TRANSPORT RESEARCH LABORATORY

TRL REPORT 204

A GUIDE TO REPAIR AND STRENGTHENING OF MASONRY ARCH HIGHWAY BRIDGES

by John Page

Prepared for: The County Surveyors' Society

Transport Research Foundation Group of Companies
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First Published 1996
ISSN 0968-4107

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EXECUTIVE SUMMARY

The County Surveyor's Society Bridges Group has produced with the assistance of TRL a Guide to the Repair and Strengthening of Arch Bridges. Forty percent of the UK highway bridges are brick, stone or masonry arches. Most are well over 100 years old and the traffic the are required to carry both in terms of weight and numbers has increased considerably since they were built. There is a continuing need to repair and strengthen them as they age and deteriorate and in addition many arches are listed structures and cannot be replaced by modern designs.

The information for inclusion in the guide was obtained from the results of a questionnaire to bridge owners seeking experience of repair and strengthening methods. The aim was to seek up to date advice on the advantages and disadvantages of particular methods together with their cost and effectiveness over time. Work carried out at TRL including current research to quantify the gain in load capacity from some typical arch strengthening methods has also been incorporated.

Various repair and strengthening methods which have been in common use for a number of years are covered . They include:

- Grouting
- Invert slab
- Mini Piles
- Prefabricated liner to soffit
- Reinforced sprayed concrete to soffit
- Relieving slab
- Replacing fill with concrete
- Repointing
- Saddling
- Stitching
- Tiebars
- Underpinning

The guide gives comprehensive information and advice on present best practice, relative costs and effectiveness for the various repair and strengthening methods. It is hoped that the document will prove to be a valuable source of core information for young engineers whilst also providing useful reference material and assistance to the more experienced.

A GUIDE TO REPAIR AND STRENGTHENING OF MASONRY ARCH HIGHWAY BRIDGES

ABSTRACT

The County Surveyor's Society Bridges Group has produced with the assistance of TRL a Guide to the Repair and Strengthening of Arch Bridges. There are about forty thousand masonry arch bridges on the British road network, about forty percent of our total road bridge stock. The earliest still in existence are mediaeval and the amount and weight of traffic they are now called on to carry has increased enormously since they were built. It is important that they continue to perform their function because it would be neither practicable nor desirable to replace them. The cost would be enormous and many make a positive contribution to the landscape.

This Guide examines the problems common to arch bridges and the methods of repair and strengthening which may be applied, together with estimates of their costs. It also describes the analysis methods which may be used to assess arch bridges and strengthening procedures, and the means of gathering the necessary data. The guide is designed to be a valuable source of information for young engineers whilst providing useful reference material for the more experienced.

1. INTRODUCTION

Masonry arch bridges are an important part of the British road network. There are about forty thousand of them, about forty percent of our total road bridge stock. In Britain, the earliest still in existence are mediaeval; Monmow Bridge for instance was built in 1272. The main period of arch bridge building however began with the construction of the canals in the second half of the eighteenth century and ended when the railway network was substantially completed at the beginning of the twentieth century. The amount of traffic they are now called on to carry has increased enormously since they were built, as has the weight of some of that traffic. It is important that they continue to perform their function because it would be neither practicable nor desirable to replace them. The cost would be enormous and many make a positive contribution to the landscape.

This Guide examines the problems common to arch bridges and the methods of repair and strengthening which may be applied, together with estimates of their costs. It also describes the analysis methods which may be used to assess arch bridges and strengthening procedures, and the means of gathering the necessary data. It is based on a variety of sources, the main of which are set out in Appendix A. The Guide has been prepared by the Transport Research Laboratory for the County Surveyors' Society, whose Bridges Group set up a Steering Group to provide guidance for it; the membership of the Group is listed in Appendix B.

The Steering Group hopes that you will find the Guide valuable; in due course the Group believes that a second edition should be published which will incorporate the results of further research and development of repair and strengthening methods, and of comments received on this edition. You are invited to provide suggestions based on your experience of work on arch bridges and your use of this Guide; a form is included at the back.

The typical construction of an arch bridge, and the terminology used, is shown in figure 1. A more comprehensive terminology will be found in (Page, 1993). The figure illustrates the simplest form of construction with spandrel fill. For long span bridges particularly, the internal construction may be more complicated, aimed at reducing weight, for example:

- Several internal spandrel walls may be found, spanned by stone slabs or brick/stone arches on which the road surface is laid. The walls are typically 450mm wide and spaced about 600mm apart. Bridges may be found with internal spandrel walls but with the spaces in between filled, see figure 5. It may be that in these cases the stone slabs had cracked and were removed and replaced by fill.
- Subsidiary arches may be built on top of the main arch, spanning in the same direction. These arches are usually concealed behind solid spandrel walls.

Cylindrical voids may be created in the spandrel fill above the haunches of the arch to reduce the dead load on the arch. The voids may be open, in which case they may also act as passages for flood water (see figure 2), or they may be hidden behind the spandrel walls.

The most common arch shapes are illustrated in figure 3.

2. PROBLEMS

2.1 FOUNDATIONS, PIERS AND ABUTMENTS

2.1.1 Settlement

Piers and abutments will be affected by settlement of the foundations, particularly if it is not uniform. The cause of

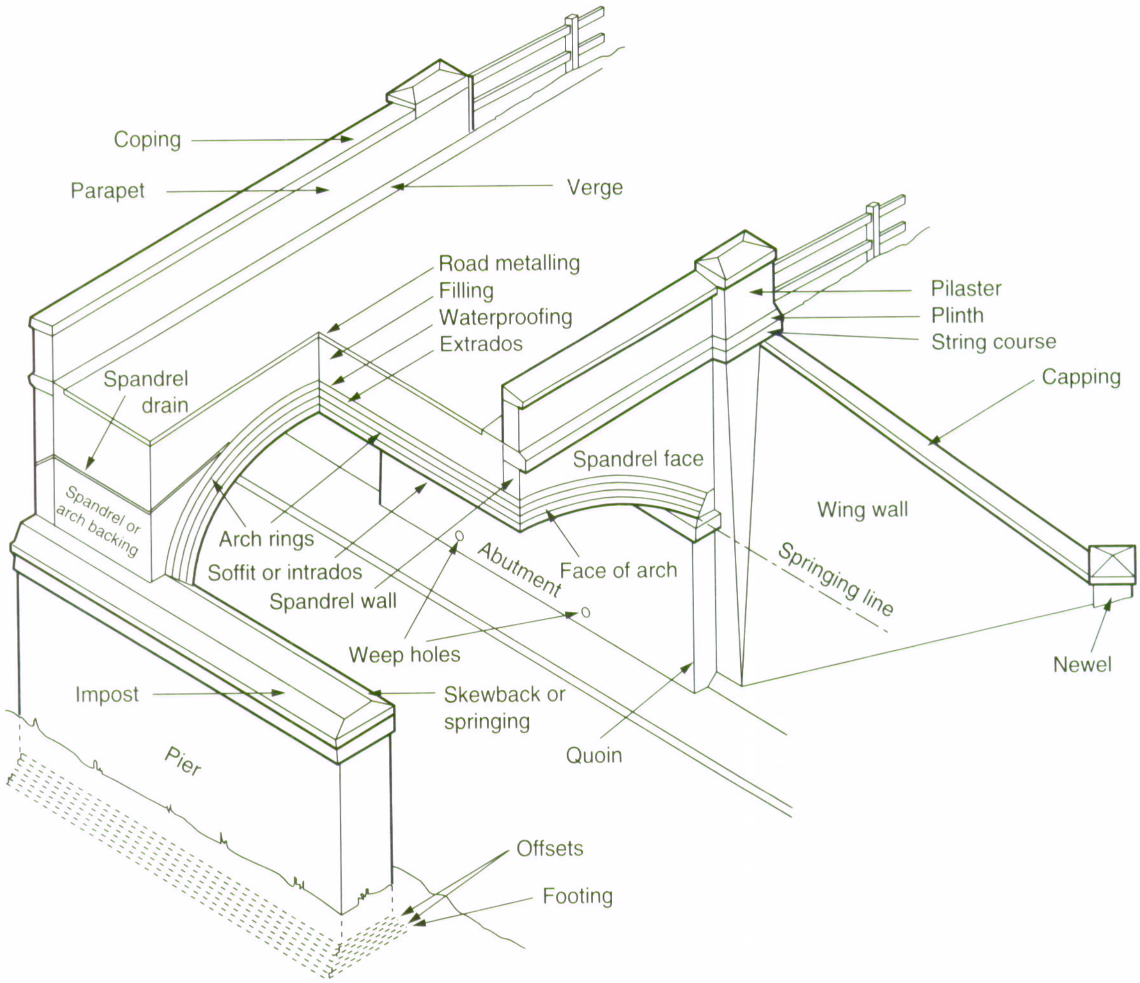

Fig. 1 Typical construction of a masonary arch bridge (Source Sowden, 1990)

Fig.2 Pontypridd Bridge, with cylindrical voids in the fill at the haunches

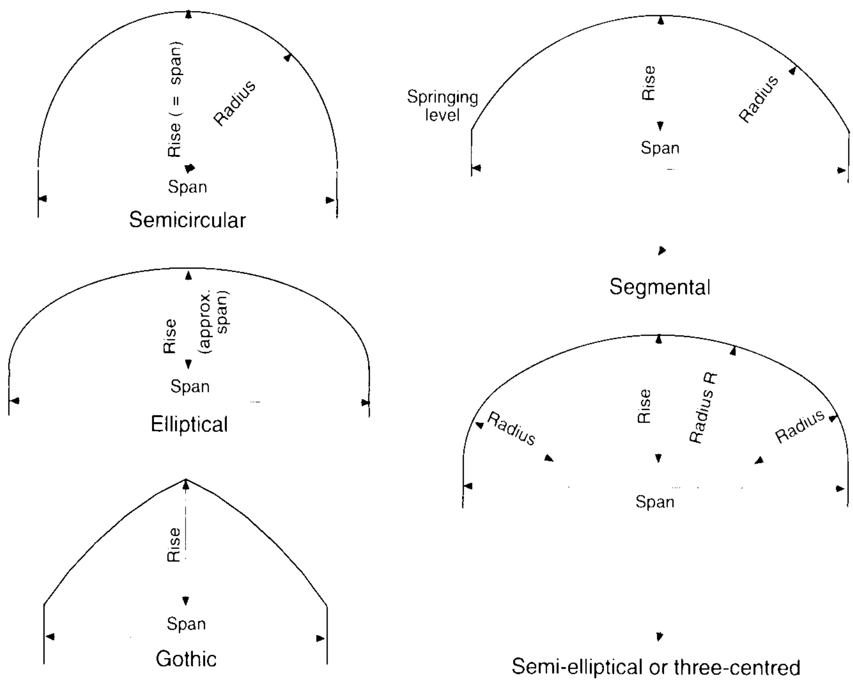

Fig.3 Arch shapes

the settlement needs to be identified, particularly if it is active. It may be due to geotechnical factors, material deterioration, or flooding. Consolidation of the subsoil, shrinkage of underlying clays, and the presence of expansive soils may be responsible. A change in moisture content or the level of the water table may be the cause, and this could be caused by a burst water main or the presence of tree roots. Mining subsidence may cause massive movements of the foundations. An increase of live loading, or of dead loading by increasing the depth of fill over the bridge, may have an effect. The effects of various forms of settlement are illustrated in figure 4.

Piers and abutments were commonly founded on timber rafts or piles. They can enjoy very long lives provided they are totally immersed in water, but they will rot if exposed to air.

2.1.2 Scour

Scour of foundations is probably the most common cause of collapse of arch river bridges, see figure 5. Their foundations are often shallow and susceptible to scour. It is difficult to detect because it is likely to be at its worst when the river is in flood and access is impossible; scour holes may then fill up when floods subside and camouflage undercutting of foundations. It is likely to be made worse by fallen trees and other debris catching in the arch when the river is in flood.

During a flood, the river bed level may fall as bed material is transported by the moving water. A bridge across the river can cause additional local lowering of the bed level. This extra erosion, or scour, has two possible causes. Firstly the bridge piers or abutments constrict the channel and cause a general increase in flow velocity; this extra erosion is called general scour. Secondly the bridge piers or abutments cause a local disturbance of the flow and this causes extra erosion, called local scour. The total depth of scour is the sum of both forms of scour.

Water flow in an unobstructed river is parallel to the river bed. An obstruction such as a bridge pier placed in the river changes the direction of flow round the pier, see figure 6. A downward flow occurs on the pier face and a reversal of flow along the river bed in front of the pier. This flow produces a vortex which extends around the sides of the pier. It is called a horseshoe vortex because of its plan shape. There will also be a wake region at the rear of the pier with vortices being given off at intervals. The shape of the pier will affect the horseshoe vortex and the wake region; streamlining of the pier at front and rear will have a beneficial effect, but any build-up of debris in front of the pier or a change of the angle at which the flow hits the pier will render the pier shape irrelevant.

The effect of any proposed change to the river regime adjacent to a bridge should always be considered; specialist advice may be needed.

Equipment to detect automatically the onset of scour has been developed in recent years; its use should be considered in appropriate circumstances.

