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Brickwork Arch Bridges

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THE BRICK DEVELOPMENT ASSOCIATION

Brickwork Arch Bridges

Contents

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David Cox's career in highways and bridges with Cambridgeshire County Council included the award winning Foxcovert Road and Railway Bridges and the cable stayed Cambridge Station Cycleway Bridge. Reorganisation of the County's Transportation Department saw the formation of the Engineering Consultancy Division which in 1995 was transferred to WS Atkins Consultants Ltd where he became Head of Bridges.

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John Page worked at the Transport Research Laboratory until 1995, with responsibilities including its programme of research on masonry arch bridges. This included a load test on Kimbolton Butts Bridge shortly after it was completed. He is the author of about sixty papers, including the TRL State of the Art Review *Masonry Arch Bridges*. He is now an independent consultant.

Front and rear covers:
Kimbolton Butts Bridge, Cambridgeshire.

Introduction

There are about one hundred thousand highway carrying bridges in the United Kingdom and about forty percent of them are brick or stone masonry arch bridges. Most of these masonry arches were built in the eighteenth and nineteenth centuries during the construction of the canals and railways. Very few have been built since the first world war when steel and concrete took over as the principal bridge construction materials.

A major programme of assessing the traffic load capacity of the UK highway bridge stock is currently underway in preparation for the introduction of heavier commercial vehicles. This programme has shown that arch bridges require less maintenance than steel and concrete bridges which suffer from corrosion of steel (including steel reinforcement), and wear and tear to bearings and expansion joints. Arch bridges do not contain these items. Despite being older and often carrying loads much in excess of those envisaged when they were built, maintenance costs of masonry arch bridges are about two thirds of those for comparable steel and concrete bridges. They also make an attractive contribution to the environment.

These factors, coupled with the need to provide a 120 year design life, have led to a renewed interest in building traditional unreinforced masonry arch bridges. Cambridgeshire County Council led the way in 1992 by building Kimbolton Butts Bridge, illustrated on the covers, which is thought to be the first completely new brick arch highway bridge of traditional construction to be built in the UK since before the second world war. The bridge replaced one of steel and concrete which was assessed to have inadequate load capacity and was uneconomic to strengthen. It is located in a conservation area and it was felt that the setting warranted an attractive bridge which would blend well with the local environment. The local residents were strongly in favour of a brick arch bridge. The construction cost was little more than that of a steel or concrete structure, and because of the low maintenance cost of masonry arch bridges, its estimated whole life cost was less.

The Department of Transport (DoT) supported Cambridgeshire County Council and is encouraging the construction of new arch bridges. To further this objective, DoT is preparing a Design Standard and Advice Note. The purpose of this BDA Special Publication is to give practical advice on brick arch bridge design and is intended to be complementary to the DoT documents. They will be referred to in this Publication as the *Design Standard* and *Advice Note.* The aim is to encourage the construction of new brick arch bridges which retain the longevity and low maintenance costs of traditional arch bridges, but which may incorporate modern techniques to help achieve this and to meet the requirements of modern highway design. This Publication draws on other BDA publications, BSI Standards and DoT Standards and they should be referred to for more detailed information; they are listed in the References, on page 14.

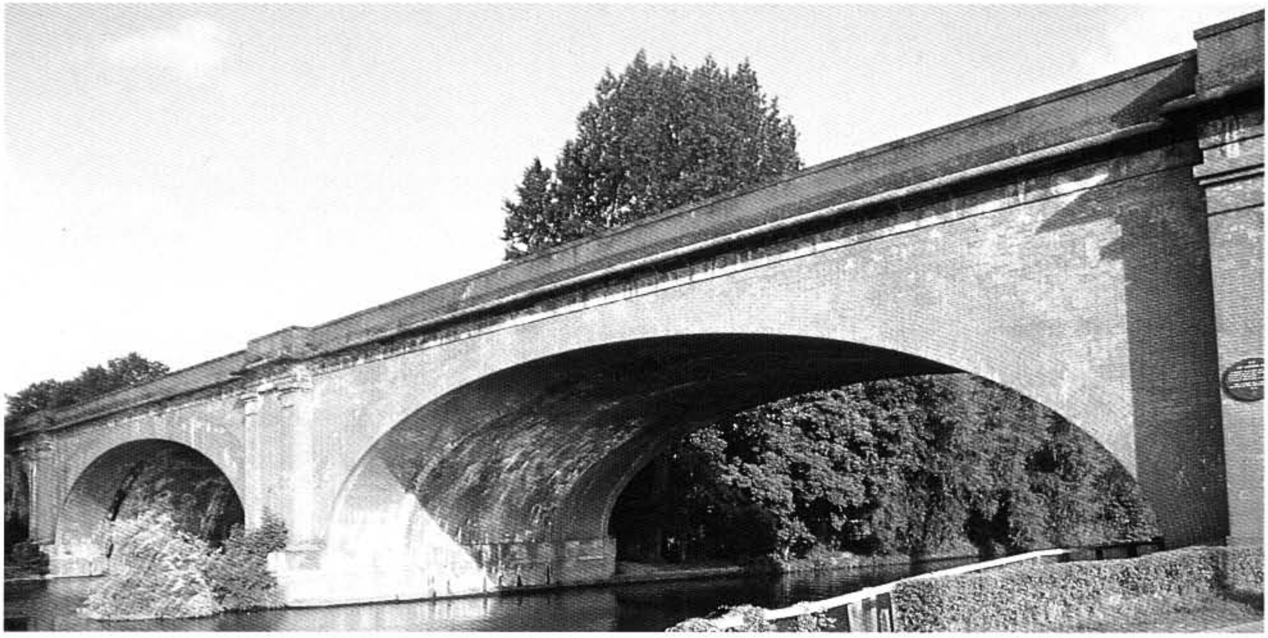


Figure 1. Brunel's Maidenhead Railway Bridge.

