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NEW BRICK ARCH HIGHWAY BRIDGES

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ABSTRACT

Engineers are under increasing pressure to design new highway works with low operating costs and minimal environmental impact. As a result, attempts are being made to develop new forms of bridge construction with lower maintenance requirements and greater aesthetic appeal than many of those currently in service. One structural form that may satisfy the aforementioned design requirements for short span bridges is the brick arch. This paper critically appraises the performance of existing arch bridges, identifies the main design requirements for new construction and describes what is thought to be the first completely new brick arch bridge to be built in the UK for about 100 years.

INTRODUCTION

Most bridge engineers routinely specify reinforced concrete, prestressed concrete or structural steel construction for new short span highway bridges, that is structures with a span of about 15m or less. Although the majority of these bridges are performing well, a significant number in the UK are in need of major maintenance or repair.

With concrete highway bridges, the main cause of deterioration appears to have been the chloride-induced corrosion of steel reinforcement resulting from the repeated use of rock salt de-icing agent on freezing highway surfaces (Wallbank 1989); similar problems have been reported in other European countries, Japan and North America (OECD 1989, Slater 1983). In many cases, the damage resulting from chloride attack has been compounded by the effects of sulphate attack, alkali-silica reaction, carbonation or freeze-thaw action. The financial scale of this problem is reflected in the total cost of repairing the corrosion damaged bridges of the United States which was recently estimated to be $29,000 M; in Europe, the annual cost of similar remedial work is in the order of 1,400 M ECU (≈ £1,120 M) (Clarke 1992).

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With structural steel bridge deck construction, corrosion is the principal cause of deterioration and protection against this commonly consists of a multi-coat paint system. In the aggressive environments that highway bridges are usually exposed to in the UK, the paint systems that are applied to exposed steel are usually required to last at least 8 years before any minor maintenance, with major maintenance consisting of major re-painting work expected after about 15 years.

As well as the direct costs of the maintenance and repair of steel or concrete structures, the unacceptable disruption to traffic caused by such work not only lowers the morale of the road users but also impairs the efficiency of many sectors of industry.

With new bridges, engineers must not only design low maintenance structures but they are also required to place greater emphasis on the aesthetic appeal than in the past. In the UK, the masonry arch bridge is generally regarded as one of the more acceptable forms of bridge construction by the public, often forming the focal point of an idyllic rural scene or a reminder of the nation's industrial heritage. Recently in the UK, there has been a great deal of interest in the arch bridge for new construction because of its low maintenance costs. This is reflected in the formation of a working party by the UK Department of Transport to develop a design standard for new arch bridges.

The main aim of this paper is to examine the case for the use of the clay brick arch for new highway bridges; the following points are considered:-

1. A critical review of existing clay brick arch bridges.
2. The design requirements for new clay brick arch bridges.
3. New brick arch bridges - A case study.

CRITICAL REVIEW OF EXISTING CLAY BRICK ARCH BRIDGES

Many thousands of clay brick arch bridges and viaducts were built in the UK between 1760 and 1900 as part of the development of the canal and railway transportation systems initiated by Industrial Revolution. Although most of these structures have been subjected to very severe exposure conditions for long periods, many are still in service and have needed comparatively little maintenance.

As new materials and construction techniques were developed and gradually adopted by the construction industry in the UK, the use of clay brickwork for large engineering structures declined. Initially, cast iron or wrought iron girders spanning onto brickwork abutments and piers were used instead of masonry arches for bridge construction. Then, with the emergence of concrete construction at the beginning of this century, the use of clay brickwork suffered further decline to such an extent that it is now used mainly as a non-structural cladding material.

If clay brickwork is to be reconsidered by highway and bridge engineers for use as a structural material, modern designs must be developed that retain any evident benefits of the old forms of brickwork construction but overcome any limitations. Some understanding of the limitations may be obtained from a critical review of the construction and performance of existing arch bridges such as the one shown in Fig.1 which is fairly typical of nineteenth century construction in the UK. Different aspects of the performance of such bridges are reviewed below.