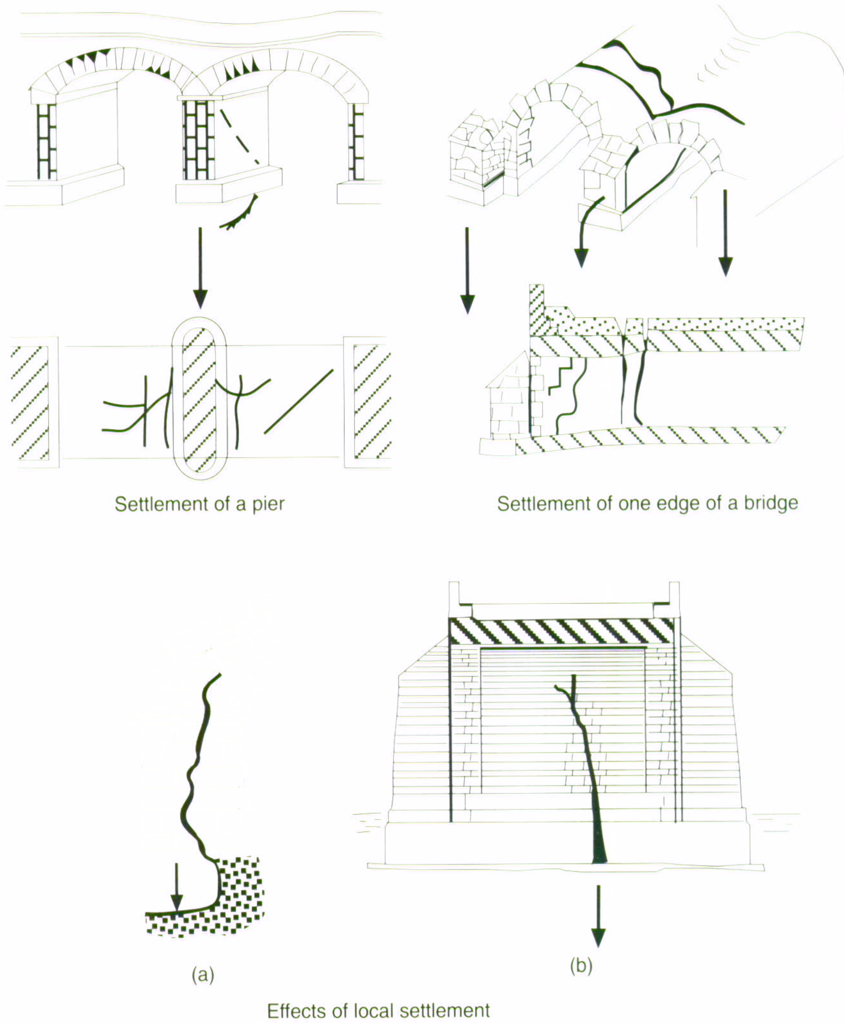

Fig.4 Effects of settlement

Fig.5 Collapse of arch bridge pier due to river in flood

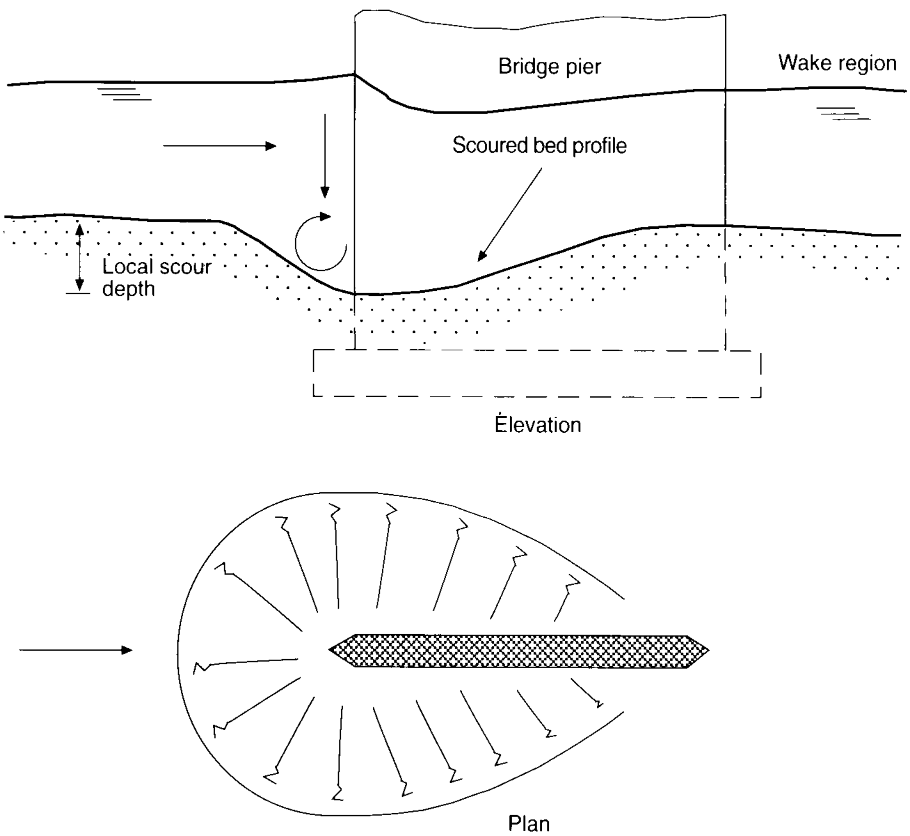

Fig.6 Typical scoured bed shape

2.2 ARCH RING

2.2.1 Splitting beneath spandrel walls

Spandrel walls stiffen the arch ring at its edges. Flexing of the arch ring due to traffic loads will produce shear stresses in the ring where the relatively flexible part with only fill above it is stiffened by the spandrel wall, and these stresses may result in a crack. A very severe example of such a crack is shown in figure 7. Bridges with stone spandrel walls and external voussoirs, with the rest of the arch in brick may be specially vulnerable to this problem. This type of failure may be assisted by rainwater getting into the structure at the parapet/surface joint and causing particular damage to the arch ring mortar where the spandrel wall meets the ring. It is also assisted by outward forces produced on the spandrel wall by the fill.

Even when the wall is fully separate from the arch ring, it provides some degree of support due to friction between the fill and the wall.

None of the present assessment methods take into account the stiffening effect of spandrel walls. It is however safe to ignore their potential contribution.

2.2.2 Problems due to movement of abutments

Abutments are subject to forces which may move them either outwards or inwards:

- the arch ring generates outward forces.
- the fill behind abutments generates inward forces.

The effect on the arch ring will depend on whether the resulting movement, if any, is outwards or inwards and whether it is accompanied by rotation of the abutments. It is likely to manifest itself as transverse cracks in the arch ring. Most arches would settle when the centring was removed during construction but would be expected to stabilise so recent cracks are a cause for concern as they indicate that fresh movement is occurring. Regular inspection and careful record keeping are essential in this situation.

The effect on load capacity may be assessed when using the MEXE assessment method (see chapter 5) by using the recommended factors in table 1 (DOT, 1993b) or for more recent methods by basing calculations on the distorted arch shape and by building into the model any pre-existing cracks.

Fig.7 Severe longitudinal crack in arch ring due to outward movement of spandrel wall

If one edge of a bridge settles then longitudinal cracks will occur in the arch ring. This may be serious if the ring divides into effectively independent segments. The effect on load capacity may be assessed when using the MEXE method by using the recommended condition factors in table 1 or for more recent methods by assessing the capacity of the segments. A crack may not affect the capacity of the bridge; for example it is common with railway bridges to have a central crack between tracks which carry traffic in opposite directions. This is because each half of the structure tends always to be displaced in the same direction. It should not reduce the capacity of the bridge because it would be normal to assess the structure under load on both tracks. That is to say the inability of the structure to distribute load across the crack is already taken into account in the loading pattern used.

If one abutment tilts relative to the other then diagonal cracks are likely to occur starting near the side of the arch at a springing and spreading towards the centre of the barrel at the crown. Recommended MEXE condition factors are given in table 1.

TABLE 1

Recommended MEXE condition factors (source: BA 16/93)

Defect	Recommended condition factor F_c
Longitudinal cracks due to settlement of one edge of bridge	≤0.4 (crack spacing ≤1m) 0.4-0.6 (crack spacing >1m)
Transverse cracks or deformation of arch due to partial failure of arch or movement of abutments	0.6-0.8
Diagonal cracks	0.3-0.7
Cracks in the spandrel walls near the quarter points	0.8

Note: where F_c is less than 0.4, immediate consideration should be given to the repair or reconstruction of the bridge.

2.2.3 Ring separation

Ring separation is a common problem with multi-ring brick arches and may be due to chemical deterioration of the mortar or may be load induced. Load tests at Bolton Institute of Higher Education and elsewhere on similar arch rings with and without ring separation have shown that load capacity may be significantly affected.

2.2.4 Other problems

It is not uncommon for the arch ring to be damaged due to the installation of services. If the depth of fill is small, a channel may have been cut through the ring at the crown to provide space.

2.3 SPANDREL WALLS

Spandrel walls probably represent the biggest single maintenance problem with masonry arch bridges. They suffer from the normal problems associated with exposed masonry, such as weathering and loss of pointing. They are also frequently affected by dead and live load lateral forces generated through the fill or as a result of vehicle impact on the parapet or by freezing of the fill. Outward movement may occur due to live load forces particularly when vehicles can travel close to the spandrel wall because there is no verge or footpath. A longitudinal crack at the junction between the surfacing and spandrel wall will permit debris to enter which will prevent any possibility of the crack closing, and also permit water to enter the structure which may then freeze in winter.

The effect may be (see figure 8) outward rotation, sliding on the arch ring, or bulging. Cracking of the arch ring beneath the inside edge of the spandrel wall is more likely to be caused by flexing of the ring as described in section 2.2.1.

2.4 WING WALLS

Wing walls will suffer from similar problems to spandrel walls. They may also suffer from shallow or inadequate foundations. Dead load lateral forces may be more important as wing walls are higher than spandrel walls. Vegetation growth and blocked drainage are common. Exposure of foundations may occur due to erosion of the adjacent bank.

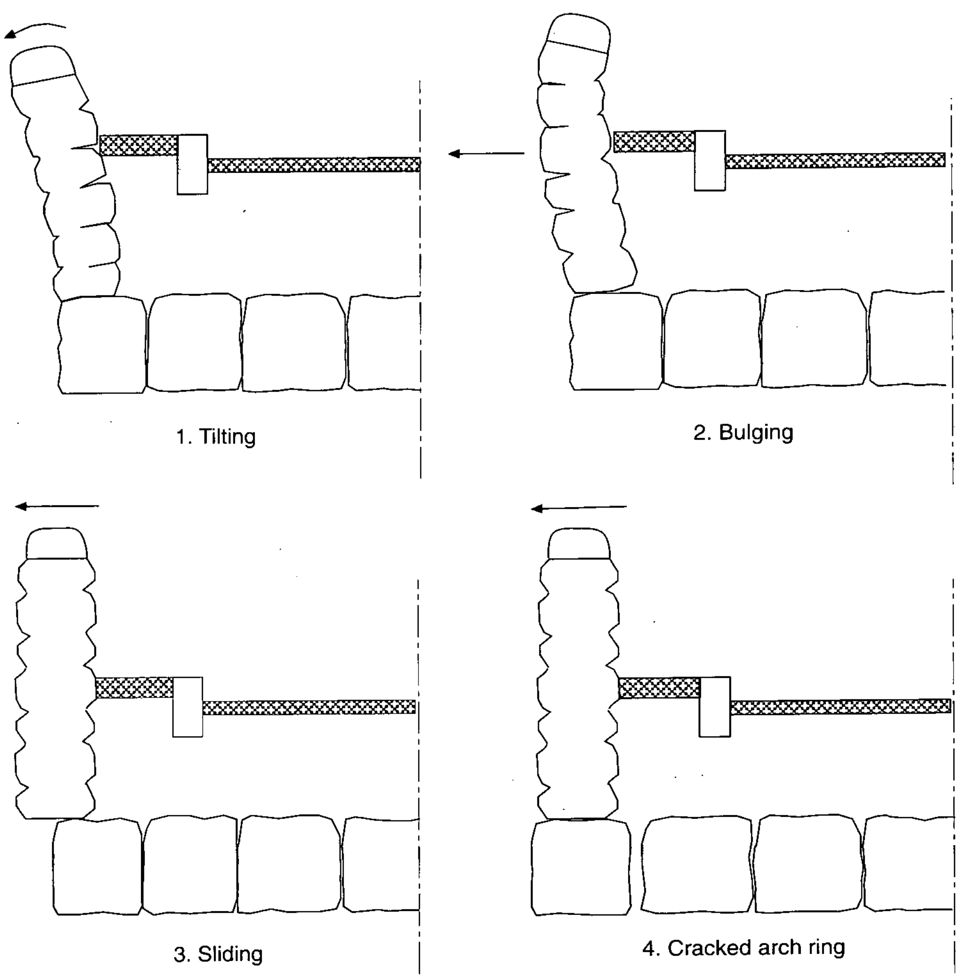

Fig.8 Spandrel wall failures (source: BA 16/93, Fig 5/1)

2.5 PARAPETS

Parapets may deteriorate because of movement of the spandrel/wing walls on which they stand. They may also be struck by vehicles. The County Surveyors' Society and others have funded research into the containment capacity of masonry parapets and the conclusions are given in *The assessment and design of unreinforced masonry vehicle parapets, Volume 1* (County Surveyors' Society, 1995). The work showed that masonry parapets with a thickness of 400mm or more and a minimum length of 10m can contain a 1.5 tonne vehicle travelling at 100kph and impacting at an angle of 20°, irrespective of mortar strength. It is believed therefore that most masonry parapets will not need upgrading or replacing. It is likely however that masonry will be thrown outwards from the bridge during the collision and if this is likely to pose a danger, upgrading or replacing is likely to be needed.

2.6 FILL AND ROAD SURFACING

The major problem likely to affect fill is that if any high level waterproofing (i.e. beneath the road surface) or the drainage breaks down, the fill becomes saturated. This is unlikely immediately to affect the load capacity of the bridge, indeed the increased weight may increase it. Longer term effects are that fines may be washed out of the fill leading to voids. Water percolating through the arch ring is likely to lead to deterioration of the mortar. Saturated fill will increase the lateral pressures on spandrel walls and even higher pressures if the fill freezes in winter, perhaps leading to outward displacement of the wall.

Breakdown of the road surfacing will allow water more readily into the fill with the effects described above. It is also likely to produce surface irregularities which will increase dynamic variations of wheel load applied to the bridge. Unsurfaced verges will readily allow water into the fill.

Utilities may cause problems:

- poor trench reinstatement is a common cause of unsatisfactory road surfacing,
- a leaking water pipe within the bridge is a common problem,
- a recently introduced procedure is to reinstate trenches using foamed concrete; if the concrete is significantly stiffer than the existing fill, it may provide a local concentration of wheel load particularly onto the arch crown.

2.7 SKEW BRIDGES

Skew arches may be built with three methods of arranging the brickwork or stone voussoirs, as illustrated in figure 9. The triangles of masonry in the acute corners receive no direct support from the opposite springings. Some early bridges were built with the joints parallel to the springings and this practice led to masonry movements and failures. The two other methods are intended to make the joints between courses of voussoirs at right angles to the skew of the arch. With the English method, commonly used for brick arches, the courses are at right angles to the skew only at the vicinity of the crown. The French method can only be applied to stone arches.

Stresses produced by wheel loads on the arch will take the shortest path to the abutments and therefore concentrate in the obtuse corners of the arch. Research is in progress at the time of writing into the behaviour of skew arches and it is at present difficult to give definitive advice on analysis. It is evident that skews as little as 20° have a significant effect and therefore the common recommendation to analyse as a square arch but using the skew span should be treated with caution. The collapse mode in laboratory tests on skew arches generally involves five hinges, so a four hinged mechanism analysis is inappropriate.