Selection, form and suitability

The ready availability of bricks in a wide variety of types means that the local environment can be complemented. At Kimbolton, for example, most village buildings are of a local red stock brick with a small number built with a buff Cambridge stock. Bricks of both types were used in the new bridge.

Brick has the advantage over stone for an arch bridge in that stone has to be cut to shape, and the shapes required can be complicated, whereas in a brick arch the shape is achieved by varying the mortar jointing thickness. This means that the construction cost of a brick arch is lower than that of a stone arch.

Long span arch bridges and viaducts have been built; Brunel's Maidenhead Railway Bridge (figure 1) has the longest span brick arches in the UK, at 39m, but today single span brick arch bridges should be competitive with steel or concrete bridges up to about 15m span.

Figure 2a. Semi-circular arch.

Figure 2b. Segmental arch.

Figure 2c. Semi-elliptical arch.

Figure 2d. Gothic arch.

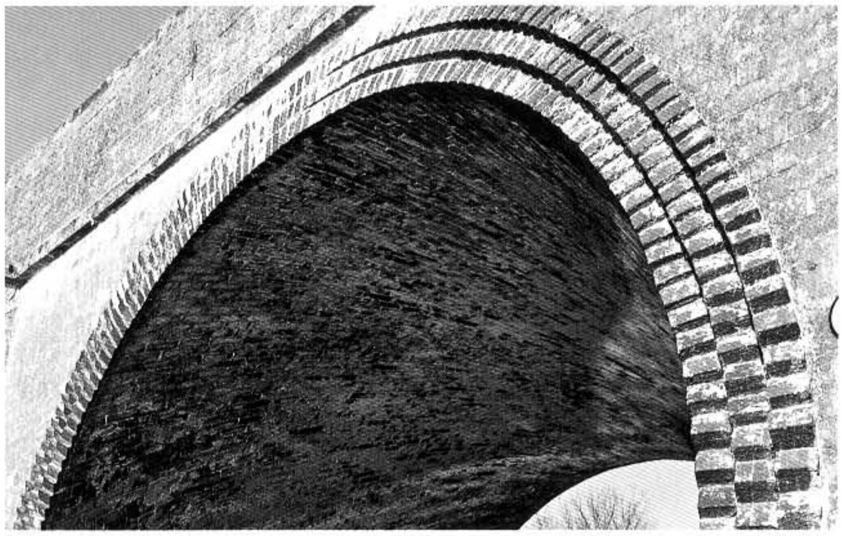


Figure 3. Skew bridge.

Span to rise ratios of 2 to 10 are feasible. This will be determined by the requirements of the site, principally the span required, the height of the roadway above the road, river, canal or railway which it is required to cross, and the clearance needed beneath the bridge. A deep arch (ie with a small span to rise ratio) has very variable headroom. This is acceptable, for example, for river crossings where the main criteria are the width of the river and the area of opening required at times of flood. Such arches may, however, have the disadvantage of providing a severe hump in the road profile which would be unacceptable for a modern bridge. Where similar headroom is required across the full span of a bridge, very flat arches are required and they also provide a better road profile. Flat arches, however, generate large horizontal forces on the abutments, which need to be resisted by the foundations supporting the arch.

The easiest shape of arch to build is segmental, that is, a segment of a circle; figures 2a and 2b show a semi-circular and segmental arch respectively.
Semi-elliptical arches (figure 2c) give more headroom towards the springings and so are commonly found on canals to provide adequate headroom for the towpath. The pointed or Gothic arch (figure 2d) is not a good structural form and is likely to be used only when it is required to match an existing structure.

Skew arch bridges are likely to be required to cross obstacles at an angle. The standard method of achieving this for brick arches is to skew the brickwork as illustrated in figure 3. It means that the brick courses meet the springing at an angle, which will require some brick cutting. It also means that a dogtooth effect will be obtained on the end faces of the arch ring. The bricks can be ground to achieve a flat surface or special shaped bricks could be used, but as each brick would have a unique shape this would be a slightly more costly and inconvenient alternative.

General durability considerations

Arch bridges are exposed structures and so many of the potential durability concerns are due to the effects of water – either rainwater, floodwater, groundwater, or water from burst pipes within the structure. Water will wash out fines from the fill, chemicals dissolved in the water may react with the mortar, or damage to brickwork may occur due to cycles of freezing and thawing. Bricks with improved and more consistent properties are now available than when most existing arch bridges were built. Nevertheless, it is important for the longevity of the bridge to protect the brickwork from water as far as possible. This can be achieved in the following ways:

- The bridge deck should be well drained and made as waterproof as possible so that little surface water gets into the structure. Water which does penetrate should be able to flow readily down through the structure to adequate and easily maintained drains which remove it.
- Faces in contact with fill, that is, the extrados of the arch ring and the back face of the spandrel and wing walls, should be waterproofed.
- Selection of brickwork should be appropriate to the position in the structure, exposure situation and constructional detailing used.
- Parapets should preferably have an adequate coping, with associated damp-proof course system, to throw rainwater clear of the outside faces of the bridge. If a flush capping is used (which will not protect brickwork from saturation), the brickwork must be of suitable frost resistant construction.
- If steel reinforcement is used in the structure, it should be of a suitable type to resist corrosion or be adequately protected. Where post-tensioning is used, the steel should be designed to be replaceable during the working life of the structure.