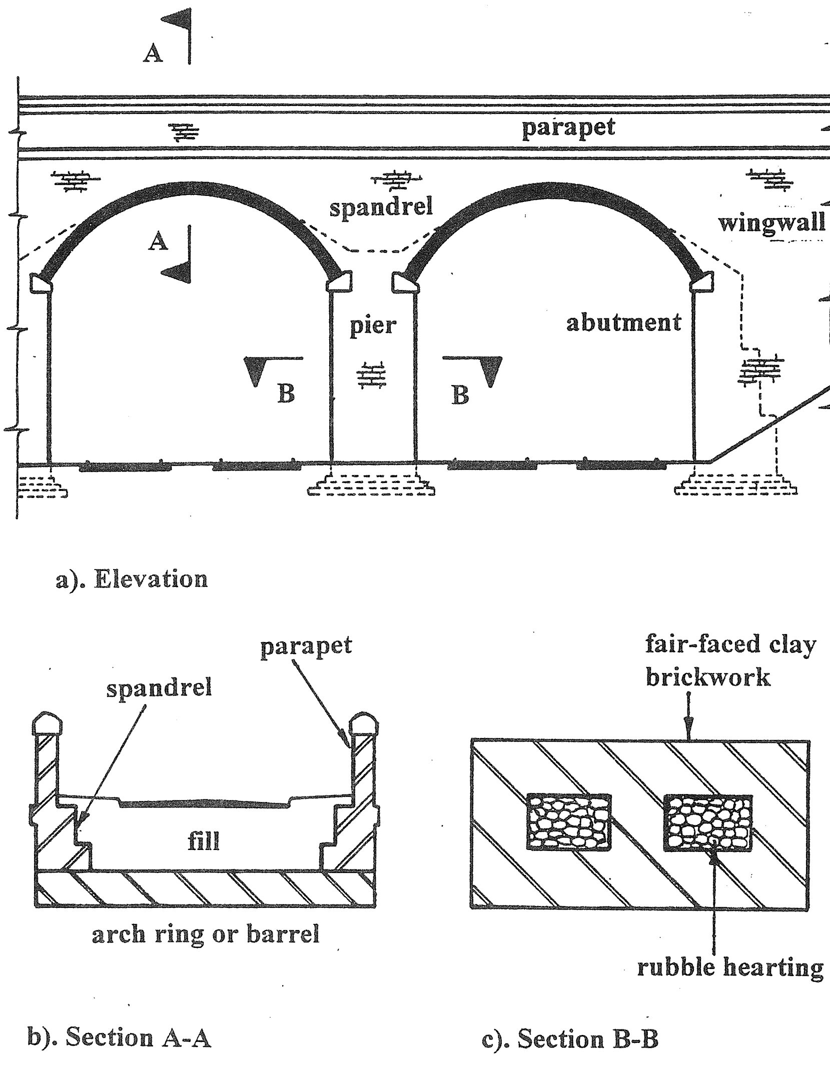

Fig.1. Typical Details - Nineteenth Century Brick Arch Bridge

Materials
Most brick arch bridges were built using weak hydraulic or semi-hydraulic lime mortar and there was usually little or no attempt to protect the joints from rainwater leaching through the fill material from the carriageway or rail track above. Although such mortars were capable of accommodating movements due to changes in the ambient conditions and small amounts of differential settlement, experience has shown that they are prone to deteriorate from the effects of frost attack and that lime can be leached out of the mortar and left as unsightly calcium carbonate deposits on the exposed faces of the brickwork. As a result, the bricks have tended to become de-bonded from the mortar to such an extent that it is not uncommon for bricks to fall out of the arch ring of the bridge. Furthermore, the aesthetic quality of some structures has been considerably reduced by lime staining and fungal growths on damp patches of brickwork. Other less common causes of deterioration include abrasion from wind and water, salt crystallisation damage and the effects of the expansive reaction between cements and sulphates in the groundwater or from atmospheric pollution.

