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STRENGTHENING OF STONE MASONRY ARCH BRIDGES

THREE LEAF MASONRY WALLS-STATE OF THE ART

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CHAPTER 1

History

1. History

Archaeologists believe that arches and vaults originated in the marshlands of Lower Egypt or Mesopotamia about five thousand years ago. The prototype was a structure built of bundles of reeds placed upright in the ground and bent over and tied together at the top to form a roof. This technique is still used in southern Iraq. The outer surfaces of some of these buildings are covered with mud plaster and this was probably an intermediate stage in the evolution of the vault. Probably the Chinese first employed the arch in the construction of bridges across small streams. It is known that bridges and other public works were built there about 2900 BC and that possibly the arch was used then.

Nevertheless, the greatest examples of their use were the arch bridges built in the Roman age. Anyone approaching the study of masonry arch bridges will be struck by the diversity of structural models and materials employed in the Roman solution of bridging a gap with an arch. Many of them still exist and some remain in service to this day, together with the considerable number of masonry arch bridges built during the centuries until the First World War.

The fundamental form of masonry bridges was surprisingly constant throughout the civilised world from Roman times through Byzantium and the Islamic world and into medieval Europe, where the church kept the secrets of masonry bridges alive. In fact, church building and bridge building were closely connected, with the same masons building both and travelling round Europe with the skills and secrets. St. Benezet who built the bridge at Avignon is well known, and the Pope was head of bridge building faculty of monks, and is thus still known as the Pontifex Maximus (Pontif) or chief bridge builder. It is interesting to note that in areas of strong nonconformist religion there were few masonry arches in the 18th century and early 19th century. The USA is surprisingly short of early masonry aches. This perhaps also accounts for the number of dramatic bridges could “Devil’s Bridge”, in that anything not buildable by the local church masons must have been built by the devil rather than the Romans, medieval monks or Moorish engineers.

The Age of Enlightenment and the scientific approach to bridge design started with the Italian Renaissance of the 15th century, which gave us the chain arch bridge and the segmental arch. But it became established in France in the 18yh century with Hubert Gautier's Traite des Ponts published in 1716 and the formation of the Ecole des Ponts et Chaussees in 1747, which gave us balanced thrust arches.

This also led later to the separation of appearance from constructional necessity. In the 19th and 20th centuries the Ecole des Pontes et Chaussees advocated that the principles of masonry arch appearance should apply even if the structure underneath was not masonry. This Beaux Arts view, which was so in conflict with Modernism, probably hastened the separation of engineers from training in aesthetics, and promoted the idea of bridges being solely about pure engineering, and the false argument that "the appearance will look after itself if the structure is functional". Hitler's fondness for masonry arches on early autobahns probably aided their rejection post-war.

1.1. Roman bridges

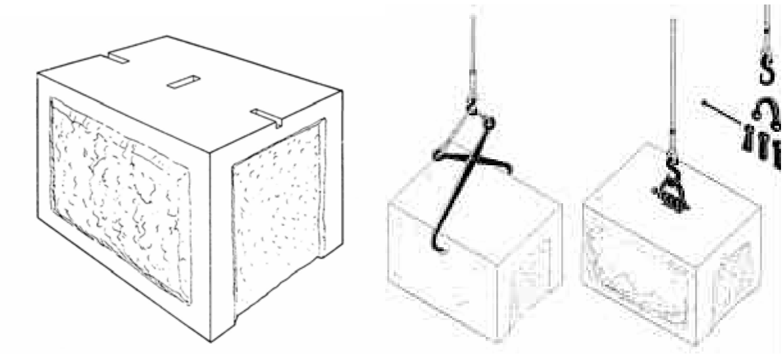
Masonry arches were built since the beginning of the earliest civilization, but the greatest examples of their use were the arch bridges built in the Roman age. Anyone approaching the study of masonry arch bridges will be struck by the diversity of structural models and materials employed in the Roman solution of bridging a gap with an arch. Many of them still exist and some remain in service to this day.

Fig. 1.1. – Roman Bridge in the city of Chaves

The Romans, with a strong and centralized empire, provided one of the most important steps in the construction of buildings. Contrasting with the Greeks, their architecture was not only concerned with temples and amphitheatres, but also with roads, bridges, aqueducts and harbours. They introduced many innovations directly related to materials, structural concepts and construction processes.

Most Roman arches were semicircular in shape but some were segmental. Piers were usually thick, with widths of one quarter to one third of the arch span, so that individual arches of a multispan bridge would be self supporting. It has been suggested that thick piers were standard practice because the Romans wished to be able to demolish one span in times of war without bringing the whole bridge down. The thrust was meant to remain entirely within the piers.

Before construction, the stone blocks were prepared carefully. Generally they were of big sizes giving a robustness effect to the structure. The stones present marks as a consequence of the use of constructive process. These marks are characterised by small holes in the faces in result of the mechanism of elevation adopted.



a) b)

Fig. 1.2 – Common roman building stone. a) Shape; b) Lifting device

The Romans were not interested in record-breaking spans, only in utility and durability. That some of their bridges remain after about 2000 years of continuous scouring, in rivers which are subject to frequent heavy flooding, says it all. Military action has removed many that would otherwise have survived.

The existent data seem to indicate that the Romans didn't divert the course of the rivers to build the foundations of the pillars. The technique of placing concrete under water by the tremie process was known; a cofferdam was built composed by two rings of wood stakes filled out amongst themselves with compacted clay, and the material was dredged out until a satisfactory bottom had been reached, when concrete was placed, the pozolana addition (ash obtained starting from a volcanic rock) it turned this concrete extremely hard and resistant to the water.

Fig. 1.3 – Cofferdam for foundation

Piles were used where ground conditions made spread footings inadequate. The piers were usually pointed upstream but flat backed downstream; hydraulically this is not a good shape and must have led to scour problems. Masonry inverts were built presumably to smooth the flow and reduce scour. It was common practice for the masonry to be laid without mortar.

The alternation of masonry units in stretchers and headers in the same course, or the presence of alternate courses of units in stretchers and headers are bonds that the Romans also copied from Greek construction, where they originally appeared when structures built with logs of wood alternately placed crosswise to grant them stability were subsequently reproduced in stonework.

Fig. 1.4 – Alternate courses

Of the two dispositions, the latter (alternate courses of stretchers and headers) is the most frequent in Roman construction, further proving its systematic nature, well suited to the Roman concepts of planning, efficiency and speedy execution.

Openings in the piers were quite common probably to improve flow in flood and possibly to reduce weight on the foundations, although some of them were so small that they would make little difference to either flow or weight.

Fig. 1.5 – Flood opening in pier

A common feature is projecting stones or slots to support falsework. Once built the pillars, the arches were mounted, stone for stone, on a wood falsework with semicircular shape (see Fig.).

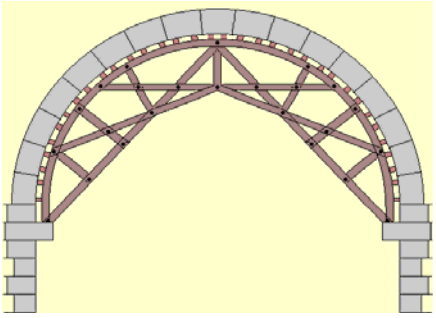


Fig. 1.6 – Falsework under the arch

Exploiting the structural form of the arch, the Romans constructed magnificent bridges and aqueducts all over their empire. One of the most outstanding examples is the Pont du Gard, an enormous aqueduct formed of three tiers of arches and, except the top tier, made from dry stone masonry.

Fig. 1.7 – Pont du Gard

The Roman bridges were thought and built inside & global logic of the big system of imperial roads, for the that they usually meet in the Roman roads referred in the Itinerário Antoaino. They denote a concern for the symmetry and for a certain unit in the group, usually tends the same arches amongst themselves and presenting a board of horizontal profile, in way to allow an easier crossing, with lateral slopes.

The fall of the Roman empire put an end to the evolution of the art of the construction of arch bridges in whole the European space. Just later, already in the medieval period, under the influence of the Church, it was attended reviving, the construction of countless masonry arch bridges across Europe.

1.2. Medieval bridges

The revival of bridge building in Europe following the fall of the Roman Empire was marked by the spread of the pointed arch westward from its origins in the Middle East. The pointed arch typically was a Gothic architectural form important structurally in the development of palaces, castles, and especially the cathedrals of western Europe, but not very important for bridges.

Fig. 1.8 – Medieval bridge in the city of

Medieval bridges are startling achievements of design and engineering comparable with the great cathedrals of the period, and are also proof of the great importance of road transport in the middle ages and of the size and sophistication of the medieval economy.

The medieval bridges have projecting piers, triangular in shape, known as cutwaters. These are found on the upper side with the point towards the stream their purpose being to protect the pier from the force of the current and from the impact of trees and other objects borne along by the water. The upper part of these piers at roadway level has refuges for pedestrians.

The spans varied from five feet in the case of small bridges to twenty feet or more in a few cases. The first were semicircular with a barrel vault. In the 13th century pointed arches replaced these arches and groined vaults replaced barrel vaults.

Fig. 1.9 – Poined arch

Here the main weight was taken on ribs of stone. Some bridges have had the ribs cut away to improve navigation. In others, the ribs have been filled with brick.