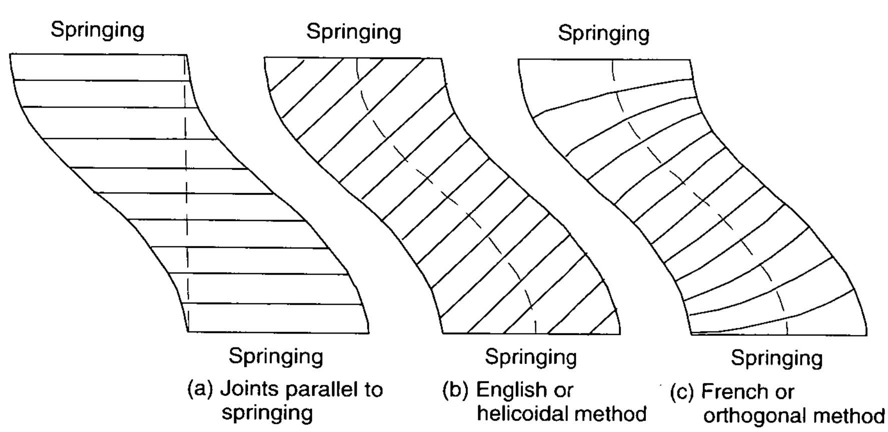

Fig.9 Cylindrical projection of the soffit of a 45° arch

Longitudinal cracks in skew arches are particularly important. If an outer section of the ring is separated from the rest by a longitudinal crack, vehicle loads must stay within the separated section which, because of the skew, may be a very flat arch.

2.8 HUMP BACK BRIDGES

Hump back bridges may suffer from any of the problems given above. In addition:

- The low cover over the majority of the arch ring reduces dead load thrusts in the arch ring. The thrust on the arch ring from the abutment may then predominate. Special construction methods such as cylindrical voids in the fill above the haunches have been employed to reduce earth pressures on the arch ring. A well known example of open voids is Pontypridd Bridge, figure 2.
- The hump increases dynamic loads on the arch and the generally small amount of fill above the ring leads to relatively high live load effects, including susceptibility to traffic induced vibration.

2.9 MULTISPAN BRIDGES

Multispan arch bridges may suffer from any of the problems given above. In addition:

- Lack of valley drainage above the piers.
- A problem affecting one span may affect the adjacent spans. In the limit, a collapse of one span may cause a progressive collapse of the remaining spans.

3. SCHEDULING AND LISTING

The following comments apply to England; similar procedures apply in Scotland, Wales and Northern Ireland.

Under ancient monuments legislation, the Secretary of State for the Environment has a duty to schedule buildings and structures whose preservation is of national importance. Some bridges may fall into this category and be Scheduled Monuments. Bridges may also be included in a list of buildings of special architectural or historic interest under section 54 of the Town and Country Planning Act, 1971. The Secretary of State (through English Heritage) is responsible for the protection and preservation of Scheduled Monuments; local authorities are primarily responsible for listed buildings. Scheduling takes precedence if a structure is both scheduled and listed. A bridge may also be protected by being in a conservation area.

All bridges built before 1700 which survive in anything like their original condition are likely to be listed, as are most built between 1700 and 1840. Between 1840 and 1914 only structures of definite quality and character are listed. Generally speaking, medieval bridges will be scheduled and later ones listed, but this is not always the case.

Listed buildings are classified as Grade I, Grade II* or Grade II according to their importance. They may not be demolished, altered or extended without "listed building consent" from the local planning authority.

Proposals to repair or strengthen such structures will be expected to provide the necessary structural integrity with the least alteration to the original fabric. This includes the whole fabric, including for instance the fill, and not just the visible fabric. On receipt of an application for listed building consent or scheduled monument consent, the local authority planning department (and English Heritage where necessary) will discuss the proposals and may suggest modifications or alternatives.

English Heritage (429 Oxford Street, London, 0171 973 3000) publishes a variety of leaflets and Guidance Notes, some specifically concerned with bridges, others primarily with buildings. The following may be helpful:

- Structural engineering for conservation
- The conservation of historic bridges
- Historic bridge parapets
- The pointing of brickwork
- Fabric consolidation of ancient monuments
- Monitoring of cracks in structures
- Principles of repair
- Historic buildings and monuments grants: notes for applicants

4. INSPECTION

An essential prerequisite of any inspection is a desk study of existing bridge records which should include previous inspection reports, enquiries to statutory undertakers, photographs, etc. It is possible but unlikely for old arch bridges that as-built drawings exist.

Regular inspections update the state of records for the bridge, provide a benchmark for subsequent inspections, and collect data to assist in prioritising cyclical maintenance.

If the load capacity of the bridge is to be assessed, the inspection should be designed to provide the data needed, and the extent and cause of any damage which needs to be repaired. If possible the inspections should be non-intrusive. The amount of data needed for assessment will depend on the assessment method to be used. The MEXE method for instance requires no information on material properties such as elastic modulus and compressive strength.

It may be that conservative assumptions about material properties will lead to an acceptable assessment, in which case material testing is unnecessary, and this should generally be the first approach. It should be borne in mind that material properties are likely to be very variable in old arch bridges, and the number of samples needed to provide statistically valid values would be substantial, and in any case not warranted by the accuracy of the assessment methods available. The likely cost of the repair or strengthening needed is likely to be an important factor in deciding the amount to be spent on obtaining data.

If samples are needed to provide the data required, sampling should be carefully planned to provide the maximum amount of data from the minimum number of samples. Cores for example could provide data on arch ring thickness, presence of haunching, presence of buttresses to the abutments, density, compressive strength (but note that the direction of applied stress in a core test is unlikely to be the same as that in the structure), and elastic modulus; the hole left by the core can be examined using a borescope. Core holes should of course be filled once the inspection is complete; the repair should use a non-shrinking material and preferably a slice of the outer end of the core used to cap the filled hole to provide an unobtrusive reinstatement.

It is likely that the best materials, particularly in a brick bridge, will have been used for the outside face. Material properties should therefore not necessarily be based on what can be seen.

4.1 ARCH RING

4.1.1 Dimensional data

These may be obtained with sufficient accuracy with the use of tape measure and surveying as appropriate.

Arch ring shape

The shape of the arch is important in determining load capacity. It can be obtained by surveying methods or by plumbing down from the barrel to a line stretched across at springing level. An accuracy of ±5mm should be aimed for; this should be possible for brick and ashlar masonry but is unlikely to be achieved with rough faced masonry. If the arch shape is segmental and is undeformed then a measurement of span and rise at midspan for each face is sufficient. For any other shape, and if there is appreciable deformation then a minimum of ten points uniformly spaced around the intrados for each face is suggested. If it is evident that there is significant distortion between the two faces, a further set of measurements should be made where the distortion is at its worst.

Arch ring thickness

Arch ring thickness may easily be measured at its outer edges. The MEXE method only requires a measurement at the crown: computer based methods can generally cater for arch rings which vary in thickness. It is possible that the thickness of the arch ring between the spandrel walls is not the same as the face thickness. The most reliable methods of determining this in the absence of historical evidence are by coring or by digging a trial trench from surface level and measuring thickness by difference.

The ring thickness used in an assessment calculation should take account of the depth of missing mortar. For the MEXE method this should be used rather than using the mortar depth factor F_d.

An arch ring with substantial cemented haunching well bonded to the ring will have a greater load capacity than a similar arch without haunching. It is advisable to do an initial assessment assuming no haunching is present and if this provides adequate load capacity then nothing further need be done. If the calculated capacity is inadequate and the presence of haunching is suspected then its extent and quality should be investigated.

4.1.2 Defects

The following defects, and if possible their cause, should be noted:

- cracks: their location, orientation and width, and whether they are recent and show signs of movement, or are old and stable (ensure that longitudinal "cracks" are not actually joints due to widening!);
- deformation (see 4.1.1);
- local bulging;
- dropped or missing voussoirs;
- hollow sound when tapped with a hammer, indicative of ring separation;
- impact damage (bridge bashing)
- movement under live load;
- mortar loss;
- spalling and erosion;
- water percolation;
- damage to extrados at crown due to statutory undertakers equipment (clearly not visible to the naked eye; wetness on the soffit may indicate its presence, or dropped masonry).

4.1.3 Material properties

The MEXE method simply requires the arch ring material to be identified. This may not be easy if the bridge is dirty. Knowledge of local materials may help. Computer based assessment methods will require estimates or measurements of density, compressive strength and elastic modulus.

Density

Densities given in table 4/1 of BD 21/93 should be used. It is unlikely to be worth considering measurements of density because load capacity is relatively insensitive to change of density. In general the calculated load capacity will increase with increase of density, so densities should not be overestimated.

Compressive strength

Values of compressive strength should be estimated initially from figures 4/2 and 4/3 of BD 21/93. Hendry (Hendry, 1990) advises that the strength of masonry assessed under axial loading may be increased by 20% if the loading is eccentric, as at a hinge.

Shear strength

The segments of multi-ring brick arches between estimated hinge points at failure may need to be checked for possible shear failure. The assumed characteristic shear strength may be taken as $0.35+0.6\sigma$ N/mm^2 with a maximum of 1.75 N/mm^2 for mortars with an expected strength exceeding 1.5 N/mm^2, and $0.15+0.6\sigma$ N/mm^2 with a maximum of 1.4 N/mm^2 for weaker mortars where σ is the compressive stress (BSI, 1992). It is probably advisable to treat the mortar as weak. There is no simple test to provide guidance although a mortar which can be scratched with a finger nail is certainly weak. The visible mortar may be stronger than that at depth either because of decay of mortar within the structure or because it has been repointed.

Elastic modulus

There is a great deal of uncertainty about the elastic modulus of masonry and this should be borne in mind in any analysis which relies on a value of modulus.

The stress-strain relationship for masonry may be assumed parabolic with a strain at maximum stress of 0.003, and ultimate strain 0.0045, see figure 10.

There is an approximate relationship between elastic modulus and compressive strength. BS 5628: Part 2 (BSI, 1985) recommends for clay, calcium silicate and concrete masonry a value of $E=900f_k$ N/mm^2 where f_k is the characteristic compressive strength of the masonry. As this is unlikely to be known, a multiplier of 500-600 on the mean strength gives an effective secant modulus at maximum stress for higher strength brickwork (Hendry, 1990). For low strength brickwork and rubble masonry the multiplier should be in the range 200-400. This is intended to apply to short term loading and a reduction to one half of this value is specified for long term effects. It would be appropriate to regard dead load and live load as long term and short term effects respectively.

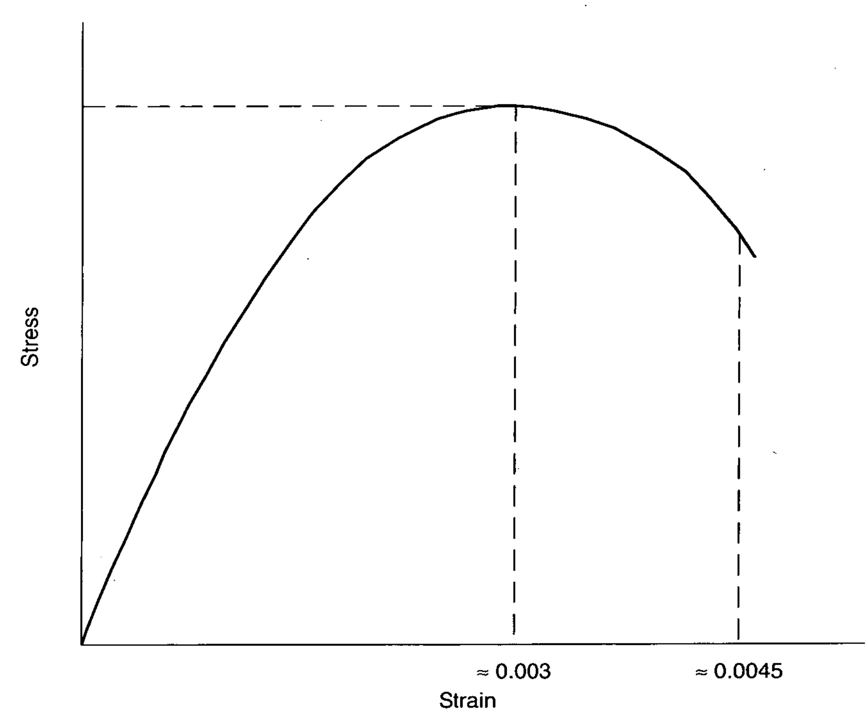

Fig.10 Stress-strain relationship for masonry

4.2 PARAPETS AND SPANDREL WALLS

BD 21/93 requires parapets and spandrel walls to be assessed by visual inspection, not calculation. The following forms of deterioration should be noted:

- tilting, bulging or sagging;
- lateral movement of parapet or spandrel wall relative to the face of the arch ring;
- weathering and lack of pointing;
- evidence of vehicle impact;
- cracking, splitting and spalling;
- blocked weepholes;
- loosening of any coping stones.

It should be particularly noted whether any of the deterioration is progressive, or whether it happened in the past and is now stable. If assessment of the spandrel walls by calculation is necessary then they may be treated as mass retaining walls subject to dead loads from the fill and live loads from traffic. It will then be necessary to know the thickness of the wall and how it varies with depth.

4.3 PIERS, ABUTMENTS AND WING WALLS

It should be remembered that although the available assessment methods calculate the load capacity of the arch ring, then this will be irrelevant if the foundations are unsound. BD 21/93 requires piers, abutments and wing walls to be assessed by inspection, not calculation. If there is sign of distress , then normal methods of assessment should be used. The following forms of deterioration should be noted:

- tilting and rotation in any direction;
- cracking, splitting and spalling;
- erosion beneath water level;
- weathering and other material deterioration, including lack of pointing for masonry and brickwork;
- growth of vegetation;
- lack of effective drainage;
- internal scour, and leaching of fill perhaps due to a leaking water main;
- settlement of fill.

It should be particularly noted whether any of the deterioration is progressive, or whether it happened in the past and is now stable.

Wing walls may if necessary be assessed by calculation in the same way as spandrel walls.

4.4 FILL AND ROAD SURFACE

The MEXE method simply requires the fill to be classified as one of: concrete, grouted, well compacted or weak. The analytical basis of MEXE only takes the dead load of the fill into account whereas computer based assessment methods treat the fill as a structural material and consider the horizontal pressures which may be generated as the arch ring under load moves into or away from the fill. Some of the methods also consider the road surface and fill separately, but only in terms of density to improve the estimate of dead load applied to the arch. They may also require the angle of distribution of the load through the fill to be specified.

The fill is likely to be variable. For example, it may be layered either deliberately or by chance, and puddled clay may have been used as a waterproofing membrane on the extrados of the arch. A major sampling exercise would therefore be needed to sample it thoroughly and this would be expensive and undesirable because of the disturbance it would cause. It must be recognised therefore that measured or deduced parameter values will provide only an approximate description of the fill.

Services in the fill must be accurately located. Service trenches may have disturbed well compacted fill and, if not carefully reinstated, represent a line of weakness. If the depth of fill at the crown is small, they may be found to have been cut through the arch ring.

The condition of the road, footpath and verge surfaces should be examined for faults which will allow water into the fill. Service trenches cut adjacent to the spandrel and wing walls may allow water into a particularly vulnerable part of the structure. Road surface irregularities which will increase dynamic wheel loading of the bridge should be noted.

Density

Values of density given in table 4/1 of BD 21/93 should be used.

