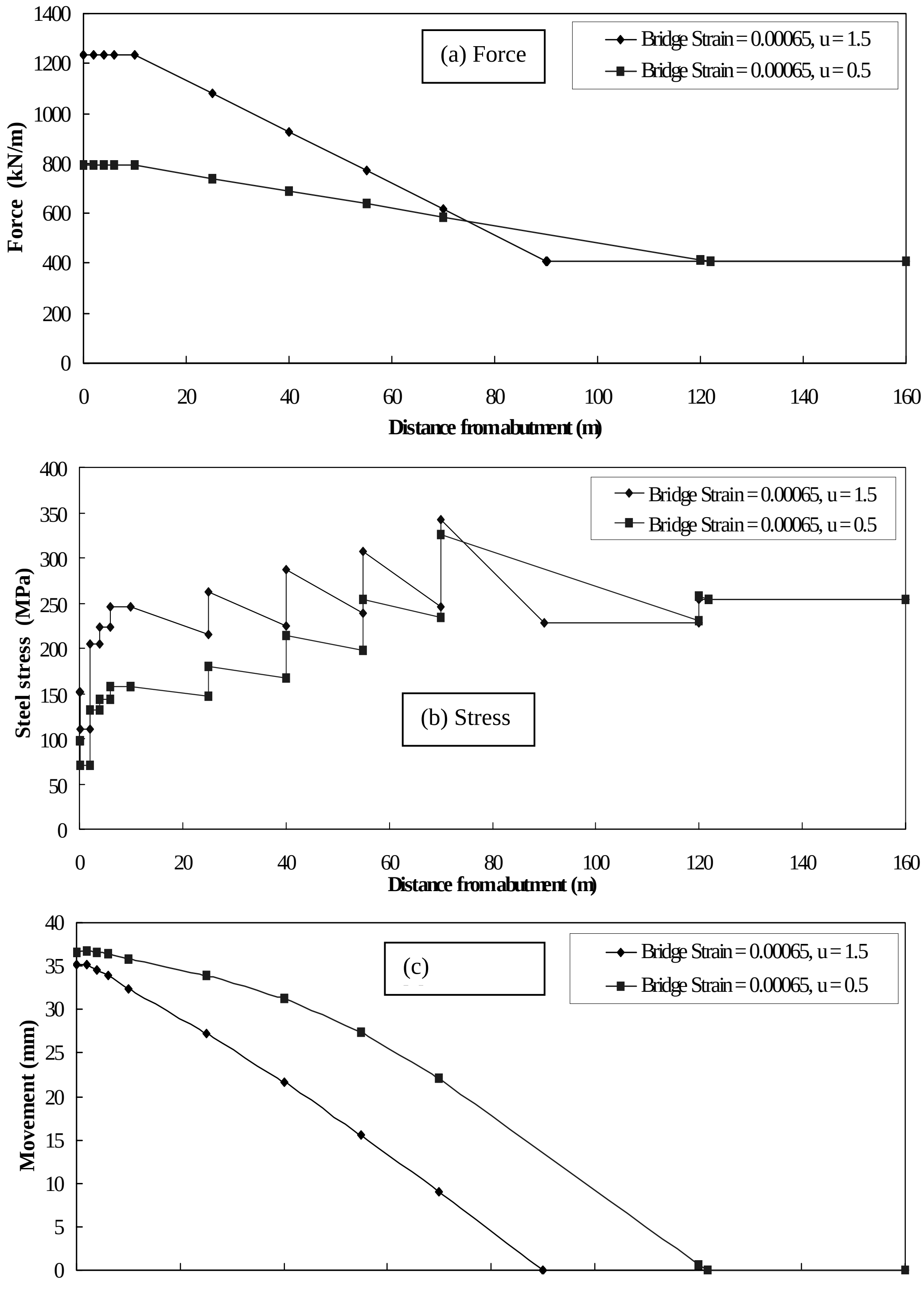

Figure 6: Force, stress and movement in pavement for expansion loading, 120m bridge

Bending Analysis. A linear elastic beam on elastic foundation model was used to assess the longitudinal bending of the approach pavement. The basic model is shown in Figure 7.

