FLEXIARCH SYSTEM: RENAISSANCE OF ARCH CULTURE

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SUMMARY

Arch bridges are strong, durable, aesthetically pleasing and require little maintenance but very few have been built since the early 1900's. However, there has been a mini renaissance of this proven form of construction since the FlexiArch was launched in 2007 as it uses precast concrete voussoirs, has no corrodible reinforcement, nor centring, can be installed in hours and is contractor friendly.

When installed the FlexiArch system acts like a traditional arch and not surprisingly, has been found to be exceptionally strong and stiff. To date over fifty FlexiArch bridges ranging in span from 4-16 metres have been installed in the UK/Ireland and this paper includes exemplars. As it is very sustainable and has very low full life cycle costs, the need for longer spans (30 metres plus), and multi-span systems has been recognized and solutions under development will be described. Its special attributes for multi-span viaducts – cultural ikons of the Roman and railway eras will also be addressed.

Keywords: *Arches, precast concrete, rapid construction, multi-spans, low lifecycle cost.*

1. INTRODUCTION

The strength, stiffness, durability and minimal maintenance attributes of arch bridges is 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 (some over 2000 years old) and in the UK alone over 70,000 are in existence [1]. Two of the shortcomings of arches were the need for centring and accurate voussoirs which meant that they could not compete in terms of speed of construction with prestressed concrete/steel beam and slab systems which rose to prominence in the 1950s and 1960s and are still widely used. However many of these beams and slab bridges, even though their specified design lives were 120 years, have deteriorated after only 20-30 years and indeed a significant number have already had to be replaced. Where aesthetics was of paramount importance, the masonry arch was overlooked as it could not be built quickly, hence rigid precast concrete arches, heavily reinforced so that they could be safely lifted into position, were adopted in some instances. However, like beam and slab bridges they are vulnerable to reinforcement corrosion and they do not have the high levels of durability associated with unreinforced masonry arches. In this context the UK Highways Agency [2] recommends the use of the arch form where ground conditions permit and also states that consideration should be given to all means of reducing or eliminating the use of corrodible reinforcement.

In summary the basic challenge was to utilise our research expertise and practical experience to develop an arch system with all the attributes of an unreinforced masonry arch but as well:

a) Can be installed as quickly as alternative types of bridges.

b) Eliminates the need for centring – expensive to construct/install and often difficult to remove.

c) Uses existing well accepted methods of analysis/design for conventional masonry arches.

d) Is cost competitive and suitable for construction off-site.

e) Uses precast concrete for the voussoirs to avoid the time/cost constraints and quality control limitations associated with the production of stone voussoirs.

In this paper the concept of the patented 'FlexiArch' system[3], developed to meet this challenge, will be described. In addition case studies will be presented for specific applications of this versatile system – chosen from over 50 FlexiArch bridges already in service in the UK and Ireland. Lastly its sustainability credentials, low full life cycle cost and particular attributes for multi-span viaducts will be discussed and solutions under development described.

2. MANUFACTURE AND INSTALLATION

2.1. Innovative concept & method of manufacture

As has already been indicated it is no longer appropriate to construct an arch in the traditional labour intensive way due to the excessive costs associated with construction/installation and removal of the centring and the preparation of precision voussoirs. Thus a radically different approach to the construction of arches was considered necessary to convince practising structural engineers that this is a viable, cost effective and sustainable solution.

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 Fig 1. More detailed information is provided in [4]. For the manufacture of each arch unit the tapered voussoirs are precast individually 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.

The FlexiArch units can be cast in convenient widths to suit the design requirements, site restrictions and available lifting capacity. 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 the shear resistance of the screed. The arch shaped units are then 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, i.e. it acts in the same way as a conventional masonry arch.

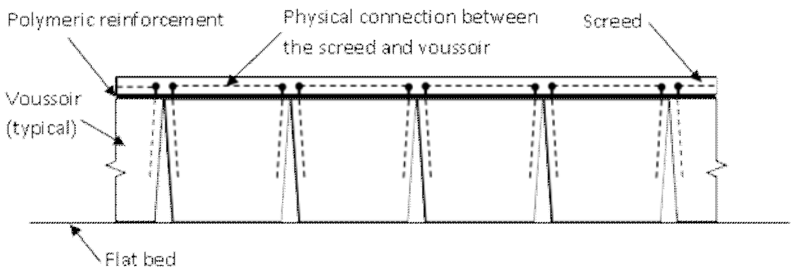


Fig. 1. *Method of Construction: FlexiArch.*

Experience of using this method of manufacturing (Fig.1) 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 (flatter arches require less taper and vice versa).
- High quality concrete can be utilised for the individual precast voussoirs:
  - To enhance the durability of the arch whilst in service.
  - To greatly reduce the variability associated with natural stonework.