Angle of distribution of load through fill

The distribution given in BD 21/93 of one horizontally to two vertically from each edge of a patch load should be used unless other evidence is available. Substantial further distribution takes place within the arch barrel; a strip of width 1.5m plus the depth of fill can be mobilised in resisting a patch load (see BD 21/93, section 6.22).

4.5 INSPECTION METHODS

A large amount of the data required can be gathered by means of a visual inspection at touching distance, and tapping with a hammer. Other methods may require specialists.

4.5.1 Methods of access

Methods available to enable a touching distance inspection of all parts of the bridge include:

- hydraulic access platforms sited beneath the bridge;
- under bridge inspection equipment sited on top of the bridge;
- complete scaffolding out beneath the arch;
- boat;
- abseiling;
- divers for underwater inspection of piers, abutments, foundations and inverts.

Safety procedures for the work must be specified.

4.5.2 Intrusive methods

Testing in the laboratory is virtually the only way of estimating the strength of old masonry, but it must be remembered that it will vary widely over the structure. British Standards give a guide to methods of testing but they only refer to new bricks and concrete. Whole bricks removed from a structure can be tested by the methods described in BS 3921 (BSI, 1985a) and it likely that they will need to be capped before testing. To estimate the strength of brickwork it is necessary to remove a whole section of brickwork. If it is considered necessary to do this, BS 5628: part 2 (BSI, 1985b) gives guidance.

Stone masonry blocks are generally too large to consider removal so cores are usually taken. A guide to the testing of concrete cores is given in BS 6089 (BSI, 1981) and the parts discussing the method of testing and size of specimens are helpful when testing stone cores. The test specimens should not contain cracks. Specimens should be tested in the direction in which they will be stressed in the structure. If this is not possible, any indications of non-homogeneity should be noted and taken into account in assessing the strength of the material.

4.5.3 Non-intrusive methods

It is clearly desirable to obtain data needed non-intrusively. Research is in progress on various methods to assess their potential. Most non-intrusive methods were developed for materials other than masonry and attempts to apply them to masonry are relatively recent. Many non-intrusive methods rely on skill and experience to interpret their results. It is essential in this situation that the interpreter is presented with as much information as possible about the internal structure of the bridge.

It is likely at their present state of development that the results of non-intrusive methods will need to be confirmed by intrusive methods such as coring and trial pits. If successful, they are likely to reduce the extent of intrusive inspection needed rather than eliminate it altogether.

The following methods have been applied to masonry with greater or lesser success:

Acoustic emission

Acoustic emission detects deterioration under load, and may therefore be considered if it is suspected that normal trafficking is causing rapid deterioration. It occurs when micro-cracks develop in loaded structures. As the cracks develop they release elastic strain energy in the form of elastic waves that can be detected by piezo-electric accelerometers. During a load test to failure of an arch bridge as part of the TRL masonry arch test programme, the bridge was monitored for acoustic emissions. In this test the number of events recorded by the accelerometers correlated well with bridge displacements. However, given the high level of background acoustic emissions produced it seems unlikely that the method would detect many events due to deterioration at the low loads produced by trafficking, nor does it seem certain that the size of signals produced bear any relationship to the severity of the damage in structural terms.

Flat jack

The flat jack method measures the stress in a structure and also measures the elastic modulus of the material. A small slot is cut in the face of the structure normal to the expected stress direction. Strain and displacement gauges are attached around the slot location prior to cutting, and the change monitored when the slot is cut. A thin flat jack is then inserted which fills the slot and pressure is applied until the measurements return to their original values. The jack pressure then represents the stress in the structure. The elastic modulus of the material may be deduced from the relation between the displacements measured and pressure in the jack.

The method was developed for use in concrete but it has been successfully applied to masonry. In bricks it is recommended that the slot is cut in the brick rather than the mortar. A very flexible jack has recently been developed at the University of Wales, Cardiff so that the stiffness of the jack itself has minimal effect on the results.

The method is not entirely non-intrusive in that a slot needs to be cut, and in the process the local stress pattern is changed.

Radar

High frequency radio waves can penetrate the earth to a depth of up to 20m. As a result ground probing radar is used to detect buried objects, cavities and geological interfaces.

It has been used to investigate the internal structure of masonry bridges. It has limited reliability when the fill is wet.

A short pulse of radio frequency waves are emitted by an antenna in contact with the ground. The pattern of reflections are then observed. These reflections and the time taken for them to return indicate the presence and distance of a back-scattering surface in the line of propagation of the wave. Pulses are transmitted at a high repetition rate so that repeated reflections can be identified with confidence. The frequency of the transmitted pulse is a compromise because the lower the frequency the greater the depth of penetration but the poorer is the ability to discriminate small dimensions. The frequency is generally between 50MHz and 5GHz depending on the attenuation of the materials being probed.

Hammer tapping

Hammer tapping involves interpreting the sound made when the structure is tapped. It can detect a variety of problems:

- ring separation (it is likely only to detect voids between the bottom and next to bottom rings);
- voids within a brick due for example to incipient spalling;
- loose bricks.

It should not be used when the brickwork is frozen. It may be appropriate to use tapping as an initial guide and then core where separation has been detected to provide further guidance. If separation of the bottom ring is widespread it is advisable for assessment to exclude it from the arch ring thickness.

Ultrasonic pulse

Ultrasonic pulse methods have been developed for use with concrete, but this is a relatively homogeneous material compared with masonry and the method is unlikely to provide useful data.

Sonic pulse

The principle of operation is that one face of the structure is hit with a hammer and the impact is recorded by an adjacent accelerometer. Another accelerometer on the opposite face of the structure records the arrival of the transmitted compression wave, and the time between transmission and reception is calculated. If this procedure is repeated over a regular grid, variations in the transmission time over the structure can be plotted. Transmission time depends on the density of the material and the presence of voids through which the wave will not travel. If a void is present the wave will travel round it, lengthening the transmission time. If the void is large or near either accelerometer, a signal may not be received at all. A study of the variation in transmission times over a structure will indicate changes in density or the presence and extent of voids.

The sonic pulse method has been used with some success on simple masonry structures where there is access to both sides of the structure, e.g. piers. More difficult to interpret however are internal construction features such as changes in wall thickness, internal arches and changes in fill.

Thermography

Thermal imaging cameras are used to record variations of temperature and to display these as different colours representing different temperature ranges. The magnitude of the ranges, or the sensitivity, depends on the requirements of the application, but very small temperature differences can be detected.

The application to masonry assumes that the surface temperature will depend to some extent on what is behind it. For example the surface may be backed by a conductive material, voids or running water, and this will affect the surface temperature. However variation in surface emissivity will also affect the results.

It has been used successfully to detect old shafts in tunnels. Possible applications might be to detect internal spandrel walls, ring separation and wet areas.

Borescope/endoscopes

Borescopes can be used to see deep into existing fissures or specially cored holes. They are therefore not completely non-intrusive but a cored hole can be filled unobtrusively after use. They may be used to explore wall thickness, internal voids or ring separation. The inspection is very local so a systematic pattern of holes may be required. A still or video camera may be attached to provide a permanent record.

The method may be valuable for checking construction features revealed by radar and sonic methods.

Strain gauges

Mechanical strain gauges such as the Demec type may be used to measure long term changes in strain or the growth of cracks. They require two small targets with central conical recesses to be attached to the structure. They are available with gauge lengths from 50 to 2000mm; 200mm is well suited to measurement of strains in masonry, and an accuracy of $\pm 6\mu\varepsilon$ is possible. The targets are small in area and need to be robustly attached; care is therefore needed to prepare the surface onto which they are glued. It is good practice to provide several pairs of targets to increase the chance of survival of at least one pair.

Vibrating wire strain gauges may be used if higher accuracies are required. Gauge lengths of 50 to 150mm are generally obtainable, and an accuracy of $\pm 0.5\mu\varepsilon$ is possible.

Displacement measurement

Telltales are a useful means of measuring change of width of a crack. An accuracy of ±0.02mm is possible. The strain gauges referred to above can also be used to measure change of crack width, to a greater accuracy than telltales. A variety of displacement transducers are available to measure short or long term displacement. British Rail Research has developed easy to set up and use equipment to measure displacements dynamically under moving vehicles.

Vibration monitoring

Research has been done to examine the response of masonry arch bridges to dynamic loads, provided either by the passage of a vehicle or by dropping a weight onto the deck. It has not so far proved possible to relate in a useful way the response to the structure of the bridge, except for simple models. A possible application which does not require this relationship to be known is to monitor the response of a bridge over a period of time; changes to the response may suggest structural changes. Care would be needed in interpretation because significant changes may occur due to reversible effects such as increase in water content, and freezing.

4.6 LOAD TESTS FOR ASSESSMENT

Load tests have long been used as part of the process of assessing the load capacity of bridges, generally for comparison with theoretical calculations. The Department of Transport takes the view that in certain circumstances they can be a useful backup to theoretical calculations; it would not however recommend their use in conjunction with MEXE. The Department of Transport has issued guidelines for load tests of bridges (DOT *et al*, 1994). A *National Steering Committee for Load Testing* is presently working on guidance for all types of bridge.

Railway engineers have traditionally used arch deflections as an aid to the assessment process. Arch crown and quarter point deflections are recorded under a load such as a locomotive or a lorry which has known axle weights. The assessment engineer then uses his experience to judge whether the measured deflections are within acceptable limits. The method may be used to follow changes with time to provide information about deterioration of the structure.

If a load test of a masonry arch bridge is contemplated, the following points should be considered:

i) A load test should be used to prove the accuracy and suitability of an analytical model.

ii) The analytical methods available all have limitations (see section 5). The MEXE and mechanism methods provide no calculations of stress or displacement for comparison with a load test. The elastic and finite element methods available at the time of writing model a two dimensional slice of the bridge and cannot take into account transverse bending of the arch ring or the stiffening effect of spandrel walls.. Material properties for arch bridges are particularly difficult to measure or estimate because they are likely to be very variable.

iii) An ultimate limit state assessment is required. To avoid structural damage, it will not be possible to apply the ULS loading so extrapolation of test results is necessary; TRL load tests to failure may be used as a guide (Page, 1995).

iv) It should not be assumed that the response of the bridge will be symmetrical. A small number of gauges may therefore give misleading results.

v) It will be necessary to check for horizontal movement of the abutments; some assessment methods assume rigid abutments.

vi) It should not be assumed that the bridge will behave elastically; evidence of creep and of residual strains have been found in TRL tests.

vii) There is no analysis method available for skew bridges at present; the response of a skew bridge to load is more complex than that of a right bridge.

viii) There is a possibility of ring separation in multi-ring brick arches, and it should not be assumed that the response of the bottom ring matches that of the bulk of the arch.

ix) The response to load in one bridge was found to change by a factor of two over a period of months, probably due to the amount of water in the structure; temperatures low enough to freeze the water may have a very significant effect.

5. ANALYSIS

5.1 SUB-STRUCTURES, FOUNDATIONS AND SPANDREL WALLS

Sub-structures, foundations and spandrel walls are generally not amenable to assessment by calculation and are assessed qualitatively by considering the condition of the structure and the significance of any defects.

However, if for any reason the dead load applied is to be increased, BD 21/93 requires that the form and extent of the foundations are determined and the adequacy of the subsoil to carry the additional loads proved using conventional analysis methods.

Spandrel walls should be assessed separately from the arch barrel and should not be assumed to provide support or strength to it.

5.2 ARCH BARREL

In general road bridges are required to be assessed by the application of limit state principles and these are applicable to masonry arch bridges. However the Department of Transport recommends that they are initially assessed by the modified MEXE method in accordance with BA16/93. This determines allowable axle and bogie loads directly and calculation of load effects and assessment resistance are not required.

5.3 ASSESSMENT LOADING

The live loading to be applied is the single, double and triple axles given in BD 21/93 for current C&U vehicles and EC vehicles up to 40 tonnes gross weight. The nominal values of the axle weights shall be determined by multiplying the gross axle weights obtained from BD 21/93, Appendix A by the appropriate conversion factors given in table 6/2. The possibility of lift-off in a double or triple axle bogie shall be considered if the conditions on the arch are likely to cause this effect (see BA 16/93). The axles shall be assumed to have a 1.8m track and shall be located within 2.5m transverse widths, with a 0.7m spacing between the track widths of adjacent vehicles.

Temperature loading is not critical for arch bridges; it may be considered if thought necessary.

5.4 ANALYSIS METHODS

5.4.1 MEXE method

This method of assessing the load capacity of arch bridges was developed during and just after the second world war to provide a military load classification system. It was then developed for civilian use and appears in its most recent form in BD 21/93 and BA 16/93. The arch ring was modelled as a two pinned centre-line rib. A variety of simplifying assumptions were made. The criterion adopted for the permissible load (dead plus live) was determined to be that which produced a maximum compressive stress at the extrados of the arch at the crown of 13 ton/ft^2 (1.39 N/mm^2).

A value of "provisional axle load" is calculated from:

$$W_A = 740(d+h)^2/L^{1.3}$$

or alternatively from a nomogram. The value of W_A is then operated on by a series of five modifying factors to give a "modified axle load" which represents the allowable axle loading for a double axled bogie with no "lift-off". Permitted axle loads for single axles and for tri-axle trailers may then be calculated for situations where axle lift-off may or may not occur. If the axle loads so calculated fall below the weight limits permitted by the Construction and Use Regulations (HMSO, 1986), then the gross weight limits to be applied to the bridge are defined.

The MEXE method is generally considered to be an approximate method and should be used for a preliminary assessment. If this provides an adequate capacity then nothing more need be done, otherwise, the result must be confirmed by a more rigorous method. BA 16 advises various limitations on the use of MEXE:

- When the depth of fill at the crown is greater than the thickness of the arch barrel, the result should be confirmed by an alternative method because there is a possibility that MEXE may be unconservative.
- It should not be applied to appreciably distorted arches. The arch could be considered appreciably distorted if distortion can be seen with the naked eye. If the distortion is localised, MEXE may be used with added consideration of the cause, effect and treatment of the distortion.
- It should not be applied to multispan arches unless each span can be considered as a separate bridge (see 5.4.7).
- It should not be applied to skew arches. A modest degree of skew may however be acceptable, say a maximum of 10°.
- It should not be applied to a span greater than 18m.
- It should not be used if the arch is flat. A maximum span to rise ratio of 8 may be inferred.

5.4.2 Fuller's Construction

Fuller's construction is a graphical method of calculating the line of thrust in an arch ring. It is described in (Heyman, 1982). It is easy to use and can give useful insights into arch behaviour. It may be particularly useful for assessment of humpback bridges.

5.4.3 Mechanism method

The mechanism method is a limit state analysis in which the load which just transforms the arch to a hinged mechanism is found. The assumed collapse mechanism is shown in figure 11. The assumption is made that a hinge is formed on the top or bottom surface of the arch, although modern methods may allow for local crushing at the hinge which means, as illustrated in figure 11, that the hinge is not at the extreme fibre.

