Masonry Arch Bridges and Tunnels
Repair and Strengthening:
A Case Study

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Introduction

There are relatively few, functional masonry arch bridges and tunnels in Australia compared with Britain and Europe and of those remaining, many are under pressure from increasing traffic volumes and loads, often exceeding levels anticipated at the time of construction.

Sympathetic, effective and economically viable repair and strengthening solutions can be difficult to find and implement. In addition, other considerations including heritage and public interest often affect these assets and can make the task even more challenging.

This paper presents a brief outline of the MARSYS - Helifix System for retrofit strengthening of masonry arch bridges and tunnels, and describes a Case Study of a masonry arch, rail-bridge pedestrian underpass strengthening project completed in Seymour, Victoria. This structure has a single span masonry arch supported on masonry abutments, with a clear span of 3.8m and a rise of 0.68m at the crown. The arch barrel consists of four arch rings, with brick on edge laid in stretcher bond. Overall, the structure is 8.57m wide and carries a single rail line. Investigations were undertaken to determine the extent of structural and other defects and devise the optimal solution for repairs and strengthening.

Figure 1. Rail Bridge Pedestrian Underpass, Seymour VIC
Development of the MARSYS - Helifix System

i) Background

In the United Kingdom, it is estimated that there are in excess of 90,000 masonry arch bridges still in use and with many being much older than the few comparable structures in Australia, they face even greater problems and challenges.

During the 1980’s a UK firm of Consulting Engineers, Structural Survey Partnership (SSP), developed a software package called ASSARC for the analysis of masonry bridges. The package was used to analyse ten redundant UK masonry bridges which were tested to destruction and it was shown to have an excellent fit to the test results. Further ASSARC analysis also showed that a large number of UK masonry bridges were under strength (Sumon & Ricketts (1995)) [1]. (Falconer et al. (1996)) [2].

ASSARC was later extended to analyse retrofitted arches and became known as MARSYS Masonry Arch Analysis Software Package (Boughton & Falconer (2001)) [3].

Between 1996 and 2005, Transport Research Laboratory (TRL) Structures Team conducted extensive research to investigate different repair and strengthening techniques including full scale laboratory tests of the MARSYS-Helifix system as part of a Link Project (DPU 9/64/80) with industrial partners; SSP Consulting Civil and Structural Engineers, Helifix Ltd, Pro tec Industrial Limited, British Waterways Board, London Underground, Railtrack and County Surveyors Society, to demonstrate the effectiveness of the systems (Sumon (2005)) [4].

To date, over 150 masonry arch bridges, tunnels, culverts and similar structures in have been analysed and strengthened using this retrofit system.

ii) The Strengthening Concept

Masonry arches generally belong to the civil engineering heritage of the railways and therefore their refurbishment requires careful consideration. Complete demolition and replacement of deteriorating masonry bridges is often not an acceptable or viable option and therefore the solution may lie in optimised maintenance, including strengthening and repair strategies [5].

A fundamental requirement is that any maintenance and rehabilitation intervention should maintain the structural integrity of the arch and be physically, chemically and mechanically compatible with the existing structure. Strengthening works that do not take account of the fundamental modes of structural behaviour are unlikely to be beneficial.

The key purpose of reinforcement systems is to increase the overall load carrying capacity of the arch barrel whilst not reducing the structure clearances or adversely affecting the appearance. The other key benefit of the MARSYS-Helifix strengthening system is that it can generally be installed quickly and with minimal disruption to bridge users compared to more conventional techniques such as saddling.
iii) MARSYS-Helifix System Design

The MARSYS-Helifix reinforcement system consists of a circumferential and transverse grid of a proprietary (Helifix), high tensile, helical stainless steel bars, installed into raked slots in the soffit of the arch. The grid is connected at intersections with similar radial reinforcement pins which also tie together the multiple rings of the arch. Figure 1

The reinforcement and pins are bonded into place with a high-bond strength injectable thixotropic (HeliBond) cementitious grout which allows the transfer of tensile loads from the masonry to the reinforcement and provide an excellent and continuous bond along the full length of the reinforcement bars and pins.

The reinforcement System helps to retain the integrity and profile of the arch structure, hence delaying the formation of the first hinge under the load line and increasing the load capacity of the arch.

