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Briefing: Arch bridges – unlocking their potential

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Arch bridges are strong, durable, aesthetically pleasing and require little maintenance but very few have been built since the early 1900s. However, this trend has changed as more than 60 FlexiArch bridges have been installed since the system was launched in 2007. The FlexiArch uses precast concrete voussoirs, requires neither corrodible reinforcement, nor centring, can be installed in hours and is contractor friendly. Details of this innovative method of construction and installation of arch bridges are given and the enormous potential of the system for multi-span viaducts is also highlighted.

1. Introduction

The strength, stiffness, durability and minimal maintenance attributes of arch bridges are acknowledged by structural engineers throughout the world. In addition, their aesthetic qualities are universally acclaimed so much so that there are hundreds of thousands of arch bridges in the world today. However, relatively few masonry arches have been built over the last 120 years and what is needed to reverse this dramatic decline is an alternative with the following attributes.

- Can be installed as quickly as alternatives.
- No need for centring.
- Uses existing well-accepted methods of analysis/design.
- Is cost competitive.
- Uses precast concrete for the voussoirs and is amenable to construction off-site.

In response to these challenges, the FlexiArch (Long *et al.*, 2013) has been developed.

2. Manufacture and installation

The 'FlexiArch' is constructed and transported to site in flat pack form using polymeric reinforcement to carry the self-weight of the arch unit during lifting but once in place it behaves as a conventional masonry arch. The preferred method of construction of the arch unit is shown in Figure 1. More detailed information is provided in Long *et al.* (2013). For the manufacture of each arch unit the tapered voussoirs are precast individually and then they are laid contiguously with the top edge touching, in a horizontal line with a layer of polymeric reinforcement placed on top. In situ screed, typically 40–50 mm thick, is placed on top and allowed to harden so that the voussoirs are interconnected. When lifted at the designated anchorage points, gravity forces cause the wedge-shaped gaps to close, concrete hinges form in the screed and the integrity of the unit is provided by tension in the polymeric reinforcement and by the shear resistance of the screed. The arch-shaped units can then be lifted and placed on precast footings at the bridge site and all the self-weight is then transferred from tension in the polymeric reinforcement to compression in the voussoirs – that is, it acts in the same way as a conventional masonry arch. Experience of using this has shown that it has a number of advantages over traditional methods.

- The voussoirs can be accurately, quickly and consistently produced with the desired taper in relatively simple shuttering.
- High-quality concrete can be utilised in order to
  - enhance the durability of the arch while in service
  - greatly reduce the variability associated with natural stonework.
- Rapid installation – site experience has shown that a typical unit can be accurately located every 15–20 min and as a consequence most bridges can be installed in well under a day, thus affording the 'FlexiArch' enormous benefits relative to a conventionally constructed arch and making the system competitive with beam and slab alternatives.

Arising from these advantages, more than 60 FlexiArch bridges have been installed in the UK/Ireland since 2007. It has also been found that bearings (e.g. to allow longitudinal expansion) are not required and thus they have not to be replaced during the lifetime of the bridge. This allied to the lack of corrodible reinforcement means that maintenance will

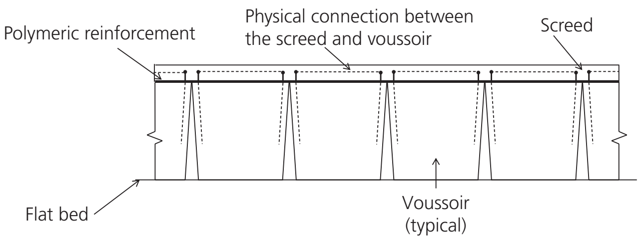

Figure 1. Method of construction: FlexiArch

be minimal and their design lives should be well in excess of alternatives.

3. Potential for arch viaducts – concept of breathing bridges

Up until 1900 multi-span masonry arch viaducts were the accepted method of carrying railway tracks across wide flood plains and they are considered to be an invaluable part of our heritage. More than 1000 arch viaducts were constructed after the first one in 1828–1830 – the Sankey viaduct near Manchester by George Stephenson for the Manchester and Liverpool railway. One of the last viaducts constructed, at Culloden (Figure 2) in Scotland, is still in excellent condition even though it is nearly 120 years old. Aesthetically, they are much admired but why have few, if any, viaducts of this nature been built since 1900. Basically, they were very labour intensive and they took a long time to build. However, the Victorian engineers, who built structures to last, must have appreciated that arch bridges needed little or no maintenance (no corrodible reinforcement) and that they were very strong (ideal for railway loading). They also have advantages over girder systems which may not be widely acknowledged by present day bridge designers. For example, in a viaduct consisting of say 20, 15 m spans (more than 300 m long), there are no expansion joints and thus no need for bearings. Why is this possible with an arch deck as opposed to a girder system – because the arch is curved in elevation and as a consequence an increase in temperature causes the crown of the arch to rise when it cannot expand longitudinally at the supports. In other words, it breathes as is the case with the rib cage of mammals. The first time the first author encountered the concept of breathing bridges was in relation to the design of a highway bridge near Niagara Falls in Canada (Campbell *et al*., 1975). As can be seen from Figure 3, this 12-span 600 m long bridge, 15 m wide, was highly curved in plan. This would have presented a problem to the designers if they had adopted the conventional approach of dividing it into three-span sections with relevant bearings. However, with the wide temperature ranges encountered in Canada, the separate elements could have gradually moved relative to each other, which is clearly highly undesirable. As a consequence, they decided to design the bridge with no expansion joints – it was fixed at both abutments on the assumption that under thermal gradients it would breathe horizontally and relevant sliding bearings were located over the 11 piers. This prestressed concrete bridge has been in service since 1970s and is performing extremely well. On close examination of the plan geometry of the bridge, it is very similar to FlexiArch bridges in elevation – thus it is evident that both will breathe while being subjected to thermal loading.