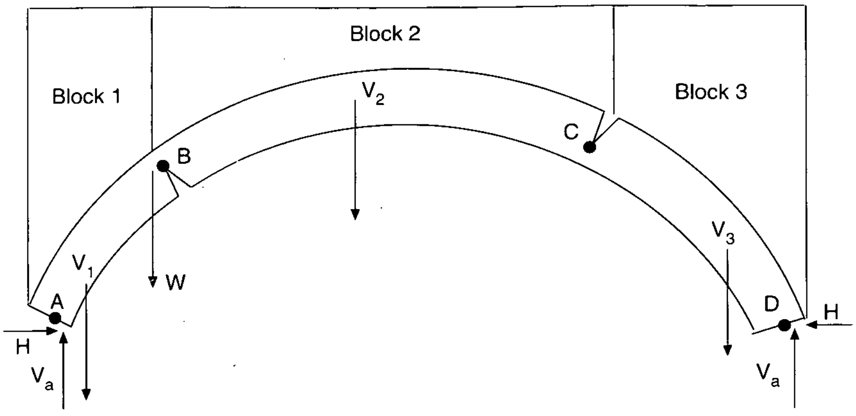

Fig.11 The mechanism method showing equilibrating forces

The assumptions made about material properties are:

a) no tensile strength,

b) infinite compressive strength (but see above),

c) infinite elastic modulus,

d) no sliding between voussoirs.

The collapse load W can be found by statics and is directly related to the weight of the three blocks V_1-V_3 which have contributions from both the arch ring and the associated fill.

Modern computer versions of the method will also make an allowance for the lateral resistance of the fill (the method will give absurdly low collapse loads for deep arches unless this is done), and will find the worst positions of the load and the hinges automatically.

A variety of mechanism programs are commercially available; at the time of writing they are (developers in brackets):

- *Archie* (University of Dundee),
- *Assarc* (Structural Survey Partnership Ltd.)
- *Arch* (Cascade Software Ltd.)

5.4.4 Thinning elastic method

An elastic analysis in which no tension is permitted in the arch ring was derived by Castigliano and has been developed into the commercially available computerised assessment method *CTAP* developed by the University of Wales, Cardiff. It also includes a mechanism analysis and an elastic analysis which permits tension (see section 5.4.5).

5.4.5 Finite element methods

A variety of finite element methods specific to masonry arch bridges have been developed in recent years but only one, *MAFEA*, is commercially available (from British Rail Research). It is non-linear, mesh generation is automatic, and defects such as ring separation can be modelled.

5.4.6 Computerised Pippard/MEXE method

BA 16/93 chapter 4 describes a computerised version of the Pippard/MEXE method. It offers greater flexibility than MEXE with respect to geometrical, material and loading parameters. BA 16/93 recommends that it be used as an additional tool following a MEXE assessment, particularly for marginal cases.

5.4.7 Assessment of multispan arches

BD 21/93 states that any individual span of a multispan bridge may be assessed as a single span arch provided the adjacent intermediate supports and spans are structurally adequate. This condition is satisfied if:

i) at the ultimate limit state when the live loading is placed on the span in order to produce the worst horizontal thrusts on the adjacent parts of the structure, no tension occurs in any cross-section of the supports or the adjacent spans;

ii) tension develops in the adjacent supports and the springings of the adjacent spans under the loading as applied in i), but provided there is no tension anywhere else in these elements when the sections with tension are represented as hinges.

These checks are unnecessary for bridges with short and stocky intermediate piers, in which case each span may be assessed as an individual single span bridge. Guidance is not provided on the definition of short and stocky. A load test to failure was conducted by TRL on a three span bridge with a pier 1.26m wide and 3.12m high between the loaded and adjacent spans. The loaded span appeared just to behave as if it were a single span bridge. It is therefore suggested that a pier with a height (to the foundations) to width ratio not exceeding 2 may be treated as stocky.

The mechanism program *Archie* contains an assessment method for multispan bridges.

5.4.8 Assessment of skew bridges

There is at present no assessment method available for skew bridges. Research is in progress aimed at providing guidance. It is commonly suggested that for modest degrees of skew the bridge should be assessed as if it were a right bridge, but using the skew span instead of the right span. However it should be noted that laboratory built bridges with a skew of only 20° behave differently to similar but right bridges. A wide but short span skew bridge *i.e.* a culvert, can probably be treated as a right bridge.

6. REPAIR AND STRENGTHENING METHODS

It is clearly essential that the cause of deterioration is understood before the most effective repair or strengthening method can be decided upon. For instance there is no point in repairing a deteriorated arch by saddling alone if the cause of the deterioration is movement of the abutments. Any repair must also be considered with reference to the effect it will have on the behaviour of the existing structure. If the inherent articulation of the stonework or brickwork is lost as a result of the repair, it may have a long term detrimental effect on the fabric of the structure, the very thing the repair was trying to save.

Many repair and strengthening methods require skill and experience in their design and execution, particularly when they are to be applied to important bridges. It is clearly not possible to provide that in this Guide; it seeks to provide general guidance on the correct applications of the methods available.

If work is necessary to one span of a multispan bridge, the effect of the chosen repair method on adjacent spans should be considered.

There are a variety of factors which influence the choice of repair method in addition to the type of fault to be repaired (more than one fault is commonly present, and some repair methods may be used to repair more than one fault):

1) Access

Access to the structure may be limited by traffic considerations. If it is not possible to close all or part of the bridge to traffic then, for example, saddling as a means of increasing the load capacity of the arch ring may be impossible. On the other hand, restrictions placed on access to the underside of the bridge by, for example, the National Rivers Authority may mean that work has to be done from above. The amount of time that access is available may also affect the repair method to be used, taking into account the time required for the repair to gain adequate strength.

2) Appearance of the repaired bridge

The aim should be not to worsen the appearance of the bridge and where appropriate to improve it. In the case of listed structures, the limitations on change imposed may be very onerous, even to non-visible parts of the structure. Consultation with the appropriate authorities at an early stage of planning the work is essential.

3) Clearances

Repairs to the arch soffit of a bridge over a railway must not interfere with the railway structure or electrification gauge. Similarly the National Rivers Authority may impose restrictions on any reduction to the waterway of river bridges.

4) Cost

Costs are discussed in more detail in section 9.

5) Life of repair

It may be that the work is intended to be a temporary measure, for example to counter the effect of subsidence as coal is mined beneath the bridge. Different criteria are likely to apply in this situation. For example the appearance of the strengthening may be unimportant, and temporary loss of clearance may be acceptable.

6) Effect on future inspections

The importance of the increased difficulty of future inspections may need to be considered. For example, sprayed concrete to the soffit of the arch ring will make future inspection of the condition of the original arch ring more difficult.

Table 2 identifies the common faults of arch bridges and the repair and strengthening methods which may be applied.

In the following sections a design method is given for most repair and strengthening procedures. This is generally the simplest method which may be used (*e.g.* MEXE). More complex methods such as finite elements may also be used if there is advantage in doing so.

Where available, observed defects have also been given for each of the methods described. These are taken from a survey of fifty arch bridges done for TRL by Ove Arup (Ashurst, 1992). The work was done to assess the effectiveness and cost of repair and strengthening methods.

6.1 REPOINTING AND MASONRY REPAIRS

Routine maintenance repointing is widely regarded as essential and may improve arch load capacity by restoring the structurally effective arch ring thickness to its full depth. If properly done when it is needed, it may prevent the bridge from deteriorating to the point where it needs more

TABLE 2

Repair and strengthening methods

Fault	Repair /Strengthening
Deteriorated pointing	Repoint
Deterioration of arch ring material	Masonry repairs Saddle Sprayed concrete to soffit Prefabricated liner to soffit Grout arch ring
Arch ring thickness assessed to be inadequate to carry required traffic loads	Saddle Sprayed concrete to soffit Prefabricated liner to soffit Replace fill with concrete Steel beam relieving arches Relieving slab
Internal deterioration of mortar - e.g. separation between rings of a multi-ring brick arch	Grout arch ring Stitch
Foundation movement	Mini-piles Grout piers and abutments Underpin
Scour of foundations	Underpin Invert slab Stone pitching Rip rap
Outward movement of spandrel walls	Tie bars Spreader beams Replace fill with concrete Take down and rebuild Grout fill if it is suitable
Separation of arch ring beneath spandrel walls from rest of arch ring	Stitch
Weak fill	Replace fill with concrete Grout fill if suitable Reinforced fill
Water leakage through arch ring	Make bridge surfacing water resistant High level waterproofing layer Waterproof extrados + improve drainage

expensive repair work. If incorrectly done it can accelerate deterioration of the structure. The mortar should not for instance be harder than the brick or stone. If it is too soft on the other hand the arch will continue to behave with a reduced effective thickness. Repointing can enhance the appearance of the bridge and there should be little disruption to traffic while it is being done.

It is advisable to use mortar of similar properties to that in the existing structure. Table 3 (de Vekey: from Sowden, 1990) gives the common formulation of both contemporary mortars and the lime mortars likely to be encountered in most civil engineering structures built before 1920. The table gives an estimate of the performance of the mortars in terms of the characteristic compressive strength of mortar and brickwork. The brickwork strength values are for standard format bricks. Mortars with a low cement content can be made more durable by the addition of polymer latexes based on butadiene-styrene or styrene-acrylic co-polymers.

The cause of loss of mortar should be determined and remedied before repointing. A minimum depth of raking out of at least 15mm should be specified, 25mm is

TABLE 3

Strength of mortars and brickwork

Mortar designation	Type of mortar (ingredients) (proportion by volume)			Mortar strength range (N/mm²)	Brick strength (N/mm²)				
	Cement: lime: sand	Masonry cement: sand	Cement: sand + plasticizer		7	20	35	50[a]	70[b]
					Characteristic compressive strength of brickwork (N/mm²)				
(i)	1:0-0.25:3	-	-	11-16	3.5	7.5	11	15	19
(ii)	1:0.5:4.5	1:2.5-3.5	1:3-4	4.5-6.5	3.5	6.5	9.5	12	15
(iii)	1:1:5-6	1:4-5	1:5-6	2.5-3.6	3.5	6	8.5	11	13
(iv)	1:2:8-9	1:5.5-6.5	1:7-8	1.0-1.5	3	5	7	9	11
(v)	1:3:10-12	1:6.5-7	1:8	0.5-1.0	2	4	6	7.5	8.5
(vi)	0:1:2-3[c]	-	-	0.5-1.0	2	4	6	7.5	8.5
(vii)	0:1:2-3[d]	-	-	0.5-1.0	2	3	3.5	4.5	5

[a] Class B engineering brick [b] Class A engineering brick [c] Hydraulic lime [d] Pure lime

preferable. The raking out should be to a uniform depth and square. Power tools designed for the job may be used if they can be shown to do no more damage to the brick or stone than raking by hand. Disc cutters should not be used. Bucket handle or struck and weathered joints (see figure 12) contribute to brickwork durability because the tooling of the joints reduces the permeability of the mortar surface and improves the seal between the bricks and mortar. Recessed joint profiles should be avoided because they increase the level of saturation along the upper arrises of the bricks with a consequent risk of frost damage. There are various ugly pointing methods such as ribbon pointing which should be avoided, similarly the pointing should not be feathered out over the face of the brickwork or stonework.

Parapets should be repointed on both sides.

If individual bricks or small areas of brick, or individual stone voussoirs have deteriorated then they should be replaced. The aim should be to use brick or stone with similar colour, size, appearance and properties to the existing. Second hand bricks may be suitable or it may be appropriate to have special bricks made. Clay bricks are available in strengths from 10 to at least 100N/mm². Engineering bricks have high strength and low water absorption; engineering A bricks have a strength greater than 70N/mm² and water absorption of less than 4.5%, engineering B bricks have a strength greater than 50N/mm² and water absorbtion less than 7%. Calcium silicate bricks should not be used for repair.

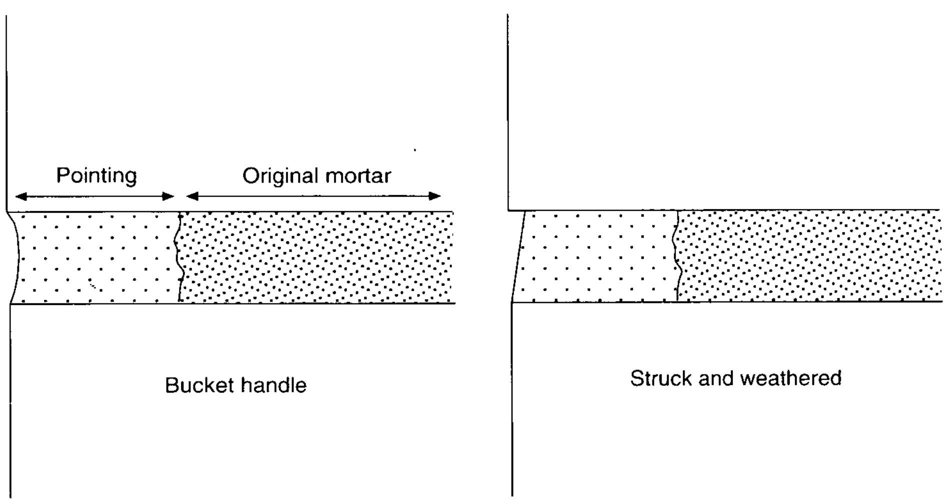

Fig.12 Suitable repointing joints

Careful consideration should be given to matching the colour of the existing brickwork or stonework. It may be that its attractiveness lies in the colour and texture which age and weathering have produced. It may also be the case that the weathered and darkened surface conceals a multitude of old repairs which would be unsightly if visible. In such instances, cleaning would be a mistake. Some masonry however was clearly designed to achieve a particular architectural effect which weathering and dirt may have diminished. Here, cleaning could be used to restore the original appearance, and new masonry needs to be chosen to match the cleaned masonry. Cleaning of masonry is beyond the scope of this document; advice will be found in BS 6270 (BSI, 1982).

Bricks may be made to practically any shape to avoid the need to cut them to fit. BS 4729 (BSI, 1990) lists those most commonly sought; they are referred to as "standard" special shapes and they are more readily available than "special" special shapes.

Difficulties may occur because standard size bricks which are now 215mmx65mmx102.5mm may be of a different size to the existing bricks.

It is possible to replace a complete ring of bricks and is most likely to give a visually satisfactory result. It would be important to ensure the mortar joint between the new and existing ring is well packed. It may be desirable to tie the new ring into the existing rings to ensure that it acts structurally.

Clay bricks expand after placing due to absorbtion of moisture. This may have the advantage of introducing some dead load stresses into the new brickwork.

Stone is likely to have come from a local quarry except perhaps in the case of major bridges. It is likely that the quarry will no longer be open, so it will be necessary to obtain a similar stone from elsewhere. Even if the quarry is still operating, the stone being quarried now may be significantly different to that used in the bridge. Artificial stone is now available and may be specified to match both the strength and colour of the existing stone.