Also the equipment used in the construction developed. Mechanisms that allowed to lift weights, were frequently used in the Antiquity, but in the Medium Age they were improved, such as the counterbalance and the double pulleys. The cranes were put on the soil if the work didn't go very high; otherwise they were put on a platform. These cranes were made in such a way that they being set up and dismounted with the few men's help.

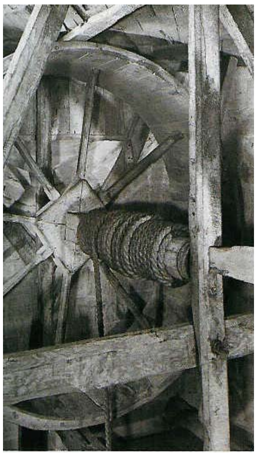


Fig.1.10 – Lifting device

Often a medieval bridge is extremely long and included a long stone causeway which leads up to it across a flood plain. This is pierced by subsidiary arches which do not regularly have channels of water flowing through them. They are used, however, at times of flood to allow the swollen waters to escape away, instead of ponding up behind the bridge.

The Renaissance infused new life into the design and construction of masonry arch bridges. There was a move away from the semicircular arch which is restrictive because its rise is determined by its span. The segmental arch was introduced which provided an increased and variable span for a given rise and also increased the proportion of clear opening to solid pier for multispan bridges.

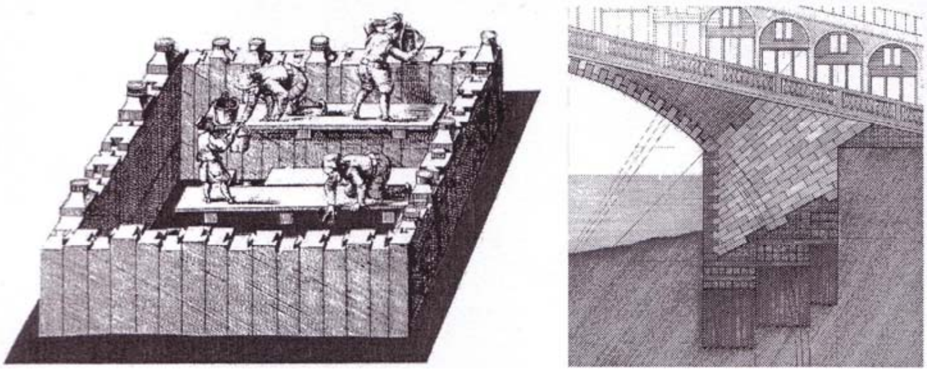


Fig. 1.11 – Foundation Construction of a Venetian bridge

Further structures connected with bridges include chapels built for bridge hermits. Gateways and drawbridges were also found.

The arch is the structural form that best explores the mechanical characteristics of the masonry and only the development of new materials (ex.: armed concrete and high quality steel) it allowed the emergence in new structural ways for the bridges.

CHAPTER 2

Masonry Arch Bridge Construction

2. Masonry Arch Bridge Construction

2.1. General

There are two fundamental structural problems when building with masonry: how to achieve height and how to span an opening, i.e. how to span vertical and horizontal spaces. Spanning vertically is done by using columns, walls and towers, and spanning horizontally is done by using lintels, beams and arches. In addition, some structural elements such as vaults and domes can simultaneously span vertically and horizontally.

The arch is one of the older forms of bridge. It is rather like an inverted suspension bridge, with all the tensions replaced by compressions.

Masonry arches, being made of relatively big voussoirs joined by mortar cannot take tension and need continuous support during construction from below. This type of falsework is called centring, and is often of the general form shown below.

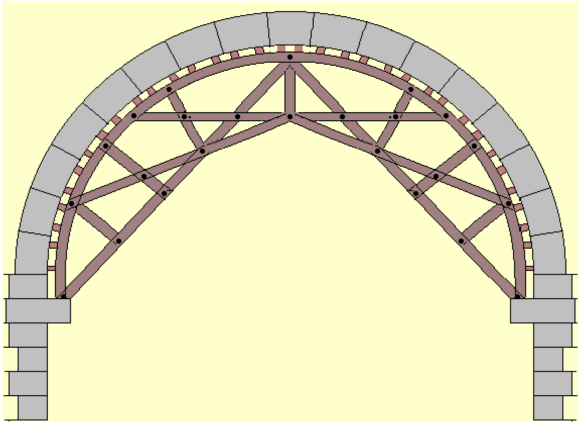


Fig. 2.1 - Centring

The type of falsework depends very much on the material of which the bridge is made, and on the size of the bridge. This picture shows the corbels upon which the centring was erected.

Fig. 2.2 – Corbels

When the centring has been removed, or struck, the arch will inevitably settle slightly. This is inevitable, because it can only generate the required compressive forces by undergoing some strain. All structures, in fact, must deflect when temporary support is removed.

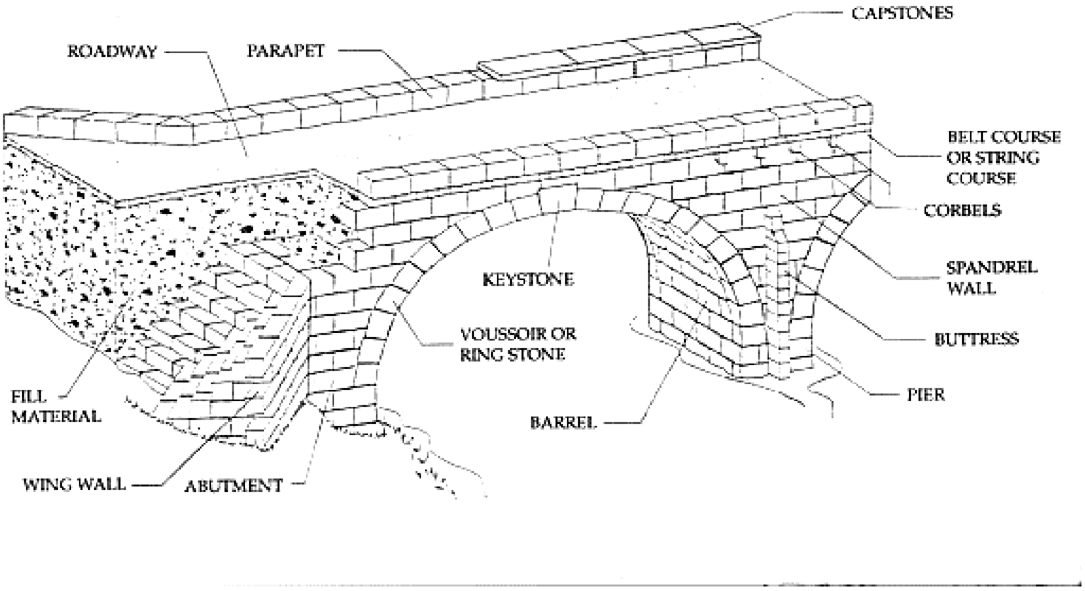


Fig.2.3 – Stone Masonry Arch Bridge

The wedge shaped blocks from which an arch is built are known as voussoirs. They are usually symmetrically disposed about a central voussoir known as the key-stone from a mistaken idea on the pat of early builders that it had a special function to perform. It is in fact an aesthetic and traditional feature rather than a structural requirement. The blocks in the abutments upon which the end of the voussoirs rest are known as skew-backs and the surface between an end voussoir and a skew-back is the springing. The highest point of the arch is the crown and the lower sections are the haunches. This is a general term and there is no hard and fast definition of how much of the structure is included in a haunch. The upper boundary line of the arch ring is the extrados and the lower line is the intrados. The under surface of the arch ring is the soffit. The outer walls which retain the fill are the spandrel walls and they become the wing-walls at either side of the arch.

2.2. Foundations

The foundations of masonry arch bridges are usually relatively shallow spread footings. Excavation would be taken down to firm material but if necessary timber piles would be used (they have been in use since Roman times). In water cofferdams would be used to provide a dry working area. A grating of large timbers may then have been laid on the river bed or on the heads of the piles as a base for the masonry of the pier or abutment. Alternatively the Romans used concrete.

Fig. 2.4 – Foundation cofferdam

The foundations may be threatened by earthquake or flood, for example.

In fact, even the normal flow of river water past bridge piers can generate scouring which can bring down a bridge. The presence of the piers changes the flow, producing acceleration and turbulence. The lifting and carrying power of a fluid increases as a high power of the speed. The ancient Romans knew about this, and took precautions. Foundations need to penetrate to secure ground, and a pavement around piers can help to protect the bed. You can often see the results of scouring around a post or a boulder on a sandy beach, after the tide has gone out. The next diagrams, which are sections at right angles to the flow, show the general effect.

Furthermore, because of turbulence, the pressure on the bridge fluctuates with a wide frequency spectrum; people on a bridge that is nearly submerged report feeling strong vibrations.

2.3. Piers

Piers are vertical structures which hold up everything else. After a disaster, they are often the only survivors. They are often founded under water or deep underground, so that we never see the complete structure. A great many bridges would look very strange if we could see them without the water in which they sit. Piers are not always the most obviously attractive or interesting parts of a bridge, yet their construction can present the most difficult problems and the greatest dangers in bridge building. Deep water requires caissons: the greater the depth, the higher the pressure.

