Rehabilitation of a Heritage Arch Bridge in Castlemaine, Victoria

Authors

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Abstract

Masonry arch bridges are typically no longer being constructed in Australia, however, many such existing structures remain as key components to the infrastructure network and are starting to require significant repair works given that many of these structures are now well over 150 years in age. Their structural behaviour differs from typical modern bridge construction and therefore suitable treatment is critical to ensure safe and effective rehabilitation works are undertaken to extend functional design life.

This paper discusses the engineering and construction works undertaken on a heritage arch bridge in Castlemaine Victoria that was originally constructed in 1862 as a masonry arch; and widened in 1895 with a mass concrete arch. This skewed bridge spans 11.9 [DA1.1][RP1.2]m over the Midland Highway and supports three rail tracks. Works included: waterproofing, strengthening, concrete lining, parapet stabilisation and temporary works design. The bridge is managed by V/Line and Victorian Goldfields Rail[DA2.1][RP2.2]; works were undertaken by McInnes construction; and engineering by SMEC.

This paper concludes by providing recommended key principles for the assessment and rehabilitation of such existing bridges by also drawing on other recent masonry arch bridge rehabilitation projects.

1.0 Introduction

Midland Highway Bridge is an 11.9 m single-span skewed masonry arch rail over road bridge managed by V/Line located at 124.714 km in the township of Castlemaine along the Sunbury to Bendigo line.

The red brick masonry arch portion of the bridge supports two rail V/line tracks and was constructed in 1862. An unreinforced concrete arch was later added to the structure to carry a third track to Maryborough Goldfields in 1895 and is currently operated by Victorian Goldfields Railway (VGR).

The asset is registered under the Victorian Heritage Register under VHR H1664.

Figure 1. Looking South-West across the southern edge of Castlemaine circa 1860

1.1 Bridge Condition

In 2017, a waterproof membrane was installed over the arch to mitigate water ingress and seepage in the arch. However, by 2020, water seepage through the arch was evident indicating that the liner may have only been effective for up to three years.

Two site inspections were undertaken by V/line Network Engineering representatives on 14/04/2023 and 20/09/2023 to assess the arch's structural condition and investigate the drainage issues. The inspections identified the following defects:

- Loose and dislodged bricks.
- Differential movement of arches.
- Longitudinal cracks along the brick barrel.
- Brick and mortar erosion.

- Failure of the waterproof membrane.
- Cracking and displacement at the spandrel wall.

1.2 Project Scope

SMEC were engaged by V/Line corporation to undertake structural assessment and rehabilitation design works on the bridge categorized as follows:

- Load rating assessment of the bridge.
- Design of a concrete lining on the intrados of the bridge to inhibit bricks from falling onto road traffic below.
- Design of a waterproofing membrane on top of the bridge.
- Restraint of the existing masonry parapets.

2.0 Bridge

The bridge supports three rail tracks:

- Two V/Line broad gauge (2.600 m wide sleepers) tracks on the east of the bridge (over the masonry arch).
- One Victorian Goldfields Rail track on the west side of the bridge (over the unreinforced concrete arch).

Under the bridge pass the following:

- Two road traffic lanes.
- Two pedestrian paths (nominally 1.2 m wide).

2.1 Original Bridge

The bridge was originally constructed as a single-span masonry arch bridge; however, the original design drawings were unlocatable despite extensive effort searching through the digital and physical archives. A previous inspection and load-rating report undertaken by Maunsell (1990, July) referred to the original design drawings and the following sketch was included in their report that was used as the initial basis of the bridge geometry:

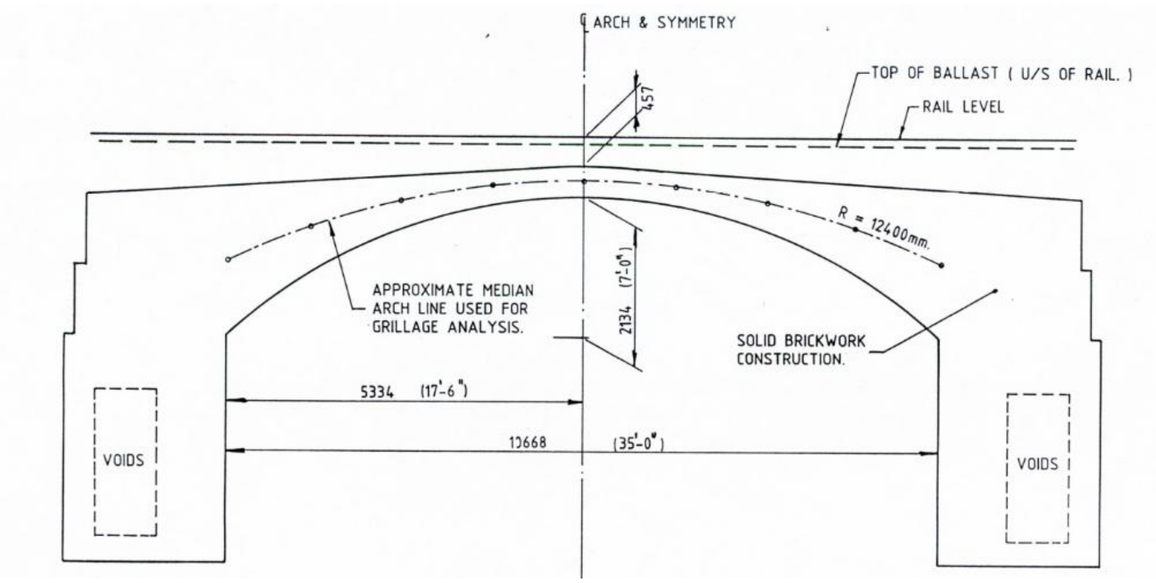

Figure 2. Schematic cross-section of arch bridge from the Maunsell report (1990, July) presumably based on the original design drawings available at the time

In the absence of the original design drawings, the following additional activities were undertaken:

- 3D point-cloud survey to determine the current geometry of the arch intrados.
- review of other design drawings of similar arch bridges located near the Midland Highway Bridge that were designed and constructed in similar time-period: between 1859 and 1862.
- site investigation activities to measure key dimensions – refer later sections of this paper.

2.2 Bridge Widening

In 1895 the masonry arch bridge was widened to include an additional rail track. The bridge was widened with an unreinforced concrete arch with the same intrados geometry as the original arch.

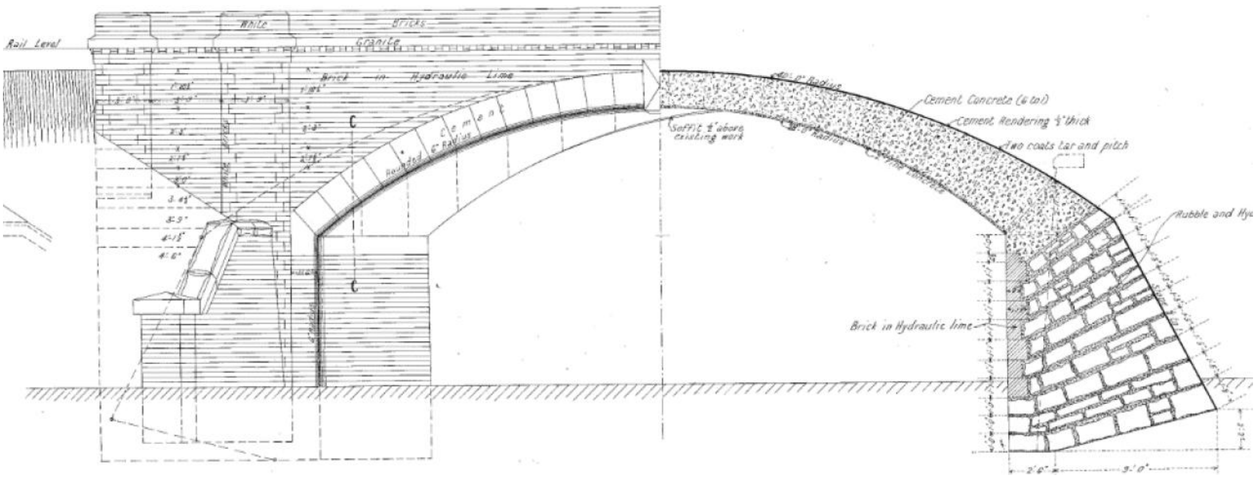

Figure 1. Unreinforced concrete arch – Elevation and section

Element	Value
Arch material	Cement concrete (6:1)
Arch thickness at crown (mm)	610 (2′ 0″)
Intrados radius (m)	8.534 (28′ 0″)
Extrados radius (m)	12.192 (40′ 0″)
Width (m) – Measured at right angles to track	5.030 (16′ 6″)

Table 1. Bridge widening

2.3 Site Investigations

A number of site investigation activities were undertaken to confirm the key bridge element geometries and material properties. The magnitude of site activities was determined based on the level of as-built documentation, confidence in the as-built documentation, risk profile of the client and stakeholders and an appreciation for the construction works to be undertaken during rail occupations and closures of the Midland Highway:

- 1 No. 30 mm diameter cores through the arch barrel.
- 4 No. 30 mm diameter cores through the abutment walls.
- 3 No. test pits.
- 1 No. 12.0 m deep borehole undertaken behind the south-west corner of the bridge abutment.