Design method

Repointing is used for routine maintenance of bridges not assessed as weak, and to strengthen bridges assessed as weak due to inadequate ring thickness because of missing mortar where weathering has eroded the joints. A MEXE analysis is sufficient.

Observed defects

Spalling and cracking of mortar was noted, possibly due to incorrect preparation of the joints, frost, incorrect application of mortar, shrinkage of mortar, water seepage, or growth of vegetation. Colour mismatch was also noted. On some structures, notably of sandstone, the stonework had eroded leaving the pointing standing proud.

6.2 SADDLING

Saddling involves removal of the fill and casting an in-situ concrete arch, which may be reinforced, on top of the existing arch. Its advantage is that the work is invisible once completed but it requires a major construction operation which will disrupt traffic flow to install. It may be necessary to support the arch ring with centring (figure 13) while the work is in progress which may rule out its use. It may be

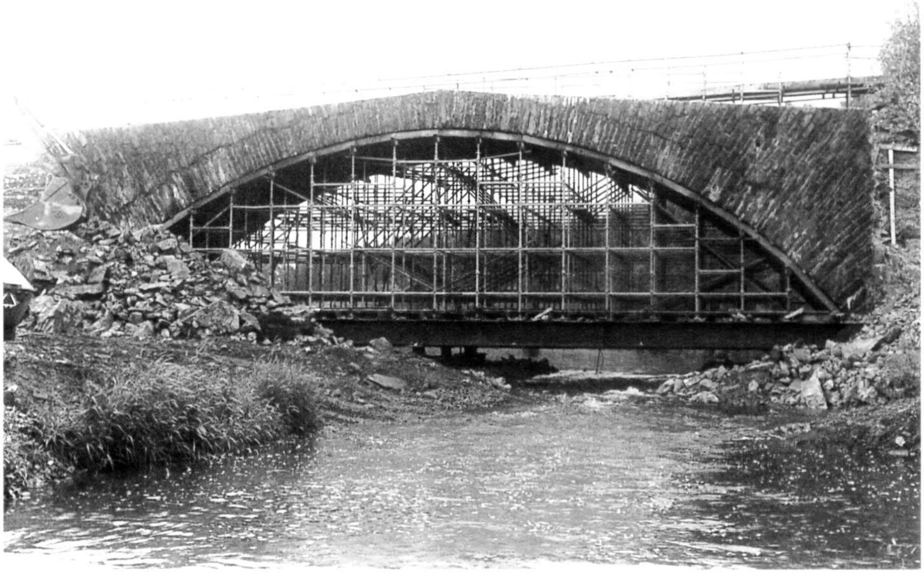

Fig.13 Temporary centring for saddling

difficult to install if there are extensive services in the bridge. It is readily combined with spandrel wall repairs, and waterproofing can be done at the same time.

The new arch may be designed to act compositely with the existing arch. In this case it is likely to have only nominal reinforcement and a means of keying it to the existing ring. Alternatively it may be designed to structurally replace the existing arch ring, in effect using it as permanent formwork. In this case it may be debonded from the existing arch ring. However, consideration must be given to the risk of future stability of the ring if it is relieved of load by the saddle, but not tied into it.

Before choosing saddling as a strengthening method, it is important to ascertain the reasons for the arch deterioration. A common reason is signs of distress in the barrel; these may be caused by movements of the abutments. The additions of a saddle will lift the line of thrust which may increase abutment movement and make the problem worse.

It is unlikely that the existing abutments will have enough capacity for the saddle. Spread footings may be built behind the existing abutments. Alternatively, piled foundations may be used with the saddle supported via spread footings onto a pilecap.

The minimum saddle thickness worth considering is about 150mm so there must be enough cover at the crown to accommodate it.

Some consideration should be given to the transverse behaviour of the saddle. Unlike in the longitudinal direction, there is little or no induced compressive stress, in fact it is more likely to be in tension. The transverse restraint at the springing may be enough to cause cracking of the saddle. It is necessary therefore to give careful consideration to the sequence of casting. A reinforced saddle is a useful way of tying together an arch with a longitudinal joint created by an earlier widening.

The fill is completely excavated down to the springings. Excavation of the fill should be done symmetrically to minimise the risk of arch collapse. Careful consideration should be given to the use of temporary centring to support the arch. The arch barrel should be carefully cleaned (normal pneumatic drills might for instance cause a local punch-through of the arch) and any reinforcement placed. Ties may also be installed in the arch ring and into the spandrel walls. The concrete should be poured symmetrically. A top shutter is likely to be required if the slope exceeds about 15°. Increasing the thickness of the saddle at the haunches may be considered to avoid the need for a top shutter.

A waterproofing membrane should be applied to the saddle extrados, and drainage at its lowest points.

Design method

A reinforced concrete saddle should be designed using reinforced concrete arch theory. Saddles with only nominal reinforcement are treated as an addition to the existing arch ring and assessed using a MEXE or mechanism analysis. A good shear connection between the arch and saddle is needed in this case. A stone arch may have a sufficiently rough extrados to provide it, otherwise stainless steel ties will be required.

Observed defects

Weathering, discolouration and leachate encrustation on the arch soffit associated with water seepage were observed.

6.3 SPRAYED CONCRETE

Sprayed concrete is widely used as a means of increasing arch ring thickness to increase load capacity, and of stabilising badly weathered masonry. In some cases British Rail have removed the original intrados ring of brickwork and replaced it with a sprayed reinforced concrete lining to minimise loss of clearance.

Pre-mixed concrete is sprayed at high velocity and adheres on impact, filling crevices and compacting material already sprayed. A layer between 150mm and 300mm thick may be applied; it is usually reinforced with at least nominal steel. It is quick to apply and does not involve disruption to services; nor does it require extensive formwork to be applied to the arch intrados. It may not involve disruption to traffic although consideration should be given to keeping heavy loads off the bridge until the concrete has gained enough strength. It reduces the size of the arch opening and it does not enhance the appearance of the bridge (figure 14) although careful design can reduce its visual impact; it should for example be contained beneath the arch, set in slightly from the edge of the existing arch (figure 15) - this example would probably have looked better if the concrete was recessed further. It will be necessary to provide adequate abutments which may be done by adding to the existing abutments, or by cutting into the existing abutments if they are sound and substantial.

It is important to remember that if the existing arch is in poor condition the addition of the concrete lining may accelerate its deterioration, particularly if waterproofing of the structure is inadequate. The lining may then in due course become the structural arch with the existing arch reduced to the quality of fill. Maintenance of existing drainage paths or creation of new ones is particularly important.

The application of sprayed concrete is a skilled job and it is important to use a reputable contractor. There are three processes available:

Fig.14 Sprayed concrete applied to face of arch ring

Fig.15 Sprayed concrete set in from edge of arch ring

Dry process

Cement and surface-dry aggregates are batched, mixed and loaded into a purpose made machine. Here, the dry mix is pressurised and introduced evenly and without segregation into a high pressure and velocity airstream which carries it to the discharge nozzle through a flexible hose. A finely atomised spray of water is introduced here to hydrate the cement and provide the right consistency for placing and compaction. It can be placed at low water: cement ratios and has no-slump characteristics. It can be placed on vertical and overhead surfaces. Admixtures and reinforcing fibres can be added. It requires a skilled and experienced operative to achieve good results. Aggregates of 10mm maximum size are normally employed. Aggregate: cement ratios are normally in the range 3.5-4.0:1. The proportion of material which rebounds, mainly the coarser aggregate, can be high. A 28 day strength in the range 30-50 N/mm^2 is typical.

Wet process

The concrete is pre-mixed and pumped along flexible hoses to the discharge nozzle. High pressure air is introduced at the nozzle to provide enough velocity to project the concrete and compact it in place. Admixtures are generally added to provide the workability for pumping. It can be placed on vertical and overhead surfaces. Quick setting admixtures may be added at the discharge nozzle. Rebound may be significantly lower than with the dry process. The maximum aggregate size is normally 20mm. A 28 day strength in the range 30-50 N/mm^2 is typical. There may be difficulty in achieving adhesion with this process.

Composite process

Concrete is pre-mixed, including all cement, aggregates and added water, and loaded into a placing machine as a wet mix. Here the mix is introduced into a high pressure and high velocity air stream and carried to the discharge nozzle. Advantages claimed are the better control of concrete quality and water: cement ratio associated with the wet process, and the lower water: cement ratio and higher placing velocity associated with the dry process. Furthermore, no admixtures are needed.

Design method

For analysis purposes it would normally be treated as an addition to the existing arch ring thickness and a MEXE assessment used. The risk that the existing arch ring will continue to deteriorate should be borne in mind.

Observed defects

All the cases investigated showed signs of cracking, made visible by seepage of water and the associated leaching of mineral salts. The lining may separate from the original arch by shrinkage of the concrete or further deterioration of the arch material at the interface which would mean that it would not increase the load capacity by as much as if it were fully attached. It was not possible to check this on the cases surveyed. Grouting of the interface may be necessary if this occurs. Rusting of the reinforcement must be a serious concern and every effort should be made to waterproof the structure.

6.4 PREFABRICATED LINERS

A corrugated metal or glass reinforced cement lining is attached to the arch soffit as permanent formwork, and the space between it and the arch ring is filled with concrete or grout. As with sprayed concrete, it is quick to apply and involves no disruption to traffic or services, but it reduces the size of the arch opening and does not enhance the appearance of the bridge (figure 16). It is particularly effective at hiding changes to the condition of the existing arch because the lining will accommodate movement without cracking.

Care needs to be taken to ensure that the space between the arch and the formwork is fully filled with concrete or grout. If grout is used it will also fill cracks, missing mortar and voids in the existing arch ring. Concrete will need to be pumped into place. A flowable concrete using superplasticiser and a 10mm maximum size aggregate would be suitable.

British Rail has used preformed plain steel sheet 12mm thick on a number of smaller arches (referred to as the *Preston Plate* method). Such sheets have the advantage over corrugated sheets of minimising loss of clearance, and reduce the amount of grout required. In this case the steel sheet may contribute significantly to the load capacity of the new composite structure and could be taken into account in design.

Design method

If a corrugated lining is attached close to the arch ring, then little increase in arch ring thickness is achieved and the repair should be assessed on the basis of improvements to the barrel, joint or condition factors for a MEXE assessment. If a significant space has been left then the increased arch ring thickness can be included in the assessment, again using a MEXE assessment. The increase in strength provided by the liner itself is usually ignored unless thick plain steel sheet is used.

Observed defects

No evidence of serious problems was found in the cases studied. However, rusting corrugated steel and fixing bolts were found, and grout loss at joints due to poor fit.

6.5 RELIEVING ARCH USING STEEL BEAMS

It is possible to roll steel I-beams about their x-x axis to the shape of the arch soffit. They may be used as a permanent strengthening or as temporary support during mining subsidence. Springings need to be cut into the existing abutments, or fixed to their face. Timber wedges may be used to pack the gap between the beams and the arch, or it may be filled with grout, or they could be encased in sprayed concrete. The firmness of the packing should be checked during future inspections.

Design method

The beams should be designed to carry all the loads, i.e. the existing arch plus fill and the live loads.

6.6 GROUTING

Arch grouting is used to fill voids in the arch ring to ensure that the full depth of section is available for load carrying. It is often used to fill voids caused by ring separation in multi-ring brick arches. It does not affect the appearance of the bridge unless grout extrudes from cracks and is not removed (it may be necessary to repoint the arch ring first).

Fig.16 Corrugated liner applied to bridge with sloping spandrel wall

The grout needs to be carefully designed to avoid premature setting before it has completely filled the voids and to ensure that its properties are compatible with the existing arch material; its viscosity will also determine the size of crack which it will fill. High pressure grouting may damage weak structures, and could therefore be a dangerous process. A limit of 0.2N/mm^2 has been used by British Rail but tests on brick tunnel linings suggest that up to 1N/mm^2 can be used in some cases. It will always take a line of least resistance which may be into fill, service ducts and drain pipes. Vacuum injection may be considered if pressure grouting may damage the structure.

Cementitious or resin grouts may be used; the most commonly used resin grouts are epoxy or polyester based. Cost considerations will normally dictate cementitious grout.

A matrix of holes is drilled into the structure. The hole spacing will depend on the structure and the ease with which grout will flow; a spacing of 300mm may be needed but 600-1000mm is more typical. Water flushing of the holes may then be carried out to remove debris and to prove continuity between holes. The grout is injected starting at the lowest point and working upwards. At each point, grout is injected until the pressure limit is reached, until it appears at adjacent holes, or until a predetermined amount has been injected (it is advisable to calculate before work starts how much grout should be used and compare with the amount actually being injected). Injection is then stopped and the hole plugged. When grout is injected with no evidence of spread to adjacent holes, intermediate injection holes may be necessary to ensure complete grouting. If an injection point accepts grout without refusal or build up of back pressure, grout must be leaking away. Possible solutions are the use of quicksetting grout, or very thick grout in successive small injections to set in and block the leakage paths progressively. Any external grout leakage should be cleaned off promptly before it sets to avoid staining of the masonry.

Grouting of bridge piers and abutments, where voids are often larger, is generally effective. However the adequacy of the foundations to carry the increase in dead load needs to be considered, particularly if it is proposed to grout a hollow pier.

Grouting of the fill has the potential to increase load capacity by improving load distribution to the arch, and raising the MEXE fill factor. It should also reduce water percolation through the fill. However the variable nature of fill materials makes the process not reliably dependable. A suitable grout for fill would be 1:5 cement: PFA with a water: solids ratio of 0.6:1.

Design method

Grouting of the arch ring is intended to make its full cross section available to carry loads. A MEXE assessment on this assumption is therefore acceptable provided this gives an adequate capacity. A MEXE assessment of grouted fill is also adequate.

Observed defects

The appearance of one bridge had been badly affected by leakage of grout.

6.7 STITCHING

Stitching comprises dowels inserted into holes drilled in the arch barrel or other part of the structure, and grouted to restore shear transfer. The holes are inclined to cross the cracks to be stitched. The method serves to unify and strengthen deteriorated masonry. It is particularly effective in repairing ring separation and the detachment of a spandrel wall facing from its backing.

Holes are generally 20-40mm in diameter. The drilling method depends on the size of hole required and the likely sensitivity of the structure to vibration. Small and sensitive structures may be drilled with electric rotary drills with diamond coring bits and water flushing. Larger structures may be drilled using rotary-percussive drills. Pneumatic rock drills may be used for massive structures where long holes are necessary. If accuracy is important, fixed hydraulic rotary drills may be used.

