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INNOVATIVE METHOD FOR THE RAPID CONSTRUCTION OF ARCHES

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ABSTRACT

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In response to this dilemma a patented system, the FlexiArch, which does not require centring and uses precast concrete voussoirs, has been developed. Nearly fifty FlexiArch bridges have been constructed in UK/Ireland and demonstrated that they:

1) can be installed rapidly, in less than a day rather than months
2) are cost competitive with alternative precast systems and
3) have all the attributes of masonry arches.

In this paper the basic concept of the FlexiArch will be described as well as a comparison of the results of comprehensive full scale tests, up to 15m span, with methods of analysis/design used for conventional arches. In order to demonstrate the versatility of the FlexiArch system four case histories will be presented, including details of the various approaches to construction. As there is no corrodible reinforcement the system is very sustainable.

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Introduction

The attributes of strength, stiffness, durability and minimal maintenance 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 along with brief details of relevant analysis/design methods and the comprehensive tests carried out to validate the system. In addition case studies will be presented for four specific applications of this versatile system – chosen from nearly 50 FlexiArch bridges already in service in the UK and Ireland.

Manufacture and Installation

a) 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 40-50mm thick, is placed on top and allowed to harden so that the voussoirs are interconnected.

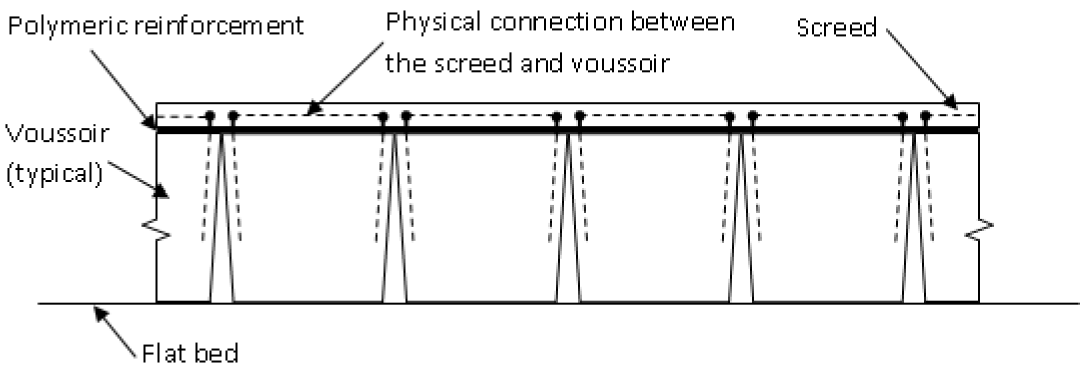

Figure 1 Method of Construction: FlexiArch

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. Here it should be noted that the degree of taper of the voussoirs controls the geometry of the arch – flatter arches require less taper and vice versa. 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.

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.
- 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 in the physical properties normally associated with natural stonework.

b) <u>Rapid Installation of FlexiArch Units</u>

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 its designated arch form into position on the precast sill beams at the bridge 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. Here it should be noted that great care needs to be taken during installation (typically a ‘Flexi Arch’ unit for a 15m span bridge can weight around 15t) but provided the recommended procedures are adopted it has been found that a typical unit can be accurately located on site every 15-20 minutes. 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.

Ensuring Safety in Service

a) <u>Comprehensive Model & Full Scale Validation Tests</u>

A wide range of static loading tests have been carried out to validate the performance of the system. As indicated[4] these have included model tests in the laboratories (at fifth, quarter and third scale) with granular or concrete backfill where they were tested to their ultimate capacity. However model tests can give rise to scale effects at ultimate and as they are not considered to be reliable at predicting behaviour at serviceability loads a number of full scale tests were carried out at Macrete where the ‘FlexiArch’ units are constructed. These included tests on 5m span × 2m rise and 10m span × 2m rise FlexiArches with lean mix concrete backfill and a test on a 15m span × 3m rise with lightweight concrete backfill (Fig 2).

Figure 2 Testing full scale 15m span x 3m rise FlexiArch

At full scale the strengths of the arches were significantly higher than the maximum capacity of the loading rigs. However, the maximum loads applied (equivalent wheel load of 320kN – or lane loading of over 1000kN) were still in excess of the maximum for the factored loads imposed on road bridges. Thus the 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.

Here it should be noted that Macrete and contractors using the FlexiArch have found that concrete backfill is preferred on grounds of economy (as no compacting is needed and it inhibits the ingress of flood water) and it also allows the bridge to be used for traffic a few days after installation.

b) <u>Analysis/Design of FlexiArch Bridges</u>

Once constructed the FlexiArch behaves as a conventional arch and as a consequence standard design/analysis tools for arches have been used in the design process e.g. Archie software analysis system [5], Ring software [6]. Both approaches give comparable estimates of strength for FlexiArches with granular backfill but were found to give significantly lower (conservative) estimated strengths than those measured in the relevant model tests in the laboratory (around three times stronger). As anticipated the strengths of FlexiArches with concrete backfill were very much higher than those estimated on the basis of granulated backfill (around ten times stronger than predicted). It was also found that both methods give comparable predictions for horizontal and vertical reactions, which proved useful for the design of the footings.