Some of these aspects are discussed in more detail later.

Foundations and abutments

Many existing arch bridges have foundations that would be deemed inadequate using modern design standards; they survive because the arch ring is an inherently flexible structure and can endure some movement without undue distress. However, foundation design for a new arch bridge should be based on the same principles as for any other new bridge. The aim is to support the dead loads applied by the bridge superstructure, including the thrust of the arch ring, and the loads generated by traffic etc, such that movements are small enough not to cause serviceability or ultimate limit state

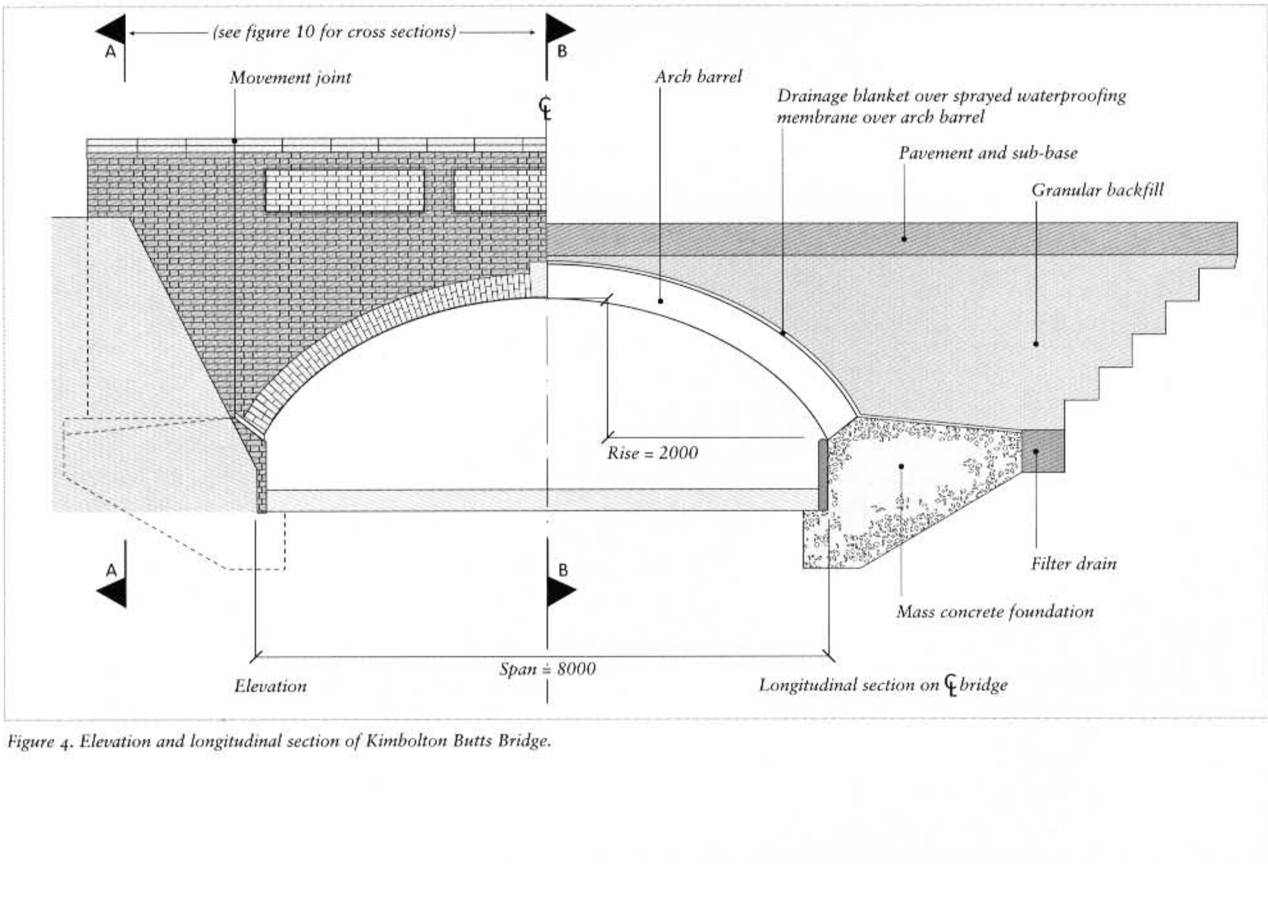


Figure 4. Elevation and longitudinal section of Kimbolton Butts Bridge.

Figure 5. Foundation/springing.

failures of the arch ring. Conventional reinforced concrete mass foundations should be used if possible; the alternative use of piled foundations will increase the construction cost of the bridge by about 20%. Figures 4 and 5 show the mass concrete foundation and abutment design used for Kimbolton Butts Bridge. For continuity of appearance, the abutment wall should be of brick. It can be a non-loadbearing skin but it is preferable to make it part of the loadbearing structure, tied in to concrete backing.

The DoT *Advice Note* will give guidance on abutment sizes.

If the bridge crosses a river, the design should also take into consideration hydraulic effects; DoT document BA 59 gives advice on this aspect.

Arch ring

Initial sizing of the arch ring may be done using empirical methods: advice will be found in the DoT *Advice Note*. For Kimbolton Butts Bridge the MEXE method (DoT *et al*: BD 21 and BA 16) was used. The design may then be refined using a variety of analytical methods which can be categorised as:

- elastic methods.
- plastic (or mechanism) methods.
- numerical methods (eg, finite elements).

