

SAVING WALTON BRIDGE

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Abstract

Walton Bridge is a two span unreinforced concrete buried arch bridge. At 115 years it is one of the oldest bridges in Brisbane and still carries an arterial road over Enoggera Creek. A previous assessment had found the bridge to be cracked and lacking in structural capacity and its replacement was recommended. This led to the imposition of a load limit and a reduction in the speed limit.

Brisbane City Council commissioned a feasibility study to produce a range of options for both refurbishment and replacement. AECOM took a different approach to the assessment, by analysing the structure as a masonry arch with no tensile strength. This type of structure can carry concentrated traffic loads by allowing the eccentricity of the line of thrust within the thickness of the barrel of the arch. This analysis was undertaken with two specialist software packages, and led to the conclusion that the strength of the arch is sufficient for unrestricted loading.

Meanwhile a monitoring program was instigated to measure displacements and crack widths to manage the risk of progressive structural damage.

The refurbishment scheme comprised the construction of a rigid pavement with waterproofing, installation of drainage systems to exclude water from the arch backfill, concrete patch repairs, and crack injection. The refurbishment has been completed and the bridge is expected to have many more years of life in service.



Figure 1 – Walton Bridge

1.0 Background

1.1 Walton Bridge

Walton Bridge (Figure 1), an asset of Brisbane City Council, is a two span unreinforced concrete arch bridge which carries Waterworks Road across Enoggera Creek at The Gap. The original bridge was built in 1900 and major modifications were made to the structure in 2002 to address some structural defects and add a cantilevered footpath structure on the northern side of the bridge. A second two lane steel bridge was erected beside Walton Bridge at that time, such that Walton Bridge now carries two lanes of city-bound traffic and the steel bridge carries two lanes of outward-bound traffic. Walton Bridge is one of Brisbane's oldest bridges and was added to Council's Heritage Register in 2004.

1.2 Previous Assessment

A detailed assessment in 2012 used a structural finite element model with shell elements. The arch capacity was based on limiting the tensile stress from combined axial and bending effects to the tensile strength of the concrete based on an assumed concrete strength. The effective depth of the section was reduced in places where an inspection had found significant cracks. Some crack widths were monitored and found to have increased slightly over a time interval of six months.

The finding was that the bridge had insufficient capacity for as-of-right semi-trailers, as well as other vehicles requiring a permit to travel. A 20 tonne load limit and a 40 km/h speed limit were implemented. The presence of four significant cracks was taken as indicative of a state of collapse having been approached. The advice was to prop or externally reinforce the bridge within six months and to replace it within five years.

1.3 Feasibility Study for Upgrade or Replacement

The state of Walton Bridge, as disclosed by the previous assessment, had resulted in an ongoing asset management and risk management task for Council. The loading and speed restrictions were unsatisfactory for an arterial road. Council invited proposals for a feasibility study to investigate options to upgrade or replace the bridge. AECOM also offered to reassess the bridge using analytical methods specific to buried arches and was engaged by Council for the study and subsequently for the refurbishment design.

2.0 Initial Inspection and Monitoring

2.1 Inspection and Monitoring

In view of the concern over the capacity of the bridge, an initial inspection was undertaken to check that the structure had not deteriorated noticeably since the previous inspection by others – which was found to be the case.

Crack width gauges were installed across five cracks and twelve targets were established to measure six dimensions between abutments, pier, and arch barrel.

The crack gauges were viewed and recorded with magnification from a telephoto camera. Crack widths could be read to an accuracy of approximately 0.5 mm and the accuracy of hand-held laser distance measurements was 1 mm to 2 mm. This monitoring could be undertaken without interrupting traffic on the bridge, and the accuracy was sufficient to detect movements much smaller than those which would be associated with serious structural distress.

All the movements were very small or immeasurable and within the degree of accuracy of the instrumentation. There was no indication that the bridge had experienced any change in crack widths or key dimensions over the course of the monitoring.

2.2 Testing and Measurement

In arch analysis, the shape and thickness of the arch are critical. In the absence of drawings, the data in **Table 1** was obtained by hand measurements and this was considered suitable for a feasibility study.