Figure 2. Core 4 through bridge abutment – 'Void' filled with mass concrete / grout (shown on the right-hand side)

Key findings from the site investigation activities included:

- Determination of the levels of the extrados of the bridge, and the thickness of the arch barrel.
- Determination of thickness of the abutments, and the material behind the abutments; and the presence of some 'voids' in the abutments as per the Maunsell report sketch (1990).
- Determination of material over arch abutment.
- Presence of 30 mm of tar / bitumen over the existing bridge arch extrados.



Figure 3. LHS: 30 mm thick tar layer over bridge extrados; MIDDLE: test pit over arch extrados; RHS: site borehole extraction

3.0 Load Rating Assessment

The load rating of this bridge was undertaken in accordance with the requirements of AS5100.7 (2017). LimitState RING 4.0 software was used to check various potential failure modes to determine the most critical load case and determine the associated adequacy factor. Such failure mechanisms assessed include but are not limited to the following:

- Masonry crushing.
- Sliding.
- Formation of hinges.
- And combinations of the above.

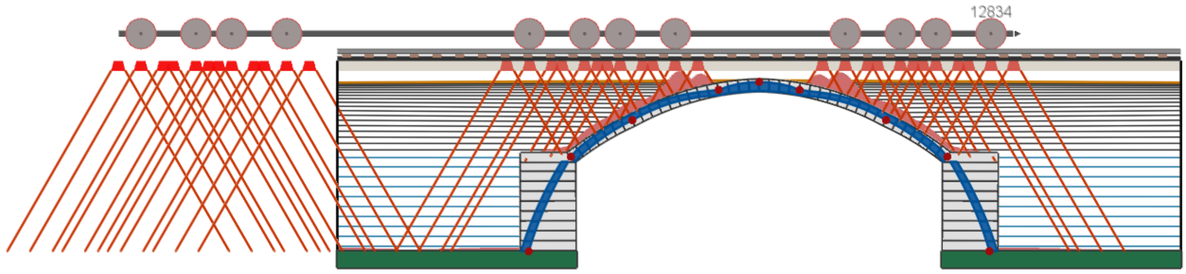

Figure 4. LimitState: RING – Analysis graphical interface for the Midland Highway bridge

The load rating assessment showed that the bridge had rating factors greater than 1.0 for the required 230LA rail loading.

3.1 Skew

The bridge has a 20 degree skew; however, LimitState: RING 4.0 is a 2D analysis software, most suitable for the analysis of bridges which span squarely between abutments. BA16/97 – Annex G provides further guidance on the assessment bridges with skew up to 30 degrees, stating:

> *The average increase in load carrying capacity of a skew bridge over a square bridge with the same span and width can be estimated from: $(b/w)^2$ where b = abutment width and w = bridge width.*

3.2 Dynamic Load Allowance (DLA)

AS5100.2 (2017) has some deficiencies with regard to the application of dynamic amplification factors for masonry arch bridges with earth backfill. AS5100.2 (2017) is based on the previous UIC code No. 776-1R (2006), which prescribes a characteristic length for arch bridges to be half the arch span (Table 9.5.2) – using this characteristic length the dynamic amplification factor calculated using Equation 9.5.3 is 0.67 (i.e. $\Upsilon_{f,dyn} = 1 + \alpha = 1.67$).

However, the based on latest UIC research regarding dynamic amplification for rail factors on masonry arch bridges with earth backfill has found that the use of a characteristic length is inappropriate for the following reasons:

- The mode shapes of a simply supported beam, on which the characteristic length calculations are based, differs greatly from the modal excitation shapes for a buried arch structure.
- The characteristic length calculations do not take into adequate consideration the high levels of dampening on the masonry barrel provided from the earth backfill.

The UIC has subsequently documented their findings in UIC 70778-3 – Appendix G (2020, May); as the use of equation 9.5.3 is typically excessively conservative. Therefore on this project, the dynamic amplification factor was also calculated UIC 70778-3. Two rating factors were presented for the bridge as part of the load-rating assessment: one rating using the AS5100.2 (2017); and another rating using the UIC 70778-3 DLA values.

4.0 Soffit Lining Works

The predefined project scope of works included the lining of the arch soffit with a reinforced concrete layer to primarily inhibit any of the deteriorating masonry bricks from falling onto the road below.

4.1 Vertical Clearance Assessment

The bridge passes over the Midland Highway that is managed by the Department of Transport and Planning (DTP) and is currently sign-posted with a 4.1 m vertical clearance.

A 3D point cloud survey was undertaken that showed that the vertical clearance between the road level and the soffit of the bridge was in the order of 4.3 m at the critical point. The bridge soffit was nominally flat, however, Midland Highway had a longitudinal sag-curve under the bridge providing additional clearance on the eastern side (masonry arch bridge) and less clearance on the western side (concrete arch bridge); the 'pinch-point' was located on the side that was not proposed to be lined.