As far as the clay bricks are concerned, there have been comparatively few problems. The main form of deterioration has been the progressive degradation of the exposed faces of some bricks due to freeze-thaw action or salt crystallisation, although this has not occurred where the bricks have remained relatively dry or where well-fired, low porosity engineering bricks have been used.

The arch barrel
The inherent strength of the voussoir arch ring or barrel is well known (Heyman 1982) and has been confirmed by a series of full-scale load tests to collapse on series of redundant arch bridges in the UK (Page 1990). Where distress has occurred it has often been due to failure of the abutments or piers resulting either from scour or from the excessive settlement typical of shallow, inadequate foundations (Jones 1991). There can be little doubt that most arch bridges built today would not suffer from such problems because of the vast improvements both in ground investigation techniques and in foundation design and construction.

Although the curved profile of the arch undoubtedly contributes to its aesthetic appeal, the low headroom close to the supporting abutments or piers of highway overbridges can result in "bridge bashing", i.e. damage from tall vehicles. In addition, flooding can occur where arch bridges span watercourses because the bridge creates an increasingly greater obstruction to flow as the water level rises.

Wingwalls and spandrel walls
These walls are subjected to horizontal earth pressure from the fill material placed at the ends and over the top or extrados of the arch ring. In addition, the spandrel walls and, to a lesser extent the wingwalls, stiffen the outer edges of the arch ring. The combined effects of lateral pressure and the central portion of the arch ring deforming under the action of live loading can lead to cracking and eventually partial collapse, as the wingwalls and spandrel walls become separated from the rest of the structure (Sowden and Jones 1991, Department of Transport 1993). This behaviour is, again, indicative of brickwork's low tensile strength and can be exacerbated by rainwater leaching through the fill material into the mortar joints (Powell 1991), as described earlier.

The craftsmen of the past were certainly aware of brickwork's very low and sometimes unreliable tensile strength. To overcome this they usually built very thick wingwalls and spandrel walls, the aim being to provide sufficient dead weight to counteract any flexural tension caused by the lateral earth pressure. As this philosophy was also used when "designing" and building masonry earth retaining walls, it is not surprising that some of the solid brickwork walls built by Victorian railway engineers to support the sides of deep cuttings were well over 2m (6'-7") thick in places.

Parapet walls
The principal function of the parapets of any highway bridge is to contain a vehicle collision in as safe a manner as possible. In the case of masonry parapets, it is very difficult to quantify the impact resistance because of the very complex behaviour of unreinforced masonry when subjected to high rates of loading from a non-rigid body such as a vehicle. In order to assess the behaviour and strength of masonry parapets when subjected to vehicle impact, the County Surveyor's Society of the UK recently funded a research programme which included a series of full-scale vehicle impact tests on masonry parapets at the Motor Industry Research Association in Nuneaton, England (Galloway 1994); all the tests were carried out in accordance with Appendix E of BS 6779 (British Standards Institution, 1992). Although most of the masonry parapets tested adequately confined the test vehicle, a major safety hazard was created by the large pieces of masonry which were broken away from the parapet on collision. Clearly this potential problem must be addressed when designing any new structures.

Piers and abutments
Although usually of solid masonry, some piers and abutments were built with an outer skin of fair-faced stone or clay brick masonry with a low cost rubble infill or "hearting", as shown in Fig.1. As the compressive stress due to the vertical loads acting on a pier or an abutment of an arch bridge tends to be greater than the flexural tensile stress produced by the lateral forces, the masonry is generally in a net state of vertical compression throughout. Therefore, provided that such compressive stress is small, the piers and abutments can remain in an uncracked and stable condition for many years. As with the wingwalls and spandrel walls, masonry piers and abutments were also usually of massive construction to ensure that there was sufficient dead weight to maintain the masonry in a net state of compression.