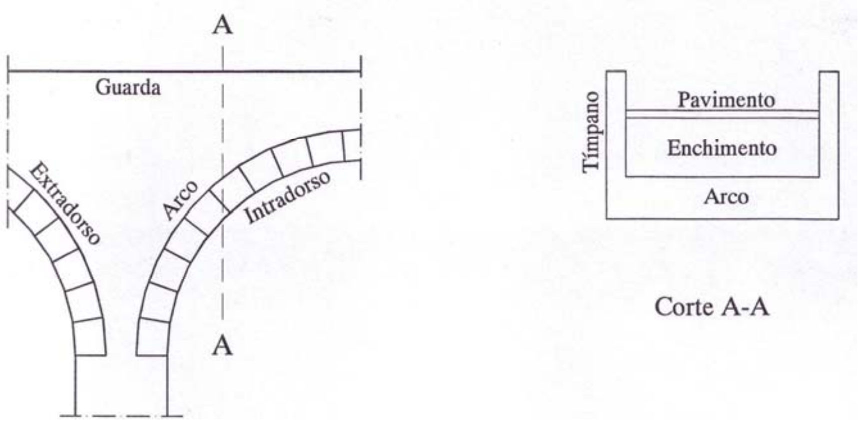


Fig. 2.5 – Masonry piers

Masonry piers are built outer stone leaves and the cavity filled with clay and big stones. Stone piers are often solid, particularly for smaller bridges. The Romans built semicircular arches with very thick piers, so that any arch would remain standing if its neighbour was removed by flood or by enemy action. The thrust was meant to remain entirely within the piers. The Romans were not interested in record-breaking spans, only in utility and durability. That some of their bridges remain after about 2000 years of continuous scouring, in rivers which are subject to frequent heavy flooding, says it all. Military action has removed many that would otherwise have survived.

In the early days of arch bridge construction, spans were constructed one at a time which meant that each pier had to be thick enough to act as an abutment. Later, several spans would be constructed at the same time which allowed more slender piers and more rapid construction. This was particularly important for tall viaducts where slender piers were essential both for appearance and for cost. Many viaducts are built with more substantial piers at intervals, known as king piers. They may have been used to provide intermediate support to economise on the number of centrings required. They would also add robustness to the completed structure and may have contributed aesthetically.

2.4. Arch

The arch is a form of construction in which masonry units span an opening by transferring vertical loads laterally to adjacent voussoirs and, thus, to the abutments. Some common arch types are as follows:

Blind -An arch whose opening is filled with masonry.

Bullseye -An arch whose intrados is a full circle. Also known as a *Circular* arch.

Elliptical -An arch with two centres and continually changing radii.

Fixed -An arch whose skewback is fixed in position and inclination. Masonry arches are fixed arches by nature of their construction.

Gauged -An arch formed with tapered voussoirs and thin mortar joints.

Gothic -An arch with relatively large rise-to-span ratio, whose sides consist of arcs of circles, the centres of which are at the level of the spring line. Also referred to as a *Drop*, *Equilateral* or *Lancet* arch, depending upon whether the spacings of the centres are respectively less than, equal to or more than the clear span.

Horseshoe -An arch whose intrados is greater than a semicircle and less than a full circle. Also known as an *Arabic* or *Moorish* arch.

Jack -A flat arch with zero or little rise.

Multicentered -An arch whose curve consists of several arcs of circles which are normally tangent at their intersections.

Relieving -An arch built over a lintel, jack arch or smaller arch to divert loads, thus relieving the lower arch or lintel from excessive loading. Also known as a *Discharging* or *Safety* arch.

Segmental -An arch whose intrados is circular but less than a semicircle.

Semicircular -An arch whose intrados is a semicircle (half circle).

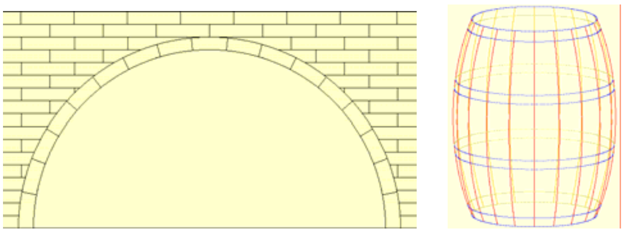
Slanted -A flat arch which is constructed with a keystone whose sides are sloped at the same angle as the skewback and uniform width brick and mortar joints.

Triangular -An arch formed by two straight, inclined sides.

Tudor -A pointed, four-centred arch of medium rise-to-span ratio whose four centres are all beneath the extrados of the arch.

Venetian -An arch formed by a combination of jack arch at the ends and semicircular arch at the middle. Also known as a *Queen Anne* arch.

One reason for the stability of many arches is that the volume between road and arch is filled in with masonry, which adds rigidity. In fact the masonry spreads a point load in such a way that its effects reach several voussoirs of the arch. The masonry holds the voussoirs together much as the hoops of a wooden barrel hold the staves.



a) b)

Fig. 2.6 – a) Masonry arch; b) Wooden Barrel

Stone masonry may be built of ashlars (square dressed stone, laid in courses with thin joints), rubble (stone which is roughly trimmed to shape), or random rubble (uncut stone). Ashlars masonry is sometimes divided into first and second class.

The thickness of the arch barrel should not be assumed to be the same as that of the ring visible on the external face. More recent arches generally have barrels of the same thickness as that visible on the exposed face. The thickness of the arch barrel may also increase from the crown to the springings, and this appears to be more common with arches made from uncut voussoirs and for longer span arches.

The arch shape will change during construction when the centring is removed. To ensure that the line of thrust remained within the middle third, recommended a German practice that three or more joints are inserted of a material such as lead covering the middle third of the joint. When the centring had been removed and the spandrels etc completed (but presumably before any fill was put in place) the joints were filled with cement.

Ashlars masonry may have been built with or without mortar. Having mortar between voussoirs reduced the stress in the stone by 30%. Also when removing the centring before the mortar is fully set stops loss of mortar by crushing which would otherwise occur.

2.5. Spandrel Walls and Parapets

Spandrel and wing walls retain the fill and carry the parapets. The spandrel walls also stiffen the arch ring at its edges and may have a considerable strengthening effect on the vault as a whole. They are commonly thickened towards their base to increase their stability and for the same reason many wing walls are buttressed or built with a sloping outer face. Wing walls can add to the strength of a bridge by restraining the in-plane displacement of the spandrels. Many walls were built curved on plan such that the bridge was at its narrowest at mid-span and this may make some contribution to their ability to resist the outward pressures from the fill. Masonry spandrel walls may consist of a relatively thin layer of dressed stone backed by a thicker layer of rubble masonry.

A problem with masonry arch bridges is that their parapets do not meet present day requirements for containment of errant vehicles.

2.6. Fill Material

Fill often consisted of materials excavated during the building of the foundations. It may nevertheless have high strength as a result of its composition and compaction over the years. A waterproofing layer may have been laid on top of the fill and below the road surface, perhaps tar or puddled clay.

The designer occasionally felt it necessary for stability to reduce the weight of the fill near the springings and buit in cylindrical opening passing completely throughout the structure. These openings also provide for floodwater. These are examples of roman bridges built with such openings. A famous example of the technique is the bridge at Pontypridd (1755) where its predecessors, similar in most other respects, collapsed shortly after removal of the centring by the weight of the haunches forcing the crown upwards.

CHAPTER 3

Structural Scheme and Principles

3. Structural scheme and principles

There are basic principles to do with materials and elements, and basic principles to do with structural form.

Voussoirs are the principle structural element, so these should generally be expressed as radiating from the arch centres. Care should be taken if expressing the voussoirs as a ring, so as to avoid visual confusion with a faced concrete ring arch.

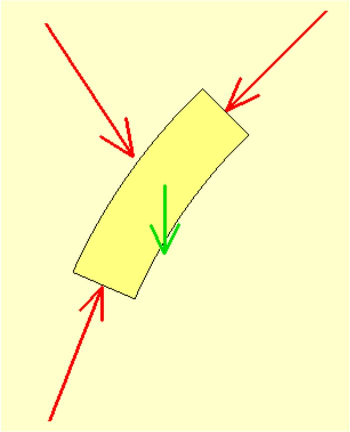


Fig. 3.1 – Voussoir

Masonry abutments on true arches have the function of resisting outward thrust by a force of mass. This mass is legitimately expressed by the massive abutment extending above the deck. Large thrust blocks beyond the abutment proper can also be used, and again should be expressed. Large size stones and simple masses can express the function well. Penetration through the abutments should be expressed as small openings to avoid diminishing the expression of mass.

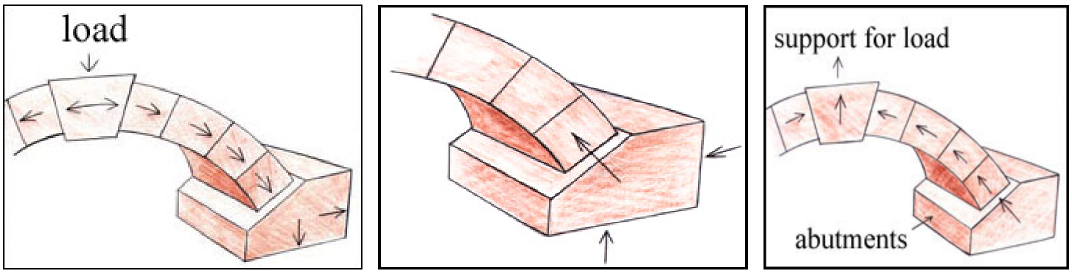


Fig. 3.2 – Forces through arches

The stone blocks of ashlar work are 3 dimensional, and can be readily cut to form 3 dimensional planar bridge geometries. If ashlar stone is to be used this should be expressed and exploited. Random and coursed rubble stonework lends itself to simpler geometries in section, but can curve in plan with ease, which can be useful in wing walls.