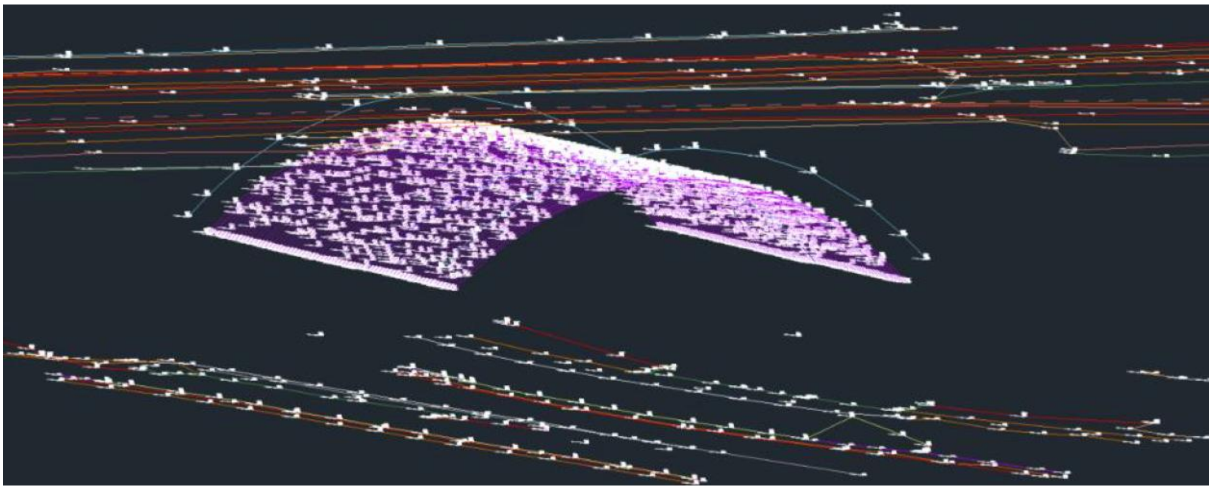

Figure 5. 3D point cloud survey of the arch soffit

DTP required that an effective vertical clearance of 4.200 m be maintained for the bridge (vehicle height of 4.100 m and with a 0.100 m minimum vertical clearance maintained measured from top of vehicle / load). DTP directed that the following two critical vehicles were assessed:

- Class 1 – OSOM 'low Loader' (30 m overall length), maximum rear overhang of 7.6 m.
- Class 2 – PBS level 2 'B-Double (26 m overall length).

Assessments were undertaken using Transoft AutoTurn Pro Software that indicated the effective vertical clearance of 4.2 m would be maintained, the bridge having adequate vertical clearance on the masonry side to support up to a maximum 338 mm of lining without impacting the effective vertical clearance; and therefore, the proposed lining design of 150-175 mm thick shotcrete (338 mm absolute maximum) would be acceptable.

4.2 Design Solution

The original reference design comprised shotcrete lining of the existing arch soffit and extending the shotcrete down inside faces of the vertical abutment walls. This design solution was used on a nearby rail over road arch bridge in Fryerstown in 1990 where the road-pavement in front of the abutment walls would have been temporarily removed to extend a 250 mm thick reinforced concrete lining vertically down to the level of the abutment foundations:

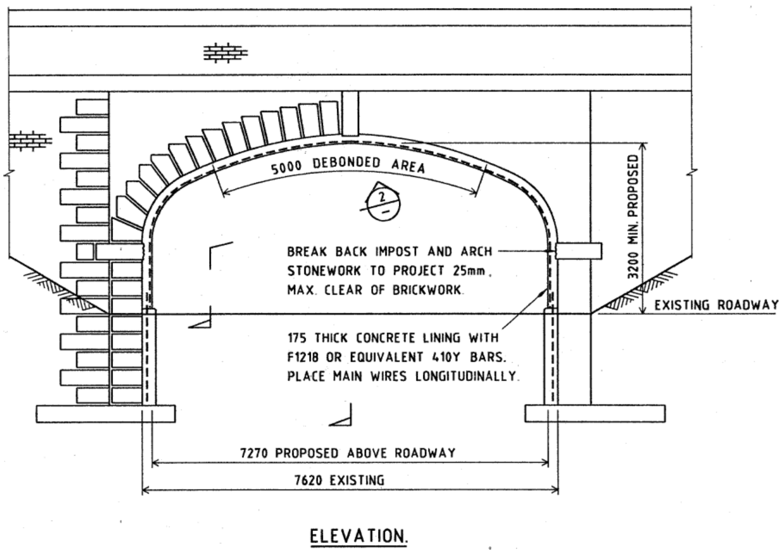

Figure 6. Fryerstown arch bridge – Concrete lining (August 1990)

However, applying such a solution at the Midland Highway bridge would have resulted in considerable impacts, some listed below:

- Demolition of existing footpath north side and south side retaining walls (note: this would also be required for the arch lining, if it were to extend below existing path level).
- Reconstruction of south side retaining wall, along new alignment (i.e. for the wider path).
- Reconstruction of the south side footpath, and handrails; change to the pedestrian path network on each side of the bridge to allow one footpath to be closed.
- Construction of a new barrier (or similar) on the north side, to restrict travel path under the arch haunches.

