AN INNOVATIVE APPROACH TO SMALL BRIDGE REHABILITATION

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SUMMARY

The vast majority of our transport infrastructure is ageing having been constructed during the first 50 years of the last century and was never designed to carry the loading or volume of traffic that is experienced today.

Downtime, diversions and disruption to service is no longer tolerated and customer service is now a key focus for all infrastructure providers. This paper will detail how this can be achieved by use of structural in situ concrete lining and will expand on how this system can be designed and adapted to culvert and small bridge renovation.

For larger accessible sub surface structures and small bridges, in situ concrete lining can be applied to increase the strength and prolong the life of our existing assets for the Road, water and Rail Infrastructure.

Design guidance will be given on how to achieve a 100 year design under either AS3600[3] or AS5100[4] together with AS3725[1] to provide a standalone structural element, or alternatively by designing as a composite structure to utilise some of the host structure's residual strength to provide cost savings

This paper considers an approach to ~~the~~ design philosophy ~~and~~ for the development of a fully structural independent rehabilitation solution that has no impact on the operations above the bridge deck.

1. INTRODUCTION

Today, a large percentage our road, rail and infrastructure systems across Australia have under the surface assets that are now at or rapidly approaching the end of what was originally considered their operational design life and as the demands that are required on the infrastructure continue to increase the need for a maintenance program is gaining greater importance as the threat of catastrophic failure increases.

Many of these structures which can include pipes, culverts and tunnels are classified as Small Bridges, particularly when the span exceed 1200mm.

When dealing with these smaller structures most design scopes often tend to revolve around the requirements of AS5100 (2004) [4] which whilst appropriate to some of the considerations that have to be made in the design concept may not be the most cost effective approach in others.

The modern day infrastructure has demands that need structurally competent sub-surface structures that are robust and have a reliability in order to handle the increased loading yet many are reaching the end of their serviceable life and unless renewed or repaired pose a risk to the daily operation of the infrastructure above.

Preventing the potential of a failure and minimising any disruption on the surface is an essential consideration for any infrastructure operator as is the need to install a rehabilitation that will last the tests of time both with regards to the aggressive environment as well as with the developments in technologies and material demands.

Understanding the problems that are common with these small bridges and arch spans is fundamental in determining how effective a potential remediation can be undertaken, however in the majority of cases insufficient data is available.

As such most designs will need to assume that the existing structure is in a fully deteriorated condition which dictates that the new design must be structurally stand-alone taking no inherited strength from the host therefore ruling out composite elements. These latter composites are recognised as structural reline options under the WRc (Water research council) rehabilitation manual.

2. Common conditions leading to potential failure.

Before commencing any design it is important to understand as much as possible about the existing structure as well as why it has deteriorated.

The most common conditions relating to potential failure are:-

- Deteriorating Arch ring material-
  - Corrosion, excessive cracking
- Loss of Arch thickness
- Foundation movement
- Loss of Arch support
- Foundation scour
- Impact damage
- Weak or uncompacted fill material
- Water ingress into the arch

Most of the above can be seen on inspection however there are some simple non-obtrusive tests that can be performed to gain further information into the existing condition

These tests can be applied equally to metal as well as concrete and masonry arches and whilst simple to undertake they require a degree of skill and experience to assess the results. The more information that is made available will reduce the level of conservatism that the interpreter will make when conducting these tests.

If at all possible the addition of some simple low cost intrusive testing such as trial holing, core drilling or cyclic hammer dynamic probing would confirm the results of the non-intrusive testing and thereby allowing the designers to optimise the proposal and eliminate the need to assume the worst and overdesign.

The following is a sample of non-intrusive testing that can be deployed to gather additional information.

2.1 Hammer Tapping Test

Using either a Schmitt hammer to test for surface hardness or hammer tapping on the surface to interpret the sound made.

The Schmitt hammer will give an indication of the strength of the masonry or concrete whilst the tapping could indicate voids or loose material within or behind the arch.

2.2 Acoustic Emission.

This involves listening to the structure as traffic moves across the bridge to detect if the structure is deteriorating under load. To undertake this would require the installation of piezo-electric accelerometers to the structure to measure the elastic strain energy in the form of elastic waves that are released through the cracks as they develop under load.