Parapets are not usually part of the principal structure, and traditionally have varied from simple boulders to classical statuary, they also can be in a different material such as timber or metal. Not only are they an important part of the elevation, they are also usually the only part seen when passing over the bridge, and can therefore be treated sometimes in a separate way from the main structure.

Arch bridges are always under compression. The force of compression is pushed outward along the curve of the arch toward the abutments. The average line of the forces should be as near the centre line as possible, and certainly within the kern.

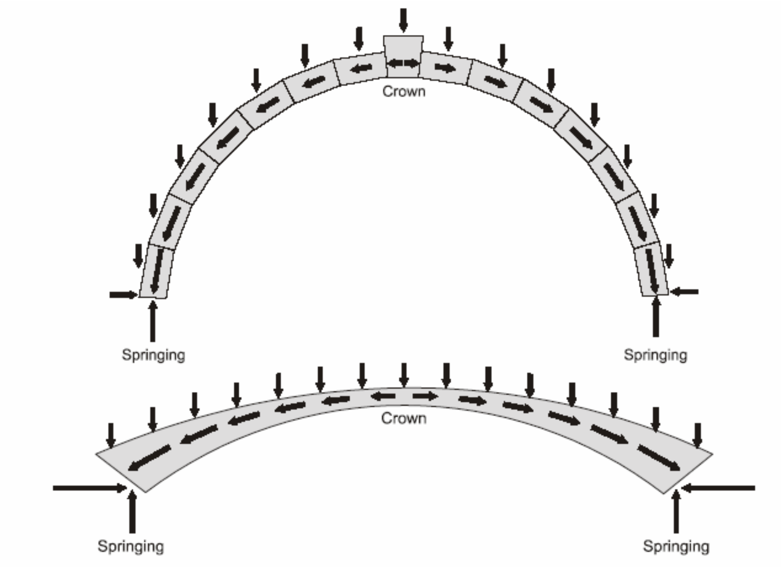


Fig. 3.3 – Basic structural scheme

In any structure, except a simple pier or column, it is impossible to have compression without tension. In the case of an arch, the tension is in the ground, which is therefore a member that costs nothing. If we take this argument further, it can prove that arch spans can be made longer than beam spans. Although the ground under an arch is in tension, the ground just outside the abutments is compressed by the thrust of the arch. Between the regions of tension and compression, the ground is subject to complicated mixtures of tension, compression and shear stresses.

The tension in an arch is negligible. The natural curve of the arch and its ability to dissipate the force outward greatly reduces the effects of tension on the underside of the arch. The greater the degree of curvature (the larger the semicircle of the arch), however, the greater the effects of tension on the underside. As we just mentioned, the shape of the arch itself is all that is needed to effectively dissipate the weight from the centre of the deck to the abutments. As with the beam bridge, the limits of size will eventually overtake the natural strength of the arch.

The keystone is the most important stone in an arch bridge, without this stone the arch would collapse. The keystone holds the arch together.

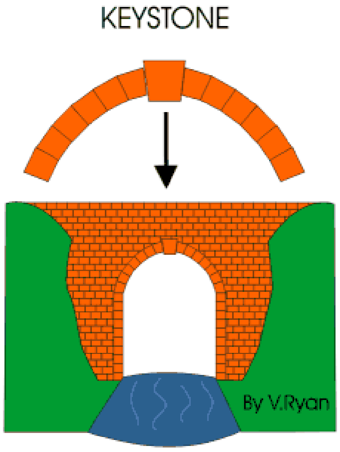


Fig. 3.4 - Keystone

An arch is in compression throughout, and it cannot stand except as a whole. It therefore requires temporary support, or falsework, until it is complete. The type of falsework depends very much on the material of which the bridge is made, and on the size of the bridge.

Masonry arches, being made of relatively small voussoirs joined by mortar cannot take tension, need continuous support during construction from below. The entire weight during assembly is taken by falsework, or centring as it is called in the case of an arch. Traditionally it took the form of a wooden truss in the shape of an arch. It has to be strong enough to hold the weight of the structure without deflecting unduly. This type of falsework is called centring, and is often of the general form shown below.

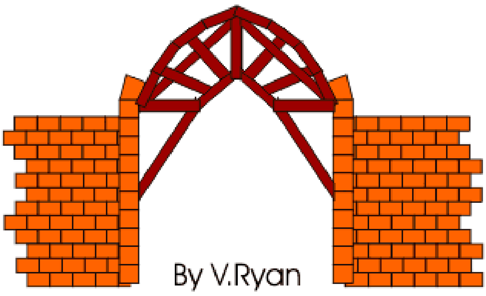


Fig. 3.5 - Scaffolding

Sometimes the centring could rest on the ground, with suitable foundations to spread the load, but in the case of tall piers it could rest on corbels - blocks which project from the main mass of masonry, as the picture shows. Once the centring was complete, the vousoirs could be laid and cemented into place. Then the spandrel masonry was placed, and the structure was left alone while the cement or mortar was curing. Eventually the centring could be struck. Sometimes it was eased in several stages.

The stress being low, failure of the material is rare in masonry arches. A more likely mode is through the formation of hinges. Under a heavy concentrated load, an arch may develop a downward deflection that is mirrored by an upward one in the other half, if the line of thrust moves too far from the centre-line of the voussoirs. To some extent, the material between the roadway and the voussoirs will spread the load.

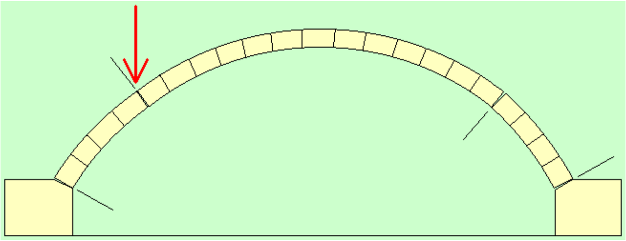


Fig. 3.6 – Formation of hinges

CHAPTER 4

Common Problems

4 Defective Masonry Arch Bridges

The sheer age of the masonry arch bridges means that virtually all such bridges can be deemed to be defective in one or more respects, whether it is spalling masonry or lack of waterproofing. However, from a structural point of view, the only defects which are of concern are those which will have a significant impact on the ability of a given bridge to successfully support foreseeable applied loading.

The causes of structural defects have been categorised into four groups:

1) Construction
2) Long-term loading
3) Transient loading
4) Environmental

The majority of the defects found in practice will arise from a combination of some or all of the above.

The ultimate construction defect in the case of an arch bridge is presumably one which is sufficient to cause collapse immediately after decentring, e.g. the arch being of the wrong shape to carry the dead loads. Well designed bridges, built to carry contemporaneous loading, are of course classed as being defective if it is perceived that they are unable to carry modern traffic loads.

There are several very common structural defects which affect stone masonry arch bridges.

4.1 Scour of foundations

Scour is probably the most common cause of collapse of masonry arch bridges. The foundations are generally shallow and therefore susceptible to scour. Scour is difficult to detect because it is likely to be at its worst when the river is in flood and access is impossible. It is likely to be made worse by fallen trees and other debris catching in the arch when the river is in flood. Scour holes may fill up as floods subside and thereby camouflage undercutting of foundations.

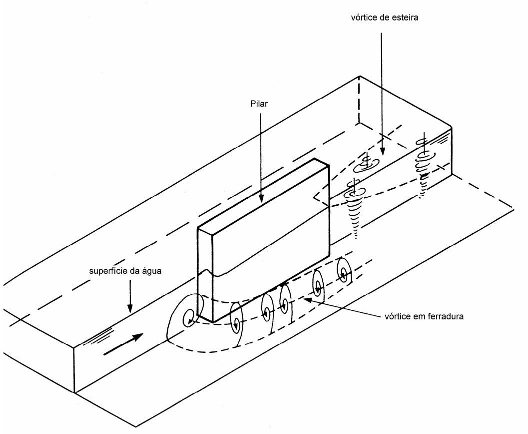


Fig. 4.1 – Disturbance of flow

During a flood, the bed level may fall as bed material is transported by the moving water. A bridge across the river can result in additional lowering of the bed level at the bridge. This extra erosion, or scour, has two possible causes, an increase in flow velocity due to the constriction of the channel (general scour), and a local disturbance of the flow due to the bridge piers or abutments (local scour). The total depth of scour is the sum of both forms of scour.

If an obstruction such as a bridge pier is placed in a river the flow around the pier does not remain parallel to the river bed, but dives. This results in a downward flow on the pier face and a reversal of flow along the river bed in front of the pier. This flow produces a vortex whose ends extend around the sides of the pier. It is called a horseshoe vortex because of its plan shape.