- Realigning (re-line marking) of Midland Highway to the north, (conditional on achieving acceptable vertical clearance).
- Reconstruction of any stormwater drainage impacted by the retaining wall re-alignment.
- Relocation of any underground utilities impacted by the works.

Considering the flow of forces in an arch structure, we were able to show that extending the reinforced concrete down the face of the abutment was not necessary, as the line of thrust through the arch would primarily extend into the mass abutment rather than vertically down the front face a vertical concrete lining of abutment. The following schematic diagram demonstrates the flow-of forces:

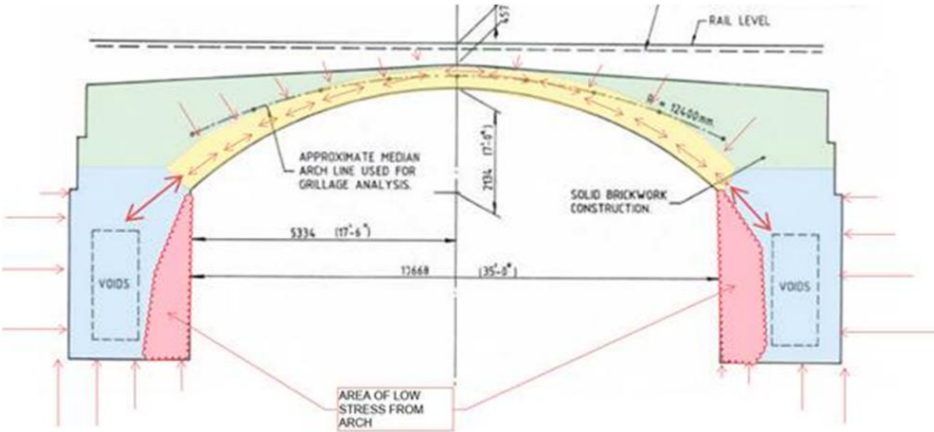

Figure 7. Schematic flow of forces in the arch bridge and abutments

4.2.1 Springer Detail

A structural detail was developed that keyed the new shotcrete lining into the abutment walls without requiring the concrete lining to extend down the front face of the abutment. This detail was effectively constructed on site using a concrete saw with depth control tooling as shown in the figure below:

Figure 8. Sawcut detail at arch springer

This design solution resulted in minimizing the impact of the bridge works on the footpaths and road-carriageway, while also minimizing the visual change to this prominent heritage structure.

4.2.2 Concrete Mix

The shotcrete mix design for the lining was developed in close collaboration with the builder and local concrete suppliers. The design solution specified a Class 2 concrete finish to AS3610.1 (2018) that would require hand troweling of the sprayed concrete to achieve. As the shotcrete was applied vertically overhead, the mix design required sufficient early strength to support its own weight. However, if the one concrete mix was applied with an accelerant additive, then there would be insufficient time after placement to trowel the concrete to a smooth finish, as it would have hardened too rapidly.

The final concreting solution comprised two concrete mixes:

- First mix design comprising the majority of the thickness of the arch lining that contained a concrete accelerator.
- Second, thinner, concrete spray that was applied after application of the main concreting; with the second layer able to be hand trowelled safely by site staff. An additional light reinforcement mesh, SL62, was included to enable the second mix to bind successfully while also minimizing the risk of shotcrete shadowing (i.e. if a heavier / denser second reinforcement mesh were used).

The concreting work was undertaken successfully on site and the required concrete surface finish was achieved.

Figure 9. Completed soffit lining

5.0 Waterproofing Works

The waterproofing design as part of these works sought to build on the lessons learnt from the failure of a previous waterproofing design by providing multiple layers of waterproofing, rather than relying solely on one layer of defense. Such an approach was even more critical for the waterproofing of this bridge given that the previous failed system only provided one waterproofing layer, and, that the rail environment is relatively harsh.

Critical to the proposed waterproofing system was the inclusion of a waterproofing layer significantly below the ballast level to avoid damage due to track operation and maintenance works – this inherently required the removal of backfill to install the waterproofing system.

The waterproofing system included the following layers:

1. **Surface-water drainage system**
   1.1 Clay capping layer (150 mm thick, installed as per NIST 2659)

2. **'Sub-surface' waterproofing system**
   2.1. Waterproofing membrane
   - PVC sheet, seam-welded durable plastic sheeting.
   - Slip sheet above primary membrane.