2.2. Rapid installation of FlexiArch units

The primary function of the polymeric reinforcement is to provide sufficient tensile strength so that the FlexiArch units can be lifted safely:

I. from the flat casting bay on to a flatbed lorry

II. from the lorry in arch form and placed on the precast sill beams on site

Thus because of the need for safe working, carefully designed tests, which accurately simulated the boundary conditions, were carried out to ascertain the strength of the polymeric reinforcement [4]. Using these results and taking account of creep effects an appropriate load factor was applied to ensure there was no risk of failure during lifting. A typical unit can be accurately located on site every 15-20 minutes and as a consequence most bridges can be installed in well under a day, thus affording the ‘Flexi Arch’ enormous benefits relative to a conventionally constructed arch and making the system competitive with beam and slab alternatives.

3. VALIDATION OF SYSTEM

3.1. Testing

As indicated4 these have included model tests in the laboratories with granular or concrete backfill where they were tested to their ultimate capacity. In addition a number of full scale tests were carried out at Macrete where the ‘FlexiArch’ units are constructed.

These tests confirmed that like conventional masonry arches, which have enormous reserves of strength, the FlexiArch system, as anticipated because of the uniformly high strength voussoirs, more than satisfied the stringent requirements for highway bridges.

3.2. Analysis/design

As the FlexiArch behaves as a conventional arch in service standard design/analysis tools for arches have been used in the design process.

4. SUSTAINABILITY ATTRIBUTES

Starrett [5] used a comprehensive database, compiled by Hammond and Jones [6], to compare the embodied energy and CO_2 with conventional alternatives. The FlexiArch systems had approximately half the embodied energy and CO_2 relative to the alternatives with shorter lifespan [5]. If a more realistic relative lifespan (three or more times) was used for the FlexiArch then this system would be much more sustainable.

5. PRACTICAL APPLICATIONS

Over 50 bridges have been constructed in the UK and Ireland over the past nine years. In this section details of two different applications of the system are given:

- Strengthening a corrosion damaged rigid frame bridge
- Innovative bridge over a railway line

A wider selection of the photographs below are available on the Macrete Ireland website [7].

5.1. Bridge strengthening, Tameside, Manchester, UK

Tameside's 78 year old Jubilee Bridge, which spans National Cycle Route 66 in Manchester, named to commemorate the Silver Jubilee of King George V, had been weakened by extensive reinforcement corrosion and spalling. Replacement was unacceptable due to the disruption to services and a key transportation corridor. Repair by applying sprayed concrete to the deck soffit had been used in 1974, but it was clearly not a long term solution nor was it considered aesthetically pleasing. Wilde Consulting Engineers, aware of other arch bridges over the linear cycleway, then suggested using the Macrete FlexiArch. Thus in December 2012 fourteen FlexiArch units (1m wide) were installed (Fig 2(a)), by the main contractor for the project AE Yates, the first ever application for bridge strengthening. The 7.4m span units were manufactured in NI and shipped to site before being individually lifted by crane and placed on lightly greased laterally extended sill beams along each abutment. Then they were pushed horizontally in pairs beneath the bridge using two hydraulic jacks (Fig 2 (b, c)). When all 14 units had been located, spandrel walls were constructed and then the gap between the FlexiArch unit and the original deck soffit was filled with foamed concrete. The £420,000 contract was completed on time and within budget and Tameside Council now have an aesthetically pleasing bridge with a design life of over 120 years (Fig 2 d).

a) Installing FlexiArch unit on extended sill beams

b) Hydraulic jacking system utilised.

c) Sliding FlexiArch units along sill beams

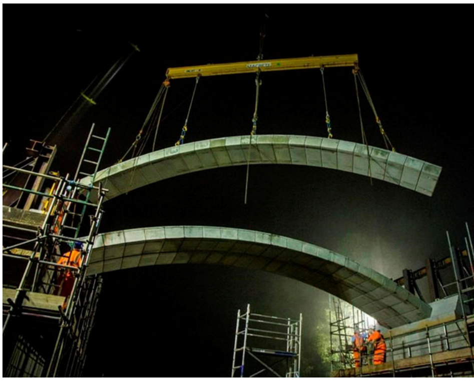
d) Finished bridge (December 2012)

***Fig. 2** Tameside, UK- bridge strengthening.*

5.2. Innovative FlexiArch bridge at Pleasington, Lancashire, UK

Macrete working closely with Network Rail and Story contracting developed an innovative and cost effective solution to eliminate the high risk level crossing at Pleasington Golf course and provide an alternative method of crossing the busy railway line. Having used precast units, specially produced by Macrete for the abutments, the four 11 m span, 1.38 m rise FlexiArch units and spandrel walls were then installed overnight in a single seven hour window. Thus causing minimal disruption to the rail timetable with no train delays being experienced during the period of construction. The completed pedestrian/access bridge now largely eliminates the risk to golfers. The success and overall benefits of this project offers Network Rail potential future savings by replicating this innovative design solution in other areas.