2.3 Radar

GPR has advanced significantly over the last 15 years with the capacity to reliably penetrate up to 10M. This is now seen as a reliable methodology of non-intrusive inspection to enable evaluation of voiding, changes in ground strata and soil density as well as potential obstructions behind structures.

2.4 Thermal Imaging

The use of infra-red and thermal cameras are used to detect variations in temperature with the imagery displaying different colours according to the temperature.

Heating the surface up with infra-red lighting which is immediately followed by a thermal camera will detect the presence of voids or water behind or within a structure as the void area loses heat at a greater rate than dense material as does water.

Thermal imagery has been used successfully to detect voids within cable ducts in post tensioned bridge spans and is now regarded as a reliable methodology for bridge inspection.

2.5 Ultrasonic Testing

Ultrasonic testing is a quick inexpensive non-intrusive means of testing for delamination's and thickness of metal structures such as corrugated steel pipes

More commonly used on metal structures but can also be used on reinforced concrete to detect reinforcement.

As well as the above, other tests with endoscopic cameras, vibration monitors, magnetometer's and strain gauges can also be easily used to gain additional information.

3. Design

The following sets out the design parameters that should be considered in the development of a lining proposal.

3.1 Design Elements

Designing a potential lining for a small bridge requires consideration on several fronts; fundamentally this will be the permanent works however the temporary works, the materials and also the construction application should also be considered in the design phase.

In particular the materials that are being proposed will have a significant bearing on the success of the solution and detailed analysis of what is available is an essential consideration.

3.2 Design Philosophy

The principle requirement is to develop a design that will service the required scope, meet the site constraints whilst servicing the project demands. ITS have successfully adapted a technology originally developed for lining Tunnels and culverts to service small arched bridges using basic engineering principles to confirm designs suitable to meet the requirements of the Australian standards.

This system called Tunneline® is a structural concrete lining which is designed as a rigid buried pipe in accordance with Australian Standards, this takes recognition of the loading, concrete, reinforcement and classification as prescribed under AS5100[4] as well as the applied loading due to soil and railway traffic, or road vehicle traffic where required, which are calculated in accordance with AS/NZS3725[1].

This standard provides a method to determine a uniform pressure at the top of the structure, and an equivalent point load to be applied to the top of the lining based on compaction of the surrounding soils.

The structural lining is then designed in accordance with the point load test procedure outlined in AS/NZS4058[2] to determine the exact concrete design actions (bending moment, shear force, axial force, etc.)

The reinforced concrete structure is deigned in accordance with the requirements of AS3600[3], or AS5100[4] where a 100-year design life is required.

3.3 Design Parameters

Parameters included in the culvert reline design include soil cover from obvert of the existing structure to surface level, structure diameter or profile and deformation (survey), Vehicle or railway traffic live load, soil type and density, host culvert installation, condition and support zone compaction

3.1.1 Information required

If possible a condition report on the structure together with a ground investigation report would be ideal however these are not always available.

If not detailed survey of the culvert or bridge should be undertaken to determine the internal dimensions of the host structure at regular intervals across the span and along its length. These dimensions were used to accurately determine the position of the Tunneline concrete liner within the host structure.

3.1.2 Live Load Requirements

Linings are generally designed in accordance with the live load requirements of AS/NZS3725[1]; which adopts the 300LA (30 tonne axle load, 30 TAL) vehicle from AS5100[4]. However each project will be different and needs to be designed with the Client requirements and reference specifications.

Soil loads on the structure are determined in accordance with AS/NZS3725[1] and AS/NZ5100[4].

The soil load calculation considers: soil cover from obvert of the existing arch to ground level, arch width, trench width, soil type and density, host structure condition and compaction of the support zone and side zone material surrounding the existing structure.

3.2 Design Considerations

In the design assessment the following issues need to be considered:

- What was the original construction method of the structure, embankment,- trenched – bored and the effect on calculation of soil load.
- If water passage is expected what likelihood is there of cavitation around the structure and loss of side zone and bedding support and the effect of this on bedding factor and soil load
- Can we consider the new lining construction equivalent to a jacked/bored pipe to reduce the soil design load.

3.3 Design Assumptions

If there is an absence of exact data a statement of the assumptions made in the lining detailed design phase should be stated in the proposal for soil density, trench width, and side zone compaction. These assumptions need to be considered further prior to construction of the reline and the design modified as necessary.

