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Archtec - Strengthening and Preserving Masonry Arch Bridges in Cumbria

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Abstract

Masonry arch bridges form a vital part of Cumbria's infrastructure and are a particularly common form of bridge construction in the local area, with over 1000 accounting for approximately 65% of the total bridge stock. Many of the bridges are in rural locations, and whilst they are not heavily trafficked, they provide essential access routes for local communities. In addition, many of the structures are well over 100 years old and have local heritage importance.

Cumbria County Council, working with Capita, (CCC) has assessed the masonry arch bridges using traditional techniques, as part of a programme to assess all the county bridges for the introduction of the 40/44 tonne vehicle. This has resulted in approximately a quarter of the bridges being found to be under strength with approximately 100 of these being masonry arch bridges. CCC is now well advanced through a strengthening programme to improve the load carrying capacity of the under strength bridges. For masonry arch bridges, feasibility studies are carried out considering the options for strengthening including saddling, gunniting and retrofitted reinforcement. The selection process considers the relative merits of each strengthening method particularly with regards to cost, technical quality, traffic disruption, heritage conservation, sustainability and the environment. The Archtec system has been chosen as the preferred method of strengthening on a significant number of the masonry arch strengthening schemes to date.

This paper describes the features of the Archtec system with particular relevance to strengthening bridges in rural areas such as Cumbria. Case studies of bridges strengthened in Cumbria are described, and the benefits discussed. It is concluded that the method has provided the client with bridges strengthened to the EC load requirements, whilst minimising disruption to the local communities and preserving them for future generations.

Introduction – Masonry Arch Bridges in Cumbria

Cumbria is the third largest county in England by area with a relatively low population. The main population areas (because of the geography of the county - with the Lake District in the heart of the county and the Pennines forming the eastern border) are located around the coastal strip or within the M6 corridor. The majority of the communities are rural and based around agriculture and consequently the majority of the county's road network comprises of minor roads linking these communities. The mountainous topography results in a large number of streams that are generally crossed with masonry arches constructed from locally sourced material. This explains why out of a total bridge stock of almost 1700 there are 1100 masonry arch bridges. The majority of these are small with spans of less than 10m, although larger spans are encountered particularly over the River Eden.

During the 1990's, CCC carried out a programme to assess all structures for the introduction of the 40/44 tonne vehicle. This programme resulted in approximately 200 assessment failures of which about 50 were masonry arches. These failures then went through a ranking process where importance of the route and severity of failure were used to place them in a priority order. The estimated cost of strengthening was added to allow a strengthening programme to be developed. This strengthening programme has been ongoing for the last 10 years to improve the load carrying capacity of the under strength bridges and this is now almost complete.

Cumbria County Council - Strengthening Options and Considerations

All masonry arches in Cumbria were initially assessed using the MEXE method. If this resulted in an arch failure the arch was generally reassessed using the 'Archie' computer software for the analysis of masonry arch bridges. This often produced a result that was no better than that given by MEXE and rarely gave any improvement of capacity. If the assessed capacity of an arch was under strength, simple solutions were initially considered that would improve the condition factors used in MEXE as part of the assessment formula. These would typically include surfacing overlay, pointing the arch barrel or pressure grouting. The results of these 'quick fix' solutions were presented with the load assessment report.

If a simple solution failed to improve the bridge capacity sufficiently the first option usually considered was if a weight restriction could be applied. This was generally only practical on remote structures where it would either be physically impossible for a 40/44 tonne vehicle to gain access to the bridge or the distance between the parapets would restrict the size of vehicle capable of crossing the bridge.

Assuming a weight restriction was not possible the next option considered was to strengthen the arch with a reinforced concrete saddle. These were usually designed where possible to carry the 40/44 tonne vehicle with the existing arch being used as permanent formwork. Concrete saddles have the advantage of removing the masonry arch from the live load carrying responsibility (although any relief of dead load can have a detrimental effect in the long term). In addition they provide a good solution where arches are badly deformed or cracked or where the lateral load on spandrels is causing problems. Saddling can also include a waterproofing membrane that seals the arch from the problems of existing and future water penetration and the resulting deterioration.

However, in certain circumstances it was not always practical to saddle the arch. These were usually where the depth of fill was large or the bridge was narrow and no suitable diversion route was available to allow the bridge to be closed to traffic. In some instances, where the depth of fill over the arch crown was minimal, the use a concrete saddle would have resulted in parapet walls having to be raised over long lengths making schemes prohibitively expensive.