Table 1 Key Dimensions

Dimension	Measurement (mm)
Clear skew span	13820
Mid-span rise	4300
Quarter-span rise	3300
Arch thickness near crown	600
Arch thickness at abutment springing	1200
Arch thickness at pier springing	1800
Pier thickness	2500
Backfill depth at crown	600

A rough estimate of concrete strength at six points was obtained by means of an impact hammer, with ten readings at each point. Only four points had a sufficiently consistent set of readings to qualify for use to either ASTM or Euronorm standards and together these indicated a 10th percentile cylinder strength of 25 MPa. Given the variability and the inaccuracy of the test method, the feasibility study assumed a concrete strength of 14 MPa, which is the Queensland Department of Transport and Main Roads (TMR) default for unidentified concrete.

3.0 Behaviour and Analysis of Buried Arch Bridges

AECOM took a different approach to the assessment by adopting methods used more usually for buried masonry arch bridges.

3.1 Fundamental Arch Behaviour

An arch carries loads predominantly and desirably in axial compression, and the smooth curve of the arch is best suited to distributed loading. Concentrated loads, such as wheel loads, are distributed to some extent through the fill above the arch but cause bending moment as well as axial force in the arch.

Masonry arch bridges are conventionally assumed to have no tensile capacity in the joints between the stones or bricks, and yet they can carry concentrated loads because the line of thrust in the arch departs from the centroid of the cross section and becomes eccentric. It is not necessary for the eccentricity to be limited to that which first causes tension on one face of the arch provided the remaining area in compression has sufficient strength to carry the thrust.

An unreinforced concrete arch can carry loads in the same fashion. While bending moments could alternatively be sustained by the tensile capacity of the concrete, if a crack should occur, due to high load or merely shrinkage, then the tensile strength vanishes across the width and depth of the crack. The structural capacity is sensitive to the presence of existing cracks or the formation of new ones. More confidence can be placed in an analysis which does not rely on concrete tensile strength.

One reason given for concern about the safety of the bridge was that the several cracks observed in the intrados of the arch barrel were indicative of the partial formation of four hinges, which would lead to collapse of the bridge. However, those four hinges do not all cause cracking on the same side of the arch. Therefore the existence of three or four cracks in the intrados is not necessarily a sign that collapse is imminent.

An unreinforced concrete arch of this size is almost certain to have shrinkage cracks originating soon after construction, and this is an alternative explanation of the observed cracks. While there are no available historical records to verify the age of the cracks, there was anecdotal evidence that cracking was present as far back as the late 1970s.

3.2 International Practice

There are few buried arch bridges in Australia and there are no particular provisions for them in the Australian bridge design code, AS 5100.

Elsewhere, and particularly in Britain, there are very many buried arch bridges still in service. The UK Highways Agency has issued several specifications and advisory guidelines in their Design Manual for Roads and Bridges which cover the assessment and design of masonry arch bridges:

- BD21/01 The Assessment of Highway Bridges and Structures
- BA16/97 The Assessment of Highway Bridges and Structures (Advice Note)
- BD91/04 Unreinforced Masonry Arch Bridges.

It is not usual to analyse a buried concrete arch structure using conventional elastic methods commonly applied to other types of structure. This is because this type of analysis does not handle unreinforced concrete elements very well and the soil/structure interaction is too complicated. The general approach would be to either use an empirical method or to use an industry recognised specialist computer program to analyse the arch. In practical terms, there are two widely used computer programs available which give an assessment of the collapse load of the arch namely ArchieM and LimitState RING. Considerable research stands behind these programs including full-scale testing and they have been widely used in the UK for many years.

3.3 Dynamic, Load, and Capacity Reduction Factors

In AS 5100, the dynamic load factor is given as a function of the relevant load – a single axle, an axle group, or a design truck, although the factors are based on beam rather than arch bridges. The factor diminishes as the depth of backfill increases. The dynamic factor was taken conservatively as 1.4. The load factor for traffic is 2.0 for assessment vehicles and 1.8 for the current design vehicle SM1600. The capacity reduction factor for plain concrete in compression is 0.6. Thus the total combined factor between nominal load and characteristic strength for assessment vehicles was conservatively 4.7.

Deadloads are distributed along the bridge evenly and do not cause any eccentricity in the thrust line so are relieving for arch performance and therefore have a load factor of 0.85. Similarly superimposed dead loads have a load factor of 0.7.

British practice uses different values for all these factors, and is generally less conservative.

None of the codes or guides define the effect of traffic speed on the dynamic factor, at least not until the speed becomes very slow (10 km/h in the Queensland TMR assessment brief). A review of the literature was unproductive. Moreover, most of the research has been on beam bridges, where there is a relationship with the natural frequency of the span. The buried arch would behave differently. There is not a generally accepted quantitative link between vehicle speed and dynamic factor. No reduction in dynamic factor has been made in this assessment, and therefore no speed restriction is implied.