Reinforcing bar is generally used, 12-20mm diameter. Stainless steel should be used unless the area is dry. Where possible, the bars should extend about 750mm either side of the crack. It may be desirable to randomly vary the length of the bars so that there is no sharp boundary between reinforced and unreinforced material. It may be desirable to anchor the bar before grouting using for example an epoxy capsule which is pierced and mixed by the insertion of the bar. Grout is usually neat cement or PFA: cement. Sand: cement grout may be used if large voids will be filled at the same time, and the material should have similar properties to the existing masonry. Repointing may be necessary first to stop grout escaping.

The method may be applied to brickwork 350mm or more thick. Random stone masonry should be at least 500mm thick.

The method is not covered by standard codes of practice.

Replacement of cracked bricks may also be described as stitching.

Design method

If the method is applied to the arch ring, a MEXE assessment may be done assuming that the full section is then available for load carrying.

6.8 REPLACING SOME OR ALL OF THE SPANDREL FILL WITH CONCRETE

This method is used to stabilise outward movement of spandrel walls. A trench is excavated behind the spandrel wall down to the extrados of the arch barrel and filled with concrete to produce a composite saddle of greater mass and stability. Sometimes the whole of the fill is replaced, when the method is akin to saddling and is likely to be used to deal with arch and wall problems at the same time. Ties should be attached to the spandrel wall to improve the bond between it and the concrete. Depths of pour of the concrete should be limited to prevent the head of wet concrete pushing off the spandrel wall.

The work is invisible once completed. Traffic and services are likely to be disrupted during installation.

Design method

If all the fill is replaced, a MEXE assessment may be used, with a fill factor of 1.0.

Observed defects

Few defects were seen except for the appearance of leachate.

6.9 REINFORCED FILL

A reinforced earth system has been used to support the fill (see figure 17), to provide a stronger fill and to relieve pressure on the spandrel wall. Removal of the fill is necessary to install the system. It has the advantage that the fill is stronger but remains flexible.

Design method

Guidance will be found in BE 3/78 *Reinforced and anchored earth retaining walls and bridge abutments for embankments* (DOT, 1987).

6.10 RELIEVING SLABS

A relieving slab (see figure 18) is a flat reinforced concrete slab placed on top of the fill. It acts by improving the load distribution on the arch; it spreads the load and transfers some of it to the abutments. Waterproofing the top of the slab will also serve to keep water out of the bridge structure; drainage should also be installed at each end of the slab. It may be desirable to install a compressible layer under the central section of the slab to relieve the arch of live load.

Design method

Design as a slab supported on two edges.

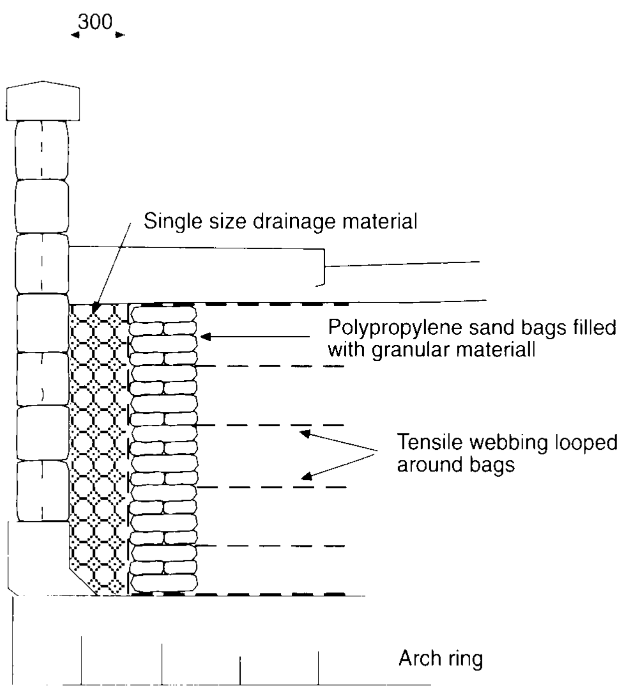

Fig.17 Reinforced fill (source: Welch, 1995)

6.11 WATERPROOFING AND RESURFACING

An important aim of any repair work should be to ensure that as little water gets into the structure from above as possible. If it does get in there should be positive means of drainage within the structure to let it out again. Waterproofing should be tackled at two main levels, at the surface and above the arch ring. The road surface should be intact so that water cannot percolate through cracks. Particular attention needs to be paid to where it joins kerbs or abuts the spandrel wall. Pavements or verges should also be waterproof; the verges may need to be paved. A waterproofing layer should be added beneath the surfacing.

A smooth road surface will minimise dynamic loading of the bridge. Consideration may be given to reprofiling the surfacing to reduce the severity of a hump-back, and hence dynamic wheel loads applied.

Design method

The load capacity of an arch bridge as calculated by the MEXE method can be increased by increasing the value of (d+h). This can be achieved by increasing the depth of the road surface. However the effect of this on the spandrel walls (and on the load capacity of the foundations) should be carefully considered. BD 21/93 does not recommend use of the MEXE method if the depth of fill is greater than the arch ring thickness at the crown.

6.12 TIE BARS

Tie bars are used to restrain further outward movement of spandrel walls. They may take two forms, pattress plates fixed to each end of a tie bar which passes completely through the structure, or a single pattress plate attached to a bar which is anchored within the structure. If the arch ring requires strengthening at the same time a more common solution is to use a concrete saddle which will also relieve the spandrel wall of outward forces.

They are installed either by drilling through the arch or being laid in a trench excavated from road surface level. Pattress plates are available in a variety of forms, some self-aligning. They are tightened only nominally as their function is to restrain further movement. They should be bedded against the spandrel wall with mortar to provide maximum bearing area.

Corrosion protection should be provided by grouting (if the bar has been installed in a PVC tube), wrapping in water-

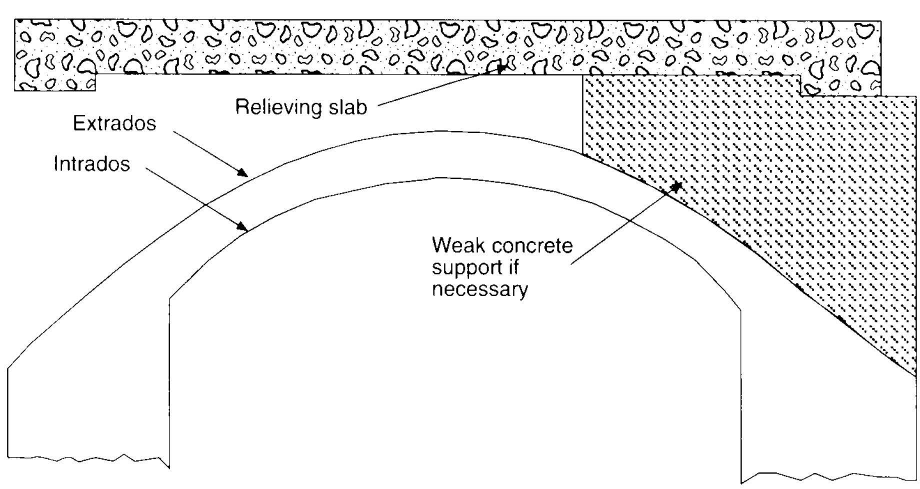

Fig.18 Relieving slab (source: BA 16/93)

proof tape, galvanising, or the use of stainless steel. The pattress plates may be painted. There is a risk that tie bars may be damaged by public utility excavations.

Visible pattress plates may not be permitted on listed structures, in which case it may be possible to recess them into the walls.

Design method

Their position and number can be based on simple calculations of allowable stress due to the horizontal bending and punching shear in the walls due to the outward forces which they are required to resist. Consideration should be given to the appearance of the bridge; in general the installation should be symmetrical about the crown. This may be difficult to achieve with heavily skewed bridges; anchorage within the structure would be necessary in this situation. A generous bar size should be used to allow for some loss due to corrosion; 40mm diameter may be appropriate.

Observed defects

In one of the cases studied there appeared to have been further movement of a spandrel wall since installation of the tie bars. Rusting of the exposed parts, in one case severe, was also found (figure 19).

6.13 SPREADER BEAMS

A beam or assembly of beams is attached to the spandrels of the bridge and held in place by tie bars, to restrain outward movement of the walls. Although it is likely to be more effective than tie bars because a greater area of wall is restrained, the appearance is unattractive and should only be used in emergencies or for bridges which have a short planned lifespan.

6.14 REINFORCED PARAPETS

Two possible methods of building reinforced parapets are shown in figure 20. In the first the reinforced core transfers its loads to a longitudinal beam spanning between pilasters. In the second case the structural action is that of a reinforced wall with pinned foot and high level ties. There is a risk that future excavations will sever the ties.

Design method

Conventional design rules for parapets should be used.

6.15 UNDERPINNING

Underpinning involves excavating material from beneath the foundations and replacing with mass concrete.

Fig.19 Rusting pattress plate

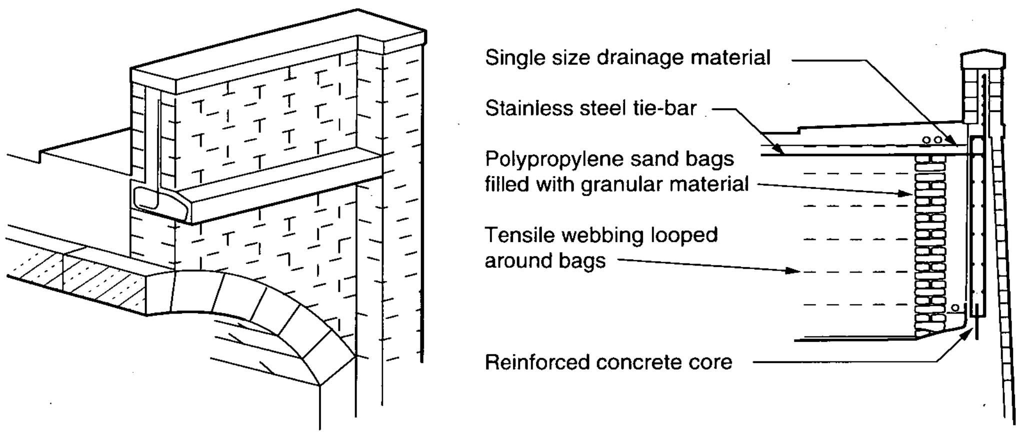

Fig. 20 Reinforced parapets (Source Welch, 1995)

A sequence of work is followed to ensure that the stability of the existing foundations is not compromised. The work is labour intensive.

A practical guide to the application of the method may be found in Algar, 1984.

Observed defects

The cases studied appeared to have been successful.

6.16 INVERT SLABS

An invert slab is a slab of concrete placed between the abutment walls or piers with its top surface at or below river bed level (older versions may be built of masonry) It helps to prevent scour and may be used to prop the abutments apart if inward movement has occurred.

Observed defects

If incorrectly installed there is a risk of scour beneath the slab, particularly at the downstream end, and this was found in one of the cases studied. A downstand beam at each end of the slab will help prevent this, see figure 21.

6.17 STONE PITCHING

Large stones may be placed on the river bed at the base of a pier to protect it from scour. The size of stones depends on their shape, *i.e.* how well they interlock, and the speed of flow. Stones of 3t upwards should be used where the flow is fast, 1.5-3t in moderate flows, and 1.5-2.5t where the flow is slow. They should extend to 0.5m below normal river bed level and may be embedded in (microsilica) concrete. In fast flowing rivers they should be taken all the way across in the manner of an invert slab. Otherwise they should be laid at a gradient of 1:2 to 1:3.

6.18 SMALL DIAMETER BORED PILES

Small diameter bored piles are a useful means of providing extra support to limit settlement or where additional

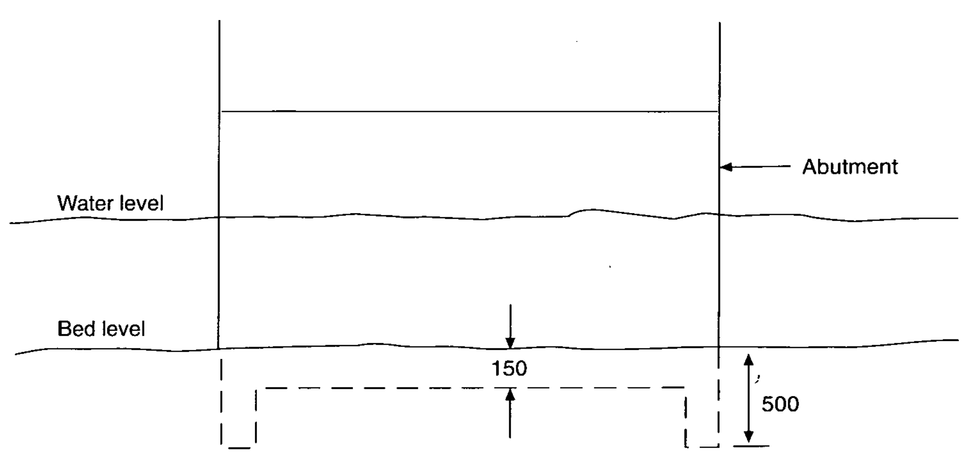

Fig.21 Cross section through invert slab with downstands

loading is expected. To provide continuity the piles may be bored through and cast into the existing abutment or pier. Where the abutment or pier is itself weak it may require grouting or stitching together, as illustrated in figure 22.

A typical procedure for installation in non-cohesive soils is carried out with a rotary drilling rig, feeding down a temporary drilling casing. Drilling fluid, usually water, is circulated through the casing to cool the cutting bit and to remove spoil. When the required depth has been drilled the borehole is filled with sand: cement grout and reinforcement is placed. The temporary casing is then removed, with grout being replenished as needed. In cohesive soils the method is similar except that the drill casing is removed prior to grouting.

The piles are normally 75-225mm diameter and 10-20m long. The safe working load is typically 100-300kN, and up to 500kN in rock or dense gravels.

The *Specification for piling* (Institution of Civil Engineers, 1988) (only covers traditional piling methods) and publications of the Federation of Piling Specialists, including *Specification for the construction of mini piles* give guidance on specifying a scheme.

Design method

Specialist contractors are normally employed to carry out the work and they may provide a design and build service.

7. COST OF REPAIRS

Calculation of the cost of repair methods should take into account future maintenance costs of the alternatives considered, in accordance with BD 36/92 and BA 28/92 (DOT *et al*, 1992a, 1992b).

A broad indication of the relative costs of repair methods is given below, based on two sources:

1) Ashurst (Ashurst, 1992) examined the cost data obtained in his sample survey and applied it to a standard bridge of span 4.5m with a semicircular arch, width 6.0m, and total deck length of 15.0m. The costs were adjusted to 1990 rates.

2) British Rail held a meeting of their maintenance engineers in 1991 to obtain consensus views on repair methods. They estimated the costs, at 1991 prices, of various methods applied to a 5m span segmental arch carrying two tracks. The estimated costs are given in table 4.

Significant differences between the costs will be noted which may be due to different working practices; the BR costs for example are direct labour costs. The figures should therefore be used as a guide to relative costs.