In the above circumstances alternative strengthening methods were investigated, usually resulting in the Archtec method of arch strengthening being chosen for the following reasons:

- Where road closures were the only practical method of carrying out the work and long diversion routes were necessary (in some instances diversion routes were in excess of 40 miles) the work could be carried out during the night to minimise the inconvenience to locals.
- The installation equipment could be moved relatively quickly so if an emergency situation occurred arrangements were made for the contractor to clear the bridge. The emergency services were informed of site contact numbers so they could give advance warning to site so the bridge could be cleared to allow the passage of emergency vehicles.
- The physical appearance of a bridge remains unchanged and the fabric of the structure is not significantly altered, which is an important factor when strengthening listed structures and obtaining planning consent.
- All the work can be carried out from the road surface and there is no need for temporary support or access to be provided beneath the bridge. This has the advantage in that the majority of rivers in Cumbria are SSSI and Environment Agency and English Nature consent are not required for temporary works.
- The additional benefit of the more rigorous analysis has in some circumstances resulted in an increase in capacity. In these instances the designers have been able to certify the structure capable of carrying the 40/44 tonne load without carrying out any strengthening work.

The major issue the County Council had with carrying out the Archtec method of strengthening was with procurement procedure. The specialised nature of the analysis coupled with the strengthening technique meant it could not be competitively tendered. The local authority's standing orders stated that schemes over £20k in value should be competitively tendered, consequently a case had to be made to the Council and the internal auditors that this method was the only practical solution in these circumstances. This was eventually agreed and having established a precedent it has since allowed a further 20 arch bridges to be strengthened that otherwise would have been impractical or prohibitively expensive.

The Archtec Solution – A Brief Description

Archtec is a joint venture operated by Cintec International, Gifford and Rockfield Software. The joint venture brings together expertise in a range of disciplines to provide a unique arch strengthening product; Cintec providing the patented anchor system and managing the strengthening projects, Gifford providing the engineering services including survey, analysis and design, and Rockfield providing the Finite/Discrete Element Method[1] (FDEM) software, Elfen, used for the structural analysis.

The design philosophy of Archtec is simple (see Figure 1), and focuses on providing extra bending capacity at the locations of hinging failure. Typically, under live loading, such mechanisms are driven by the formation of a primary hinge at the quarter or third span location. The Archtec system works by inserting Cintec anchors in the arch, to work compositely with the masonry, thereby providing the arch with the bending capacity required.

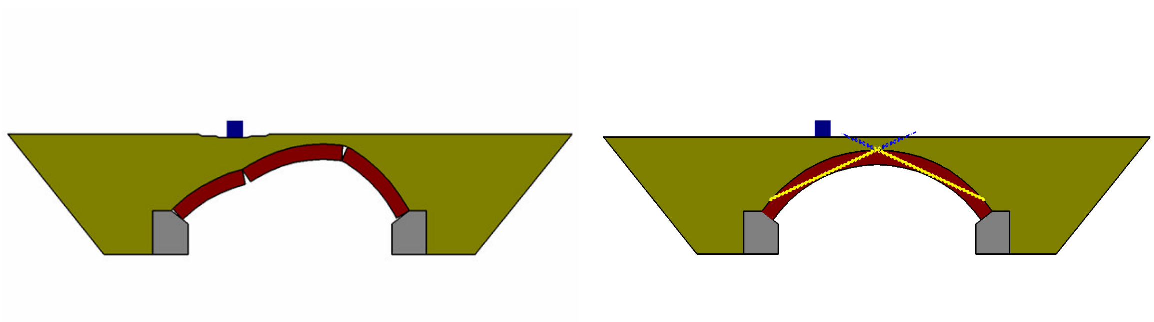

Figure 1 : Archtec design philosophy

The strengthening system utilises the Cintec Anchor, a socked stainless steel anchor system that is ideal for use in masonry structures. The use of stainless steel and a high performance grout ensures enhanced durability whilst the unique fabric sock ensures a reliable grout to masonry bond with full control over the grouting process. Figure 2 shows the Cintec Anchor.