3.4 Modified MEXE

MEXE, the (British) Military Engineering Experimental Establishment, developed a semi-empirical method for assessing the capacity of buried arch bridges for military purposes. The method has been modified for general use in civil engineering, and calibrated for a 40/44 tonne British truck having 20 tonne load on a double axle and 24 tonnes on a triple axle, both being more severe than legal limits in Queensland. In this simplistic method a provisional axle load is determined based on span, ring thickness, and depth of fill which is then modified by factors to account for arch profile, shape, constituent material, condition, cracks, and arch deformation to derive the assessed capacity,

Assessment of a masonry arch bridge to BD21/01 adopts the Modified MEXE method for the initial analysis. More complex methods are undertaken if the arch parameters do not fit the recommended range of parameters for Modified MEXE, or if it gives an inadequate capacity, or if there is reason to believe that it is unconservative. It is known to yield unconservative results for arches with crown fill depths greater than the arch barrel thickness.

The accepted view that Modified MEXE is a simple and conservative method has been challenged in the literature, but this applies mainly to spans much shorter than at Walton Bridge.

3.5 Three-Pin Arch Method

A three-pin arch is a stable structure. If a fourth pin is formed, the structure becomes a mechanism and collapses. The computer program ArchieM calculates the position, load, and size of the line of compressive thrust within the physical boundaries of the arch ring and the abutment and pier supports. This thrust line can be adjusted to find the most favourable outcome, considering the loading at all points on the structure. In general, the line of thrust is eccentric and can thereby transmit both compression and bending moment. The method ignores the tensile strength of the arch. It is a two-dimensional model, for which the transverse distribution of load is taken from BD21/01.

The analysis satisfies equilibrium and is a lower bound estimate of the arch capacity.

3.6 Four-Pin Arch Method

A four-pin arch is a mechanism on the point of collapse. This method is analogous to the plastic design of steel frames. The method can be employed in practice through the computer program Limitstate RING. It is an upper-bound method which uses optimisation algorithms to find the collapse load.

RING idealises a bridge as a series of blocks. It disperses live loads through fill in accordance with BD21/01 onto these blocks which are in contact but subject to crushing, sliding, and hinging. The movement of the arch is restrained by its self weight and by backfill elements through passive resistance. Unlike ArchieM the user has to identify the worst vehicle position by hand.

4.0 Capacity Assessments

4.1 Assessment Vehicles

The basic assessment vehicle, as used in the previous investigation, was a 42.5 tonne gross mass six axle semi-trailer. This vehicle has as-of-right access on Waterworks Road without permit. The truck has a triple bogey carrying 20 tonnes and a double bogey carrying 16.5 tonnes.

Council further requested that the bridge be checked for SM1600 loads to AS5100.2 as well as two Council bus configurations. The calculations were completed for a Volvo B7R bus with a peak single axle load of 10 tonnes and a Volvo B12R bus with a double axle load of 14 tonnes.

4.2 Structure Configuration

The unreinforced concrete arch bridge comprises two skew spans of 13.82 m clear with a nominal skew of 9°. The arch barrel dimensions are detailed in **Table 1**.

The bridge width is 8 m and has been widened to accommodate a cantilevering footway which is assumed to be supported by the spandrel walls. The bridge supports two lanes of traffic so one lane of traffic is assumed to be supported by an arch structure 4 m wide. There were no longitudinal cracks in the intrados that would limit the width of distribution.

The bridge has approximately 600 mm of fill above the crest of the arch barrel and it is assumed to be level across the structure. This 600 mm of fill includes road base and surfacing materials.

The bridge is supported on abutments of unknown thickness and a 2.5 m wide unreinforced concrete pier. The abutments and pier are approximately 2.3 m high. A review of previous geotechnical reports provided by Council revealed sound granite rock head located between 2 m and 3m below ground level as shown in **Figure 2**. It is likely that the foundations are mass unreinforced concrete and founded directly on this rock.