3.4 Engineering Considerations

Not all structures are uniform and often deformation or damage exists. Due to this variability of the host structure the thickness of the concrete reline will vary across the arch and along the length of the structure. The reinforcement design needs to considered this and detail for all conditions that may be accounted with an economical reinforcement detail agreed.

3.5 Modelling

Ideally the lining should be modelled using finite element (FE) analysis. Various models are now on the market that provide both two-dimensional beam models as well as 3 dimensional analysis. These may also consider the point load test procedure outlined in AS/NZS4058[2], with point loads applied to the crown of the lining, as calculated in accordance with AS/NZS3725[1], and the invert of the culvert restrained as required by AS/NZS4058[2].

Where necessary three-dimensional FE modelling can be used to consider the distribution of load along the length of the arch if rebar cover and lining thickness is an issue.

Other considerations on action (bending moment, shear force, axial force, etc) outputs from the FE model are then used to determine concrete strength and reinforcement requirements.

3.6 Reinforcement Design

Reinforcement design will be relative to the loading requirements specified in the scope and will be different for each project.

Designs can either be standalone elements assuming 100% of the loading condition or if being used with existing masonry or concrete arches, they can be designed as composite elements taking some of the property of the host structure. In the case of the latter, there is generally a saving in the reinforcement and lining thickness due to the development of a composite action.

For linings to masonry structures It can be argued that when designed as a Stand-alone element that whilst a structurally sound lining results, it is generally over reinforced with regard to the established structural codes for reinforced concrete and therefore oversized and can be uneconomic in that respect.

In the UK a number of designs have been undertaken where other structural considerations than Crown Arch Bending have had to be taken into account. These have been undertaken under Limit State design concept to BS5400, (AS5100) [4], BS8110, BS9295 (AS4058) [2] and BS5628, and it is found that the use of these well-established structural codes are compatible with the Tunneline process designed as a composite lining suitable for a design life in excess of 120 years in the UK.

In the design review, consideration should be given to the methodology for fixing the reinforcement and the stability of the cage in the temporary condition prior to the installation of the lining formwork.

To consider this reference should be made to a study by the UK's Temporary Works Forum in particular a paper titled "Stability of Reinforced cages prior to concreting" [5] reference to this will enable designers to calculate the effective strength of the cage when tied so that it was capable of supporting its own weight with a safety factor of over 3.5.

3.7 Formwork Design

Tunneline uses a unique light weight shutter system based around a modular format that fit together then is compressed around the host structure to form a rigid form into which the concrete is placed.

The formwork is spaced off the host structure with screw bars that can be adjusted to set the required thickness of lining.

Formwork can be manufactured to almost any shape and can be full or part profile as required on the project.