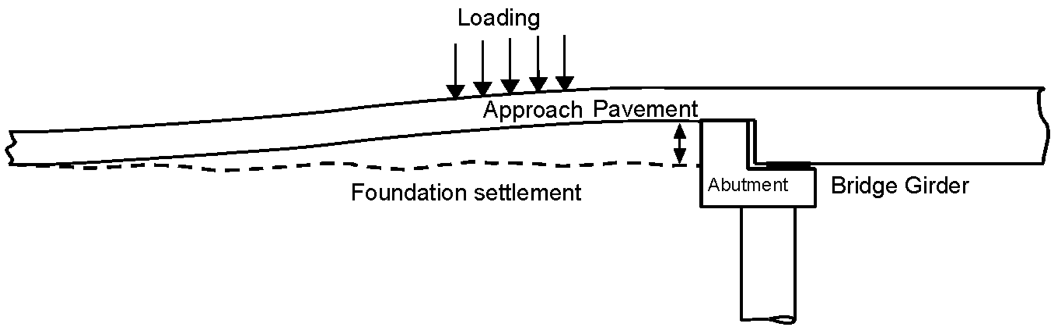

Figure 7: Approach Pavement

A range of subgrade stiffness values, derived from the RTA Pavement Design Manual (Roads and Traffic Authority 1991), was investigated. Allowance was made for embankment subsidence and/or poor compaction in the Approach Zone by assuming no pavement support within 6m of the abutment.

A summary of the embankment settlement and transient traffic load effect is provided in Figures 8 & 9. Of particular note is the effect of embankment settlement on pavement span and bending moment. When the settlement is less than 50mm, the pavement spans approximately 7m while the pavement spans 12m when the embankment settles 100mm. As a result, the pavement curvature (and bending moment) does not vary proportionally with the embankment settlement. This behaviour means that a 100% increase in embankment settlement (from 50mm to 100mm) only results in a 50% increase in pavement bending moment.

Post-Elastic Response. The pavement design has significant post elastic reserves in bending. The approach pavement can tolerate embankment settlement of the order of 400mm, being twenty times that anticipated, before the reinforcement yields. Even under these circumstances the pavement remains capable of supporting the full SM1600 load, as the approach pavement will span between the embankment and the abutment in beam action with a plastic hinge formed at the abutment.
Motorway maintenance requirements would not tolerate embankment settlements of the order of 400mm, nor are they likely to occur on the WM7 project where foundation conditions are relatively good. However this assessment of the post elastic response demonstrates that the design is a ductile structural solution that will provide very effective early warning signs of distress before any structural failure occurs.

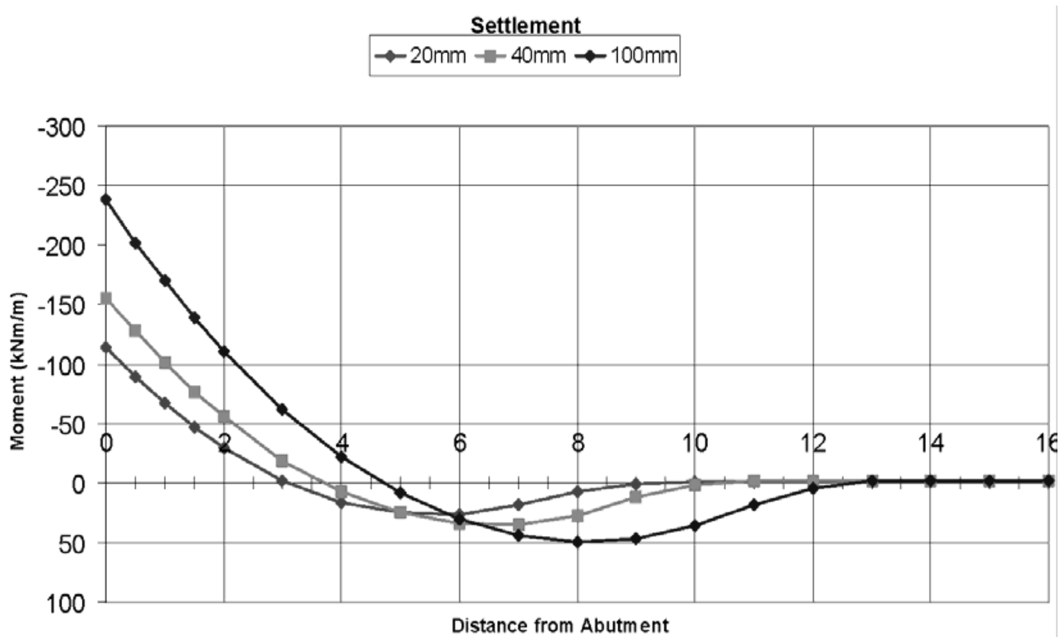

Figure 8: Approach Pavement Movements for embankment settlement

Figure 9: Approach Pavement Deflections

Closure Pour Design

Construction of the seamless pavement involves linking of a completed bridge structure to a completed approach pavement. The analysis described above is based on the assumption that the pavement and bridge are joined instantaneously and have full strength. Clearly the connection of the pavement/bridge system takes place over a finite time, with consequent changes to both the applied temperature strains and the closure pour concrete strength.