As mentioned previously, lime mortars were used extensively in brickwork construction. The compressive strength of such mortar was invariably an order of magnitude lower than that of the bricks. Hence, it is very likely that the compressive stresses in the bricks of existing structures are very low which may explain why there have been very few collapses resulting from compression failures. Where piers and abutments have failed, it has usually been as a result of tensile stresses or instability caused either by scour, excessive ground movements or the effects of severe overloading produced by modern traffic.

Construction
The arch rings of masonry bridges were constructed in-situ on temporary centering. This was usually of timber construction and often consisted of an elaborate array of inter-connected diagonal members which was necessary to provide a stiff platform on which to build the arch. Invariably the installation of centering was very time consuming and

often fraught with delays arising from the combination of inclement weather and the complexity of construction.

As noted previously, most vertical structural elements of arch bridges were of fairly massive construction to provide stability. As a result, arch bridge construction was very slow and very labour intensive, sometimes involving huge numbers of bricks, for example, the 544m (1785') long, 27 arch Victorian railway viaduct in Stockport, England (Hayward 1988) is thought to consist of some 22 million bricks.

Taking into account the slow, labour intensive construction methods and the difficulties experienced with the construction of centering, it is not difficult to appreciate why there was a decline in the use of masonry as stronger alternative materials such as cast iron, wrought iron, structural steels and reinforced and prestressed concrete were developed.

Workmanship
Judging by the results of many highway schemes that have involved the use of brick clad reinforced concrete it is clear that, with adequate supervision, very high quality brickwork can be achieved.

A possible advantage of brickwork is that the main construction defect, namely poorly filled mortar joints, can be detected by visual inspection. With reinforced concrete construction, durability is highly dependent on ensuring that the permeability of the surface zones of concrete is reduced as much as possible in order to provide the maximum protection to the steel reinforcement. This is generally achieved by using well compacted concrete with a relatively high cement content and a low water:cement ratio; surface porosity is further reduced by good curing. In practice, however, it is difficult to check the porosity and permeability of the concrete because the capillary pores in the cement paste, which permit the ingress of chloride ions and other deleterious substances, are microscopic. Hence, although the finished concrete may appear satisfactory to the naked eye, there is no way of easily checking that the quality of the cover concrete is adequate without carrying out in-situ permeability measurements. In short, it is not possible to visually inspect the concrete for quality. The water:cement ratio of the mortar in brickwork construction, however, does not have the same influence on durability and only very inaccurate batching of the mortar mix constituents is likely to cause major problems in the future.

Hence, although defects can and do occur in brickwork as a result of poor workmanship, they can usually be detected during construction and can be minimised with the use of good supervision.

DESIGN REQUIREMENTS FOR NEW BRICK ARCH BRIDGES

All structures must be strong, stable, robust and safe. Taking into account the points raised in the critical review, the additional design requirements of new brick arch highway bridges are summarised below.

Construction methods
Construction methods must be simpler and quicker than in the past and must involve less labour and materials. Mortars in which the principal binding agent is ordinary portland

cement rather than lime should also be used as the rate of strength gain is conducive to ensuring the rapid construction times required by most Clients.

Structural form
Judging from the problems that do occur with old arch bridges, it appears that major improvements need to be made to the laterally loaded structural elements, namely the parapets, spandrels and wingwalls. To improve structural performance and to reduce construction times and cost it is necessary to adopt more efficient forms of construction that make optimum use of brickwork's relatively high compressive strength but overcome its inherently low tensile strength. It is therefore suggested that reinforced or prestressed forms of brickwork construction should be used as alternatives to the massive forms of construction used in the past.

Compressive stresses
Although modern cement-based mortars are much stronger than lime mortars, in order to reduce the risk of overstressing the bricks, a low compressive stress limit should be used when designing new brickwork structures.

Durability
New brickwork structures must be durable and easy to maintain. In particular, where any steel is used in construction, the risk of corrosion caused by chloride attack from de-icing salts and other sources must be minimised. More durable mortars should be used instead of the lime-based mortars of old which were very prone to weathering and erosion.