In order to get a better understanding of the behaviour of the system with concrete backfill FlexiArches with a range of geometries were analysed using the ABAQUS finite element software [7]. Using a two dimensional approach in conjunction with relevant material properties for the concrete in the arch (50N/mm^2) and the backfill (10N/mm^2), McGovern [8] found that the deflections predicted were in good agreement with those measured in the full scale tests. For example under a wheel load of 32t the tests on the 15m span ×3m rise FlexiArch gave a deflection of 7.2mm whilst the numerical model predicted 6.4mm. Here it should be noted that no attempt was made to try and model a brittle material like concrete beyond its elastic limit. As anticipated the predictions were very much in line with the findings of the full scale tests at Macrete which were still behaving elastically at the maximum load which could be applied using the loading rigs. Thus even though the loadings applied were well under the likely ultimate capacity they were still very much greater than any potential load which could be applied by a vehicle.

c) Performance of the FlexiArch under Seismic Loading

Relatively little research has been carried out in the seismic behaviour of arches. Possibly because experienced earthquake engineering researchers have found that they perform well under seismic loading whereas other structural forms do not.

Visiting seismically active areas in the Mediterranean region one can find numerous arches, many dating back to the Roman times, as well as other structural forms. By simply looking around at the damage caused by earthquakes which have taken place over the past 2000 years we can draw some conclusions. It is common place to find in the ruins of a typical Roman town that all beam and column structures have collapsed whereas in contrast masonry arch structures have maintained their integrity. The only aspect of arch bridges which would appear to be vulnerable are the planar masonry spandrel walls [9]. These observations are supported by the enormous amount of photographic evidence on the internet on the effects of earthquakes on bridges. Such structures made up of beam elements resting on tall piers can be very vulnerable whereas there is little evidence of arches having collapsed during the same earthquake.

Relatively recent research on the seismic behaviour of arches has been carried out in MIT [10] and it has been found that a conventional masonry arch is remarkably resilient. In a FlexiArch, the precast spandrel walls are unlikely to be a problem relative to masonry walls and the presence of the polymeric reinforcement and the interconnecting concrete screed should mean that the system will outperform a conventional arch under seismic loading. This has been confirmed by shaking table tests in California [11].

Sustainability of FlexiArch Relative to Alternate Bridge Systems

Starrett [12] used a comprehensive database, compiled by Hammond and Jones [13], to calculate the embodied energy and CO_2 for a range of spans including 14m, where a prestressed concrete girder and slab system was compared with a FlexiArch with a) granular backfill and b) lean mix concrete backfill. All the products were manufactured by Macrete and Starrett had no problem finding out the relative quantities of steel, concrete etc. Both forms of FlexiArch systems had approximately half the embodied energy and CO_2 relative to the precast beam system even though the same lifespan was assumed for each system. If a more realistic relative lifespan (three or more times) was used for the FlexiArch then this system would be much more sustainable.

Practical Applications

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

- Replacing a bridge destroyed in severe flooding
- Bridge widening/replacing section of bridge damaged in flooding

- Retention of services by sliding FlexiArch units underneath
- Strengthening a corrosion damaged rigid frame bridge

Relevant videos of two of these bridges are available [14, 15]. Some of the photographs below are available [16].

1 Replacement Flexiarch bridge, Sheinton, Shropshire, UK

In 2009 the old bridge in the small village of Sheinton, Shropshire was irreparably damaged by flooding and a temporary Bailey Bridge was installed to restore communication across the tributary of the River Severn. Engineers from Shropshire Council decided to replace the three span bridge with a much longer single span arch to greatly reduce the risk of flood damage in the future. As they wished to reduce construction time to a minimum and avoid the use of a bridge with corrodible reinforcement they selected a 13.7m span x 2.7m rise 'FlexiArch' and ordered eight one metre wide units from Macrete Ireland, Ltd. Each unit weighed 13 t, shown in Fig 2(a), was placed on the precast sill beams in a matter of 10-15 minutes. Once all the 'FlexiArch' units had been located and the precast spandrel wall installed the bridge was ready for the lean mix concrete backfill (Fig 2(b)). The spandrel walls were then finished in stonework (Fig 2 (c)) to produce an aesthetically pleasing solution. The contractor, DEW Construction worked closely with Shropshire Council and Macrete Ireland Ltd, to complete the £450 000 contract on time and within budget, in 2010.

(a) Lifting 13t FlexiArch unit

(b) Nearing completion

(c) Finished bridge (October 2010)

Figure 3 Sheinton Bridge, Shropshire, UK

2 Bridge widening, Bouthray, Cumbria, UK

In the devastating flooding experienced in Cumbria in 2009 severe damage was caused to a two span arch bridge at Bouthray. After inspection Cumbria County Council engineers decided to replace the upstream face (over 2m wide) with an arch system without corrodible reinforcement. The main span 6.6m x 1.77m rise and side span 3.72m x 1.2m rise 'FlexiArch' units selected were supplied by Macrete and transported to site by lorry before being lifted (Fig 3(a)). An overall view of the site during construction after the precast concrete spandrel walls were located (Fig 3 (b)). Local stone was utilised to face the spandrel walls and the finished bridge (Fig 3 (c)) is not only aesthetically pleasing but should have a design life of over 120 years. The contractor was IT Shaw and Sons and the client Cumbria County Council (Contract value £150 000).