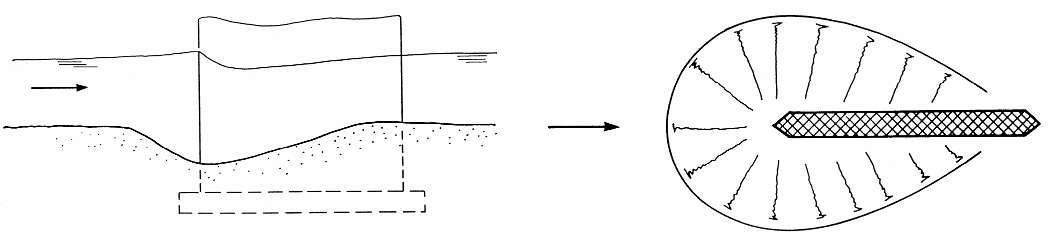


Fig. 4.2 – Scour of foundations

River bed profiles may be determined by poling or by a leadline but it must be bond that a scour hole produced when the river was in flood may have refilled as the flood subsided but that the material will not be compacted and will provide relatively poor support to the foundations.

Fig. 4.3 – Damaged foundation

Underwater inspection is also difficult during periods of fast water flow. Knowledge of the foundation depth is also essential if there is any possibility of scour occurring.

4.2 Arch Ring

4.2.1 Splitting beneath the 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.

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.

The effect of spandrel stiffening is not fully understood at present but it is known that 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.

Fig. 4.4 – Splitting beneath the spandrel walls

The effect on load capacity of splitting beneath the spandrel walls is more complex for multi-span bridges. Individual spans may continue to fail as if they are single spans without any spandrel wall influence. The reduction in load capacity which is applicable to multi-spans is however associated with the flexibility of the pier and this is less likely to occur since the spandrel walls will continue to stiffen the piers despite the loss of integrity between the walls and the arch ring.

4.2.2 Problems due to movement of abutments

The defect of abutment moving need only be of concern if it is ongoing and giving rise to substantial geometry changes of the arch barrel (resulting from insubstantial foundations to support the arches thrust). The hinge cracks associated with small abutment movements, needs to be of great concern-the arch simply being transformed to a statically determinate structure (three hinged arch), with no likelihood of failure. However there are some concerns that in practice the presence of three well defined hinges in an arch may allow the latter to articulate under service loading, perhaps giving rise to a loss of mortar or other undesirable effects.

Arch rings generate outward pressure on their abutments and may lead to outward movement. The fill behind abutments will resist the outward movement and may cause inward movement. The effect on the arch ring will depend on whether the movement is outwards or inwards and whether it is accompanied by rotation of the abutments. It is likely to manifest itself as transverse tracks 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.

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.

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 ends 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.

4.3 Spandrell Walls

Spandrel walls probably represent the biggest single problem with masonry arch bridges. However very little research has been done on the causes of or cures for those problems. 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.

The effect may be 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.

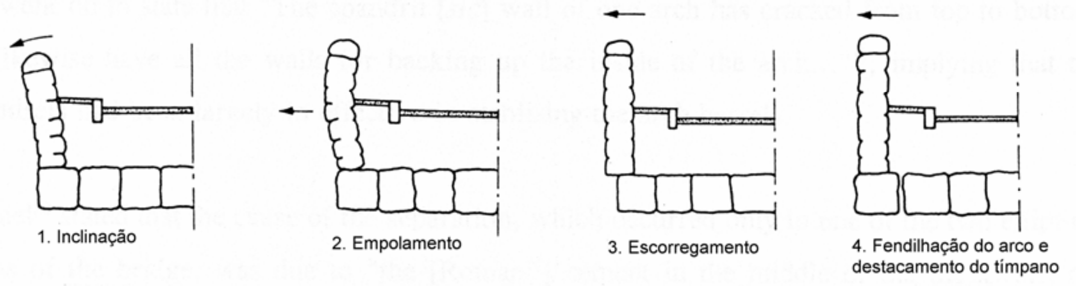


Fig. 4.5 – Defects on spandrel walls

A survey of ninety eight arch bridges showed that twenty seven had leaning spandrel walls, forty nine bulged, forty nine had outward movement of a wall relative to the arch ring, and twenty three had cracking in the arch ring beneath the inside edge of the wall. Sixty nine of the bridges had one or more of these defects.

4.4 Fill Material

The concern in protecting the materials of the water has been a constant in the construction, because the durability of most of the construction materials is seriously affected in the presence of water. In fact, the water is the largest enemy of the bridges. The durability of the materials used in masonry structures could be seriously damaged when subjects to long saturation periods.

The major problem likely to affect fill is that the road surface waterproofing or the drainage breaks down and the fill becomes saturated. This is unlikely immediately to affect the load capacity of the bridge, indeed the increased weight will 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 substantially increase the lateral pressures on spandrel walls and even higher pressures if the fill freezes in the winter perhaps leading to outward displacement of the wall.

4.5 Natural Stone

The Romans and the Fratres Pontifices of the Middle Ages (since about 1100) and of later master builders were built with stone masonry. The arches and piers have lasted for thousands of years when hard stone was used and the foundations constructed on firm ground. With stone one can build bridges which are both beautiful, durable and of large span (up to 150 m). Unfortunately, stone bridges have become very expensive, if considered solely from the point of view of construction costs.

Over a long period, however, stone bridges, which are well designed and well built, might perhaps turn out be the cheapest, because they are long-lasting and need almost no maintenance over centuries unless attacked by extreme air pollution.

Granite masonry was preferred for piers because it resists erosion by sandy water much better than the hardest concrete.

But there is an old masonry proverb that says, "Stone is simply a way-stop for sand in its progress back to the sea."

The effects of weathering can change only the appearance of the stone or they may change its structural properties in the worst case causing it to destabilize. The factors that cause many of these effects are present in any environment and can never be entirely mitigated. Inevitably, the stone is going to change over time.

Salt Crystallization

One of the most common corrosive substances around is perhaps the most common cause of weathering on stone, especially porous stone. Impermeable stones will show effects of salt crystallization only under special circumstances.

In general, salt crystallization is indicated by the formation of efflorescence, a visible growth or film on the surface of the stone that is usually light in colour. The film later dries to form a powder, which will flake off or can be washed off, often taking very small amounts of the stone with it. In regions close to the sea, crystallization effects can be dramatic, going far deeper than the surface of the stone and eventually leading to massive decay of the stonework. The simple solution is a soft brush, water, and some elbow grease. Most efflorescence can and should be removed as part of regular maintenance.

Air Pollutants

Much of the visible weathering of stonework in industrial areas can be attributed to air pollutants and acid rain. In extreme cases, buildings can be blackened by tarry build-up and the stone can absorb the stain deep into its pores, making cleaning difficult.

As you might expect, the effects of air pollutants are more pronounced on lighter than on darker stones. Limestone and marble can be impacted in areas that have significant acid rain conditions, evidenced by pitting and degrading of honed and polished finishes. In general, the effects will be more pronounced on areas that are seldom touched by rain or water run-off, such as the area directly below a crown molding, resulting in uneven discoloration of the surface.

Freezing

More of a concern in areas with heavy freezes during the winter, freezing can have surprising effects on stone. These effects occur only when stone is frozen while wet. This is most likely to occur in parts of the structure where water can accumulate without running or drying, such as the tops of stone steps.

When water is cooled along the surface of the stone, crystallization can cause parts of the stone, usually in flakes, to break off and wash away when the ice melts. The detached piece is often thin, but the shape can be dramatic and noticeable, as the newly exposed stone beneath can be of a different colour than the remaining stone.

Fig. 4.6 – Stone masonry damaged by freezing

In rare cases, a stone can crack all the way through during the thawing process, rendering it unstable. The best cure for this condition is selecting the proper stone, and paying close attention to proper installation details and techniques that assure water can drain out of and away from the stone.

Plant Growth

Those in the North are probably familiar with the sight of ivy climbing a stone or brick wall. If left unchecked, climbing plants such as ivy can root in the joints of stonework and cause structural problems. If they stay rooted in the ground, they are mainly harmless and can be cleared off easily.

Fig. 4.7 – Stone masonry affected by plant grouth

Other types of growth, like algae and lichen, can have more permanent effects on the appearance of your stone. Because algae and lichen do not require soil for nourishment, they can spread over the entire surface of the stone, forming large patches.

In the short run, plants and organic growth may not seriously damage stone; however, restoration of stone structures involves careful cleaning and removal of both organics and pollutants.

Human Traffic

On pavers and steps, one of the most noticeable weathering effects is human traffic. Walking on stone surfaces can scratch the surface when hard materials, such as pebbles in the sole of a shoe, are dragged over it. In outdoor settings these scratches are less noticeable, while in delicate interiors they may be unsightly.

The second main effect of human traffic is the honing, or polish, that feet and wheels leave behind on stone. The process of walking or driving on stone hones the surface, making it less porous and harder at the surface, and causing a waxy, mellow shine called a patina. Though the process that brings about this patina is similar to polishing a stone, nothing but time can duplicate it. Honing involves the deposit of years of dirt and other matter along with the simultaneous progression of other weathering effects. Like all weathering effects, the formation of a patina also indicates the natural aging of the stone.

CHAPTER 5

Repairs and Strengthening Techniques

5. Repair and Strengthening Techniques

Virtually all the defects of the arch bridges can be repaired relatively easily. Practicalities regarding the execution of various repair techniques have been fairly widely documented, although the philosophy behind the application of some of the techniques has sometimes been somewhat dubious, perhaps resulting from a fundamental lack of understanding of the structure under consideration.