With no restraint prior to the closure pour, the free ends of both the pavement and bridge are constantly moving. If the closure pour is made when the gap between the free ends is closing, compression will arise which will not be able to be carried by the fresh concrete. If the closure pour is made when the free ends are opening, tension will arise which can cause cracking of the closure concrete.

For the initial closure pours, reinforcement across a 2.5 m wide gap was welded and the closure pour completed during the hottest part of the day. This procedure is very dependent on the weather conditions, as the concrete pour must be completed with the pavement at a lower temperature than that at the time of reinforcement welding.

An alternative closure pour sequence, which relies on the closure gap reinforcement resisting compressive forces, was developed. The closure gap was reduced to 1m, thus minimising the effective length of the compression strut. Pairs of 32 mm diameter bars project from one side of the joint and lap with a single 32 mm diameter bar projecting from the other side. Prior to joint closure the three 32 mm diameter bars are welded together in a stiff triangular arrangement.

Typical tensile force distributions in the pavement for three load cases are shown in Figure 10 and compared with the design case of final contraction assuming a full strength bridge and pavement cast integrally. By analysing the stress conditions in the steel for various temperature changes, the effectiveness of the 32 mm diameter bars was confirmed.

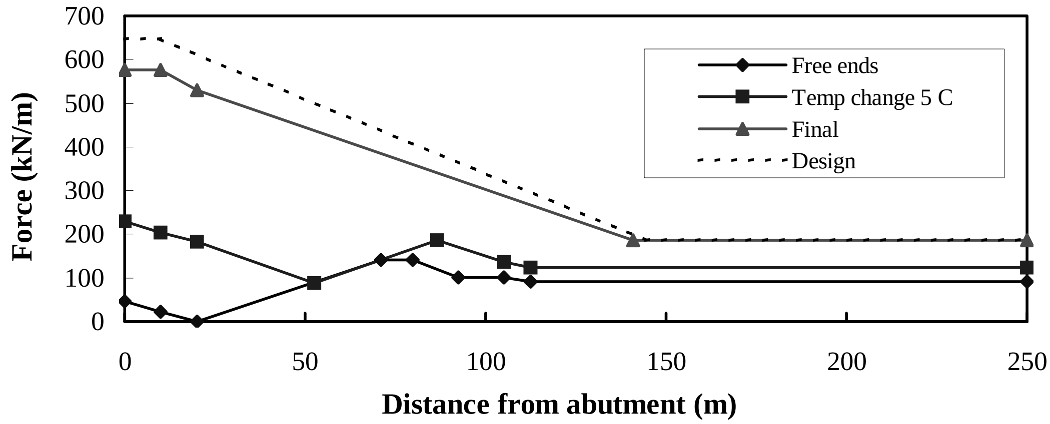

Figure 10: Effect of Closure Pour on Final Load Distribution

Field Monitoring Results

The construction risk management strategy stipulated that the seamless pavement be closely monitored for a minimum of six months to confirm that pavement behaviour is consistent with the design predications. Summaries of the major results from these studies are described below:

Visual Observations. Visual inspections of the completed pavement were undertaken at regular intervals. Cracks within the CRCP were consistent with the normally expected spacing of 1m to 3m, while crack patterns within the transition zone have developed at closer spaces. This reduction in crack spacing is consistent with the design models and is the result of increased reinforcement in this area.

No noticeable change to the cracking of the bridge decks has been detected and the general appearance of the entire area is very good.

Friction Trials. The coefficient of friction between CRCP and sub-base was recognized as a critical variable in the seamless pavement performance. If the coefficient of friction was significantly higher than the design values, this would be detrimental to the seamless pavement and could reduce the bridge capacity.

Tests carried out during design development confirmed the design values nominated in the Austroads Pavement Manual. These tests were performed using the techniques outlined by Rasmussen and Rozycki (Rasmussen and Rozycki) and involved the measurement of forced movement of a 2 m square concrete base constructed on sub-base. Three identical panels were tested using the same materials and construction techniques (two wax coats) that were proposed for the hand poured pavement sections. To benchmark the design, tests were also carried out using a bitumen seal and two sheets of plastic. A test was also performed with no debonding material between the CRCP and the sub-base.