All these methods are available as commercial computer software packages. Most methods permit the fill to behave structurally, that is, it will disperse wheel loads from the road surface onto the arch ring, and it will resist movement of the arch ring by the development of passive pressures.

Where mortar pointing is used as the method of joint finishing, the pointing depth should not be relied upon to carry dead load stresses. For structural design purposes it is advisable to reduce the chosen arch ring thickness by about 25mm and this will take account of mortar pointing and also the likely need to repoint mortar joints during the working life of the bridge.

Brick arch bridges were commonly built with multiple rings of brick, with the rings bonded only by mortar. Ring separation is a common feature of these bridges, with the mortar in between rings having deteriorated due either to the applied loading or to chemical attack on the mortar, or a combination of these factors. It is possible to design against this occurring by bonding the arch brickwork through the depth of the ring. Bonding of each row of bricks transversely is also necessary. Possible bonds may be as follows:

- A ring 215mm thick can be obtained by laying all the bricks as headers (figure 6a). Alternatively an English bond could be used so that half the bricks are headers and half stretchers, to give better transverse bonding (figure 6b). This ring thickness could be used up to a maximum span of about 4m.

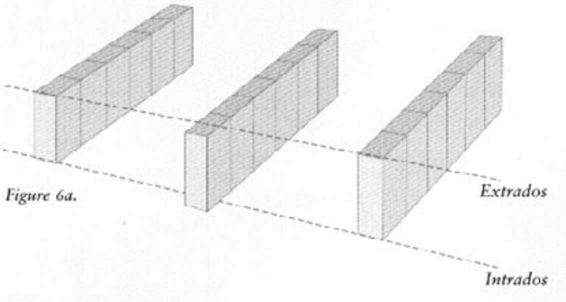


Figure 6a.

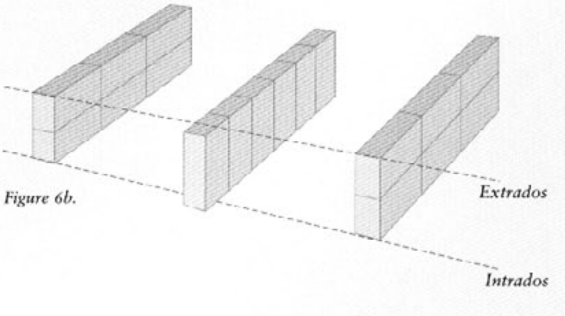


Figure 6b.

Figure 6. Arch ring bonds.

- A ring 328mm thick can be achieved as shown in figure 6c. This ring thickness could be used up to a maximum span of about 8m.
- A ring 440mm thick can be achieved as shown in figure 6d. The English bond used at Kimbolton is illustrated in figure 7. This ring thickness could be used up to a maximum span of about 15m.

Figure 6c.

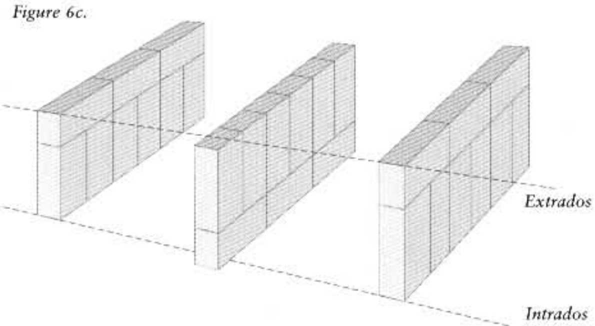
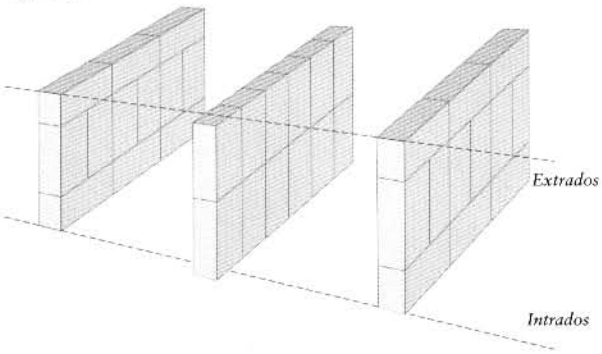


Figure 6d.



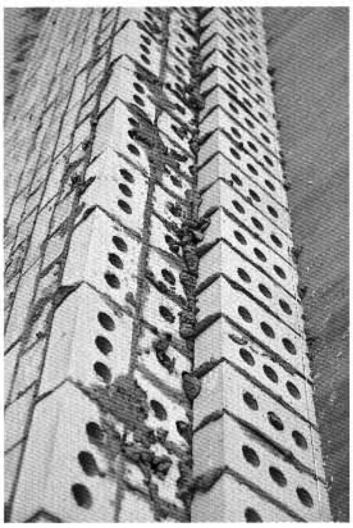


Figure 7. Kimbolton 440mm arch ring bond.

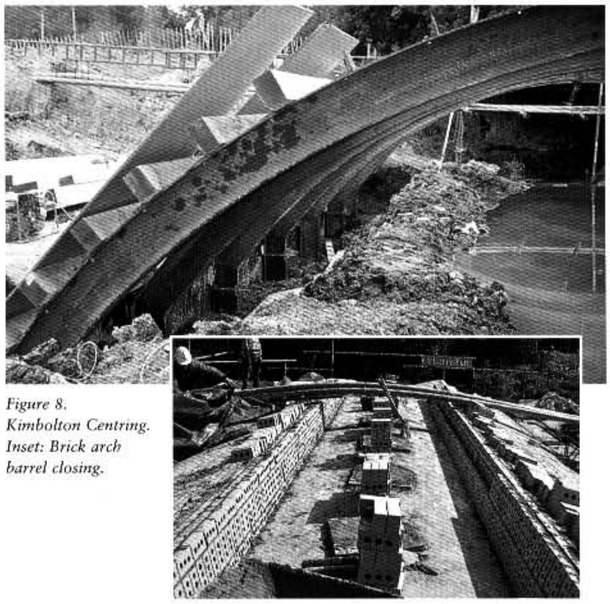


Figure 8. Kimbolton Centring. Inset: Brick arch barrel closing.