Nowadays, a great variety of intervention techniques exists, of which it suits to distinguish, as for the materials:

- Traditional techniques: they use materials and identical construction processes exclusively to the originals;
- Techniques modern or innovative: they try to adapt more efficient solutions than the traditional ones through the use of materials and modern equipments;

The choice among solutions traditional or innovative is controversial, but if with traditional techniques it is possible to obtain satisfactory solutions of the structural point of view, economic and constructive, its use should be preferred, not only for aesthetic and cultural reasons, but also for compatibility reasons between the new elements and the original ones.

Frequently it is not easy to repair the structural damages with the exclusive resource to a traditional solution, because no longer they are available original materials, as mortars or wood, because qualified labour doesn't exist ("artisans") for this type of constructive techniques, or still for economical reasons. The most frequent reason to go through modern techniques or innovations is related with the need of significant increases of resistance, that are only gotten with much more efficient materials than the original ones. However, whenever possible the "interventions in masonry should be made with masonry".

Before the decision for the use of any repairing techniques or reinforcement is quite necessary to establish and to understand the causes of the found damage. On the other hand, it should be evaluated, the effect of the intervention about the behaviour of the structure after intervention.

5.1 Identification of Defects

Identification of many of the defects affecting masonry bridges (spandrel wall bulging, bowing or detachment, gross abutment movement) is straightforward, visual inspection being sufficient.

Abutment movement can be identified by the presence of a crack in the region of the crown, or by settlement of the parapet walls. Spandrel wall detachment can be identified by the presence of continuous longitudinal cracks in the arch barrel beneath the internal faces of the walls. Unfortunately, some other defects may be less evident. In this cases either partial dismantling of the structure, coring through sections of the structure or the use of NDT (on-Destructive-Testing) techniques will be required. This methods would prove impractical or expensive for the majority of bridges requiring assessment, but useful for assessing small numbers of important structures, or a sample of representative structures.

5.2. Pressure pointing and grouting

An economical method and one usually involving little traffic disruption. Grouting of the contained ground above and behind an arch can be a useful measure: with suitable receptive grounds (not high in clay or silt) and in the absence of complications such as drainage systems, the method is very effective and very economical.

Fig. 5.1 – Repointing of the joints

It increases the assessment factor to 0.9 and improves the arch ring condition factor by filling cracks and voids in the extrados. Grout quantities can be hard to predict and considerable variation is to be expected.

5.3 Tie bars

Tie bars are used to restrain further outward movement of spandrel walls. They consist of a bar passing through the full width of the bridge, with pattress plates at each end, generally secured by a nut and washer, to provide the restraint to the wall. 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.

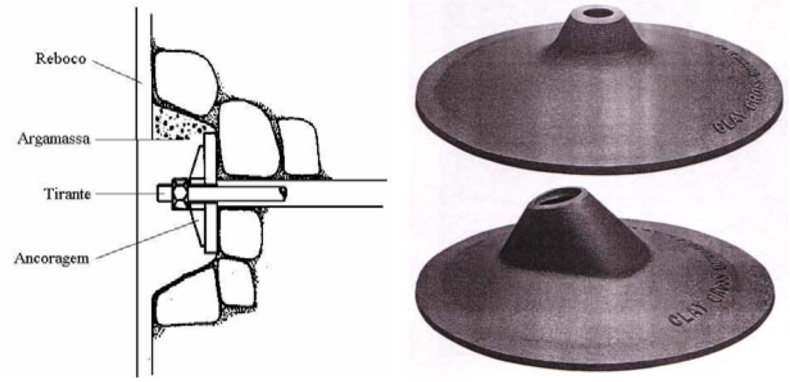


Fig. 5.2 – a) Anchorage system; b) Anchorage plates

One of the advantages of using tie bars is that they can be inserted with little or no disruption to overtraffic. However their effectiveness has never been scientifically proved and many engineers are worried that sections of the spandrel wall may fracture around the pattress plates or spreader beams, the walls then becoming potentially unstable. There is no real guidance as to suitable spacing for tie bars.

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. The use of stainless steel bars could be considered, or the application of cathodic protection.

5.4 Rebuilding bulging spandrel/wing walls

With sufficient road width or the acceptability of a road closure and with minor services present, the simple solution is to excavate behind the wall and rebuilt it conventionally. To back the wall with mass concrete is a possibility, but to do so creates a deep, stiff beam edge to the arch, inconsistent in structural action with that of the arch. A more harmonious structural action results from incorporation of a reinforced earth system to support the fill. This prevents excessive pressure developing against the spandrel wall and the space between reinforced earth and back of wall is filled with single-size drainage material.

5.5 Saddling

A particularly common repair technique which has been used in the case of a wide variety of arch bridges exhibiting almost any sign of distress is that of saddling. The technique is used in response to the observation of cracks of virtually any kind.

The merits are that with a rough existing extrados, composite structural thicknesses is increased, cracking is retained, historical widenings can be integrated, the saddle can carry a sprayed (ideally polyurethane) waterproofing membrane.

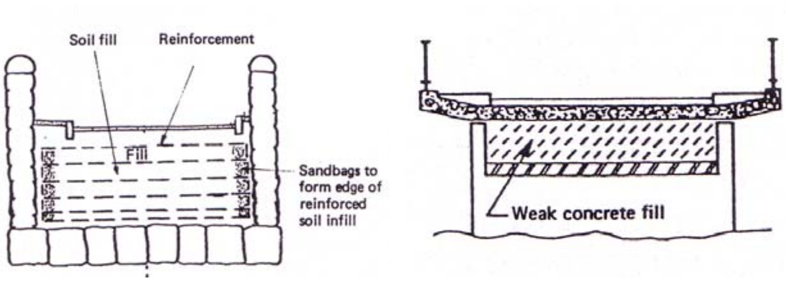


Fig. 5.3 – Strengthening of the fill material used for reducing the pressure on the spandrel walls

Drawbacks are that the arch is too narrow to allow single line traffic to pass while the arch is treated, due to the deep excavation necessary. Occasionally, historically widened arches may retain the old original spandrel at low level: this can be used again to facilitate ¨half and half¨ strengthening.

Saddles are typically 150-200mm thick, of relatively weak concrete and can ,if judged necessary, be articulated to harmonise with the arch ring’s structural action, either by bands of transverse brickwork or an inert transverse Debonding lamina.

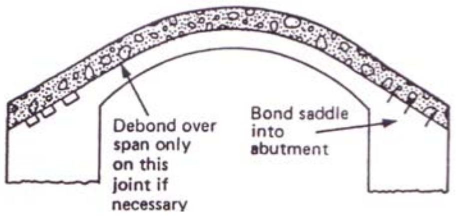


Fig. 5.4 – Saddling the extrados of the arch with a layer of concrete

Inclusion of fibres in the concrete has merit: polypropylene fibres confer resistance to surface shrinkage cracking. Stainless steel fibres confer considerable strength and structural ability to unite arches and to bind cracks.

Saddling clearly changes the fundamental nature of the bridge and as such may often cause more problems than were originally present (e.g. the lack of stress in the original arch after saddling could give rise to the hazard of falling masonry blocks, additionally the ability of the arch to freely adjust to a changing environment is removed).

5.6 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.

If incorrectly installed however, there is a risk of scour beneath the slab, particularly at its downstream end.

5.7 Stitching longitudinal cracks

This system is applicable where more extensive dismantling or saddling is very disruptive to traffic or economically impossible.

Typically, alternate voussoir stones are cored laterally (30mm diameter) and the cores retained. A 30 mm hole is drilled normal to the spandrel and at mid-depth of the arch ring, to a length some 750mm beyond the crack to be tied. A practical maximum drilling length is about 12m. Installation of a CINTEC-type hollow stainless steel bar, with enclosing sock, takes place and the grout injected down the bar fills the sock, expanding it to key into all recesses.

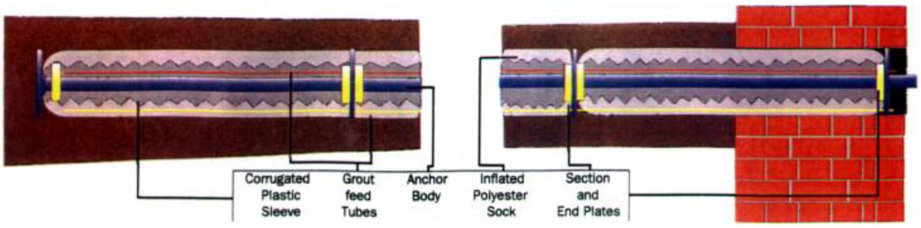


Fig. 5.5 – Cintec anchorage system

The cracks are then pressure pointed and the ends of the stone cores reinsertedto plug the holes at the face.

5.8 Guniting of Soffit

A widely adopted technique, being non-disruptive to carried traffic and relatively economical. There are two principal drawbacks: firstly, the structure may be a Listed Building or Ancient Monument, in which case the treatment would be visually unacceptable. Secondly, and of more significance for the future durability, is the failure of the method to address the most common cause of arch defects, water ingress from above. With time, this will detach the gunite skin from the arch barrel.