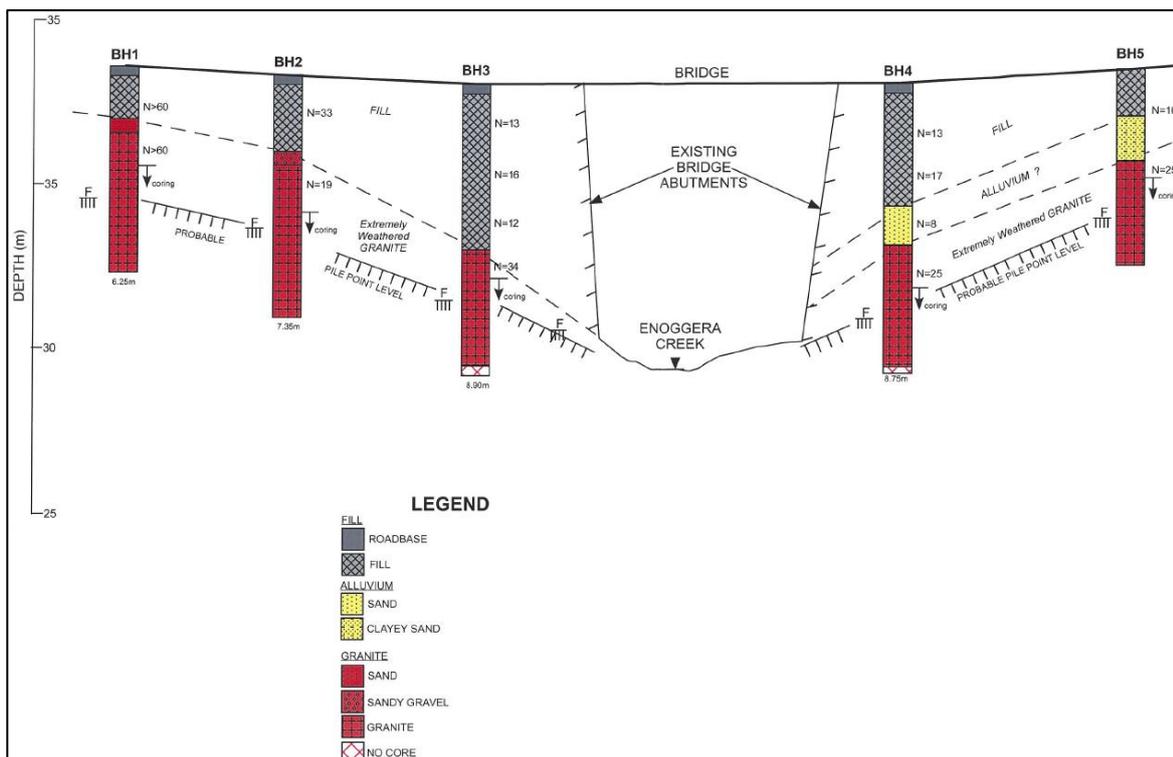


Figure 2 Extract from BCC Geotechnical Report detailing the assumed ground profile

4.3 Modified MEXE

This method shows that the bridge can comfortably carry the full 40/44 tonne British assessment vehicle and hence also the assessment vehicles described in **Section 4.1**.

As the method may be unconservative when the depth of fill at the crown is greater than the ring thickness, the analysis was repeated with a nominal reduction in the depth of fill from 600 mm to 400 mm, in which case the capacity is still sufficient for the full 40 tonne truck.

As an extreme case, an analysis using a 400 mm thick arch ring thickness with 300 mm depth of fill gave an allowable truck mass of 32 tonnes.

In UK Highways Agency practice, the Modified MEXE capacity takes precedence over alternative methods, even if they give lower results "unless there is good reason to believe that it is unconservative for the case in question, for example where the fill depth is greater than the arch thickness".

Nevertheless, it is prudent to consider an alternative method of analysis as well.

4.4 Three Pin Arch

A three pin arch analysis was undertaken using the program *ArchieM*. Using the measured geometry, a number of analyses were conducted to explore:

- Various assessment vehicles – 42.5 tonne semi-trailer, 22.5 tonne rigid truck, two Council bus configurations, and SM1600
- A range of concrete strengths – nominal 14 MPa and 12 MPa and 16 MPa
- Both Australian and UK dynamic load, and capacity reduction factors
- Single and dual lane loading (with the same vehicle in each lane)
- Two assumptions on pier height (to ground level and to assumed rock head).

An excerpt from the *ArchieM* output is shown in **Figure 3**, and the results are summarised in **Table 2** which gives the ratio of the available capacity to the vehicle loading at ULS. A ratio greater than 1.0 indicates spare capacity. All vehicles apart from SM1600 loads were found to be within the capacity of the arch bridge.