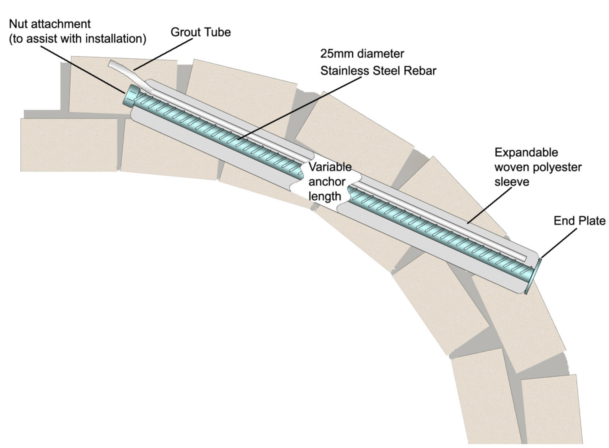

Figure 2 : The Cintec Anchor

Whilst the design philosophy is simple, in reality each arch is unique and therefore determining the exact position and amount of retrofitted reinforcement is not straightforward. To facilitate efficient and reliable design and assessment, Gifford have developed the use of FDEM, available in the explicit dynamic version of Elfen, for the analysis of masonry arches[2]. FDEM is ideally suited to the analysis of masonry; the heart of the technique is concerned with automatic contact detection, including friction and cohesion between potentially thousands of interacting components. FDEM can therefore be used to represent almost any structural arrangement of masonry arch bridge including multiple spans, multiple rings, irregular shapes, existing concrete slabs or saddles and other unusual features.

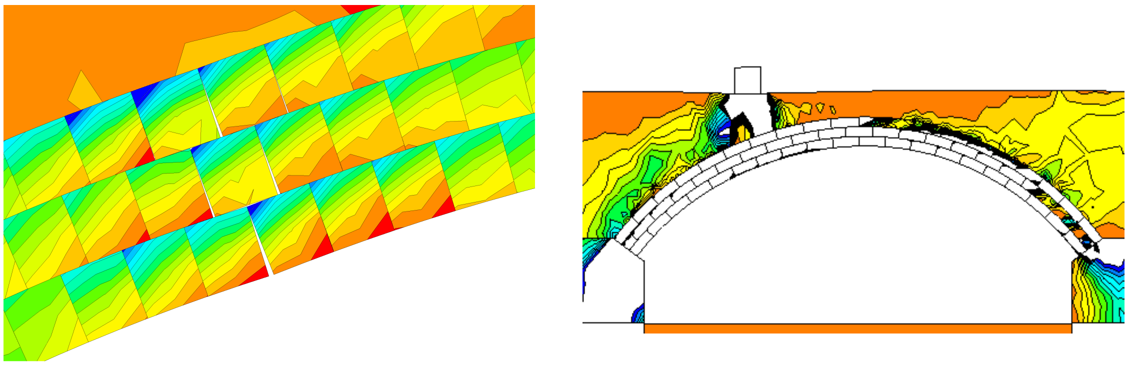

Figure 3 : The Finite/Discrete Element Method applied to masonry arches

To confirm the accuracy of the analytical approach and efficacy of the strengthening methodology, analysis results were verified against full-scale arch tests carried out at the TRL[3,4] and also other tests carried out on real masonry arch bridges[5]. The tests confirmed the ability of the analysis to predict the strength and displacement characteristics of both unstrengthened and strengthened masonry arches more comprehensively than other techniques[6]. The tests also confirmed that the method of strengthening dramatically increases the ultimate capacity, delaying the onset of hinging and providing a gradual and ductile failure mechanism. Significant benefits were also observed relating to serviceability behaviour[7].

The strengthening method relies on very precise setting out and drilling to position the anchors at the tangent location with the arch intrados. To ensure accuracy, total station survey methods are employed, paying particular attention to the arch intrados and road surface. Using a 3D CAD model, setting out information is provided to the contractor defining precise drilling points and vertical angles. Close cooperation between Gifford and drilling contractors has been necessary to develop the appropriate setting out and work procedures in order to achieve the high accuracy required.

As previously highlighted, the installation of the strengthening does not require significant excavation or temporary works, and is therefore totally flexible enabling traffic to continue to flow during busy periods or to allow the passage of emergency services. The system also has significant environmental and heritage benefits; it does not require large quantities of natural resource and requires minimal intervention with the fabric of the structure. In addition the appearance of the structure is completely unaltered. These benefits make Archtec ideal for historically significant or aesthetically pleasing structures and a valuable bridge strengthening option for local authorities such as Cumbria.

Case Study – Musgrave, Eastfield and Blandswath Bridges

The three bridges (pictured in Figure 4) each carry the B6259 over the beautiful River Eden as it meanders from the village of Great Musgrave to Kirky Stephen in Cumbria. Blandswath is a single span arch of 16.5m with a rise of 3.3 metres and had previously been assessed at 10 tonnes. Eastfield is a single span arch of 16.8m with a rise of 3.2m and was assessed at 7.5

tonnes. Musgrave is a two-span arch with two equal spans of 15.2m with rises of 2.9 metres and a short stocky pier. It had previously been assessed as having a live load rating of 17 tonnes.