A durable combination of bricks and mortar which is resistant to frost and chemical attack must therefore be specified. Based on the guidance given in BS 5628: part 3 (British Standards Institution 1985b), the use of frost resistant clay bricks with a low soluble salt content is recommended; such bricks are defined as "durability designation FL" in BS 3921 (British Standards Institution 1985a). In addition, it is suggested that the bricks should be specified with a maximum water absorption of about 10 - 12% and a minimum compressive strength of about 50 MPa (7250 psi). Where the brickwork is likely to remain saturated for long periods, the use of bricks with a lower water absorption may be necessary.

The most appropriate mortar mix for highway structures will generally be a weigh batched 1 : ¼ : 3 opc:lime:sand mix. Some engineers also recommend the use of a styrene butadiene rubber (SBR) latex additive in the proportion of 6 litres (1.52 US gallons) of SBR per 50 kg (110 lbs) of OPC. The SBR acts as a bonding and waterproofing agent and may help reduce lime staining of the mortar joints and facilitate the removal of graffiti. New brickwork highway structures must also be adequately waterproofed and drained to reduce the risk of deterioration from freeze-thaw action.

Aesthetics
Brickwork highway structures must be aesthetically pleasing. In addition to providing adequate waterproofing and drainage to prevent the occurrence of damp patches and the growth of unsightly fungi, measures must also be taken to minimise the risk of efflorescence and lime staining.

Movement
Cement mortars, which often contain a non-hydraulic lime plasticiser, are used exclusively in new construction; such mortars are much more brittle and therefore more susceptible to cracking than their hydraulic lime-based predecessors. As a result, with brick arch bridge construction it is essential to provide joints in those elements of construction that are vulnerable to the effects of moisture and thermal variations such as the wingwalls. In the case of the arch ring, to accommodate minor ground movements as well as the small amount of movement likely when removing the centering, the use of a 1 : 1 : 6 (opc:lime:sand) mortar is recommended.

Cost
Ideally, brickwork bridges must be cheaper to construct than the concrete or steel alternatives. Many engineers are familiar with concrete or structural steelwork design and construction and are, perhaps, reluctant to use alternatives. Although some engineers may accept that clay brickwork structures can have very low whole-life costs, the prospect of initial cost savings is probably required to motivate most to consider brickwork as an alternative to structural concrete.

NEW BRICK ARCH BRIDGES - A CASE STUDY

The improvements in ground investigation techniques and the design and construction of foundations referred to earlier, coupled with the development of lightweight, easy-to-install falsework suitable for centering may make the brickwork arch an economically viable form of new construction for small span bridges. Furthermore, experience in the UK has shown that the maintenance costs for masonry arch bridges can be in the order of 30% less than those for other forms of short span bridge construction (Halsall and Cox 1994). The aesthetic appeal of the unreinforced brick or stone masonry arch and the anticipated savings in whole-life costs has prompted many bridge owners in the UK such as the Department of Transport, the Scottish Office (Scottish Office 1992) and some local and regional Highway Authorities (Halsall and Cox 1994, Harvey et al. 1988) to recommend the use of the masonry arch form of construction for new short span bridges; one of these, Kimbolton Butts Bridge, is briefly described below.

Kimbolton Butts Bridge, Huntingdon, England
This is thought to be the first completely new brick arch bridge built in the UK for almost 100 years. Designed by the engineers of the Transportation Department of Cambridgeshire County Council, the bridge carries the 6.2 m (20'-4") wide B660 highway over the River Kym in Huntingdon, near Cambridge and was opened to traffic on 16 December 1992. It has a span of 8.065 m (26'-5") and is 9.3 m (30'-6") wide between the traffic faces of the parapets. Details of the bridge are given in Fig.2.