Points to note:

- Capacities are less than those given by the Modified MEXE method.
- Capacities using UK load and capacity factors are about 10% higher than using Australian factors.
- Variation of concrete strength by 2 MPa affects capacity by less than 5%.
- Single lane capacities are 11% higher than for dual lane loading.
- No reduction has been made to the dynamic load allowance, therefore no speed restrictions are implicit.

4.5 Four-Pin Arch Method

A four pin arch analysis was undertaken using the program *RING*. This program was used to check the results of the three pin arch analysis.

The same assessment vehicles were used namely a 42.5 tonne semi-truck with or without its trailer, 22.5 tonne rigid truck, two Council bus configurations, and SM1600 vehicles.

The same assumptions and factors were used that were also used in the previous analysis.

An excerpt from the *RING* output file is shown in **Figure 4**. All the vehicles assessed were found to be within the capacity of the bridge, refer to **Table 2** for full results.

In order to try to more closely replicate the results obtained from ArchieM a number of variables were adjusted. Even by adjusting the concrete compressive strength and passive earth resistance to minimal values the analysis still gave enough capacity in the arch to support the loads.

In the program there is an option to introduce areas of mortar loss between adjacent rigid blocks to model a cracked arch. Although there was a drop in capacity even by introducing modest areas of mortar loss at all four quarter points the structure was still showing adequate capacity for the assessment vehicles.

It should be noted that in this assessment the passive earth resistance has been limited to 30% of the normal passive resistance in line with British practice, as significant movement would be required to mobilise full passive resistance.

Table 2 Assessment Results – Ratio of Available Capacity to Vehicle Loading at ULS

Vehicle	GVW (T)	Governing axle	ARCHIE-M	RING
Bus B7R	16	Single	2.61	3.91
Bus B12R	20	Dual	2.07	2.92
Semi Trailer	42.5	Triple	1.61	2.43
Rigid Truck	22.5	Dual	1.64	2.42
SM1600	170	Triple	0.98	1.54

4.6 Qualitative Assessment

Although the presence of spandrel walls is known to positively influence the capacity the arch, both ArchieM and RING model the arch in 2D and do not consider them. Consequently these walls are usually assessed qualitatively by looking for signs of distress or distortion. Although the walls do show some defects no further work was deemed necessary as they were strengthened in 2002 with ground anchors and walings.

Inspection showed no significant cracking in the abutments or piers and monitoring indicated no sign of movement so qualitatively they are considered adequate for the current road traffic. The wing walls had been previously strengthened with ground anchors.

4.7 Traffic Load and Speed Restrictions

Modified MEXE, ArchieM, and RING all indicated that the traffic load and speed restrictions were not necessary and could be removed.