   2.2. Corner detailing
   - Sprayed waterproofing membrane locally applied in the corner.
   - BiTac – Bitumen impregnated tape the corner.
   - Use of flashing detail with reglet cut into parapet mortar.

   2.3. Existing waterproofing tar
   - The site investigations confirmed that the extrados of arch bridge was originally coated in a tar or bituminous layer to keep water from penetrating through the arch barrel and washing out the mortar / lime; this layer was kept as part of the waterproofing system.

Figure 10. Waterproofing works – Looking down-track

Such historic structures have often been modified over their design life with full details of such changes poorly or completely undocumented. Prior to the rail occupation it was unclear whether the original masonry arch bridge parapet on the western side of the arch bridge had been removed or modified during the widening of the bridge structure in 1865. The site team were altered to the unknown components of the insitu structure prior to the rail occupation and a number of design solutions for the waterproofing over this internal parapet. The internal parapet was indeed found to be intact after removal of the ballast and capping, and one of the pre pre-designed waterproofing details was able to be implemented at this location.

Figure 11. Waterproofing membrane and geofabric protection layer

5.1 Temporary Works Design

Typical bridge construction in Australia utilises modern materials – steel and reinforced concrete – that provide significantly greater ductility masonry arch structures. As masonry arch structures behave quite uniquely, careful coordination with the builders, McInnes, was required to develop a suitable construction methodology for the works.

SMEC developed a construction methodology for the safe earthwork removal and replacement over the arch bridge – this methodology comprised three main stages, with each stage having limitations for the size of the pant on the bridge (3t, 8t and 18t excavators, hi-rail, vibratory plate and a 27t tipper truck). The most critical stage during the works was when the majority of the backfill over the arch had been removed but with significant plant located on the bridge – during this construction stage the arch has the smallest amount of compressive thrust force and the smallest thickness of fill to distribute local axle loads – therefore during this stage only the lightest plant was allowed on the arch bridge.

Strict controls were required regarding the location and use of the tracks of the plant on the structure in addition to limiting the speed of plant movement. The bridge was divided into four different regions with various controls to limit the differential height of the backfill between respective zones at various stages of the excavation.

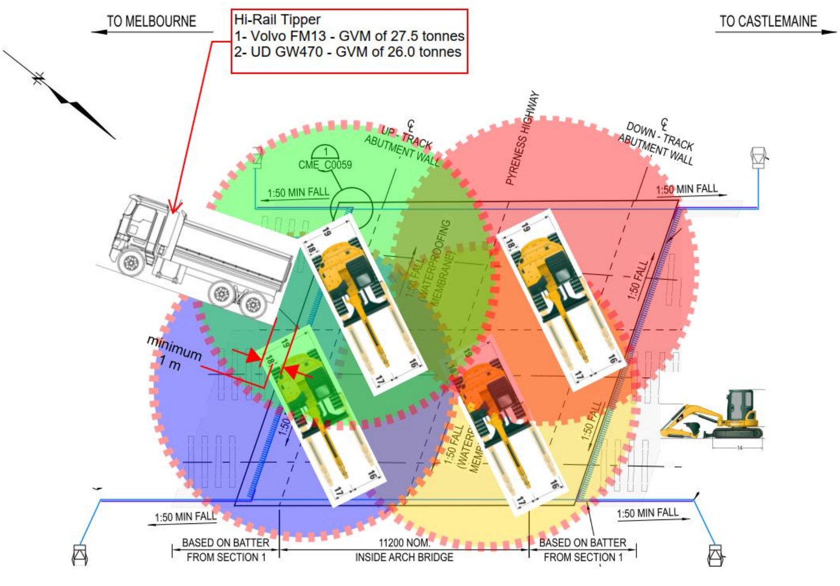

Figure 12. Four works zones as part of the staged temporary works methodology

Each of the construction stages, fill depths and construction vehicles were assessed using a mixture of hand calculations and LimitState: RING software to ensure sufficient factors of safety were achieved at all stages.

The soffit of the arch was surveyed prior to the commencement of the rail occupation and earthwork activities; the arch soffit was also surveyed at regular intervals as part of a traffic-light risk-based control technique noting that the Midland Highway was open under the bridge during the majority of the works. The construction works were successfully undertaken safely during the limited rail occupation program.

6.0 Parapet Restraint

6.1 Defect

During inspection works, a longitudinal crack was observed between the existing spandrel wall and parapet for the masonry bridge arch barrel. Water was leaking through this joint at the crown of the arch.

Figure 13. Longitudinal crack between the spandrel wall and the arch barrel

Longitudinal cracks between arch barrels and spandrel walls are very common in such structures for a number of reasons, including:

- Differences in stiffness between the arch spandrel and the arch barrel.
- Lateral loads from the ballast, capping and fill material that push-out against the spandrel wall.
- Loads from rail traffic push-out against the spandrel wall due to surcharge pressure, and rail nosing loads.