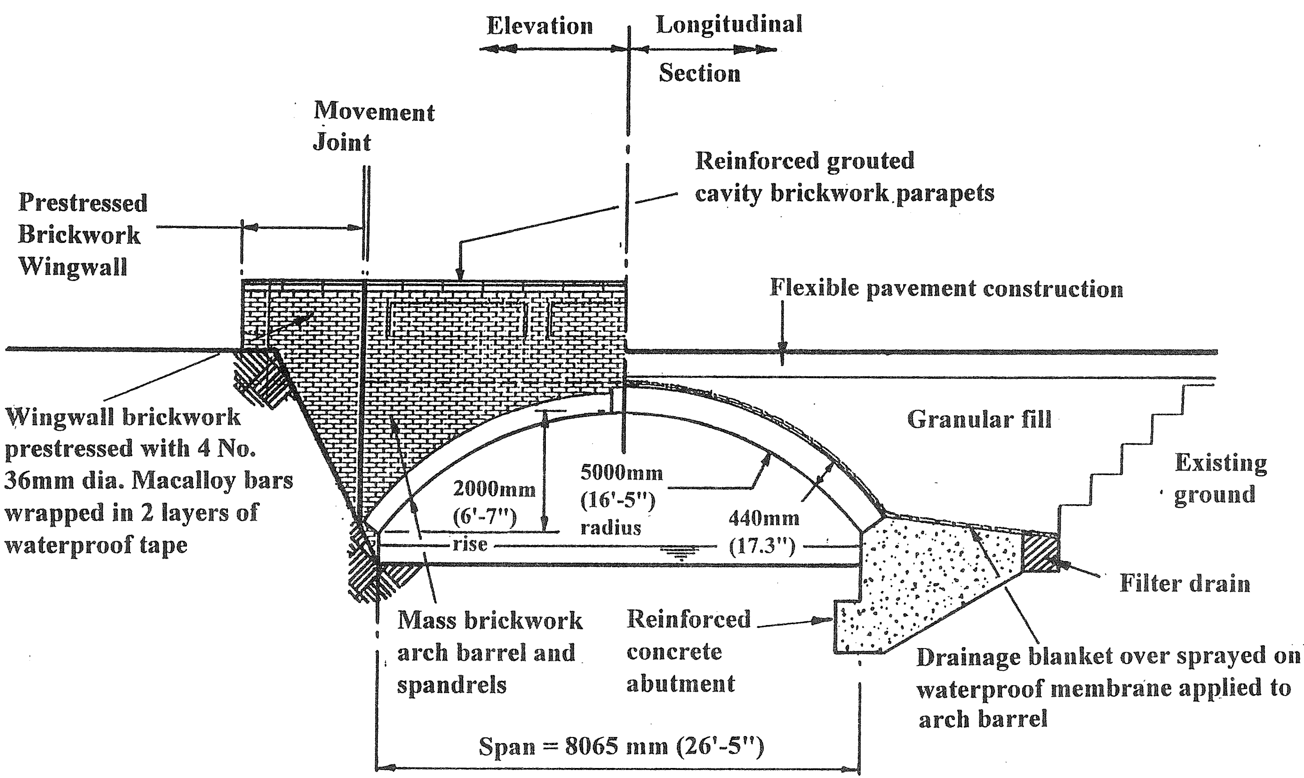

Fig.2. General Details - Kimbolton Butts Bridge, Cambridgeshire, England

The original structure, which was not strong enough to carry modern highway loading, was of composite steel beam/concrete deck construction. In addition, the parapets, which were of tubular steel handrail construction, did not satisfy modern vehicle containment standards. At the early stages of the design of the replacement bridge, a conventional structure with a precast prestressed concrete beam deck was compared with the design eventually adopted; each bridge was estimated to cost approximately £100,000 (Halsall and Cox 1994). The arch bridge was selected because it was judged to have the greatest aesthetic appeal for its rural location, it was much preferred by the representatives of the local Parish Council and the anticipated maintenance costs were less than that for the concrete alternative.