The principle of the reinforcement is to provide both tensile ability between the bricks making up an arch ring and provide greater resistance against the onset of the hinges. In addition, the radial pin component of the System provides a bond between the arch rings comprising the arch barrel to prevent arch ring separation thus enabling the arch rings to act as one single arch barrel.

The System improves resilience by helping to constrain existing cracks and the onset of new potential cracks and provides large increases in “pseudo ductility”, allowing the strengthened structure to deform without collapse (as observed by Ismail et al. (2011)) [6]. Another study showed, “significant increases in strength and ductility (particularly the latter) can be achieved using the [Helifix] stainless steel reinforcement” (Masia et al. (2010)) [7].

Consideration should be given on the degree of strengthening that is permissible and whether the repaired performance of the bridge after strengthening will be detrimental to its future serviceability. For instance the increase in load transmitted to the foundations could cause additional settlement, which a stiffer reinforced arch may not be as capable of resisting, or compressive stresses within the arch material could be increased to unsatisfactory levels [8]. In the case of the masonry arch at Seymour pedestrian underpass, consideration was given to the stability of the abutments and their foundations, resulting in the resin injected underpinning works prior to the strengthening of the arch.

iv) Verification

Extensive investigation has been undertaken to verify the adequacy of the strengthening system by full scale testing.

Un-strengthened arches were analysed to determine the failure modes and capacity.
The analysis technique has been used to model both the TRL collapse test on Torksey Bridge in Lincolnshire [9] and also a further TRL test conducted on a full scale model bridge, built and tested under laboratory conditions [10]. The TRL laboratory test considered a 5 metre span, 3 ring brick arch. A line load was applied above the quarter point of the bridge and a test to failure carried out under displacement control. Figure 2 shows the progressive collapse predicted by the computer analysis of the un-strengthened bridge.

![Figure 2: Simulation of the TRL laboratory test of an un-strengthened bridge](image)

The calculated failure load using the DE method was 18.6 tonnes which compares well with the actual failure load of 20 tonnes.

Retro-fitted reinforcement strengthening techniques were then tested by TRL in October 1997 through to September 1999.

The installation of small diameter stainless steel reinforcing was distributed throughout the arch rings on three models at the masonry arch facility at TRL where they were tested to investigate the increased load capacities and associated effects. Data from these tests was then used to calibrate finite element models to examine the range of applicability of the systems to larger structures and a range of differing material strengths [11]. The partners involved in these tests included: British Waterways Board, Railtrack Civil Engineering, Helifix Ltd, London Underground Ltd, Oxfordshire County Council, and SSP Consulting Engineers.

Masonry arches containing ring-separation were strengthened and tested to failure. The 'Helibeam' (Helifix) System was used to strengthen and test two of them. One arch was strengthened using a prototype and the other arch used a modified version, developed as the result of the first test. The other arch was strengthened using a modified version of the Masonry Arch Repair and Strengthening ('MARS') System, which was developed following earlier tests under a separate programme at TRL. Both systems consisted of a network of stainless steel wires (helical profile in the Helibeam System and standard ribbed in the MARS System), that are installed and bonded into rebates cut into the soffit of the arch. Radial pins were also used for tying together the separated arch rings [11].

The multi-ring masonry arch bridges containing built in ring-separation were then tested under the worst case load conditions.

The tests showed that the load carrying capacity was significantly increased by the strengthening. Radial and circumferential reinforcement provided additional stiffness into the barrel and this limited the movement of the separated rings in both the radial and circumferential directions making them behave in a composite manner. This type of strengthening would be most beneficial for an arch with mortar or masonry because it distributes the reinforcing effect evenly over a large area of the ring. [11].

Compared to sprayed concrete or saddling, minimum reinforcement is required to achieve a significant increase in the strength of the structure. Hence using small diameter reinforcement is an effective method of strengthening masonry arch bridges [11].
Case Study

Rail Bridge Pedestrian Underpass, Seymour, Victoria.

i) Assessment

Following an initial inspection several key defects were identified to the arch barrel, the abutment and the spandrel walls which indicated structural distress and potential overloading.

There were several diagonal cracks in the arch barrel around the concrete plug in the crown of the barrel approximately 4m in from the downside elevation. At least one no. crack was visible on the extrados (following a trial pit excavation), indicating that the cracking was through the entire barrel thickness. (Figures 3 and 4).

