Winchelsea masonry arch bridge: First major maintenance

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The existing three-span stone arch bridge across the Barwon River at Winchelsea was opened on 3 December 1867 by HRH the Duke of Edinburgh, Prince Alfred. For 145 years, this now heritage-listed bridge has carried traffic on the Princes Highway West without loading restrictions. An inspection in 2012 revealed significant cracking of the voussoirs and a load rating of 23 t was posted. The Princes Highway West upgrade project will provide a new river crossing so that the stone arch bridge will revert to carrying pedestrians and cyclists. However, during the construction of the new bridge, the existing stone arch bridge is required to be reopened to traffic without a posted load limit to carry one lane of traffic for up to 2 years. An engineering investigation was therefore required to determine what rehabilitation works were required to facilitate this. This paper presents the results of an engineering investigation to determine a reliable way of replacing the cementitious material between the voussoirs of the bridge. The experience obtained during re-grouting of the three stone arches, which was successfully completed in January 2014, is also discussed.

1. Introduction

It is remarkable that many of the eighteenth century masonry arch bridges that were built to provide the road and rail links that supported the growth and development of the Australian nation’s economy are still in service today. One example is Winchelsea Bridge, which was opened by HRH the Duke of Edinburgh, Prince Alfred, in December 1867.

1.1 Bridge details

Winchelsea Bridge carries the Princes Highway West over the Barwon River. The bridge is 8 m wide and has three arch spans of 10 m, 18 m and 10 m (Figure 1). The stone used for the bridge is bluestone, taken from the same quarry as that which supplied the stone for the construction of Barwon Park. This majestic 42-room bluestone mansion was built for Thomas and Elizabeth Austin close to the bridge site in 1871.

Victorian builders in 1867 had a reasonable expectation that maximum bridge loading would be a steam traction engine or possibly a steamroller with a maximum load of 5–10 t. Until a recent bridge inspection, there was no restriction to road-legal vehicles using Winchelsea Bridge. However, a close engineering inspection of the masonry arches in 2012 discovered extensive loss of mortar in the stone arches and longitudinal cracks in the stone voussoirs. VicRoads therefore imposed a load limit of 23 t for the bridge.

The Princes Highway West upgrade works includes a new bridge to take through traffic off the existing masonry arch bridge. An alternative to modify the existing bridge was considered and rejected on technical grounds (Morris, 2011). However, the existing masonry arch bridge is needed to take a temporary diversion of a single lane of traffic until completion of the new bridge in 2015.

1.2 Legacy

The greatest bridge builders of antiquity were the Romans: they perfected the masonry arch form and examples of their bridges (e.g. Pons Fabricus in Rome, shown in Figure 2) have survived for over a millennium.

In Victoria, Australia, masonry arch bridges built during the reign of Queen Victoria are still an essential part of the road and rail infrastructure. If they are to be retained in service, engineers must thoroughly appreciate the particular technical and practical issues of this familiar, but not well understood, form of structure.

These bridges pass every current test for sustainable construction. With a little judicious maintenance, there is every reason to expect that they will continue in service, subject to proper consideration of load capacity (Steele et al., 2002).

1.3 Deterioration

The weathering and deterioration of structures of this age need careful consideration. Masonry arch bridges do not usually receive the maintenance they require, even when vehicle loading is increased (Al-Jolahy and Kulaib, 2006). For Winchelsea Bridge in Victoria, the following two issues have been addressed.
Spreading and bulging of the spandrel walls due to traffic wheel loads compacting the retained soil fill, which applies higher earth pressures on the walls. This was rectified by the installation of tie bars and pattress plates.

Mortar had been washed out from the joints between masonry blocks. A trial hole opened up on the bridge indicated that the mortar cap, which originally sealed the arch extrados, had broken down and was little more than pervious friable sand. Repointing was carried out on the Winchelsea Bridge spandrel walls using modern cement-rich strong mortars. Out of all the arches, only a few joints of the Colac arch (within reach of the adjacent footway) were repointed.

2. The engineering problem

The basic problem with masonry arch bridges is that they are complex statically indeterminate structures, which few civil engineers design today. Even fewer engineers understand the design, detailing and construction of those that were built over a century ago.

A bridge designer who prepares a new design to current codes of practice knows that the required design life in Australia is 100 years, and thus applies the required provisions (loading, factors, and material, section and overall performance). The artificers who produced many of the simpler masonry arch bridges used rules of thumb based on what they knew had worked before, from their experience (or that of others). They verified their design, usually by considering the line of thrust in the arch (Hendry, 1995). The real test of their designs came when the timber centring was removed, the arch dead load transferred to the abutments by way of thrust through the arch and, finally, when the bridge was tested with the heaviest load available, often a steam tractor or a steamroller. Physical tests are still essential for verifying theoretical developments in the understanding of masonry arch bridges (Melbourne, 1990).