The design of the arch ring was based on the Department of Transport's guidelines for the strength assessment of masonry arches (Department of Transport 1993). The 440 mm (17.3") thick arch ring consists of durability designation FL clay bricks with a minimum compressive strength of 70 MPa (10150 psi) and a maximum water absorption of 7% laid in a 1 : 1 : 6 (opc:lime:sand) mortar. The ring was built in English bond to avoid any planes of weakness that could lead to ring separation or delamination which is known to severely reduce the strength (Melbourne and Gilbert 1995). The problem of spreading spandrels and wingwalls and the need to contain the damaged masonry resulting from vehicle collision with the parapets, was solved by using prestressed brickwork diaphragm walls for the wingwalls and reinforced grouted cavity brickwork for the parapets; the comparatively small spandrel walls were of mass brickwork construction. Although the vertical settlement of the abutments was estimated to be in the order of 15 mm, because a masonry arch is known to be capable of accommodating small movements, spread footings rather than piled foundations were judged to be adequate. Durability designation FL clay bricks with a minimum compressive strength of 56 MPa and a maximum water absorption of 11% laid in 1 : 1 : 6 (opc:lime:sand) mortar were used for the wingwalls, spandrels and parapets.

The arch ring was built on centering consisting of plywood sheet decking nailed onto timber members which were fastened to curved, rolled steel universal column sections spanning across the river between the reinforced concrete foundations of the bridge. The top surface of the arch and the inner faces of the wingwalls and spandrel walls were waterproofed with a spray applied, two-coat acrylic membrane. Drainage was provided using a polymer-based fin drain laid over the extrados or upper surface of the arch barrel which was subsequently backfilled with freely draining well-graded granular fill. Since the mid 1980s, Cambridgeshire County Council engineers have designed several major brickwork highway structures; it is interesting to note that, to date, they have not experienced any difficulty in finding bricklayers with adequate skills to cope with the construction of arches, reinforced brickwork or prestressed brickwork.

CONCLUDING REMARKS

a) The excellent long-term performance of many of the existing brick arch bridges and viaducts, which were built well over 100 years ago in the UK, has demonstrated that clay brickwork can withstand the severe exposure conditions experienced by most highway structures. A critical review of these existing structures has identified several limitations that need to be addressed when designing new brick arch bridges.

b) The specification and use of durable clay bricks and mortars, movement joints, waterproofing membranes and drainage details for new construction should minimise the risk of water penetration, leaching of the mortar joints, frost damage and unsightly staining caused by efflorescence, lime bloom and plant growths on the exposed parts of the bridge.

c) The vast improvements in ground investigation methods and in the design and construction of foundations since the last arch bridges were built in the UK will result in a major reduction in the risk of excessive ground movements or scour.

d) The cost and construction times of new arch bridges can be reduced considerably by using structurally efficient reinforced or prestressed brickwork for the abutments, wingwalls, spandrels and parapets.

e) The aesthetic appeal, longevity and low maintenance costs of many existing brick arch bridges coupled with the success of the Kimbolton Butts project presents a very strong case for the use of brick arch construction for new short span highway bridges.

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VERY LOW EMISSIONS CORDWOOD COMBUSTION IN MASONRY HEATERS AND MASONRY FIREPLACES - EARLY RESULTS WITH POSSIBLE IMPLICATIONS

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ABSTRACT

Woodsmoke emissions are an increasing health concern in populated areas with certain geographical features. Site-built open fireplaces now face severe restrictions in a number of jurisdictions. The author and colleague J. Frisch have conducted emissions and performance tests on several masonry appliances over a period of three years. A new result is that a masonry fireplace retrofitted with an airtight door was able to operate with particulate emissions that were considerably lower than previous published results, and an order of magnitude lower than reported results for open fireplaces. A second type of fireplace known as a masonry heater, characterized by a high burn rate and and the ability to store energy in a masonry thermal mass, was able to operate with emissions that were an order of magnitude lower than current requirements for woodstoves certified to the new Canadian Standards Association (CSA) emissions limits.

INTRODUCTION

This report deals with testing that the author and colleague J. Frisch conducted on three woodburning masonry appliances - a standard masonry fireplace with an airtight door, a standard 18" contraflow masonry heater, and a prototype 27" contraflow heater with bake-oven. All appliances were set up at a test facility (Lopez Labs, Seattle) specifically constructed for this purpose.

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