It was identified that there was a lack of cover over the arch barrel, which combined with the positioning of a concrete sleeper directly on the crown of the arch, was adversely affecting the structures integrity. Figure 5.

Subsequently there were indications that the formation of hinge mechanisms had already formed and therefore the structure required immediate attention.

Figure 3.

Figure 4.

Figure 5.
A diagonal crack on the country abutment from the invert to the springing point approximately 2.9m in length was identified, indicating distress/possible settlement in the foundations. Figure 6.

ii) Feasibility

The structure was in need of immediate attention as the formation of a mechanism has been established. This was visible in the form of cracks opening and closing as the hinge locations responded in compression and tension as the trains individual axles passed over the structure.

A resin injection ground stabilization and underpinning technique (Uretek) [12], was carried out to lift and in the short term to stabilise any further movement beneath the abutment, and allowed the structure to remain operational, at a restricted speed, whilst a long term solution could be developed.

During a feasibility study, the following options were explored:

- Strengthening of the arch barrel
- Partial replacement with a box culvert
- Sleeving with a concrete / corrugated steel pipe.

However, early on in the investigations it was identified that the structure was heritage listed, which limited the options and favoured the strengthening option.

The strengthening of the existing structure required detailed structural analysis to be undertaken and MARSYS software was utilised in order to determine the reinforcement required and to calculate the strengthened capacity of the bridge following the implementation.

iii) Soil Properties

The software takes into account the behaviour of backfill as a result of arch barrel movements and subsequently calculates the associated passive pressure. These horizontal backfill pressures act to stabilise
the arch barrels and have been found to increase the carrying capacity of the structures as found by (Melbourne & Gilbert (1997)) [13].

The effective angle of soil friction and the cohesion of the fill material are required for analysis of the horizontal backfill pressures. Previous testing carried out at Bolton [13], has shown that typical values of well compacted, consolidated backfill materials are:

- $\phi = 50^\circ$; and
- $c = 5$ KN/m$^2$ (dependant on soil type)

However, given that no test data was available to determine these parameters, it was assumed that there is no cohesion and the value of the co-efficient of passive pressure ($m_pK_p$) was taken as 1.23 in the unrehabilitated condition, which was deemed to remain conservative given the poor saturated backfill conditions reported. The fill in most arch bridges will be very well compacted (due to trafficking and consolidation) and hence relatively large passive pressures can be expected to mobilise, even when arch displacements are relatively small. Thus, we can determine $\phi$ from:

$$m_pK_p = \frac{1}{3} \times \tan^2 (45 + \phi/2),$$

Therefore, when $m_pK_p = 1.23$, $\phi = 35^\circ$

**iv) Characteristic Strength of Masonry**

As no coring or strength tests were carried out on the masonry material at the structures, conservative values using engineering judgement were assumed.

From testing carried out on similar structures constructed approximately during the same period, the characteristic masonry strength of the clay brick was calculated to be 5.66MPa, as shown in the calculations below;

If $n<10$, $f' = k_n f_{spl}$  (B2(1), AS3700-2011)

- $k_n = 0.811$ (Table B1, AS3700-2011)
- $f_{spl} = 21.5$ MPa (Lowest Test Value)
- $f' = 17.43$ MPa

The characteristic strength of the masonry is then $f'_m = k_hf'_m$ (AS3700-2011 clause 3.3.2)

- $f'_m = k_m f'_m$, $k_m = 1.1$ and $f'_m = 4.6$ (Table 3.1, AS3700-2011 assuming a worst case mortar classification(M2))

Therefore $f'_m = 2.35$

- $k_h = 1.3 (h_u/t_j)^{0.29}$, where ($h_u = 76$ mm (typ.) and $t_j = 9$ mm (typ.), $k_h =2.41$

hence $f'_m = 5.66$ MPa

Therefore by applying a conservative reduction to take into account the unknown masonry clay brick strength, a characteristic masonry strength of 5MPa was adopted, with an upper limit of 5.66MPa.
v) Inter Ring Sliding / Ring Separation

In analysing the arch in its deteriorated condition, the analysis software has several types of brick bond available for the arch barrel construction. Seymour Arch Bridge has been constructed using a stretcher bond which inherently has a weak inter-ring bond, and can be modelled using the ‘Multi-ring (debonded)’ selection. The analysis software will subsequently model all of the arch rings as separate entities, with only a frictional interaction with one another which simulates the behaviour of arches with identified delamination/arch ring separation.