The results of these tests are summarized in the following table.

Table 2: Results of friction tests

Debonding Material	Coefficient of Friction	
	μ_{peak}	μ_{steady}
Plastic	0.5	0.4
2 Coats Wax	0.8	0.6
Bitumen Seal	1.4	0.9
None	1.5	0.8

Pavement Thermal Profile. In order to define the relationship between pavement movement and induced strains, thermocouples were cast into the approach pavement to measure the internal concrete temperature at five locations over the depth of the section. An average pavement temperature was determined by integration across the section.

These results demonstrated that there is no clear relationship between air and pavement temperature other than that there is a time lag between ambient air and pavement temperature maxima and minima. The pavement temperature is also affected by the amount of solar radiation and the temperature history over a period of a few days.

Pavement Observations Prior to Closure Pour. Linear potentiometers were used to measure movement at the bridge and pavements ends of the closure gap. Strain gauges were also attached to the closure longitudinal reinforcement to measure load in the bars after welding.

Figure 11 shows the relationship between average pavement temperature and the movement at the bridge side of the closure pour. Figure 12 shows the relationship between average pavement temperature and the movement at the pavement side of the closure pour. The calculated movements using the design models described earlier are superimposed on the graphs. The magnitude of the movements, and the movement change with variation of temperature, demonstrate reasonable agreement between the field results and theoretical predictions.

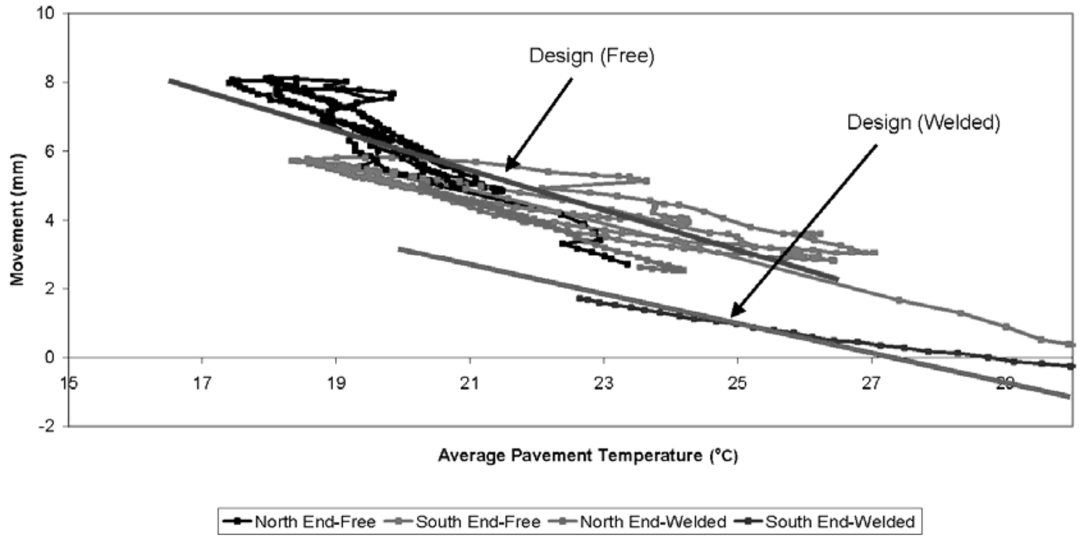

Figure 11 – Movements at Closure Pour (Bridge Side)