Having established that many masonry arch bridges have survived for centuries and have accepted substantial increases in live load, the question that needs to be addressed is ‘at what point in the life of a masonry arch bridge does it become unsafe and need essential engineering intervention?’ (Figure 3).

The engineer’s problem is, in some respects, more challenging than an original design. Undocumented serviceability failures (cracks, displacements and distortions) that have occurred over a relatively long timescale must be considered. The bridge must be proven to be capable of carrying the required live load with an acceptable safety margin.

2.1 Popular assessment

In wartime Britain, the problem of deciding which of the 70 000 masonry arch bridges could safely carry heavy transport was solved by the Military Engineering Experimental Establishment (MEXE), and their simple method for Royal Engineers in the field was based on Pippard’s work from the 1930s. It was quick and easy to use, and has remained popular among bridge assessment engineers to this day (Wang et al., 2010). The modified MEXE method (Highways Agency, 2001) is mandated as an initial analysis in the UK, but there are growing concerns.
that the modified MEXE method of assessment has significant limitations and it is difficult to rationally advocate its continued use (Gibbons and Fanning, 2012).

2.2 Structural safety
To answer the question 'is this masonry bridge safe?', an appreciation of the way in which such bridges fail is essential and it is preferable that any proposed assessment method is validated against physical tests. A number of masonry bridges have been load tested (Crisfield and Packham, 1987) but the data collected were unfortunately limited (Melbourne, 1990). A series of smaller scale tests has also been carried out, providing an improved understanding of masonry arch behaviour under different loads and taking into account some of the key variables (backfill resistance and load distribution) (Callaway et al., 2012).

Where different design and construction practices are used (for example, masonry bridges in the USA adopt smaller abutments than is the case in the UK), different failure modes can become significant (Boothby, 1995). Regular specialist inspection of masonry arch bridges is thus required to check for the types of cracking in the arch that indicate the onset of certain modes of failure (Proske and van Gelder, 2009).

2.3 Load assessment
A practical alternative to the modified MEXE method as the initial load capacity assessment is the mechanism method (McKibbins et al., 2006). The most common software packages for this method have been compared with an elasto-plastic model (Audenaert and Beke, 2010; Gilbert, 2007) for validation of the output. The better the data used in the analysis, the more reliable the result (Otto et al., 2010). Where the analysis forms a key part of a decision concerning use of the bridge, reliable information about the bridge, material properties and any existing damage should be obtained.

The construction of a masonry arch bridge imposes a radical structural change prior to completion. The masonry in the arch is built on falsework (known as centring). At that stage the arch is ineffective, as it is supported on an independent timber structure. As soon as the centring is removed, the arch carries the self-weight and the backfill in compression to the arch springing points. The arch deforms, and the abutments move as they transfer the load to the supporting backfill. Clearly, the initial state of the arch at this stage has an influence on the load-carrying capacity of the arch. Determination of this initial state may be important in assessing the long-term performance of the arch (Hughes and Bridle, 1990).

The ultimate resistance of masonry arches is what normally concerns assessing engineers. However, the accumulation of fatigue damage in the brittle arch stones also needs some consideration (Tomor and Wang, 2010; Tomor et al., 2013). Fatigue damage can lead to local material failure, which may advance to a stage where repairs are uneconomical.

2.4 Repair
There is a significant amount of experience in the repair and strengthening of masonry arch bridges in the UK (Ashurst, 1992; Page, 1996; Sowden, 1990) and other countries (Al-Jolahy and Kulaib, 2006; Wilmers, 2012). This is valuable information when considering similar structures often built by British bridge builders in Australia.

3. Investigation, assessment and repair of Winchelsea Bridge
The approach taken for Winchelsea Bridge was conventional, with four boreholes used to find the depth of the foundation and the depth of stone backing above the springing of each arch. The geometry of the bridge is shown in Figure 4.

3.1 Investigation
An initial non-destructive examination using ground-penetrating radar (GPR) attempted to prove the thickness of the stone arches and the depth of fill over the arches. The information obtained, however, was not sufficiently consistent to provide definitive data on arch thickness or depth of fill. The reason for the inconsistency appeared to be in the rough face of the intrados of the arch. The use of GPR on rough-faced stone arches appears to require a new method for providing reliable and consistent acoustic coupling with the exposed surface to yield reliable data.

The thickness of the stone arches was determined by taking full-depth cores through each arch. The physical thickness was measured, and the thickness of the arches was found to be different from the apparent thickness of the dressed external arch stones by up to 100 mm. An allowance for potential variability between arch stone thicknesses was made. The strength of the
arch stone was determined from uniaxial compression tests on the retrieved core material. The bluestone was found to have a compressive strength of 25–32 MPa (see Figure 5).