The crack appeared wider at the top of the arch compared to closer to the abutments and therefore the spandrel wall may have been rotating about an axis parallel to rail traffic at datum closer to the springing line.

6.2 Design Solution

Two design options were considered to tie the spandrel back:

- Steel ties through the arch backfill and ballast across the full width of the bridge.

- Epoxy anchor into the arch barrel.

The epoxy anchor solution was selected over the steel ties for the following reasons:

- Ties through the ballast would introduce the risk of being struck in the future when cleaning the ballast and or tamping the track. With Victorian Goldfields Rail (VGR) operating the third track, this solution would introduce an additional risk if extending the ties under the VGR tracks from a maintenance perspective.
- The through-tie solution would have required very long ties and connections on both sides of the bridge.
- The horizontal alignment of the Goldfields Rail track did not provide significant tolerance between the skewed sleepers and the ties located parallel perpendicular to the rail.
- The epoxy anchor was a simple and effective treatment.

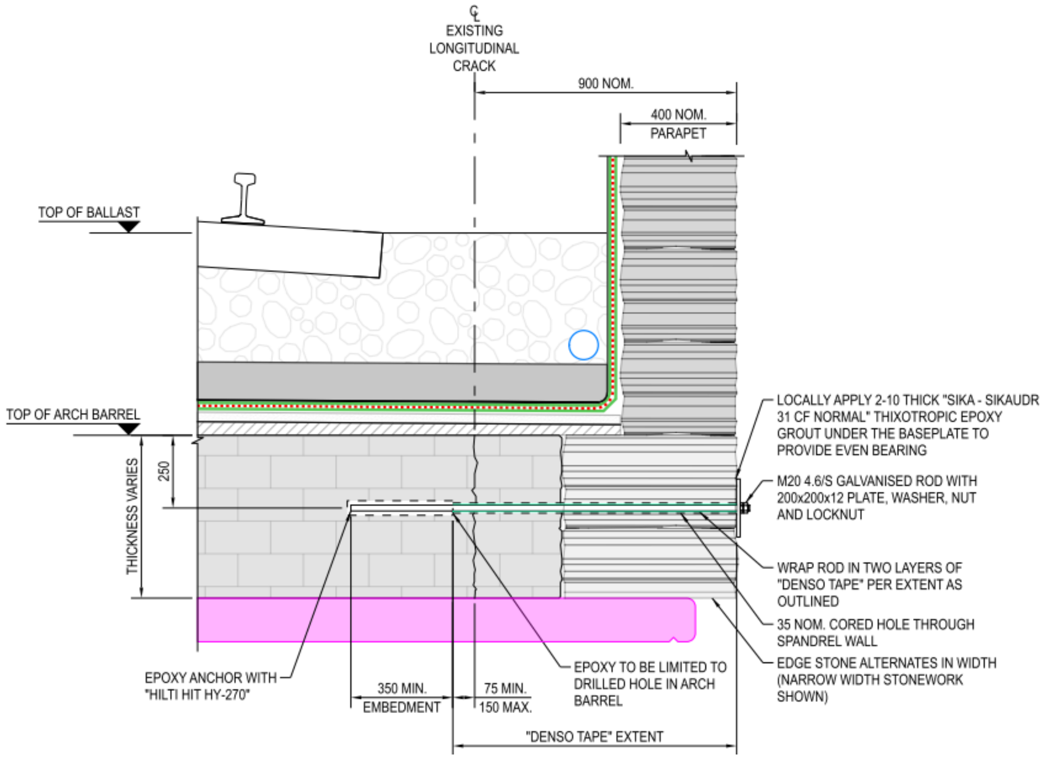

Figure 14. Parapet restraint detail

The anchor was detailed using grade 4.6 threaded rod to provide sufficient ductility; and the anchor was located in an oversized cored hole through the full width of the spandrel wall to provide tolerance and flexibility due to any future vertical translation / movement.

6.3 Construction

Installation of the epoxy anchors was difficult to achieve on site due to small voids within the brick-and-mortar arch barrel courses that enabled the flowable epoxy to disperse too quickly before hardening. The use of expansive anchors and rock anchors was considered as a back-up solution; however, ultimately the epoxy solution was able to be achieved after close collaboration with the site engineers. The final solution included epoxy capsules that were faster setting and able to be pushed into place as opposed to the initial pumped epoxy design.

7.0 Arch Rehabilitation General Principles

In recent years SMEC have worked on a number of masonry arch bridges in Victoria in addition to the Midland Highway arch bridge, including: High St, Northcote; Glenferrie Rd, Hawthorn; Seymour station brick arch viaduct; Barkers creek; and Woodend station.