This range of thicknesses should be sufficient for bridges which might be considered viable at present (the maximum spans above have been estimated using the MEXE assessment method applied to a semi-circular arch). It is easy to construct centring to the required shape of the arch using modern proprietary support systems. Curved steel sections supporting timber bearers for plywood centring were used at Kimbolton Butts as shown in figure 8.

The top surface of the arch ring should be waterproofed on completion, continuously with the inner faces of the spandrel and wing walls, using a spray applied proprietary system. Figure 9 shows the waterproofing of Kimbolton Butts Bridge.

Spandrel walls, wing walls and fill

Spandrel walls may be designed as mass brickwork retaining walls to resist the dead loads from the fill and the superimposed loads applied by traffic.

Outward movement of spandrel walls is a common feature, due to outward forces applied to them by and through the fill. The risk of the spandrel wall sliding on top of the arch ring may be reduced by tying the wall into the ring using suitable austenitic stainless steel ties.

Wing walls may be designed in the same way as spandrel walls. The wing walls for Kimbolton Butts Bridge were designed as post-tensioned brick diaphragm walls in accordance with BS 5628: Part 2. This method was chosen to deal with the effects of possible impact on the parapets (see Parapets). The walls were approximately 2.4m high and 665mm wide, and were separated from the spandrel walls by vertically positioned movement joints. Cambridgeshire County Council had previously used post-tensioned brick abutments on the A15 Foxcovert Bridges, as described in BDA File Note 12.

Traditionally the spandrel fill was an unbound material. It may simply have been the material dug out to create the foundations of the bridge, or anything else locally available. The options now are greater and include:

- A well drained granular fill.
- A reinforced earth structure designed to relieve pressures on the spandrel walls.
- Foamed concrete.

A granular fill provides a more flexible structure than concrete, allowing the bridge to tolerate some degree of movement.

Parapets

The *Design Standard* specifies that parapets shall be in accordance with BD 52 (DoT *et al*) and BD 37 (DoT *et al*). The requirements are onerous.

A reinforced brickwork grouted-cavity wall was adopted for Kimbolton Butts Bridge as shown in figures 10 and 11.

Figure 9. Kimbolton waterproofing.

Austenitic stainless steel reinforcement and wall ties were used. The parapet wall was structurally secured to a reinforced concrete torsion beam which spans between the brick diaphragm abutment walls. The beam was anchored to the abutment walls by post-tensioning bars which were stressed down to the concrete foundations (figure 12). The post-tensioning bars were designed to be readily removed and replaced during the working life of the bridge. This arrangement made it possible to install services close to the parapets.

Research has recently been carried out on the ability of unreinforced parapets to contain vehicles (County Surveyors' Society, 1995). The research showed that unreinforced parapets have a greater containment capacity than had previously been thought.

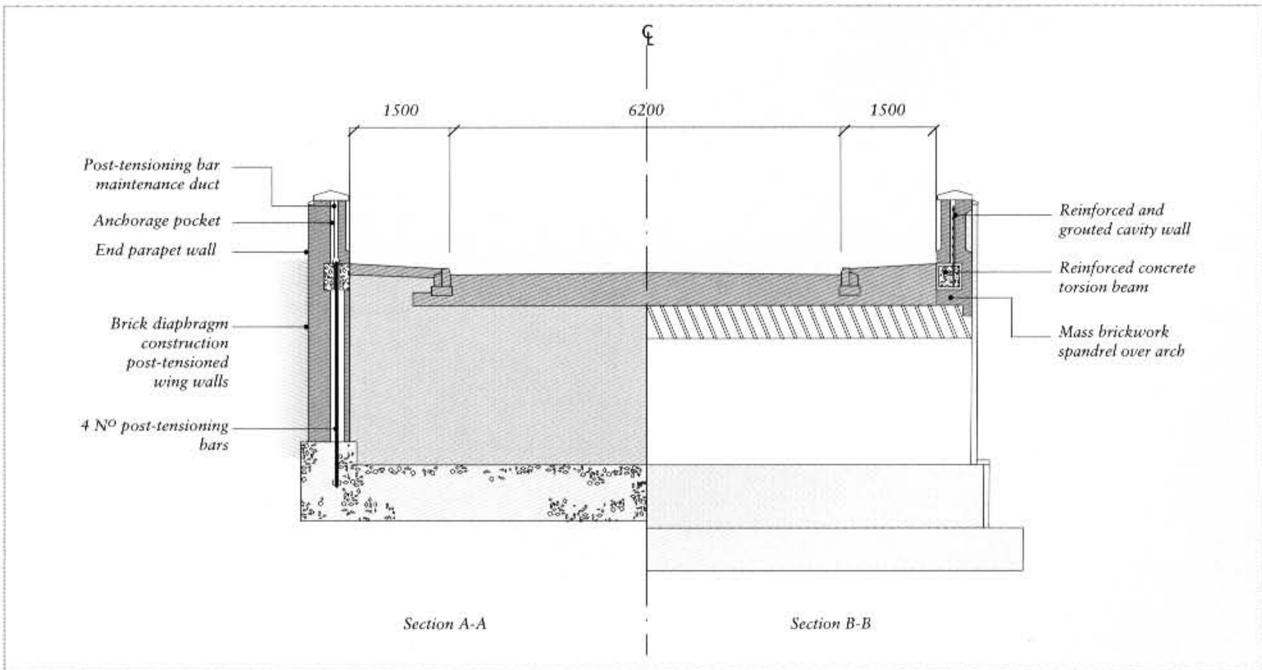


Figure 10. Cross sections of Kimbolton Butts Bridge.