Figure 4 : Clockwise from top-left: Blandswath, Eastfield and Musgrave bridges

The three structures fell into the category where low fill depth would have required extensive lengths of parapet to be raised with cost and planning implications for a traditional concrete saddle solution. In addition, the diversion route on an equivalent class of road was excessively long and disruption to the local communities had to be minimised. Whilst the bridges are not listed structures, all three are aesthetically pleasing and therefore changes to the external appearance were unacceptable. Consequently, in May 2000 a contract under ICE 5th Edition was let to Cintec to design and construct a strengthening solution before Christmas that year. At the time the three bridges comprised the most ambitious Archtec strengthening project undertaken. Although a project with more complex drilling had been completed in Lancashire a sequence of three relatively large bridges along the same route had not previously been done.

Shortly after the strengthening contract was awarded, Gifford sent a team to Cumbria to carry out an inspection of the arches and complete the total station survey. All three arches were found to be of similar construction, each with random rubble masonry and lime mortar arch barrels and parapets (except Blanswath whose eastern parapet had been demolished and replaced with iron railings). All arch barrels were found to be of good shape and had varying degrees of mortar loss. No significant defects were observed that were relevant to the strengthening design.

Following the inspection and survey, the design team prepared FDEM models of each of the arches and carried out an assessment of unstrengthened capacity in accordance with BD 21/97[8]. This assessment confirmed the shortfall in capacity and identified the failure mechanisms governing the required location of retrofitted reinforcement. Following further analyses, strengthening schemes were developed for each of the bridges as summarised in Table 1 and for Musgrave Bridge in Figure 5.

	No of anchors	Anchor size	Steel grade	Anchor length	Hole length	Hole diameter
Blandswath	14	S25	500/304S31	7.8m	8.2m	65mm
Eastfield	18	S25	500/304S31	7.6m	8.6m	65mm
Musgrave	40	S25	500/304S31	8.1m	9.5m	65mm

Table 1: Summary of design requirements for Blandswath, Eastfield and Musgrave bridges

