Summary

Masonry arch bridges are one of the oldest forms of bridge construction and have been around for thousands of years. Brick and stone were the original materials used and these bridges have proved to have a high level of durability, as most of them have remained serviceable after hundreds of years. In contrast, many bridges built of modern materials have required extensive repair and strengthening after being in service for a relatively short part of their design life and subsequently unable to meet current European loading standards [1][2]. This paper describes the development of a flexible concrete arch system that has virtually no embedded steel and can be constructed without centring thereby providing a highly durable and cost effective structure.

Keywords: Arch, Concrete, Pre cast, Un-reinforced, polymer, durability.

1. The Arch system

It is no longer economically viable to construct a masonry arch in the traditional method due to the cost of skilled labour required to build the accurate centring and the cutting of masonry blocks. Progress on this type of work is usually slow and can be weather dependent. The Queens University of Belfast in collaboration with Macrete Ireland Ltd, under a Knowledge Transfer Partnership (KTP), are developing an arch bridge made of un-reinforced pre-cast concrete voussoirs. This is in line with advice given by the UK Highways Agency [3] where the arch form, plain structural elements and the elimination of corrodbile reinforcement are recommended. The arch is constructed and transported in the form of a flat pack using a polymer grid reinforcement to carry the self weight during lifting but behaves as a masonry arch once in place.

There are two options for the construction of the arch unit. The voussoirs can be pre-cast individually, laid contiguously horizontally with a layer of polymer grid material placed on top. An in-situ layer of concrete, approximately 40mm thick, is placed on top to interconnect the voussoirs. The same unit can be made in a single casting operation by using a shutter with wedge formers spaced to simulate the tapered voussoirs. Both forms of construction are shown in Fig 1. The arch unit can be cast in convenient widths to suit the design requirement, site restrictions and available lifting capacity. When lifted, the wedge shaped gaps close, concrete hinges form in the top layer of concrete and the unit is supported by tension in the polymer grid. The arch shaped units are then placed on a precast footing and all self-weight is then transferred from tension in the polymer to compression in the arch.
Fig. 1 Construction Methods of Precast Arch Unit

2. Materials

The Polymer grid used was PARAGRID ® [4] and is available in a range of mesh sizes and strengths. The manufacturer’s data sheet indicates that the material code gives the longitudinal and transverse tensile strength in kN/m. Thus 100/15 material has a tensile strength of 100kN/m. Table 1 summarises the data from material tests carried out at Queen’s University.

Table 1 Paragrid Properties from test results at QUB

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Tensile strength of material from manufacturer (kN/m width)</th>
<th>Tensile strength of material from test results (kN/m width)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100/15</td>
<td>100</td>
<td>43.6</td>
</tr>
<tr>
<td>150/15</td>
<td>150</td>
<td>72.2</td>
</tr>
</tbody>
</table>

The differences between target and actual strengths may be accounted for by the use of BS EN ISO 10319:1996 Standard Test Method for Tensile Properties of Geotextiles by the wide strip (200mm nominal) method used for data sheet strengths whereas the tensile tests were carried out in QUB on a (900mm) long sample having a width smaller than 200mm, which was double folded at the end for gripping. The first 0.35m wide trial arch used the 100/15 material but the 1m wide prototype used the 150/15 to improve the overall factor of safety during the construction phase.

The Paragrid material is shown in Fig 2. The concrete used for casting the Voussoirs was the standard pre-cast mix used by Macrete Ireland Ltd and strengths are given in Table 2. The concrete used for casting the Voussoirs was the standard pre-cast mix used by Macrete Ireland Ltd and strengths are given in Table 2.