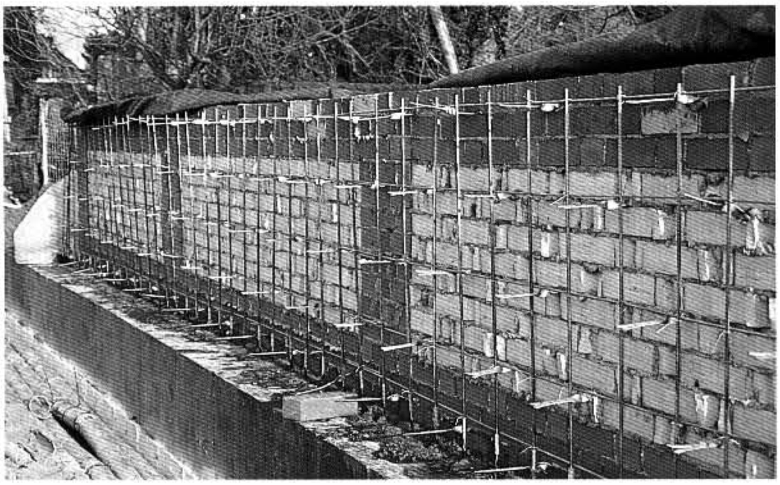


Figure 11. Reinforced brickwork grouted-cavity parapet wall under construction.

Figure 12. Post-tensioned walls.

This suggests that simpler solutions to the provision of an adequate parapet may be possible. Designers are advised to consider what may be permitted relevant to the classification of the structure.

Brickwork design

General

Brick and mortar specifications should be selected on the basis of performance, usually compressive strength and durability. Brickwork appearance will usually also be an important factor. The brick type and mortar may need to vary in different parts of the bridge.

The principal reference for clay brick specification is BS 3921. For engineering design BS 5628:Parts 1 and 2 provide recommendations for the structural design of brickwork masonry while BS 5400 provides design guidance specific to bridge structures. BS 5628:Part 3 gives guidance on components, materials and workmanship aspects which includes design of brickwork for durability. Guidance on design for durability of brickwork is also given in BDA Design Note 7.

Engineering performance

The principal form of loading in brickwork for bridge structures will be compressive forces which can be direct compression in unreinforced brickwork elements such as the arch ring, or bending compression in laterally loaded brick elements such as reinforced brickwork parapet walling and reinforced brickwork earth retaining walls. Shear strength may be a limiting factor in highly laterally loaded members such as reinforced walls. Brickwork flexural strength is unlikely to be used for the design of bridges.

Design stresses will determine the required compressive strength of brickwork. The engineer has the choice of designing an element with high strength brickwork and a relatively thin section, or alternatively with less strong brickwork and a thicker section. High strength brickwork is not essential for bridge design except perhaps for very flat arch rings where thrusts and hence

TABLE 1

Classification of clay bricks by compressive strength and water absorption

Class	Compressive strength (N/mm^2)	Water absorption (% by mass)
Engineering A	≥70	≤4.5
Engineering B	≥50	≤7.0
Damp-proof course 1	≥5	≤4.5
Damp-proof course 2	≥5	≤7.0
All others	≥5	No limits

Note 1: There is no direct relationship between compressive strength and water absorption as given in this table, and durability.

Note 2: Damp-proof course 2 bricks are recommended for use in external works.

compressive stresses are high, and in post-tensioned brickwork elements. The load tests for Kimbolton Butts Bridge undertaken by the Transport Research Laboratory showed that under a 30-tonne single axle load the estimated compressive stress in the arch ring was about one sixth of the characteristic compressive strength of the brickwork used.

The classification of clay bricks, summarised from BS 3921, is given in table 1.

Durability

Most arch bridges will be subjected to severe or very severe exposure conditions including saturation and freeze/thaw cycling of much of the brickwork.
To achieve a 120 year minimum design life to meet current Department of Transport standards for highway bridges and structures clay bricks should be specified as FL or FN to BS 3921. Where normal soluble salts content bricks (FN) are used, particularly where wetting and saturation are prevalent, then mortars made with Sulfate-resisting Portland cement should be considered to avoid the risk of mortar sulfation.