Figure 3: View of screw bar through shutter onto host structure

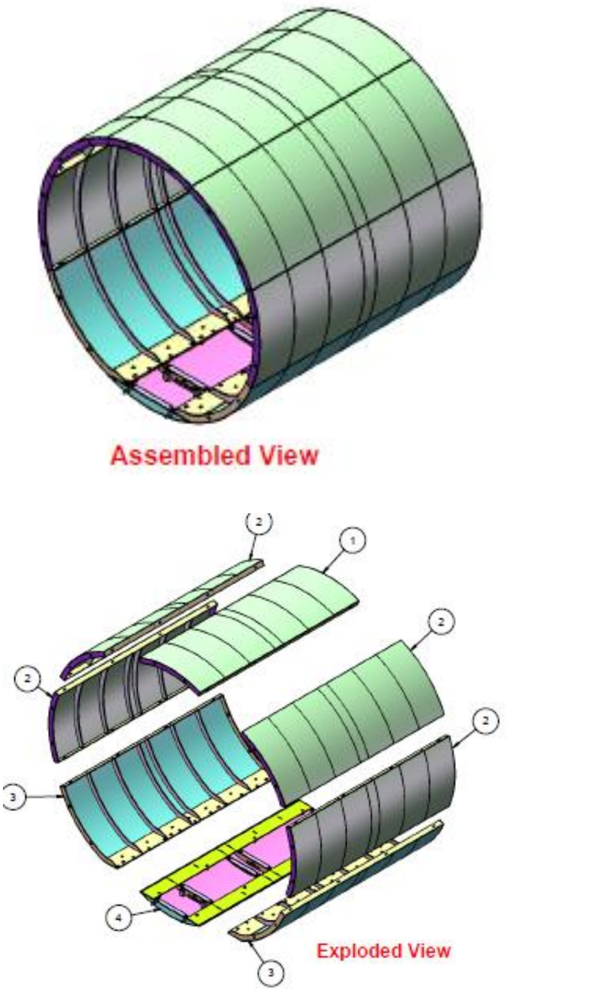

Figure 4: Assembled and exploded 3D view

Generally the hydraulic flow of a completed Tunneline is more efficient than the host structure as the friction co-efficient of the new lining is superior to corrugated steel.

Colebrook – White Roughness Coefficient (K) [2]

Reinforced Concrete (Ferro Cement) = 0.015

Corrugated Steel pipe (CSP) = 3.00

One of the key benefits of using an arched or circular cast in place lining that is constrained behind a fixed rigid formwork is that it quickly adopts the structural properties of an arch which is an ideal element for the application to reinforced concrete,

Figure 5: Half circle obvert lining to brick arch.

Concrete trial mix tests undertaken in advance of the works commencing will indicate 24-hour strengths. This needs to be in excess of 10 MPa. Design checks taken in accordance with the loading requirements will indicate when the shutters can be removed safely without risk to the integrity of the new lining.

3.8 Concrete Design

A fundamental element of the design is establishing the concrete mix and after many years of installing Tunneline experience has concluded that if anything is going to go wrong it will be due to the concrete therefore determining the right mix and maintaining a rigid quality regime is paramount to the success of any project.

Most clients have a suite of preferred design mixes however not all of these will be suited to the Tunneline technique so it is vital to establish the performance requirements and environmental class of the structure and how it will be exposed in the life cycle of the structure.

Minimum cement content of not less than 390 kg with a maximum 25% fly ash replacement is a good starter. Water cement ration (WCR) of between 0.4. to 4.25 and a slump range was set between 220 to 260 mm with an optimum target of 240 mm is a good place to start from.

Mix proportions can vary but a blend of fine aggregate/coarse/fine sand in the ratio of 2:1 per cubic metre is reasonable however this will vary depending on the exact property of the source material. In this respect it is essential to review the material petrology and certification prior to developing the final mix design.

Generally a mix design would stipulate that at least 90% of the coarse aggregate had to pass the 9.5 mm sieve in order to maximise the penetration of the mix around the host unit.

Water reducing additive and super plasticiser-would also be required in the mix development to ensure workability.

4. SITE WORKS

4.1 Installation of Reinforcement

The importance of accurately spacing and locating the reinforcement cage is fundamental to the functionality of a Tunneline rehabilitation regardless of where it is being installed. If positioned out of tolerance the design will not function as intended therefore great care is taken in the positioning of the initial cage and spacers.

As well as accurate location stability of the cage during erection and prior to installing the formwork is also a major safety

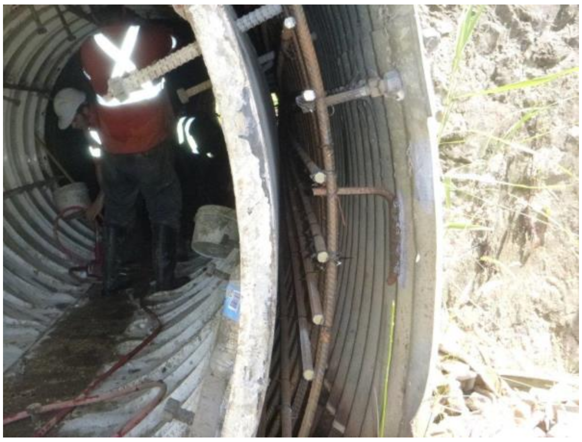

Figure 6: Spacing Bar Located Inside the Host Structure.

Once the main primary distribution bars are installed the arch or hoop bars are then tied along the culvert length to the correct spacing followed by the remainder of the primary cage distribution steel. After the main cage is fixed and checked for tolerance the additional reinforcement is attached as required by the design.