Mortar courses on the spandrel walls adjacent to the middle arch appeared to dip slightly at mid-span, so the arches were checked for arch distortion. The shape of the middle arch was surveyed using a three-dimensional laser survey. Sections through the arch were found to conform to a circular curve radius.

For a bridge of this age, it was expected that the joints would be formed using lime mortar. The existing mortar was sampled and tested. The mortar analysis found the constituents to be lime and sand in the ratio of five parts sand to one part lime.

An underwater diving survey was carried out to determine the conditions of the submerged parts of the stone piers. The survey discovered that some of the mortar courses had mortar loss of up to 150 mm. An experienced bridge engineer carried out a close inspection of the intrados of the arches from a bridge inspection platform. From observations of cracking in the arch stones, it was concluded that cracks were regularly found where mortar in the transverse joints was missing and stone was bearing directly on stone (see Figure 6).

### 3.2 Load capacity assessment

A load assessment for the existing bridge was undertaken using Ring 3.0 and the investigation test data were used for the analysis. Sensitivity tests on the analysis were carried out based on different assumptions for average mortar loss in the joints. The results broadly agreed with the existing load rating for the bridge (23 t).

From on-site clues and local knowledge, it was noted that the bridge is subject to flooding. The flood marker adjacent to the bridge indicated that the maximum flood level was above
the crown of the arches. Submerged densities for the stone and fill were therefore used in the load assessment. The mode of failure for the refurbished bridge identified by the load assessment analysis is shown in Figure 7.

The assessment indicated that reinstated mortar in the joints of the arch had improved the capacity of the bridge. The reinstated bridge was found to have the capacity to safely carry a single lane of 75% M1600 loading (according to AS 5100 part 2 (SA, 2004)).

3.3 Repair

The main concern with stone arches is cracking in the arch stones where the ‘cushioning’ effect of the lime mortar has been lost. To control the development of further splitting cracks, it was necessary to fill the joints with a cementitious material. From a heritage perspective, the preference was to replace the original lime mortar with an equivalent material, which works with the structure, tolerating small amounts of movements between the stones.

The material used in the pointing was a proprietary fine filled, extremely light-weight cementitious mortar (normally used for the repair of concrete). The proprietary mortar mix contained lime (5–25% by weight). The published properties for the mix indicated a 28 d strength of 7 MPa with 3 l of water added to 15 kg of the mortar mix.

A series of experimental trial mixes were made to identify a mix with the required consistency for application to the joints and acceptable 1 d and 28 d strengths. Just sufficient water needed to be added to the mix to enable it to be pumped. With too little water used, the mix would not pump and the resultant blockage would require a complete pump strip down. If too much water was added, the mix had the consistency of whipped cream and was unusable. The contractor therefore needed to gain experience in producing a mix that could be pumped rather than relying on a measured quantity of water. For 15 kg of mortar mix and 4 l of water, an average 28 d strength of 5.6 MPa was achieved.

A method of pointing was developed to enable this material to be provided with acceptable finish: the mortar was left in place for approximately 1 h and then excess mortar was cut back to achieve an acceptable joint finish (see Figure 8).

Figure 6. Arch stones: (a) edge stones in 1867 edge stones; (b) internal stones in 2014

Figure 7. Bridge assessment: mode of response for critical load case
Once the joints were sealed with mortar, a pumpable proprietary grout was modified with lime and introduced to the joints in a systematic manner. Typically, four joints per day were grouted and left to cure. Figure 9 shows the installed grout pipes and the systematic introduction of grout using the adjacent grout pipe to witness when the grout filled the section. The material used for joint grouting was a proprietary general-purpose grout with an expected 28 d strength of 64 MPa for 20 kg of mortar mix and 4 l of water. The proprietary grout mix was modified to provide a lower strength pumpable mix. After a series of trials, a suitable mix was obtained with 20 kg of grout mix, 10 l of water and 1.5 kg of lime, for which a 28 d strength of 12.1 MPa was achieved.

After completion of the arch it was observed that, after significant rainfall, penetration of rainwater through the repaired arch joints had virtually stopped. Alternative drainage for the backfill was provided by new weep pipes installed at the abutment and pier positions.

4. Conclusions
In many cases, masonry arch bridges are the oldest bridges supporting roads and rail track in Australia, and are carrying significantly more live load than when they were built.

Masonry arch bridges need
- a more reliable understanding of load capacity than is provided by the modified MEXE assessment
- proper investigation of the basic data that are relied upon in a load assessment
- consideration of potential load-capacity-reducing events such as flooding
- basic maintenance in order to provide ongoing reliable service.

REFERENCES
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