By selecting ‘Multi-ring (debonded)’, the model considers each ring as a separate entity with only a frictional relationship between rings. This assumption is adequate to account for any unidentified ring separation, and therefore no additional reductions were applied.

Note – By assigning contact zones between arches as zero, no inter ring friction would be present upon ring separation. Previous testing shows that the value of friction for cracked mortar joints has an indicative value of 0.64 (Melbourne & Gilbert (1995)) [15], which represents the interaction during inter ring sliding.

If there is no sign of de-lamination of the arch barrel, then individual rings making up the barrel could be combined in the analysis model as a “single-ring” to obtain an upper bound for the critical load factor. However, actual number of rings should be used where possible to give more realistic critical load factors. Note, beyond span/rise ratios of approximately 4 (3.8m/0.68m = 5.6 at Seymour Bridge), the inter-ring stresses rapidly increase with load, which can lead to underestimating the ultimate capacity in some instances if this concept is adopted.

The strengthening design at Seymour Bridge was to include the use of radial pins which prevent arch ring separation, and therefore any allowance for ring separation in the model was removed.

vi) MARSYS - Helifix System Prescribed Solution

The bridge rehabilitation works, which also included abutment stabilisation, replacement of backfill material, improved drainage and a track lift, were analysed and designed by Opus International Consultants, and verified by Helifix using MARSYS Masonry Arch Analysis for the un-strengthened arch, the temporary condition during construction, and the completed rehabilitated condition.

This analysis was typically undertaken by idealising the structure based on survey information retrieved during the inspection.
Figure 7.

A snapshot of the MARSYS design model for Seymour is provided (Figure 8) below:

Figure 8.
vii) Site Works and Implementation of the MARSYS - Helifix System

Once the abutment foundations were stabilised utilising the ground injection technique described previously, the following work was undertaken:

- Phase one consisted of the drilling and installation of (Helifix, CemTie Super6) radial reinforcement pins in a grid pattern and spacing of approximately 450mm centres into the four arch rings making up the arch barrel, and followed up with the installation of the (Helifix, HeliBar Super6) longitudinal and transverse near surface reinforcement, also grout bonded (using HeliBond), into narrow slots chased in the arch intrados approximately 40mm deep and 450mm centres. Figures 9 and 10.

![Figure 9](image1)

*Figure 9.*

The reinforcement bars also extend into the abutment walls by at least 400mm, as can be seen in Figure 10.

![Figure 10](image2)

*Figure 10.*
Phase two involved the removal of the backfill material, exposing the areas behind the abutments and replacing the fill material with a well graded and well compacted material.

Phase three involved raising the track levels to allow for more cover to be provided over the structure to allow for improved load distribution and finally making good the track and re-commissioning of the bridge and track.

Figure 11. Removal of rail track and backfill in preparation of installation of new extrados waterproof membrane

Figure 12. Exposed arch crown with cores drilled to confirm thickness and barrel ring separation.

Figure 13. Cutting of transverse and circumferential slots for reinforcement system

Figure 14. Installation of MARS/Helifix system
Project Conclusion

The **MARSYS - Helifix System** provided a sympathetic and cost effective retrofit strengthening solution for the masonry arch rail-bridge pedestrian underpass project in Seymour, Victoria. This Heritage listed Rail Bridge asset has been preserved and functionality improved as a result of the work.

**Key Achievements:**

- **Majority of the work was carried out** between Christmas and the New Year, during the scheduled **four day shut-down** of rail traffic from 28\(^{th}\) to 31\(^{st}\) of December, 2013.

- **Minimal disruption** and inconvenience to the rail and pedestrian traffic during the course of the work.

- **Minimal visual impact** to the external features of the heritage listed asset and ongoing improvement expected with further weathering.

- **No reduction in clearance heights** in the arch.

- The project **completed within the planned programme time and budget**.

- **Masonry arch remediation**, combined with the backfill and track lift works **increased load capacity** of the arch by **approximately 100%** compared with original pre-strengthened capacity.

- **Preservation of Heritage asset**.
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