Figure 7: Reinforcement cage in position inside Box Bridge

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4.2 Concrete Quality Control

Maintaining a strict quality control regime for the concrete supply is a key deliverable for the success of the lining and the need to develop a fully traceable solution is a key factor that has to be addressed.

The constituent materials that are available for the concrete design need to be studied and a suitable mix design developed. It is recommended that Fly ash or GGBS be considered in Concrete designs to assist in the control of shrinkage and thermal movement.

Once this has been determined trial mix testing and pumping tests need to be undertaken to make sure the concrete performs as expected .

If correctly batched spans in excess of 8.0m can be successfully delivered.

Figure 8: Parabolic formwork to 6.0m Bridge Span

Figure 9: Completed lining

4.3 Shrinkage and Thermal Movement

Most design codes provide guidance on restraint reinforcement content for these crack propagation criteria. However, from the expression provided it is clear that this extent of reinforcement is meant to cover for situations where the structure member is considerably more exposed to both shrinkage and thermal movement than is present in a rehabilitation lining.

Crack propagation is a complex matter and generally considered in time dependant phases. Considering each phase against a lining situation:-

a) Plastic Cracking.

This is a severe condition affecting an exposed face and greatly aggravated on hot dry days when rapid drying out of an exposed surface is allowed; severe cracks usually open up at each rebar position within a matter of hours of the concrete being placed.

There is no exposed face in the Tunneline lining process, if the local condition is hot and dry a curing agent should be applied to the exposed concrete face as soon as the formwork is removed.

b) Early Age Cracking.

Usually develops within the first 3 to 7 days and is generally related to high thermal gradients between core and surface, and predominantly high initial hydration temperatures with inadequate control of temperature drop at the concrete surface.

A thin lining does not develop high temperature or gradient levels and the existing surface temperature release is retarded on the rear face by the existing structure and from the front face with the application of a curing agent as soon as the tunneline formwork is removed.

c) Shrinking Thermal Movement Cracking.

This longer-term effect is also militated, in that thermal movement is over a far more limited range than structures above ground, both from diurnal and seasonal changes in temperature. Shrinkage is also less with permanently saturated or wet concrete, which also assists in crack potential self-healing from the concrete constituents.

With the lining bonded to the original structure, restraint is also provided to the rear face as well as restraint from the longitudinal secondary steel to the front face, such that shrinkage strains that do arise should be evenly distributed throughout the lining.

d) Construction Joints/Movement Joints.

Whilst the lining is almost always cast in full profile, occasionally discreet bay lengths are cast depending on the shuttering process and depth of the span which can create construction joints at intervals from 10m to 20m apart.

It has not been reported that these construction joints provide shrinkage movement relief and is probably unlikely if there is a bond restraint to the rear face.

It seems therefore that reinforcement over that provided, as the secondary reinforcement minimum is not required for crack propagation restraint.

4.4 Compressive stress in the Existing Masonry

In the UK a Limit State Code for use of masonry BS5628 part 1 “Structural Use of Masonry” [8] has been in use for a number of years. It is currently under revision and will be complementary, initially, to Euro code 6 with DD ENV 1996 – 1:1

These documents are intended to provide data and advice on new construction under a quality control regime. Nonetheless, they provide a range or compressive values for brickwork masonry, relative to unit and mortar strengths; fundamentally from a wide range of test panel results.

Further analysis work has been undertaken by mathematically modelling masonry as an isotropic linear elastic brittle material (G.N. Pandel et al – University College Swansea). [7]

With the present state of knowledge and fundamentally that the quality of the brickwork or other medium comprising the existing structure cannot be obtained in quantitative terms, the assumptions for the upper limit allowance should be placed on compressive capacity and should be stated in the design summary.

It seems that for an analysis such as has been carried out in the Sensitivity Analysis (Appendix B) that based on what is evident in the intrados of the basic structure, and of internal distortion as a guide, an upper bound value of 3N/mm² is the safe limit, without application of a factor of safety.

Above this level of stress, it is generally advisable to restore the compressive zone of the existing structure to a sound condition which is normally undertaken by stabilising the soil around the arch with a cementitious grout.

In particular cases where localised cracking is the main result of distress in the original structure, a more satisfactory level of restoration may be achieved by epoxy grout injection.