Very exposed brickwork elements such as parapets and particularly those with flush detailing such as cappings will need special design attention. Clay brickwork cappings should be laid in a designation (i) mortar (1:0-¼:3 cement:lime:sand). A protective coping incorporating generous overhangs and drip throatings to throw rainwater clear of brickwork faces is a preferable solution (figure 13). If practically achievable, a damp-proof course system should be placed within the wall head zone. Some proprietary interlocking copings

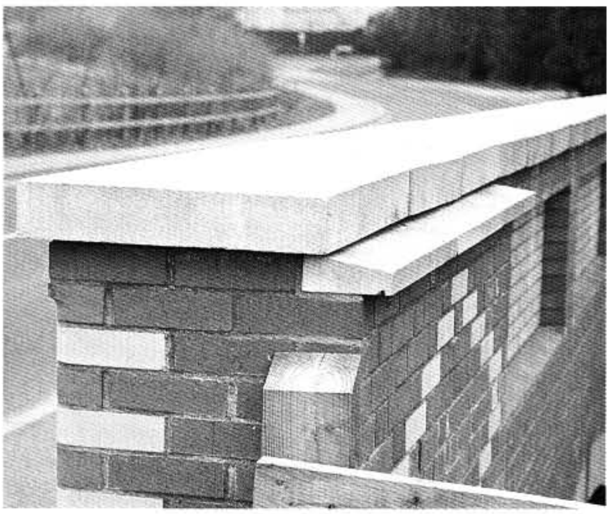


Figure 13. Copings to parapet walls.

incorporate damp proof courses. The use of a coping with an associated damp-proof course system also reduces the risk of brickwork staining.

Mortars

Mortars need to be selected on the basis of both strength and durability. Portland cement based mortars will be stronger and more durable, but less accommodating of movement than the hydraulic lime:sand mortars used in many old structures. Mortars should be strong enough for engineering requirements and of suitable composition for durability. Table 2 provides guidance on minimum mortar quality for use in brick bridges.

Detailing

Brickwork should be detailed in accordance with BS 5628:Part 3. For bridges it will usually not be practicable to use separate sheet damp-proof course systems at the bases of walls because structural continuity and integrity would be reduced. Damp-proof course bricks (see table 1) laid as a minimum of two bonded courses in a designation (i) mortar should be used.

Recessed mortar joint profiles should be avoided as they increase the risk of water penetration and also reduce the

TABLE 2

Recommended mortars

Location/element	Mortar designation
Work below or within 150mm of finished ground level	(i) or (ii)
Work 150mm or more above finished ground level:	
• Abutments, spandrel/wing walls, piers and parapets	(i) or (ii)
• Unreinforced arch ring	(iii)
• Reinforced/prestressed brickwork	(i) or (ii)

Note 1: Mortar designations correspond to proportions by volume of Portland cement:hydrated lime:sand as follows (reference BS 5628:Part 3):
(i) 1:0-¼:3.
(ii) 1:½:4-4½
(iii) 1:1:5-6

Note 2: Alternative mortar mixes such as cement:sand with plasticizer may be suitable for some uses (see BS 5628:Parts 1 and 2).

Note 3: Where FN classification bricks are used or where sulfates are naturally present in soil or groundwater in sufficient quantities to be damaging then Sulfate-resisting Portland cement based mortars should be used.

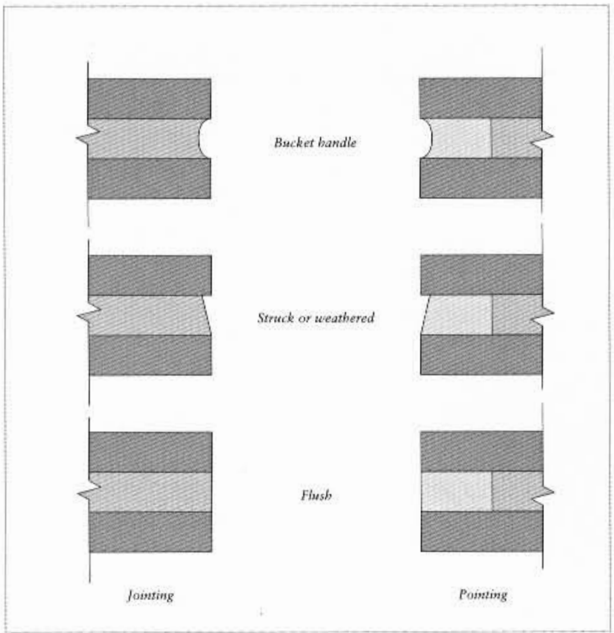


Figure 14. Suitable mortar joint profiles for walling.

effective structural brickwork section. Flush type and tooled mortar joint profiles are preferable. Figure 14 shows suitable joint profiles. The bucket handle and struck or weathered profiles will be more waterproof than the flush profile because of the tooling used. Special measures may be required if a good finish is needed to the mortar on the soffit of the arch. The method used at Kimbolton was to insert a strip of neoprene rubber material into the bottom of the joint during brickwork construction. This was removed after the centring was dismantled and the joints then mortar pointed. Gun pointing was used successfully; the pointing mortar should be of similar composition to that used in the rest of the construction so as to avoid hard nibs. In some cases it might be appropriate to use this method but to leave the joints unpointed, recessed slightly. Where the appearance of the soffit is unimportant, no special measures are required.

Movement accommodation

Movement in the brickwork of a bridge may be due to several factors:

- long term irreversible expansion of clay brickwork due to moisture.
- seasonal moisture movements (usually relatively small).
- seasonal thermal movements.
- creep of highly stressed elements such as prestressed brickwork.
- movement of foundations.

The provision of movement or control joints in spandrel walls, parapets and at junctions of spandrel and wing walls needs careful design consideration. In unreinforced clay brickwork walling, vertical joints to control horizontal movement will normally be required at 15m maximum horizontal centres, but are more typically provided at 9 to 12m horizontal centres to reduce the width of the joint. Figures 15a and 15b show a movement joint at Kimbolton Butts Bridge. For unreinforced parapets where exposure and the potential for saturation of brickwork is high, vertical joints for movement control will need to be spaced more closely, probably at horizontal centres not exceeding 6m. Movement joints need to be taken through cappings and copings. They should be filled with a suitable compressible filler with a sealant applied over.