This section of the paper outlines a few key principles relevant to working with masonry arch bridges from our recent project work:

- **Information**
  - Complete and accurate as-built drawings of these historic arch bridges are often not available, and therefore every effort possible is required to obtain sufficient information regarding the structure's insitu condition to enable effective engineering decision making and design.
  - Additional insitu investigation works is recommended to confirm the bridge geometry (both intrados and extrados), location of any voids, any pre-existing waterproofing and understand the material properties of the relevant structural and geotechnical elements.
- **Cover depth**
  - Local loading – Arch structures perform well when subject to uniformly distributed loads across the entirety of the span. Such historic arch bridges were not originally designed for high axle loading as required by modern rail and road bridge loading standards.
  - Structurally – Often the lack of cover between the top of the vehicle traffic level and the extrados of the arch limits the structural capacity of the bridge. Furthermore, additional fill over the arch typically improves the structural performance by increasing the precompression in the arch barrel and centering the zone of thrust through the arch barrel.
  - Waterproofing – Low levels of cover over the arch extrados limit clay capping layers from functioning and increases the susceptibility for waterproofing membranes to be damaged at the arch crown from high local axle loading.
  - Levels – Opportunities to increase the magnitude of cover extrados of the arch at the crown should considered the primary good-practice technique in passively extending the service life of the masonry arch structures.
- **Backing**
  - Historically, arch bridges were constructed with a backing over the arch extrados that provided significant additional structural capacity. The presence and importance of the arch backing should not be understated as the backing provides additional pre-compression into the arch, assists distributing local

axle loads more evenly across the arch, as well as providing a level of confinement for the arch barrel itself enabling the primary thrust zone to remain within the structural arch barrel.

- **Waterproofing**
  - Any waterproofing system should comprise a number of waterproofing layers, as reliance on any one protection layer alone results in a system more susceptible to failure, especially where the bridge is subject to heavy vehicle loading and maintenance works (e.g. track tamping and ballast cleaning).

8.0 Conclusion

It is expected that in the coming years further existing masonry arch bridges will require strengthening to support the heavier rail loading on the transport networks. This paper has discussed lessons learnt from works on the Midland Highway arch bridge, while also summarising key general principles that are recommended to be applied when working on other similar structures based on recent work on both the Midland Highway arch bridge and other similar structures. With appropriate on-going engineering and maintenance, these historic arch structures should hopefully remain key active elements within our transport infrastructure networks for many years to come.

9.0 References

- Australian Standards (2017) AS5100 Bridge design
- Australian Standards (2018) AS3600.1 Formwork for concrete, Part 1: Specifications
- Australian Standards (2018) AS3700 Masonry structures
- Axelsson, E. and Syk, A. (2013, June) Effect of axles load spreading and support stiffness on the dynamic response of short span railway bridges. TKH Architecture and the built environment
- BA 16/97 (2001, November) Volume 3 Section 4 – Highway structures: Inspection and maintenance assessment - The assessment of highway bridges and structures
- BA 91/04 (2004, November) Volume 2 Section 2 – Highway structures: Design (Sub structures and special structures) materials – Unreinforced masonry arch bridges
- Bayraktar, A., Turker, T., and Altunisik, A. C. (2015) Experimental frequencies and damping ratios for historical masonry arch bridges. Construction and building materials 75 (2015) 234-241
- British Standards (1992) BS5628 Part I – Code of practice for use of masonry
- CIRIA (2006) C656 - Masonry arch bridges: Condition appraisal and remedial
- CIRIA (2022) C800 – Guidance on the assessment of masonry arch bridges
- Harvey, W. J. (1995, December) The origin and treatment of longitudinal cracks in masonry arches. The Structural Engineer Volume 73, 411 - 412
- Institute of Civil Engineers (ICE) (2008) Manual of bridge engineering
- LimitState: Ring 4.0 – User manual
- Melbourne, C. & Gilbert, M. (1995) The behaviour of multiring brickwork arch bridges. The Structural Engineer 73, 39–47
- Melbourne, C. & Hodgson, J. (1995) The behaviour of skewed brickwork arch bridges, 1st Int Conf. on Arch Bridges, Bolton, pp. 309–320
- NR/
- Pallot, R. and Islam, S. (2022) Strengthening of the Glenferrie Road arch bridge over Gardiners Creek. Austroads Bridge Conference
- UIC 776-1R (2006, August) Loads to be considered in railway bridge design, 5th edition
- UIC 70778-3 (2020, May) Recommendations for the inspection, assessment and maintenance of masonry arch bridges, 2nd edition

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Dia Alwash is a Principal Structural Engineer with 16 years of specialised experience in the design, assessment, and strengthening of major transport infrastructure. Dia holds a Bachelor's degree in Civil Engineering and a Master's degree and PhD in Structural Engineering. His primary area of focus is the structural assessment and strengthening of railway bridges.

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