5.9 Oversalbbing

At its simplest, this consists merely of providing a load spreading slab to reduce local load intensity. It is of benefit to the barrel in that it allows the option of high-level waterproofing and it reduces lateral pressure on spandrel walls.

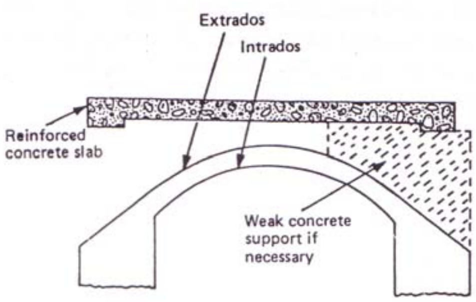


Fig. 5.6 – Overslabbing

5.10 Underpinning

Underpinning involves excavating material from beneath the foundations and replacing with mass concrete. A sequence of work is followed to ensure that the stability of the existing. Structure is not compromised. The work is labour intensive. The cases studied appeared to have been successful.

5.11 Replacement of edge voussoirs

Edge ring voussoirs are particularly prone to decomposition, due to their exposed position and the perpetual tendency for lateral load on spandrels to cause the face of the ring to detach.

To replace edge stones, it is usually necessary to provide a band of soffit shuttering to support the whole ring. While it is possible to remove stones individually without support, considerable awkward cutting is finally necessary to achieve a good soffit profile and displacement of the masonry above can occur.

5.12 Part reconstruction

When arch ring damage is extensive, the only real resource is to rebuilt to a major extent. Construction is traditional in that it is necessary to build off centring, although several variations of constructional form have been adopted. These are essentially mass concrete rings with articulating bands. Articulation can be achieved, at springing and quarter span points, by hard plastic formers, by bands of lime-mortar joined masonry or by open-laid bands of brickwork.

5.13 Maintenance

Routine maintenance consists of:

1) keeping the road surface in a good condition to maintain the waterproofing and to minimise dynamic loading from traffic due to potholes etc.
2) removing vegetation growing on the structure
3) repairing small areas of deteriorated mortar.

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

CHAPTER 6

Case Study

6. Case Study

The engineer when considering strengthening and repair of the bridge has in mind the primary objective of the bridge continuing to fulfil its function. Moreover, the engineer attempts to seek a solution in which a bridge will provide unrestricted passage. To the engineer a bridge that does not or partially fulfils its function is an anathema. Similarly the engineer will often wish to rectify aspects of the bridge, which appear to be out of keeping with the original structure.

Strengthening and repair of listed bridges may introduce disparate requirements. On the one hand the bridge is to be preserved in all its aspects such that its character and appearance remain unchanged and on the other it is required to form a link in a road network.

The extent and character of works of strengthening and repair will depend on the deficiency in strength of the bridge and the condition of the materials of construction. The works will also depend on the degree to which the full function of the bridge is to be restored.

Donim Bridge

6.1 General Data

This project concerns the study on the conditions of stability and strengthening of Donim Bridge. The bridge, that crosses the river Ave, has been built during the Middle Ages, probably during the XVI cent. This bridge became part of the old itinerary that linked Guimarães to Póvoa of Lanhoso.

The bridge has a total length of 63m, and 3.44m of width of carriageway. The deck of the bridge is plane supported by three arches of masonry of perfect turn that present spans of unequal dimensions 9.39, 11.80 and 6.57m, respectively measured from north to south and free heights from 7.52, 10.10 and 7.79m. The central arch presents a larger span and it is supported by two massive piers, endowed with two triangular cutwaters at upstream and two rectangular cutwaters at downstream.

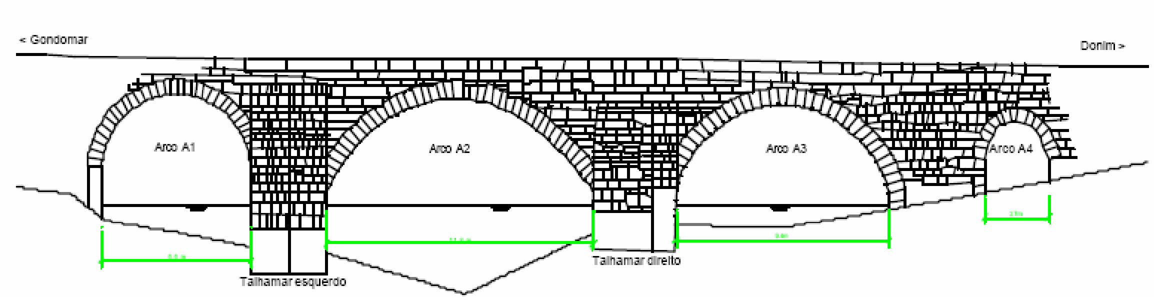


Fig. 6.1 – Donim Bridge – Upstream View

On the right shore it is placed a flood arch, with a span of 2.7 m, constituting a 4th arch. Some observation done by diving allowed concluding that the foundations of the pillars seat in solid rock.

The spandrel walls, just as the parapets, were built in stone masonry but successive maintenance works carried out along the years changed some original characteristics. As it can be observed, the parapet was partially rebuilt with concrete blocks as well as the stone of granite paving in the pavement, during the XX century.

Fig. 6.1 – Donim Bridge – Road way

Due to the precarious conditions of safety, the local authorities asked for a complete research of the bridge, as well as the description of a group of compatible measures with the modern techniques of intervention, to restore the safety of the structure.

6.2 Previous Report

After the accomplishment of the inspection of the bridge, the existence of excessive vegetation was verified, that it led to the occurrence of several fissures. In agreement with the report of study of the conservation state, the arches located in the ends of the bridge presented fissures in the longitudinal direction, denoting a separation between the spandrel wall and the arch. The spandrel walls were subjected to lateral movement and are clearly out of plumb. The right pier is very damaged, where some stone blocks are cracked and a foundation stone is missing.

a) **b)**

Fig. 6.2 – Important damages:

a) Longitudinal cracking in the arch A1; b) Longitudinal craking in the asch A4

a) **b)**

Fig. 6.3 – Important damages:

a) Damages in the right downstream cutwater; b) Abundance of vegetation

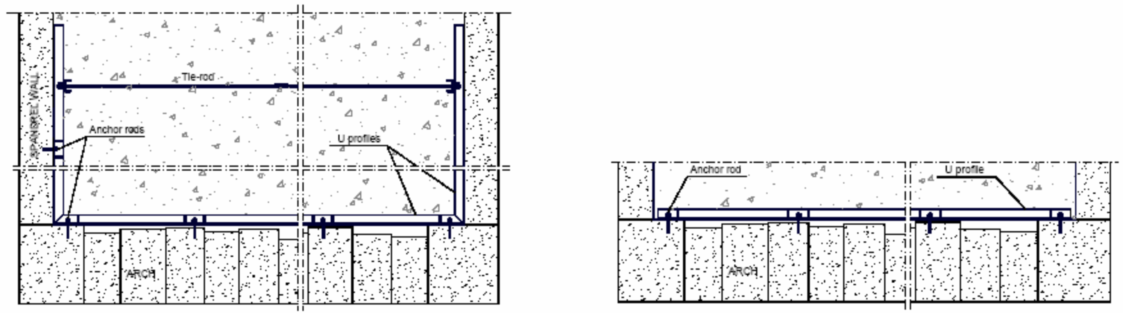
The general pattern of the observed damages was originated by the lack of maintenance together with an increase of the traffic loads.

The accomplished inspection allowed concluding that the defects presented by the Donim Bridge are excessive and incompatible with its actual use, being essential to precede an intervention on the bridge to re-establish its safety. The intervention project of the bridge purposes the following repairing measures: dismantling and reconstruction of the most damaged areas, realigning the spandrel walls, closing of the joints, the cleaning of the vegetation, waterproofing and drainage of the fill.

The structural consolidation of the bridge went by an intervention on the arches A1 and A4 and downstream cutwater of the right pillar.

To reduce the enormous longitudinal cracking, in the intrados of the arch A1 (width of cracks larger than 8cm), and to put the thickness of the joints in their original width, the works regarding the first arch, consisted of the removal of the filling material and in the relocation of the voussoirs of the arch, through rope-stretchers put along the intrados of the arch. For this operation, the arch had to previously be propped along its span.

The adopted strengthening comprises the fixing of six stainless steel U profiles to the extrados of the arch and to both spandrel walls, by means of anchor rods.



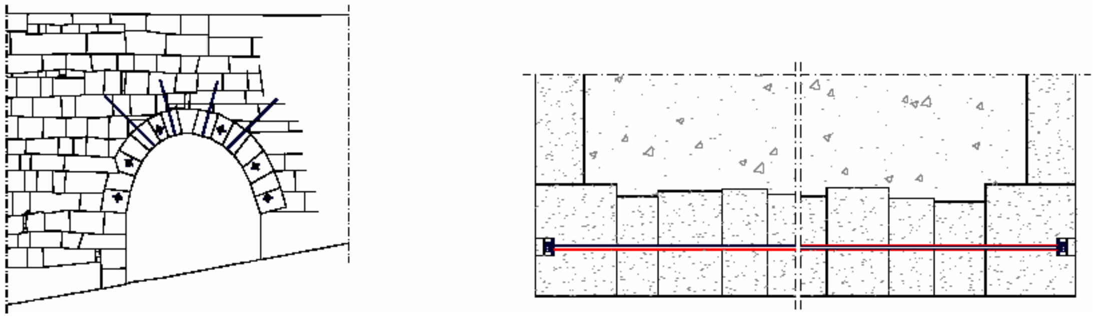
a) **b)**

Fig. 6.4 – Strengthening of arch A1 with metallic profiles

a) General; b) Crown

The metallic brace, with a diameter of 16mm, put in the top of the vertical profiles is tight through a dynamometric wrench. This binds the two spandrel walls, and it reduces the deformation of the profile considerably. Close to the crown, due to the proximity of the pavement, it was only possible to put only one U profile, fixed to the arch with anchor rods. After the finishing of these works, they proceeded to the relocation of the filling material on the arch.