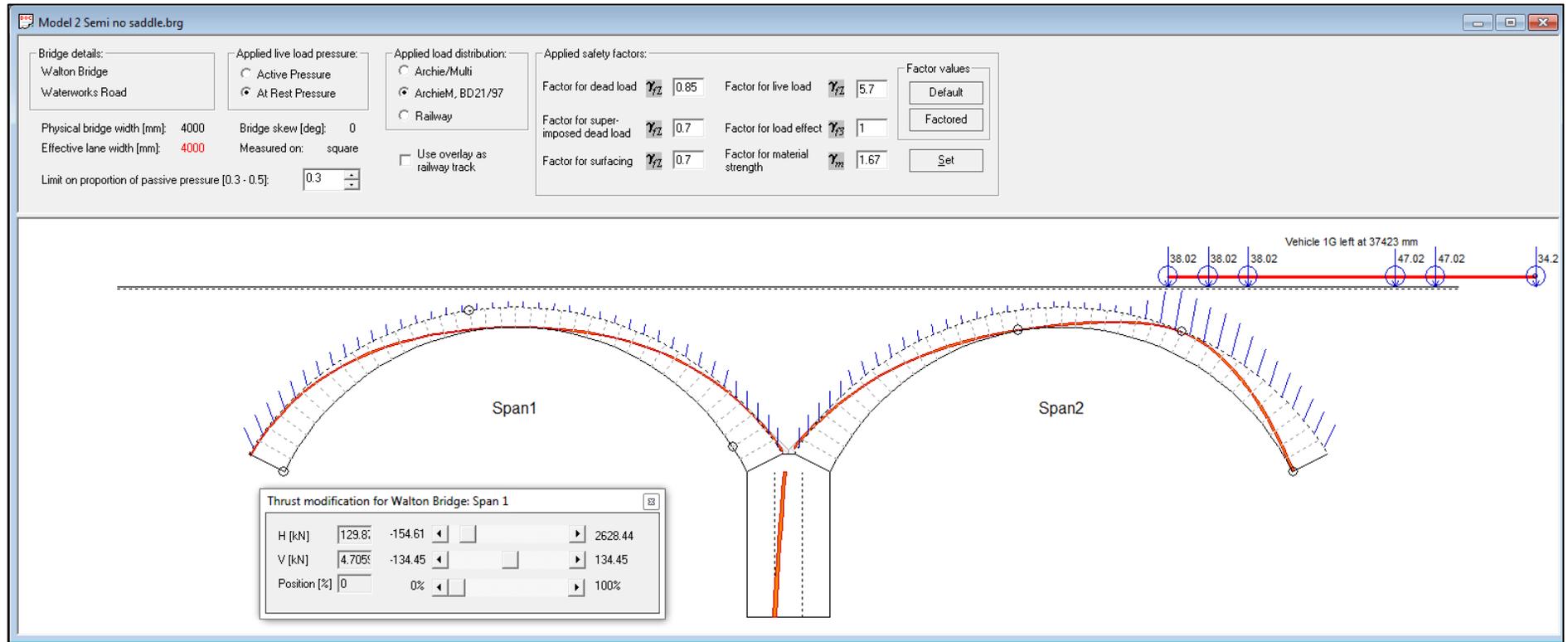


Figure 3 ArchieM Model for Semi-trailer, also showing the dialogue box for manual thrust modification