(a) Lowering longer span unit onto sill beams   (b) Prior to installation of lean mix concrete backfill

(c) Finished bridge (October 2011)

Figure 4 Bridge widening Bouthray, Cumbria, UK

3 Locating FlexiArch units under services, Siddington, UK

In 2011 engineers in Gloucester were faced with having to replace a deteriorated arch bridge in Siddington. Unfortunately the bridge incorporated a number of vital services which could not be disrupted hence they sought a system which had all the characteristics of a masonry arch (including no corrodible reinforcement). Gloucester Highways concluded that the only system which satisfied their requirements was the 'FlexiArch', manufactured by Macrete Ireland Ltd, as a conventional arch (with centring) could not be constructed in this restricted environment. Thus seven one metre wide 'FlexiArch' units (4m span x 1.5m rise) were ordered. These units were delivered in flat pack form and when lifted gravity forces transformed them into the required arch shape (Fig 4(a, b)). After a 'FlexiArch' unit had been placed on the extended sill beam it was jacked horizontally under the services (Fig 4(c) shows that minimal clearance was necessary). The final bridge (Fig 4(d)) satisfied all the site constraints and the client (Gloucester Highways) and the contractor ENVEX found it to be a user friendly system which could be rapidly installed on site (Contract value £200 000).

(a) Lifting a FlexiArch unit

(b) Lowering unit into position

(c) Sliding FlexiArch units under services

(d) Finished bridge (August 2011)

Figure 5 Siddington, UK- avoiding disruption to services

4 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 5(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 5 (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 120 years (Fig 5(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)

Figure 6 Tameside, UK- bridge strengthening

FlexiArch Developments

a) <u>Short Term</u>

The four exemplars give an indication of 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 if deemed to be necessary. For the longer spans the 'FlexiArch' could be transported to site in two lengths for interconnection prior to installation.

2 For the construction of new or the replacement of existing multi-span bridges where the lateral forces could be minimised so that very slender intermediate piers could be utilised. With reference to the plan view in Fig (7) the ends of the first three 'FlexiArch' units to be installed could be tied together (as in Jubilee Bridge, Tameside) but once in place the remaining units could be installed without ties.

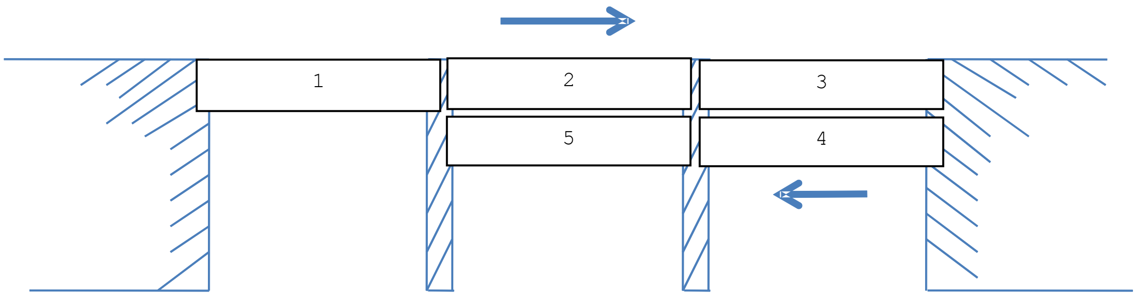

Figure 7 Multispan bridges with slender piers

3 Full advantage should be taken of the sustainability credentials of the FlexiArch, which has no corrodible reinforcement, relative to beam and slab alternatives. As can be seen from the discussion below this could have profound implications for bridge infrastructure in the future.

b) <u>Long Term Contribution to Infrastructure Sustainability</u>

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 to the benefit of us all.
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.

Concluding Remarks

The experience gained from constructing nearly 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 arches can be produced to the precision required by designers without the need for 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 simple with no unforeseen problems.

3) As a typical 'FlexiArch' unit can be lifted into position in 15-20 minutes the speed of installation is comparable with precast concrete/steel beams, hence it can be used for road bridges over railway lines where construction windows are restrictive.

4) The ‘FlexiArch’ should have exceptional durability as it is made of high quality precast concrete and hence minimal maintenance as there is no corrodible reinforcement. Total life cycle costs are therefore minimal.

5) Standard methods of design for conventional arches can be used to give safe but very conservative estimates of the strength of ‘FlexiArch’ bridges. Actual failure loads (from the model tests) with concrete backfill were some 9-10 times higher whilst the full scale tests showed little signs of distress at 5 times this load.

In general, after contractors, designers and clients have been involved in the installation of a ‘FlexiArch’ bridge they have become much more 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

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