For brickwork walls an alternative to the provision of frequent vertical joints is to provide continuous horizontal bed joint reinforcement at frequent vertical centres in the height of the wall. Movement joint spacings of 18-24m are then possible, depending on the frequency and size of the reinforcement. It is advised that movement joint widths are sized on an assessment of the potential movement occurring along the actual horizontal length of brickwork between joints. Grade 316 austenitic stainless steel is suitable for bridges where deicing salts are applied to the road in winter.

In continuously reinforced walls such as reinforced brickwork grouted-cavity construction, vertical joints for the control of movement can typically be spaced at 15m

Figure 15a. Movement joint under construction.

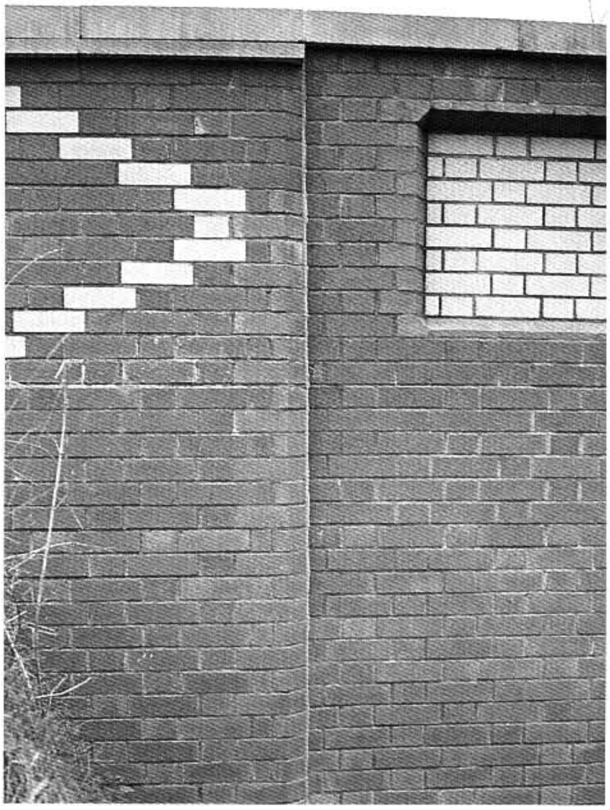


Figure 15b. Elevation on movement joint.

maximum horizontal centres due to the crack control influence of the continuous secondary reinforcement.

Further guidance on design for movement is given in BDA Design Note 10.

Competitiveness

Current evidence suggests that brick arches can be competitive in cost with steel/concrete designs. The estimated construction cost of a steel or concrete bridge at Kimbolton Butts was £95,000 and the actual cost of the brick arch bridge was £104,000.

With experience, some parts of the structure such as the parapets could have been built more economically. The cost of maintenance of the various options has to be taken into consideration. Records of Cambridgeshire's bridges show that the annual cost of maintaining a masonry bridge is two thirds that of a steel or concrete bridge. For the 120 year design life, the estimated whole life cost for Kimbolton Butts Bridge was £185,000 for a steel or concrete structure compared with £163,000 for a brick arch bridge (figure 16).

Conclusions

Brick arch bridges fulfil a functional role and make an attractive and worthy contribution to the environment, but they have not been built for most of this century. The problems associated with the steel and concrete bridges which succeeded them have recently focused attention on the advantages of brick masonry arch bridges. The innovative work of Cambridgeshire County Council in building Kimbolton Butts Bridge has shown that brick arch bridges are a viable alternative to steel or concrete bridges, at least for spans up to about 15m.

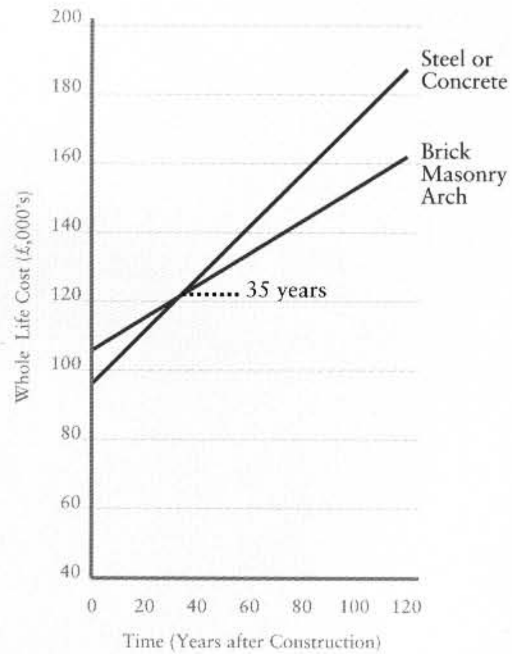


Figure 16. Whole life cost comparison for Kimbolton Butts Bridge.

Construction costs may be slightly greater but maintenance costs are lower and so whole life costs are likely to be competitive. The durability of brickwork is well known; modern bricks and construction methods should ensure that new bridges will last as long, if not longer, than older bridges. The purpose of this Special Publication is to encourage the design and construction of new brickwork arch bridges which will be assets for many years to come.

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(The Design Standard, BD, and Advice Note, BA, on the construction of masonry arch bridges are in the course of preparation).

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Frank Walter, cover photographs
British Waterways, Figs 2a, 2b, 2c, 3
John Page, Fig 2d
BDA, Figs 1, 5, 7, 11, 12, 13, 15a, 15b
David Cox, Figs 8, 9

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