4.5 Installing Tunneline

Installing the Tunneline formwork starts by laying the base or kicker panels which are set to line and level by the site Engineer

Once this is complete the remainder of the shutter panels are erected to form a completed profile, generally 2.0 m in length, as this is undertaken the screw bars are lightly tightened against the host to aid stability prior to repeating the cycle with the next set of shutters, and then the next until the complete formwork is assembled.

When all of the formwork is installed the line and level is rechecked, adjusted where necessary before the screw bars are fully tightened to lock the formwork into place. On completion of this, the final brace supports are installed and tightened and the stop-end is set to complete the sequence. Again, throughout the formwork installation process constant QA checks need to be undertaken and recorded to confirm that the correct cover is maintained to the reinforcement at all times

Figure 9: Erection of the shoulder panels

Figure 10: Records of reinforcement cover as the shutter is erected.

Concreting is undertaken by placing the concrete into the formwork through a purpose made injection port, the first of which is located at one end of the shutter in the obvert. Concrete is pumped in through the port and the shutter is progressively filled from this end port until it is full and begins to travel along the formwork.

Ports are established every 2.0 m along the shutter however the pump line is not moved to the adjacent port until the concrete has travelled past this point such that, when moved and reconnected concrete is then pumped into the previously placed concrete continuing to push it further along the shutter therefor eliminating the potential to create trapped air pockets.

As the concrete is pumped into place inside a constrained rigid shutter the effect of this creates intense compaction that requires no vibration. On completion of the pour the screw bars are removed as the concrete is retaining the formwork.

Figure 11: Works in preparation for Arch lining

Generally each concreting operation will take 3 to 8 hours depending on the length of arch and depth of span.

Striking of the formwork is normally undertaken on the day after the concrete has been placed. The pre commencement works on testing the design mix will have determined the early age strength to enable this.

4.6 Works Completion

Most small bridges have single spans and depths around 8 to 10m therefore most will be lined using a single pour however some may contain multiple spans or could be up to 100m depth- Many culvert structures greater than 1200mm diameter are classified as Small Bridges under Australian standards. If when lining a multi span or long single structure as each section of the formwork is taken down it is moved through the structure and reassembled for the next pour. This cycle continues until the lining is complete.

Figure 12: Working platform for infilling screw bar holes and pump ports

Figure 13: Completed liming to a small RC arched bridge designed as a mirrored parabolic ring (with fish passage)

As the formwork is fabricated from profiled steel the resulting surface is extremely smooth, almost polished with minimal work required to finish. The holes left by the screw bars and pump ports are filled with a high strength non-shrink construction mortar.

5. CONCLUSION

The use of the Tunneline system is an alternative approach to small bridge renovation and can deliver savings in time and cost over conventional lining systems with no impact to the operation of the infrastructure that is running above.

Road closures, rail shutdowns, diversion routes, speed restrictions are not required

When using Tunneline there is often no need to undertake any pre-remedial works: the host structure acts as a temporary external shutter for the new lining, and the lining concrete will penetrate any external voiding as long as passage to the cavity is made available. Existing degrading structures can be encapsulated without the need for demolition.

Wing walls revetments, aprons bases and headwalls can all be incorporated into the lining design and these can be linked together to act as ground staples in the case of a settling embankment.

The system has a reduced carbon footprint from less site traffic and vehicle operation and benefits from a reduction in noise and general disruption all round There are significant time saving from a one-pass operation.

The advantages of considering a Tunneline lining option are:

Full Compliance with Australian Codes and Standards.

- No disruption to the infrastructure above.
- Flood immunity is not compromised
- No lane or track closures.
- No speed restrictions.
- 100 year design life.
- Short construction program
- Ability to enlarge width of bridge structures
- Works with existing flows

6. REFERENCES

[1] AS/NZS3725 – 2007 Design for installation of buried concrete pipes

[2] AS/NZS4058 – 2007 Precast concrete pipes

[3] AS3600 – 2009 Concrete structures

[4] AS5100 – 2004 Bridge design

[5] Temporary Works Forum TWf2013:01 “Stability of Reinforcement Cages Prior to Concreting” Oct 2013.

[6] Colebrook White Roughness Coefficient

[7] G.N. Pandel, Isotropic linear brittle material

[8] BS5628 part 1 “Structural Use of Masonry