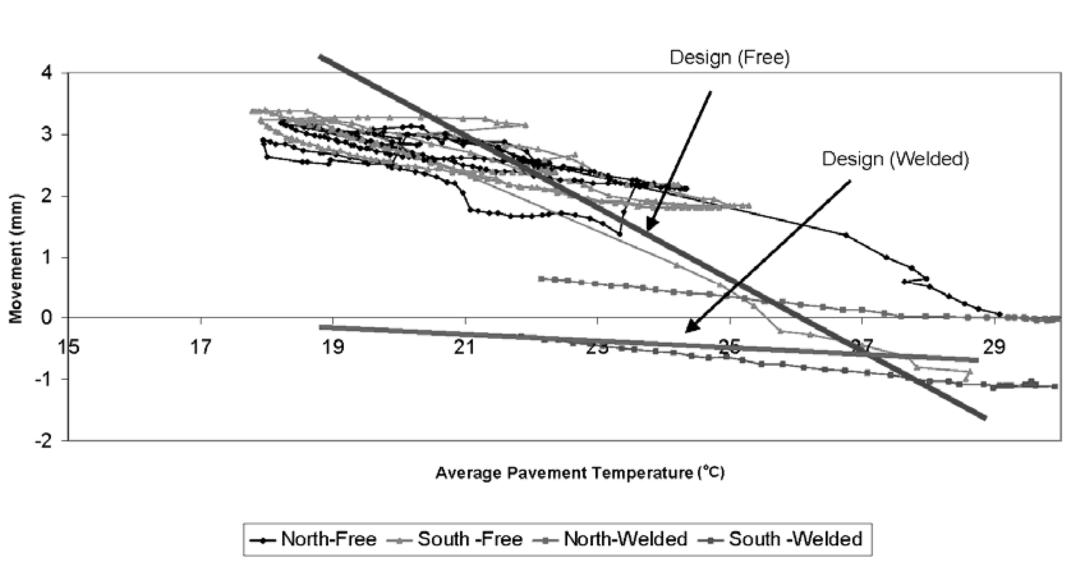

Figure 12 – Movements at Closure Pour (Pavement Side)

Figure 13 shows the relationship between the average pavement temperature and the loads measured in the longitudinal reinforcement, along with the estimated load from the design model. Although there appears to be some spurious readings because of inherent problems with strain gauge measurements on reinforcing bars, the overall trend as shown by the average slope of the lines suggests that the design model is providing reasonable results.

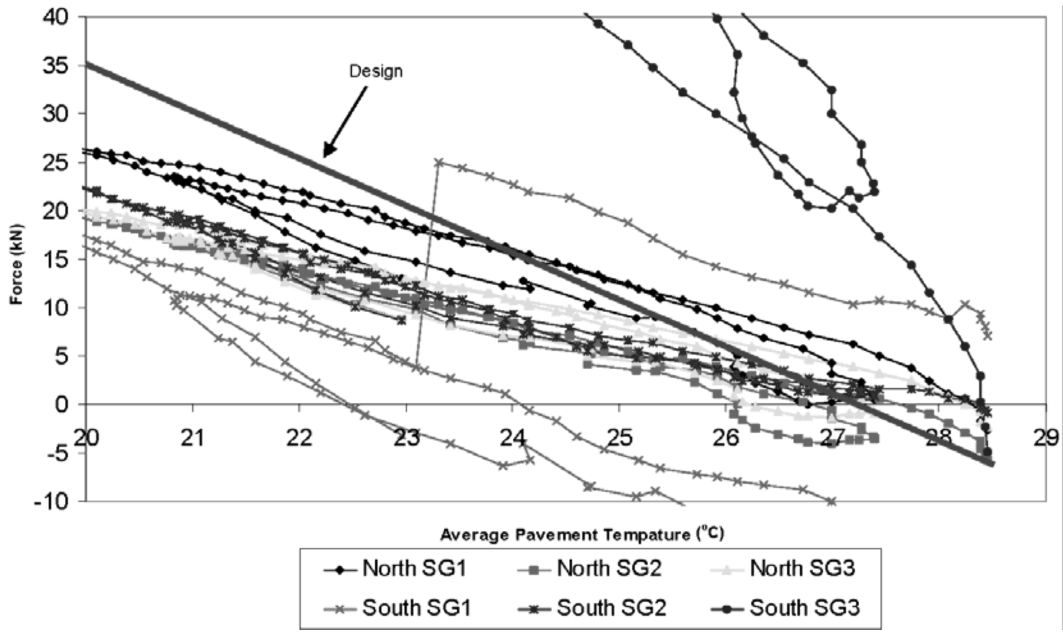

Figure 13 – Closure Pour Reinforcement Loads

Embankment Settlement. Embankment settlement recorded since pavement construction is less than 5mm. Monitoring is continuing.

Pavement Construction

Whilst the advantages of the seamless pavement to long term maintenance and ride quality were clear from the outset, the construction team experienced a significant period of trial and error, increased costs, design development, rework and lost time before the construction benefits were fully realised.

The introduction of any innovation cannot be implemented effectively without addressing risks associated with the change. Construction risk assessment concluded that the highest level of control needed to be imposed on construction around the transition zone to ensure that both the design intent and specification requirements were satisfied. Consequently a number of additional hold points were introduced to enable the designers and project certifiers to carry out detailed inspections. This proved to be time consuming at the start of the pavement construction.