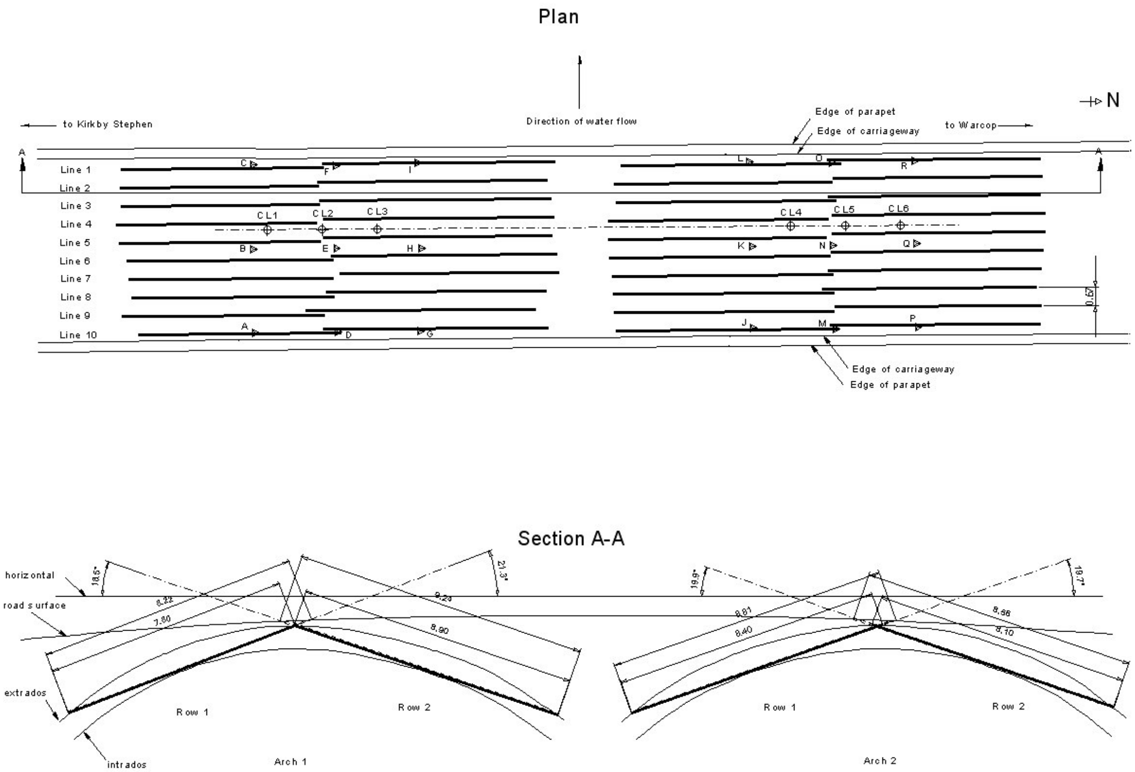

Figure 5 : Strengthening design for Musgrave Bridge

Due to geometric and environmental constraints, the drilling for each bridge was to be carried out from the road surface. It was decided that, because Blandswath was relatively narrow, in the interests of Health and Safety the road would be closed during drilling work. In order, therefore, to minimise inconvenience to the local community the work was carried out at night, although the road would be fully reopened every day. Eastfield and Musgrave offered greater flexibility and road closures were only needed for the short period of drilling nearer the centre of the carriageway.

Despite meticulous planning and design, shortly after work commenced on site a problem was discovered with the anchor production. As the anchors were relatively long, when they were fabricated at the Cintec factory they were fitted not only with end plates but also spacer plates at the centre of each anchor to prevent sagging. It became apparent that the 60mm diameter spacer plates would not fit inside the 65mm OD mining barrel. Unfortunately this was only discovered when the drilling subcontractor had already inserted all available mining barrel into the drilled holes to act as linings prior to anchor insertion. The mining barrel could not be withdrawn from the hole for fear of fill collapsing into the open hole and there was no more mining barrel available to continue the drilling work. This dilemma threatened to disrupt the tight construction programme. To exacerbate the situation further the subcontractor could not obtain more mining barrel from their factory because, at the time, the factory based in Lewes, Sussex, had been completely washed out by the worst floods in over a century. The flexibility of the anchor design and the Archtec partnership came into play to resolve the problem and keep the project on track. The anchors were immediately returned overnight to the Cintec factory in Newport where smaller plates were fitted and the anchors returned to site within 24 hours. Another specialist drilling contractor, working nearby, transferred extra mining barrel to site so that drilling could continue whilst the anchors were being modified.

Further problems were encountered by wildlife when bats were discovered at Musgrave Bridge. The random rubble and open joints had created an ideal roosting location for the bats within the arch barrel. Work was limited to certain parts of the bridge until a licensed bat handler could attend the site to survey the bat locations and advise on how to proceed. The flexible and minimal intervention approach of Archtec enabled work to continue with anchors installed around the bat roosting locations without disturbing the bats.

Figure 6 : Working around wildlife presents an unusual design constraint

Some other minor issues were encountered with these bridges during installation as follows:

- Where property was close to the bridge there were obvious concerns about noise during the night and at some sites complaints were received. Consequently noise levels were monitored and where necessary the compressor used was housed in a sound-proof shed to address this issue.
- Very occasionally the drill hole ‘broke through’ the soffit due to the tolerance of the drill angles and the irregularity of the random masonry arch soffit. When this happened a sympathetic repair of the arch masonry was carried out with no impact on the visible appearance.

Despite the anchor modifications Blandswath was finished to programme. The anchors for Eastfield and Musgrave were modified before work started and, apart from the bats in the bridge at Musgrave, the overall contract went to programme without any further hitches. The total cost of strengthening the 3 bridges, including design and traffic management, was £257,000.

Construction was completed with minimal disruption to the local communities and maintaining key routes during all but the quietest of traffic periods. The works involved a minimal amount of construction plant and materials resulting in little noise and disruption to the local residents. The work had very little direct or indirect environmental impact and left the external appearance of all bridges unaltered for future generations to enjoy.

Concluding Remarks

To summarise, Archtec offers a unique combination of benefits to local authority clients. In choosing the Archtec system these benefits have been recognised by Cumbria County Council (CCC) as offering the best all round solution for many of their under strength bridges. These benefits include:

- Rigorous engineering based on extensive testing and verification
- Minimal intervention to the fabric of the structure and no change to the external appearance
- Significant environmental benefits and a sustainable approach
- Flexibility in traffic management and maintaining key rural links
- Preservation of structures for the use and enjoyment of future generations
- Significantly reduced cost compared with some alternatives

Since the strengthening of Musgrave, Eastfield and Blandswath bridges, a further 21 bridges have been strengthened for CCC out of a total of 140 strengthened in the UK. In addition, 4 CCC bridges were found to be strong enough when assessed using the FDEM out of a total of 30 in the UK that avoided the need for strengthening. Strengthening projects have also been completed in the USA, Australia and India. Building on this success, the Team is now about to embark on the assessment and strengthening of 9 bridges in Greece.

Acknowledgements

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