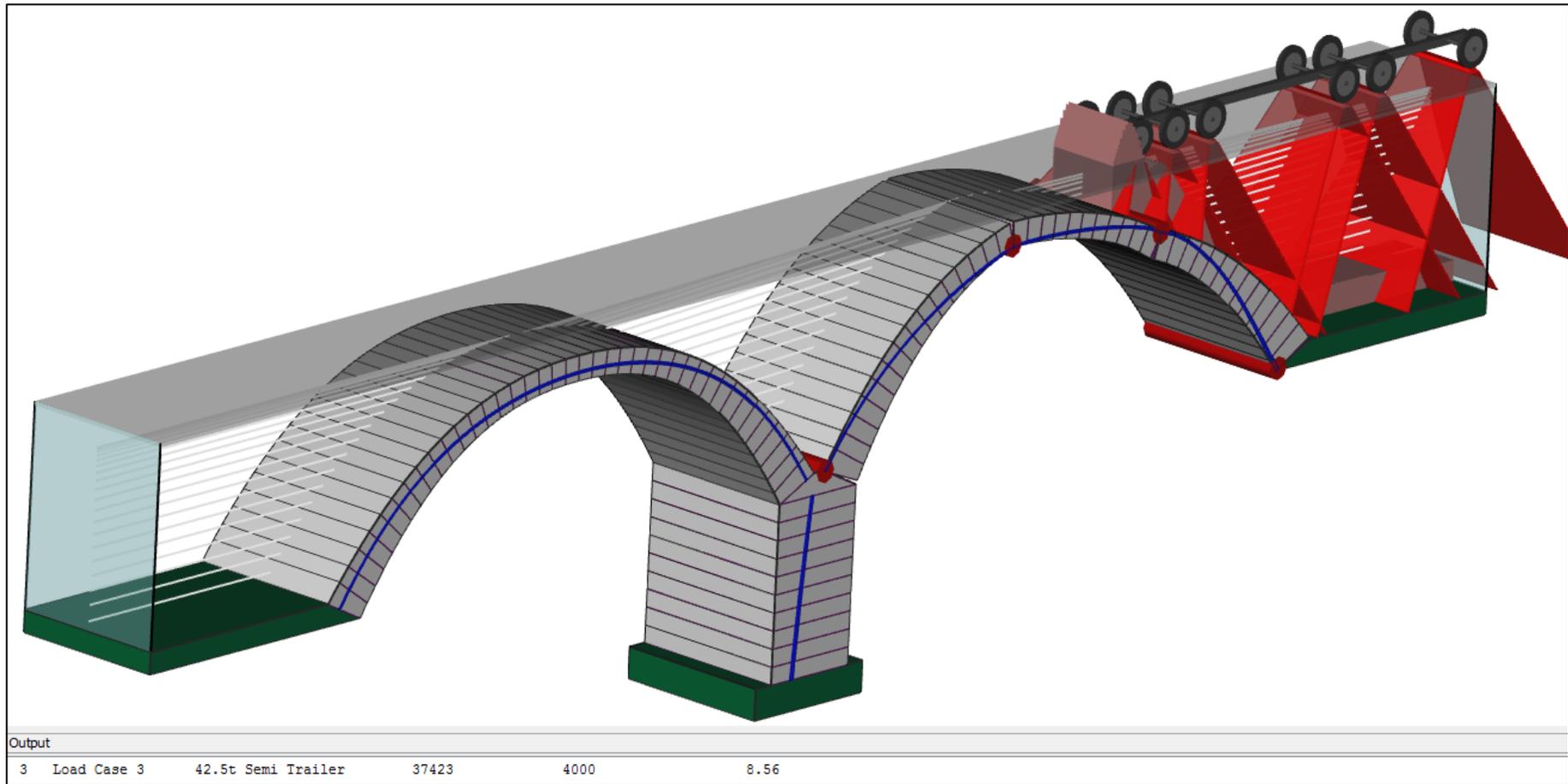


Figure 4 RING Model for Semi-trailer

4.8 Confirmation of Design Parameters

As the project moved from feasibility study to detailed design, it was appropriate to undertake further site investigation including.

- Services searches and scans – to determine construction constraints
- Crack and defect mapping - sufficient for quantifying purposes.
- Topographic survey – including the arch profile. No major differences.
- Geotechnical Investigation. Three boreholes were completed to confirm soil properties for arch analysis and pavement slab design. Fill properties used in the feasibility study were retained.
- Ground penetrating radar (GPR). GPR was used to confirm arch barrel thickness, to locate voids and to confirm pavement thickness. Thickness was also confirmed using a pilot hole cored through the crown of the arch. The bridge was scanned from the road surface and from beneath the arch. The instrument under the arch was unable to penetrate fully through the arch ring to confirm its thickness at the springing points and the GPR Survey provided typical details rather than a comprehensive survey. The significant finding was that the minimum depth of fill at the crown of the arch was 430 mm rather than the 600 mm used in the feasibility study.
- Concrete cores. Cores were collected from four points in the arch barrel. These samples were tested in a NATA certified laboratory to determine compressive strength, for arch analysis. The strength used for the reassessment was increased from 14 MPa to 19.5 MPa.

Reanalysing the arch using the above parameters gave a structural rating very similar to those determined during the feasibility study.

5.0 Options for Upgrading

Despite the favourable analytical outcomes, options for upgrading the bridge were investigated, falling into three categories. All the options were compared considering cost and impacts on traffic, land, the creek, and heritage value.

5.1 Repairs

The bridge was certainly not without defects, and repairs were recommended:

- Sealing of significant cracks, especially where there was sign of water leakage and efflorescence, which might locally degrade the cement matrix in the long term.
- Concrete patch repairs at points of spalled or defective concrete.
- Installation of drainage and waterproofing.
- Reinstatement of anti-graffiti coating.

5.2 Strengthening

Three options for strengthening the existing bridge were investigated. This included modelling the effect of each strengthening option in ArchieM.

- Concrete saddle, ie casting a thickening on top of the arch. This is very effective but would require a lengthy road closure.
- Concrete slab at road surface. This increases capacity only slightly by improving the distribution of wheel loads, but it provides a base for waterproofing at deck level.
- Grouting the fill over the arch. This would require a specialist contractor and there was uncertainty about existing services, the suitability of the fill material, and some risk of polluting the creek.

5.3 New Bridge

The options for the construction of a new bridge were investigated:

- Precast concrete arches (replacement) – built on-line after demolishing the existing bridge.
- Deck unit bridge (encapsulation) – built on-line and above the existing arches which are retained.
- Super-tee bridge (preservation) – built off-line and the existing bridge survives, unused.

6.0 Walton Bridge Upgrading

6.1 Design and Construction

The installation of a waterproofing saddle was initially recommended as it offered the most durable solution. However, on detailed examination the presence of a large number of existing services over the structure made this impractical and the associated traffic disruption would have been severe. Council chose to proceed with the repairs and to construct a concrete slab at road level with a waterproofing system. By forming a slab at pavement level excavation depth was minimised and it was possible to form the slab in two halves without lengthy road closures.