Table 2 Material Test Results for voussoirs

<table>
<thead>
<tr>
<th>Nr of days</th>
<th>Concrete Compressive Strength (N/mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>40</td>
</tr>
<tr>
<td>28</td>
<td>55</td>
</tr>
</tbody>
</table>
3. Manufacturing of arch unit

A prototype arch unit of 5m span, 2m rise and 2.5 m internal radius was constructed and lifted. The arch required twenty-three voussoirs which were 1m wide and 200mm deep with a 40mm slab interconnecting in-situ screed. The arch was lifted at approximately the quarter span points with additional nominal support at mid span region. During lifting the arch drags at the each end and the mid span point tends to sag; hence the need for the additional support. When the end cantilevers are fully effective they produce a hogging moment at the mid span region which assists the configuration of the arch form. During this operation a critical case occurs when the arch is fully formed and suspended at the lifting points. A maximum bending moment occurs at the lifting points for the cantilever ends and to simulate this condition a series of short beam elements were tested to establish the capacity and investigates the rate of creep in the low modulus polymer reinforcement. A summary of the results of these tests are given in Table 3 and were found to give an adequate factor of safety during the lifting procedure. The lifting sequence is shown in Fig 3.

Table 3 Results for Test Beams

<table>
<thead>
<tr>
<th>Arch Load Test No.</th>
<th>Applied Ultimate Load: excluding the self weight (kN)</th>
<th>Ultimate Moment: including the self weight (kN.m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>14.0</td>
<td>7.5</td>
</tr>
<tr>
<td>2</td>
<td>16.0</td>
<td>8.3</td>
</tr>
</tbody>
</table>

3a. “Flat Pack”

3b. Arch Unit during Lifting
The arch unit complete with tapered seating is shown in Fig 4. Subsequently, an anchor block detail was designed for the seating of the arch ring. The anchor block caters for the slope of the last voussoir enabling the arch to form correctly. It also provided some lateral restraint to the arch ring both during construction, prior to completion of the arch system with spandrel walls and backfill, and in the long-term under live loading.

Fig. 4 Second Lift of Arch Unit Using Tapered Seating Units

4. Stability Test

4.1 Test set-up

Due to the flexibility of this system, a stability test under backfilling operations was conducted and the arch unit was monitored for horizontal deflections, vertical deflections and strain at the voussoirs joints. Figure 5 shows the instrumentation set-up. It was originally intended to backfill the arch with Type 6S granular backfill under the Specification for Highway Works, Volume 1. However, after a preliminary cost estimate, it was decided to trial the use of lean mix concrete as a backfill option. Shuttering for the backfill was set-up independently to the arch ring to allow free movement under loading.

4.2 Test procedures and results

The backfilling operation was carried out by placing approximately 250mm deep layers of concrete to each side of the arch up to 1.5m horizontal distance from the back face of the anchor block. The distribution of load to either side of the arch ring was aimed at minimising the effects of asymmetric load. The depth of the concrete was measured and the transducer and strain gauge readings were recorded at each increment of backfill load. The readings showed a reasonably symmetric response to the backfilling operation.
40mm screed connecting voussoirs

Backing material (not used with concrete backfill)

Cross section: arch ring

= 2 vibrating wire strain gauges

= 4 Displacement transducers
50mm in from edge of arch
(2 vertical & 2 horizontal)

Typical elevation on internal arch ring

Fig. 5 Monitoring of the arch during backfill operations

A summary of the deflections at various times throughout the backfill operation are given in Table 4 and Fig. 6 shows the arch after completion of the backfill.

The maximum movement in the crown (V1 in Fig. 5) was 0.8mm upwards in the back face and occurred at the full height of the concrete backfill. This was due to the lateral pressure of the wet concrete creating an inwards movement at the sides of the arch which in turn caused the crown to rise.

Fig. 6 Arch after completion of the backfill operation

<table>
<thead>
<tr>
<th>Batch No.</th>
<th>Height of backfill at LHS (m)</th>
<th>Height of backfill at RHS (m)</th>
<th>Average vertical deflection at crown, V1 (mm)</th>
<th>Average vertical deflection 1m LHS, V3L (mm)</th>
<th>Average horizontal deflection 1m LHS, H7L (mm)</th>
<th>Average vertical deflection 1m RHS, V3R (mm)</th>
<th>Average horizontal deflection 1m RHS, H7R (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>1.9</td>
<td>1.8</td>
<td>-0.35</td>
<td>0.7</td>
<td>1.1</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>19</td>
<td>3.0</td>
<td>3.0</td>
<td>-0.5</td>
<td>1.65</td>
<td>1.9</td>
<td>0.7</td>
<td>0.9</td>
</tr>
<tr>
<td>@ 17hrs (creep check)</td>
<td>3.0</td>
<td>3.0</td>
<td>+0.1</td>
<td>1.6</td>
<td>1.5</td>
<td>1.2</td>
<td>1.5</td>
</tr>
</tbody>
</table>