The pavement section depth varies over the length of the transition zone. This requires that the surface of the uniform depth sub-base slopes 'downwards' on approach to the bridge abutment, which in turn requires the subgrade to be trimmed to a slope. Such trimming is complex at skewed bridge abutments. At skewed we squared up the slope change.

Normally the single layer of reinforcement in the CRCP is placed with a mechanised jig. Two layers are, however, required in the transition zone, which can extend up to 100m in length. A cost effective method for placing this steel was developed involving the use of the mechanised jig for the placement of the bottom layer with the upper layer placed by hand.

Development of this new concept resulted, inevitably, in not all design and construction details having been addressed when construction started. Changes had to be incorporated into the design as the first sections of pavement were being connected to the bridges. This proved to be a challenge in view of the criticality of the closure pour. Early attempts to complete the closure pour resulted in cracking of the closure concrete as the slabs on either side expanded and contracted with temperature change. This problem has been addressed with the development of the bundled 32mm reinforcing bars.

Conclusions

The transition between the highway pavement and bridge deck has long been one of the major sources of highway operational and maintenance problems. The seamless pavement addresses these problems in a simple, cost effective way by considering the bridge and pavement as a continuum rather than as discrete project elements. It eliminates all transverse joints in the highway pavement along with pavement terminal anchors and subgrade beams, thereby improving the final carriageway surface and simplifying construction.

Whilst the direct construction cost is similar to that for traditional CRCP, the construction benefits of the seamless pavement system result from the time saved to complete the interface between the concrete pavement and the bridge deck, the rapid provision of access for construction plant (particularly paving machines) across the bridge decks and accelerated completion on ancillary works around bridges.

Monitoring of the WM7 pavement and bridges has demonstrated good correlation between the field results and theoretical predictions. The general appearance of the entire area is very good with pavement crack patterns and widths similar to normal CRCP construction.

The seamless pavement connection will be used at all WM7 bridges less than 120m long. A practical limit on the applicability of this form of construction is a subject for further investigation and is likely to be dependent on the capacity of the bridge deck to carry the additional longitudinal loads and the cost effectiveness of the additional reinforcement in the approaches.

The major objectives of the original concepts were satisfied on the WM7 project but the experience gained during construction suggests that further enhancements are possible. Theoretically a single layer of reinforcement can carry the longitudinal loads generated by the bridge and pavement strains, provided that it can be demonstrated that there is adequate pavement capacity.

Acknowledgements

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References

Austroads. (1992). “Section 5 and Section 9.” *Pavement Designs – A Guide to the Structural Design of Road Pavements,* Sections 5 and 9, Austroads, Sydney.

Bridge, R. Q., Patrick, M., and Wheeler, A. T. (2000). “Crack control of beams.” *Reinforced Concrete Building Series – Design Booklet RCB-1.1(1), Guide to Reinforced Concrete Design,* OneSteel Reinforcing, Sydney.

Bridge, R. Q., and Smith, R. G. (1982). “Tension Stiffening Model for reinforced concrete members.” *Proceedings, 8th Australasian Conference on the Mechanics of Structures and Materials,* Newcastle, 4.1-4.6.

Bridge, R.Q., Griffiths, S.J. and Bowmaker, G.J. (2005) “The Concept of a Seamless Concrete Pavement and Bridge Deck.” *Proceedings, Australian Structural Engineering Conference,* IE Aust, Newcastle, Australia.

McCullough, B. F., and Herber, F. (1966). Á report on continuity between a continuously reinforced concrete pavement and a continuous concrete slab.” *Research Report 39-3, Evaluation of Terminal Anchorage Installations,* The Texas Highway Department.

Rasmussen, R. O., and Rozycki, D. K. “Characterisation and modeling of axial slab-support restraint.” *TRB Paper Number 01-2948- Committee A2B02.*

Roads and Traffic Authority (RTA). (1991). “ Chapter 7: Jointing and Structural Design.” *Concrete Pavement Manual- Design and Construction (incl. Revisions to 1996)”*, Roads and Traffic Authority.

Standards Australia. (2004). *Australian Standard. Bridge design Part 1: Scope and general principles.* Standards Australia International, Sydney, AS 5100.

Tinni, A. (2003). *A brief on the behaviour of terminal anchors for continuously reinforced concrete pavements,* Abigroup.