8. ROUTINE MAINTENANCE

Routine maintenance consists of:

1) keeping the road surface in a sound condition to minimise water leakage into the structure and to minimise dynamic loading from traffic due to potholes etc.,

2) removing vegetation from the structure, and

3) making good small areas of deteriorated mortar.

These three areas of maintenance involve modest expense compared with that which may result from neglect.

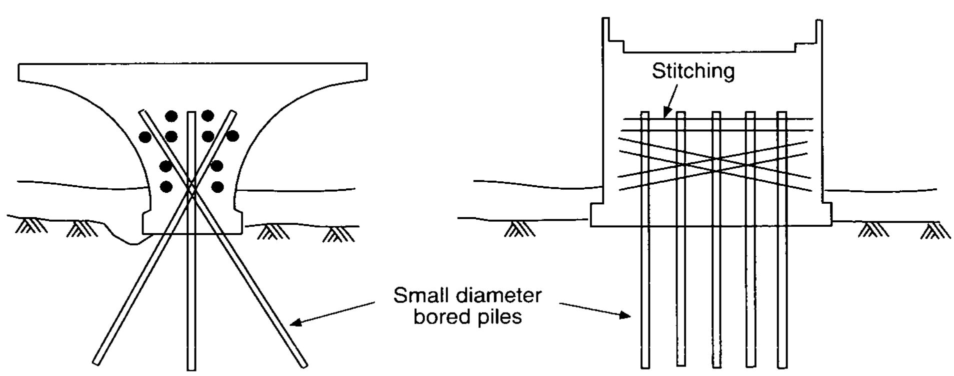

Fig.22 Small diameter bored piling and stitching (source: BA 16/93)

TABLE 4

Estimated repair costs

Repair method	Cost (£k) Ashurst	BR
Repoint arch ring	4	
Tie bars		1-2 per bar
Repoint bridge	10.4	
Sprayed concrete	10.8	
(150mm thick)	20-30	
Grout arch ring	15.3-24.7	8-10
Waterproofing		10-15
Relieving slab		12-15
Stitch arch ring		15
Saddle	23.4	12-40
Steel lining	57	10-15
Steel arch ribs		20

9. CASE STUDIES

9.1 PONT LIMA, NEAR BETWYS-Y-COED, GWYNEDD

This study illustrates possible difficulties of drilling through fill, the possibility of concealing tie bars, and the extra weight which may be added to a structure by grouting which may have consequences for adequacy of foundations.

Pont Lima (figure 23) is a two square span (12.2m, 5.5m) Grade II listed stone masonry bridge built in 1862, carrying a minor road over the River Conwy. The stone is of mudstone/shale and the mortar is lime. Work was carried out in 1979 because of cracking of the masonry in the main span and pier, bulging spandrel walls, voids in the pier, deterioration of pointing, and water flow through the structure. Vegetation also needed to be cleared.

Failed and eroded pointing was raked out and flushed clean with water and air jets. Pressure pointing was done using a 1:1 sand: cement colloidal grout with PFA added to produce a colour match. Grout holes of 25mm diameter were drilled at 1m centres vertically and horizontally beginning at the base of the piers and abutments, a total of more than 400 holes. An attempt was made at this stage to drill the holes for tie bars but movement of larger pieces of fill resulted in jamming the drill casing, so it was decided to grout the fill first. Grouting was begun at the lowest level, using a 1:1 sand:cement mix. This was changed to 2:1 sand:cement for the fill above the arches. Lifts were limited to 1m per day to remove the risk of fluid grout causing further outward movement of the masonry. Grout was contained at the ends of the bridge by drilling and injecting curtain holes at 750mm centres down through the road. A total of 285 tonnes of cement and 420 tonnes of sand were injected.

Fig.23 Pont Lima

To strengthen the foundations of the pier and abutments, 2m long 16mm diameter high tensile stitching bars were grouted into 30mm diameter inclined holes, drilled in a reticulated (network) pattern at 1.5m centres through the masonry into the underlying mudstone bedrock.

The pier and spandrel walls were strengthened with tie bars. Two 25mm diameter ties, 6.8m long, were installed in the pier longitudinally, and ten 2.2m long transversely. Eleven ties were installed in the spandrel walls, 32mm diameter and 7.2m long. The short holes through the pier were drilled percussively and the others using a rotary hydraulic rig. The bars were wrapped in Denso tape and placed in ribbed plastic tubes within the holes, and finally grouted. The bearing plates were recessed behind the face of the masonry so that they were invisible.

Finally, PVC pipes, 50mm in diameter, were inserted in selected locations to act as weep holes.

The work done is illustrated in figure 24. The work took six months and cost £80k at 1979 prices. MEXE was used to assess the work to be done. The methods chosen enabled the bridge to be kept open during most of the work.

9.2 POULTERS BRIDGE, BASINGSTOKE CANAL, HAMPSHIRE

This study illustrates that the actual structure may not be as it appears on the outside, and the use of NDT to detect concealed structures. It illustrates that at times it may be impossible to avoid disruption to traffic both on and below the bridge, in which case a rapid construction sequence is essential.

Poulters Bridge (figure 25) is a single span (6.5m) Grade II listed brick arch bridge built in 1790 which carries an unclassified road across the Basingstoke Canal. It is a typical hump-backed canal bridge built to carry little traffic; the records show that a fire engine grounded on it a few years ago and the firemen had to proceed on foot!

The bridge was strengthened by saddling in 1994 because it was assessed to have only a 3 tonne capacity (using MEXE). The bridge records show that a variety of repairs had been done in the last thirty years (which is as far back as the records go). Tie bars were installed in 1965: note that there is some corrosion showing on the face of the spandrel wall. Repointing and replacement of damaged bricks was carried out in 1977. Repointing and some rebuilding of the parapets was done in 1987. The depth of surfacing was increased in 1992 to increase the load capacity of the bridge but in the process a local punch through failure of the arch ring occurred and it was decided that more major measures were required. Preliminary investigations showed that the arch ring comprised a single ring of bricks laid as headers, although at its face it appears to be half as thick again. Two ribs of brick had been laid over the arch spaced a cart axle track apart to provide better local load spreading (figure 26). Part of the preliminary investigation was a ground radar survey, and this detected something in the location of the ribs, but it was thought to be possibly metal girders.

It was decided that saddling was the only method which would resolve the problems, although closure of the bridge gave access difficulties to a small number of houses. In addition it was deemed necessary to prop the arch because the ring was so thin (figure 25). This meant that a closure of the canal was required. To minimise inconvenience to local residents and loss of use of the canal, work was timed to be completed in three weeks, before Easter.

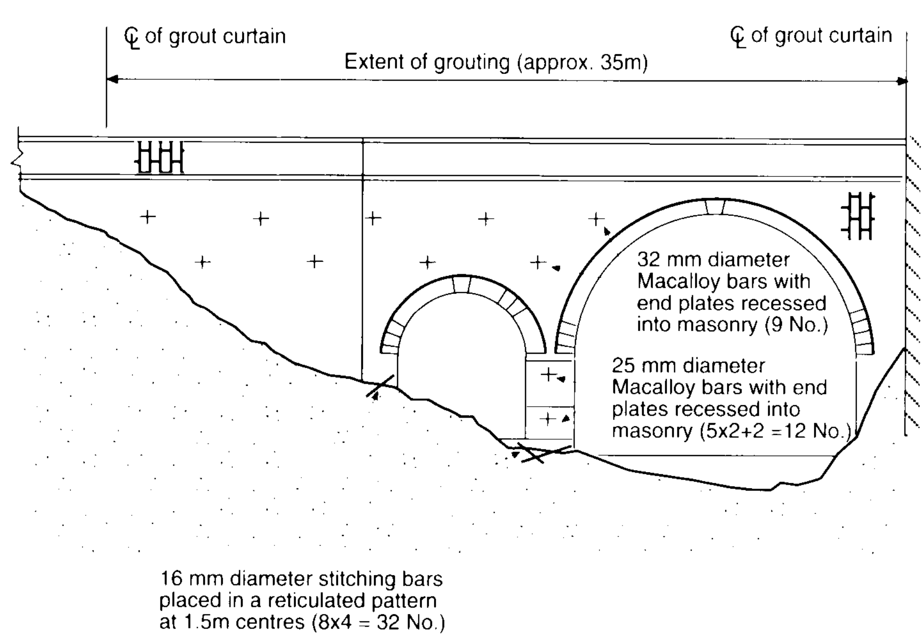

Fig.24 Work done on Pont Lima

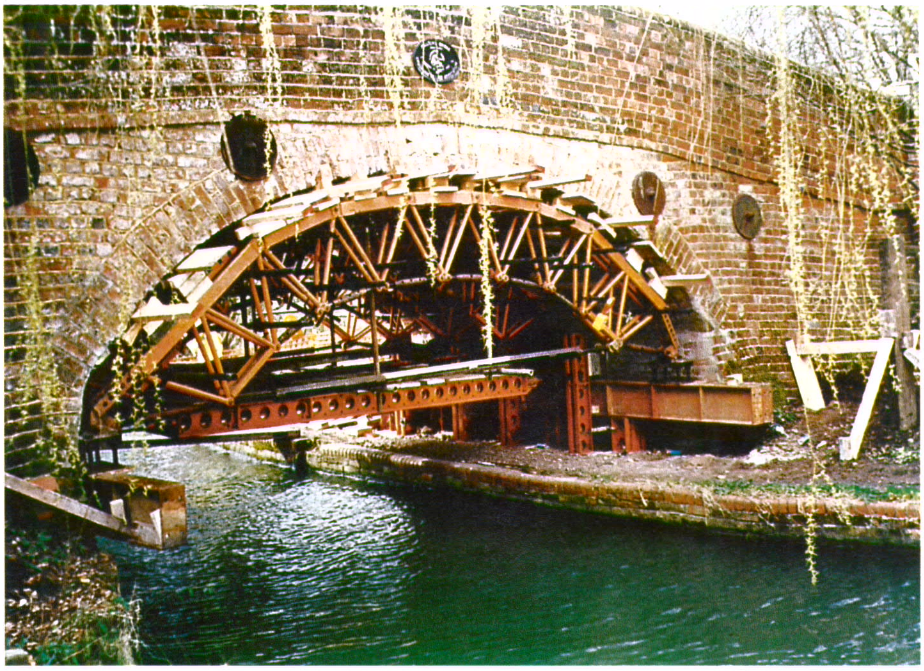

Figure 25. Poulters Bridge

Figure 26. Poulters Bridge showing brick ribs on arch extrados

A variable depth saddle was designed, to completely replace the existing fill. It was designed using a mechanism analysis to full HA loading, and the existing ring was taken into account in the design.

The fill was removed to a vertical face one metre behind the back of the abutments, and to a sufficient depth to provide foundations for the saddle. No vibrating or percussive equipment was allowed because the arch ring was so thin. The existing tie bars were left in place, and wrapped in waterproofing tape. The existing arch ring was tied to the saddle using double triangulated stainless steel ties at 500mm spacings to reduce the risk of brickwork falling out in future. Reinforcement for the saddle was placed and the saddle cast of C40/20 concrete with sulphate resisting cement, the concrete being placed so as to maintain a symmetrical loading on the arch. The bridge was surfaced with a 60mm dense bitumen macadam base course and a 40mm thick close graded macadam wearing course.

The construction cost was £30k, plus £9k for design, supervision and project management.

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APPENDIX A: MAIN SOURCES OF INFORMATION FOR THIS GUIDE

1. *An assessment of repair and strengthening techniques for brick and stone masonry arch bridges* by D Ashurst (Department of Transport, TRRL Contractor Report 284. Transport Research Laboratory, Crowthorne, 1992).

   This examination of repair methods was carried out in 1990 for TRL by consultants Ove Arup & Partners. Details were obtained of work done and costs for about 180 bridges and then about 50 were selected for a more detailed examination to identify the advantages and disadvantages of the various repair and strengthening methods and their relative costs. An assessment of the effectiveness of the methods was made by inspection: however the work had been done relatively recently so it was not possible to assess long term effectiveness. Frequently more than one method is applied. The costs identified were initial costs, data were not available to attempt to identify whole life costs.

   The work did not set out to examine the structural effectiveness of the various methods (see item 6).

2. *Masonry arch bridges* edited by J Page (TRL State of the Art Review, published by HMSO, 1993).

3. *The maintenance of brick and stone masonry structures* edited by A M Sowden (published by E & F N Spon, 1990).

A very valuable book.

4. Various British Rail reports to which Railtrack kindly provided access.

5. A questionnaire prepared by the CSS Working Group asking for details of examples of repairs and strengthening. The questionnaire was distributed to County Council bridge offices and others by the CSS. The returned questionnaires show that it is common for more than one repair or strengthening method to be used. Sixteen bridges had one method applied, ten two methods, six three methods, four four methods, three five methods, and one had six methods applied. The most common repair/strengthening methods reported were repointing, saddling and replacing fill with concrete. Gwynedd and Hampshire County Councils are acknowledged particularly for allowing Pont Lima and Poulters Bridge to be used as case studies.

6. Research in progress at the Transport Research Laboratory into the structural effectiveness of arch bridge repair and strengthening methods. A series of 5m span 3 ring brick arches are being built, and repair and strengthening methods applied. They are 2m wide and have a rise of 1.25m at midspan. Fill is placed above the arch, contained by steel spandrel walls which are designed to contain the fill but not constrain movement of the arch. A line load is applied at quarter span and increased until failure occurs. The maximum load for the three models tested to date are summarised in the table below.

7. *The assessment of highway bridges and structures.* Departmental Standard BD 21/93 and Advice Note 16/93 (published by Department of Transport *et al*, 1993).

Model no.	Description	Maximum load (kN)
1	Unstrengthened	240
2	Sprayed concrete to soffit, 150mm thick	900
3	Saddle, nominal reinforcement, 150mm thick	700

APPENDIX B: MEMBERSHIP OF COUNTY SURVEYORS' SOCIETY STEERING GROUP

The User Guide was prepared by the Transport Research Laboratory for the County Surveyors' Society. Their Bridges Group set up a Steering Group to oversee its production. Its membership has included the following:

Mr R Fish	Cornwall County Council
Mr P Mallinder	Sheffield City Council
Mr S Pearson	Derbyshire County Council
Mr B Tingle	Humberside County Council
Mr P Welch	North Yorkshire County Council
Mr D Hanson	Railtrack
Mr A Packham	Railtrack
Mr J Powell	British Waterways Board
Dr R Woodward	Transport Research Laboratory
Mr N Ricketts	Transport Research Laboratory
Mr J Page	Formerly Transport Research Laboratory

The Guide was compiled by J Page

COMMENTS ON GUIDE TO REPAIR AND STRENGTHENING OF MASONRY ARCH HIGHWAY BRIDGES (TRL204):

Please send to Transport Research Laboratory, Civil Engineering Resource Centre, Old Wokingham Road, Crowthorne, Berkshire, RG45 6AU.