+ = movement inwards and - = movement outwards
As the concrete hardened, the lateral pressure reduced and the deflection response at the crown reversed in direction. That is the upward movement ceased and the crown deflected very slightly downwards. Seventeen hours after the start of the backfill operation, the cumulative deflection was 0.1mm downwards at the crown or midspan region (V1 in Fig.5). The maximum movement at the sides of the arch occurred in the transducers at a height 1m from the base of the arch ring (V3 and H7 in Fig 5). The movement was inwards due to the lateral pressure from the wet concrete. At the end of the backfill operation the maximum horizontal and vertical deflections were 2mm and 1.7mm respectively although these reduced very slightly after seventeen hours. The strain gauges also showed the maximum movement occurred between 1m and 1.5m height in the internal face of the arch ring. The maximum joint expansion was 0.015mm and occurred when the backfill was at a height of 1.8m from the base of the arch ring. The results of the monitoring showed very little movement in the arch ring and it was concluded that the arch was stable under the backfill operations.

5. Analysis of arch unit

An analysis of the arch unit was conducted using ARCHIE [4], a numerical analysis package which allowed for interaction with the arch backfill. It is important to note that this software is also used by the DRD Road Service in Northern Ireland for load assessment analysis of their arch bridges [6, 7]. Therefore, validation of the manufactured arch unit using ARCHIE was an important task in this project. The arch unit was analysed under different wheel loading conditions and various observations were made. A typical case of arch unit analysis is shown in Figure 5. An arch unit of the required geometry can be created and loaded with the standard wheel loads. A line of thrust is indicated in Figure 7. Under design loading, the position of the thrust line in the arch unit gives information about the stability of the unit. Furthermore, it was found that the thrust line is affected by the application of Passive Pressure (PP) and Backing Material (BM) at the springing level (Figure 7). Therefore, for a particular loading condition, using a suitable value of PP and BM, the required thickness of the arch unit can be found. Further analysis using Non Linear Finite Element Analysis (NLFEA) is currently taking place.

Fig 7 Analysis of Arch Unit using ARCHIE Software
6. Concluding remarks

Experience has shown that arch bridges are very durable structures requiring little maintenance in comparison to other bridge forms. However, there has not previously been a UK standard for the design of new unreinforced arch bridges. Therefore the objective of the new Highway Agency Standard [1] is to encourage a renaissance in arch building using unreinforced masonry materials.

The first part of the project has been successfully completed with the construction of the prototype unit. Some of the advantages already identified are:

1. As the Arch system is cast horizontally it can conveniently be transported to site in a “flat pack” form.
2. As centering is not required during installation which should greatly enhance the speed of construction.
3. As there is no corrodible reinforcement the long term durability should be assured.

The next stage will include constructing a complete 5m wide arch bridge with a 5m span and 2m rise complete with spandrels, fill and surfacing. The bridge will be load tested and all necessary data recorded to compare with theoretical predictions. The proposed test arrangement will involve a heavily loaded lorry to produce axle loadings which will be critical for this short span.

The project will subsequently involve the construction of a replacement bridge on a “live” road in conjunction with DRD (NI) Roads Service. Current data indicates that in the UK alone almost 3500 bridges with spans between 3m and 9m need to be strengthened or replaced at an estimated cost of £80 million. There is obviously a potential market for a bridge system that guarantees high quality pre-cast concrete units, ease of transport and simplicity of erection. Early indications are that this flexible concrete system will also be very cost effective when compared with alternative forms of construction.

References

[1] THE HIGHWAY AGENCY: BD 91/04 Un-reinforced Masonry Arch Bridges
[3] THE HIGHWAY AGENCY: BD 57/95 & BA 57/95 Design for Durability
[5] TERRAM LTD: Geotextiles for soil Reinforcement: Pontypool, GWEWT NP4 0YR.
[7] THE HIGHWAY AGENCY: BD 21/01 The Assessment of the Highway Bridges and Structures