Figure 2. Culloden viaduct, Scotland. Credits to Quaysides.co.uk

This characteristic has been recently remarked upon in an extract from New Civil Engineer (NCE) of May 2015, which is quoted *verbatim*.

Title: £45 m Bermondsey dive under project

> The engineer wanted the arches to behave in a similar fashion to long lengths of masonry arch viaducts that breathe under thermal loading and do not distribute loads longitudinally along the viaduct.

As has already been explained, the FlexiArch has all the attributes of a masonry arch when in service thus it could lead to a renaissance of multi-span arch viaducts. In addition, it has the advantage over masonry arches in that relatively slender piers can be used as the lateral forces exerted when individual FlexiArch units that are being installed are relatively small (and indeed can be eliminated if the ends are tied together during installation). As well they could be built much more rapidly than masonry arch viaducts.

It should be noted that one of the most famous arch viaducts in UK, at Glenfinnan in Scotland, was built using mass concrete. It is still performing well some 120 years later and has

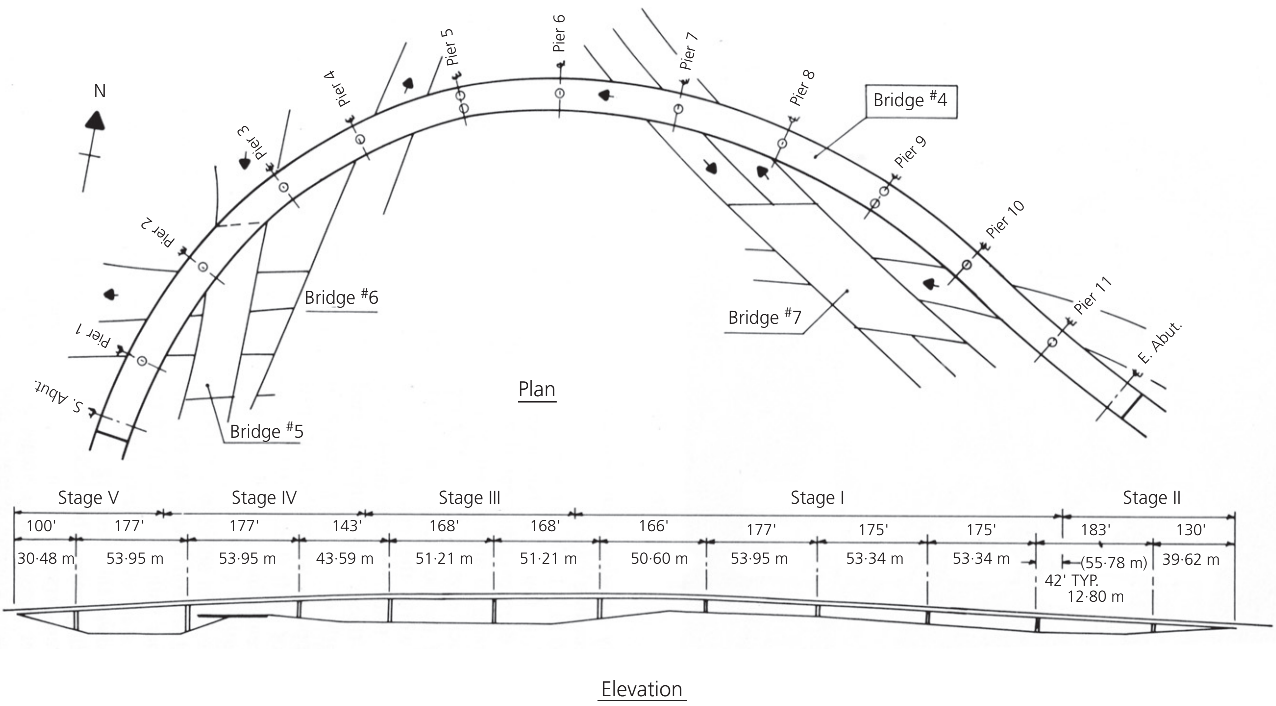

FIG. 2. General layout

Figure 3. Niagara Falls Bridge

much in common with a FlexiArch system with full strength concrete backfill. Thus, it is now possible to utilise this aesthetically pleasing form of construction as costs will be similar to other precast girder systems, but there will be no need for expansion joints/bearings and maintenance costs will be minimal as there is no corrodible reinforcement.

The outstanding aesthetic qualities of multi-span viaducts have been recently recognised in the USA in the Coton Bridge in Virginia. This award-winning bridge, however, utilises heavily reinforced rigid arches which will be susceptible to corrosion in due course. By making use of the FlexiArch feasible in this instance, this problem would have been eliminated.

Appreciation of this concept, apparently recognised in the Victorian era, could have implications for the future – for example, for HS2 and high-speed rail more generally. In this context, high-speed systems tend to make much more extensive use of tunnels and viaducts than conventional railways – for example, the Archidona viaduct (Millanes *et al*., 2014) recently constructed in southern Spain. This may help British railway engineers to regain their world prominence in this field as was recently suggested in the feature article in NCE in March 2016.

By using arch viaducts and recognising the breathing bridge concept, the need for sophisticated bearings could be avoided (costly to replace periodically for bridges with long lives) and minimal maintenance requirements fulfilled.

4. Concluding remarks

By taking full advantage of the attributes of the FlexiArch system, the full potential of (*a*) arch bridges can be unlocked and (*b*) multi-span arch viaducts can be achieved.

The lack of corrodible reinforcement, expansion joints and bearings will minimise maintenance. As a consequence, a highly sustainable bridge infrastructure can be realised in the future.

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