In January 2015, Story contracting were presented with the outstanding project award of the UK rail industry for the Pleasington arch bridge.



a) Installing FlexiArch units *b) General view with precast abutments*

c) Installing spandrel wall *d) Finished bridge (December 2014)*

Fig. 3. *Bridge over railway line, Pleasington, UK.*

6. POTENTIAL FOR MULTI-SPAN VIADUCTS

Up until 1900 multi-span masonry arch viaducts were the accepted method of carrying railway tracks across wide flood plains. They were a well-established part of our culture and many are still in existence where they are considered to be an invaluable part of our heritage. Fine examples, such as the Culloden viaduct (Fig. 4) in Scotland are still in excellent condition even though it is nearly 120 years since they were built. Aesthetically they are much admired but why have no viaducts of this nature been built since 1900. Basically they were very labour intensive, initial costs were high 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 had advantages over girder systems which may not be fully appreciated by present day designers. For example in a viaduct consisting of say twenty 15m spans (over 300 m long) there are no thermal expansion joints and thus no need for bearings. Why is this possible with an arch deck as opposed to a girder deck – 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. This characteristic has been recently remarked upon in an extracts from New Civil Engineer of May 2015, which is quoted *verbatim.* Title: £45m 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 this multi-span system. In addition, it has the advantage over masonry arches in that relatively slender piers can be used as the lateral forces exerted by a small 1m wide FlexiArch are much reduced (and indeed can be eliminated if the ends are tied together as in the Tameside exemplar). As well the viaducts can be built much more rapidly than conventional masonry arches.

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 much in common with FlexiArch system with full strength concrete backfill. Thus it is now possible to utilize 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 or bearing and maintenance costs will be minimal as there is no corrodible reinforcement.

Fig. 4. *Culloden viaduct, Scotland. Credits to Quaysides.co.uk.*

The outstanding aesthetic qualities of multi-span viaducts has been recently recognised in the USA in the Coton bridge in Virginia (Fig. 5). This award winning bridge however has the disadvantage that heavily reinforced rigid arches were utilised which will be susceptible to corrosion in the future. If instead use had been made of FlexiArches this problem would have been eliminated.

Fig. 5. *Coton multi-span bridge, Virginia. Credits to Contech Engineered Solutions.*

7. FUTURE DEVELOPMENTS

7.1. Short Term

The two exemplars and the 50 bridges to date show the versatility of the ‘FlexiArch’, however the authors firmly believe that the system has yet to achieve its full potential. For example:

1 The maximum span could be increased to 25-30m for highway loading and even more for pedestrian bridges where necessary. For the longer spans the ‘FlexiArch’ could be transported to site in two lengths for interconnection prior to installation. In such cases higher span to depth ratios (8-10) could be utilized which would still meet strength requirements.

2 Full advantage should be taken of the sustainability credentials of the FlexiArch, which has no corrodible reinforcement, relative to beam and slab alternatives. In addition as with the multi-span viaducts there is no need for expansion joints/bearings thus greatly reducing the maintenance costs relative to beam alternatives.

As can be seen from the discussion below this could have profound implications for bridge infrastructure in the future.

7.2. Long Term Contribution to Infrastructure Sustainability

Many countries in the world spend around 50% of their construction budget on the repair and maintenance of their infrastructure. One area which is of great concern is bridges as most constructed since the 1950's have life spans which are much shorter than their 120 year design life. As already indicated the FlexiArch has a much higher life expectancy. Thus, if a fraction of the bridges designed using reinforced, prestressed or steel systems were replaced by FlexiArches the percentage of the budget spent on repair, maintenance and replacement could reduce. These savings could allow more money to be spent on building essential new infrastructure.

This concept needs to be developed further as it could help reverse the downward spiral in the state of our existing bridge infrastructure. The added benefits of improved aesthetics should not be overlooked. It represents a real challenge for structural/civil engineers to take up this gauntlet and persuade their governments to adopt a more positive, economical and sustainable approach to infrastructure development.

8. CONCLUDING REMARKS

The experience gained from constructing over 50 'FlexiArch' bridges in the UK and Ireland and from the extensive tests at full and model scale have allowed the following conclusions to be drawn:

1) By manufacturing the voussoirs using accurate moulds, interconnecting them via a screed and polymeric reinforcement precision arches can be produced without centring.
2) Lifting the 'FlexiArch' units onto flat bed lorries, stacking them in their flat pack form, transportation to and installation on site have proven to be straightforward.
3) As a typical 'FlexiArch' unit can be accurately located in 15-20 minutes the speed of installation is comparable with precast concrete/steel beams, hence it can be used when time constraints apply.
4) The 'FlexiArch' should have exceptional durability/minimal maintenance and therefore a lower lifecycle cost, as it is made of high quality precast concrete, there is no corrodible reinforcement and expansion joints/bearing are not necessary.
5) Standard methods of design for conventional arches can be used.

In general, after contractors, designers and clients have been involved in the installation of a 'FlexiArch' bridge they have become very favourably disposed to the system. When this experience is combined with the competitive cost, aesthetics, sustainability and durability of the 'FlexiArch' system it has the potential to reduce the percentage of the construction budget spent on the repair, maintenance and replacement of bridges.

ACKNOWLEDGEMENTS

The financial support provided by the ICE R&D Enabling Fund, KTP Scheme, Invest Northern Ireland, DRD Roads Service (NI) and the Leverhulme Trust is gratefully acknowledged. Input by K. McDonald, B. Rankin, J. Kirkpatrick, S. Taylor, and I. Hogg is also acknowledged.

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