Selected cracks were injected progressively from one end as shown in **Figure 5**. Injecting to a hidden far surface leaves open the possibility that the full depth of the crack is not filled. Epoxy was not used in case partial filling might prevent closure of part of any part of the crack when needed to transmit an eccentric thrust. The purpose of the crack filling is not to restore strength but to close the express route to water and help prevent the further leaching of material from the concrete matrix. For this reason a relatively soft polyurethane grout was selected. Polyurethane is reactive to water and expands to seal the cracks, it has a very low viscosity to penetrate deep into the cracks and is flexible, maintaining the seal if the crack should become wider. Due to the practicalities of crack injection techniques only cracks greater than 0.2 mm width could be treated. Close inspection during construction revealed many cracks of that width and the limit was relaxed.

To maintain full arch barrel thickness several localised areas of spalling were cut back and treated with proprietary concrete repair products.

The deck slab was designed as a continuously reinforced concrete pavement and was isolated from the arch structure to prevent direct load transfer into the spandrel walls or the transverse beams under the pavement that support the cantilevering walkway.

The bridge is located near the bottom of a sag vertical curve and longitudinal fall encourages both subsurface and surface water onto the structure. Subsoil drains were installed at either end of the bridge under the new pavement slab with the intention of forming a cut off wall to intercept the groundwater before it can reach the structure. Additional weepholes were formed through the spandrel walls to outfall pavement drains and further holes were formed in the abutments and over the pier to drain the structure. The existing stormwater gullies on the high side of the bridge were also refurbished.

The refurbishment was completed in February 2015 whereupon the loading and speed restrictions were removed.

Walton Bridge is inherently durable, founded on stable ground, and amply strong. It is expected to perform satisfactorily far into the future.

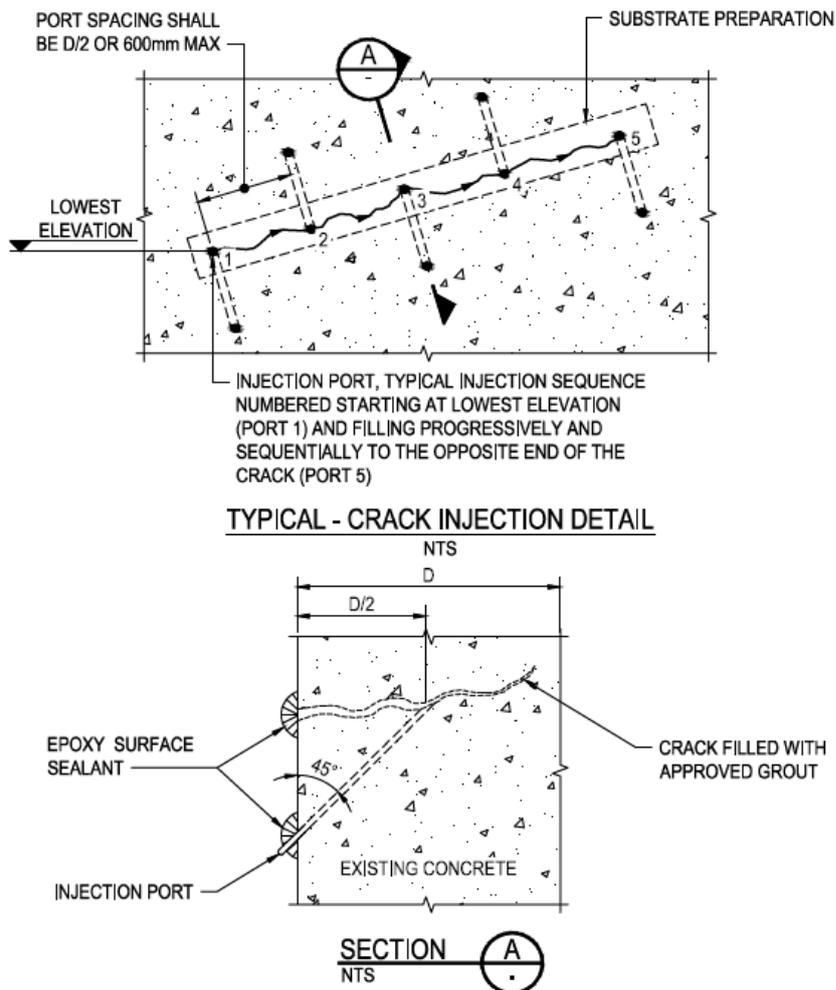


Figure 5 – Crack Injection

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