The cracking pattern observed in the flood arch A4, showed less damage intensity, with crack widths below 4cm. Here, the objective was not to return to the arch its original geometry, but to prevent any progress of propagation of the cracks and to assure its stability.



a) **b)**

Fig. 6.5 – Strengthening of arch A4 with stitching anchors

a) Stitching scheme; b) Horizontal Anchorage

For the rehabilitation of the arch A4, was fallen back upon six horizontal anchorages, on the width of the bridge, endowed with cylindrical anchorage plates on each side of the arch.

In each anchorage, after having perforated a hole, a metallic bar of 16mm in diameter involved by a sleeve, it is put in the hole and subsequently injected with a cement grout. The injection was done under low pressure between the bar and the sleeve. The use of the sleeve increases the efficiency of the anchorage system, because it prevents that the injected grout doesn't get lost in the voids, inside of the structure, or flee through the cracks.

No tension was applied to the bars, other than a tightening force resulting from their adjustment using a dynamometric wrench. Later, the closing of the openings is accomplished through stone carotes and mortar of the same colour.

For the connection between the arch and the wall of the spandrel wall, a similar solution was developed. Four punctual anchorages were used on each side of the arch, varying among 1200mm and 1500mm of length, with the purpose of joining the spandrel walls to the external staves.

As for the right cutwater, it was repaired by dismantling, after the numbering of all of the constituent stones, and subsequent reconstruction using the same stones (or similar stones of the area when the original stones could not be used due to their bad state), being used metallic elements of connection. It is important to outline that the mortars used in all the joints was constituted by whitewash and sand to the ratio 1:3, to which powder of form stone should be added to approximate the mortar to the colour of the stone of the bridge, while the existent cement mortars should be substituted by mortars of whitewash and sand to the same colour.

In order to prevent the fines to be washed out of the fill, leading to voids and thus affecting the load capacity of the bridge, it is recommended to execute the waterproofing and drainage of the pavement.

6.3 Implementation of Actions

Closing the bridge

The strengthening works started with the closing the bridge to all wheel traffic and maintaining the bridge only as a footpath. This measure was required both for stopping the further damage of the bridge and for the constructor to install the necessary equipment.

Fig. 6.6 – Blocked access on the bridge

Blocking the water flow

Access was gained to the intrados of arches A1 and A3 by blocking the water flow and redirecting it through the middle arch, A2. Trucks filled with heavy stones and sand from a nearby location were unloaded on the both sides of the river Ave close to the water. With the help of a back-acting excavator the rocks and the sand were pushed in the water under the arches until the water level was exceeded with about 1m, and consequently the flow was blocked. As a result of this action the access under the arches A1 and A3 was facilitated and the scaffolding could be erected on solid ground.

a) **b)**

Fig. 6.7 – Blocking the water flow

Temporary Stability and Scaffolding

Temporary stability was important since the schemes required the complete removal of fill from the arch A1. A rectangular scaffolding system was erected on the compact soil throughout the entire intrados of the arch. Between the voussoirs and the scaffolding, timber decking had to be placed for a uniform propping of the arch.

a) **b)**

Fig. 6.8 – Scaffolding

Also for the removal of the vegetation, the access to the external spandrel walls and cutwaters had to be facilitated. Consequently, scaffolding had to be assembled along the whole bridge.

a) b)

Fig. 6.9 – Scaffolding

Temporary bridge

In parallel with the strengthening works the building of temporary footpath bridge was considered. A requirement for a temporary bridge arose for a variety of reasons such as not redirecting the human traffic to other bridges. One bridge option was considered being feasible, that of a truss overbridge parallel to the existing bridge.

a) b)

Fig. 6.10 – Temporary bridge

It is to be mentioned that because of some unexpected rainfalls and rising water level, the temporary bridge was partially damaged and had to be rebuilt. During the reconstruction of the temporary bridge the works on Donim Bridge were interrupted and the human traffic was permitted. The second temporary bridge was erected on the cutwaters of the stone bridge, and this proves out to be a more safe solution to the problem.

Repairs on Arch A1

The repairing works of the arch A1 consisted in removing the filling material and in the closing the joints between the voussoirs of the arch.

Prior to the intervention, the temporary propping of the arch along its entire span was made to assure the stability of the arch when the fill material was removed.

Fig. 6.11 – Propping the arch A1

Moreover 5 tie bars were used to restrain further outward movement of spandrel walls. They consist of two bars passing throughout the full width of the bridge one at the parapet level and the other under the arch. At each end they were fixed on a metallic profile with a nut and washer, to provide restraint to the wall.

Fig. 6.12 – Tie bars

a) **b)**

Fig. 6.13 – Tie bars

Fig. 6.14 – Tie bars – Restrain mechanism

The excavation begun with the dismantling of the existing steel beams and steel deck that were part of an earlier attempt to reduce the loads on arch A1. Than the road pavement made of cubic granite stone was removed. The constructor allowed that the first layers of the fill material to be removed with the back-acting excavator but as it got closer to the arch the mechanical removal was replaced with the manual dismantling of the stones. The reason is that the vibrations and the force of the excavator can cause major damage to the arch such as moving of the voussoirs and widening of existing cracks.

a) b)

Fig. 6.15 – Excavation of the fill material:

a) Removing the steel deck; b) Removing the fill material by hand

Once the entire mass of the fill material was removed carefully, the enormous longitudinal cracking in the intrados of arch A1 could be obviously seen also on the extrados (crack width greater than 8 cm). The closing of the joints was performed by tightening the tie bars slowly, along several days.

a) b)

Fig. 6.16 – Existing cracks in the arch A1:

a) General view; b) Cracks wider than 8 cm

When the gaps reached a desirable dimension, the strengthening solution was implemented. Six stainless steel U profiles were fixed to the extrados of the arch and to both spandrel walls, by means of anchor rods.

a) b)

Fig. 6.17 – Arch A1 after the closing of the cracks

a) Reduced cracks; b) General view

a) **b)**

Fig. 6.18 – Repairs on arch A1

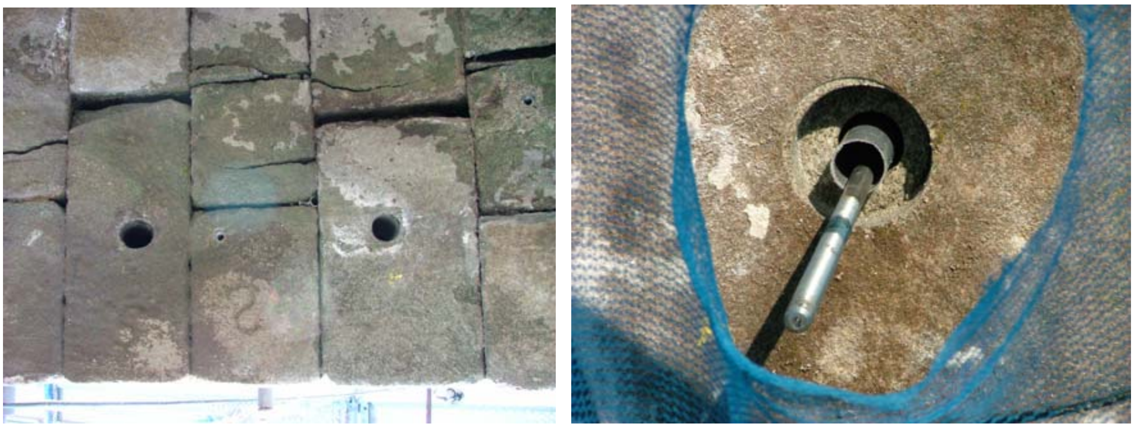
a) Metallic profiles; b) Drill for the stitching anchor rods

A stainless steel tie rod, with a diameter of 16 mm, was placed at the top of the vertical profiles and tightened with a dynamometric wrench that binds the spandrel walls together and reduces considerably the bending of the profile. Close to the crown, the proximity of the pavement allowed only the use of a U profile clamped to the arch with anchor rods. After the completion of these works, the infill was put back in its place and the prop was finally removed.

Repairs on Arch A3

The cracking pattern in the flood arch A4 was not so severe as that in the arch A1. The maximum crack width didn’t reach 4 cm. This is why it was not implemented the same strengthening technique as the previous one. The objective was not to return the arch to its original shape, but to prevent any further displacements of the arch and to assure its stability. Thus, it was proposed to use six horizontal anchors across the full width of the bridge, endowed with cylindrical anchorage plates at each side of the arch.

During installation, oversized holes were bored using a rotating cutting device in the voussoirs.



a) b)

a) b)

Fig. 6.19 – Repairs on arch A4

a) Holes drilled in the intrados of the arch; b) Stitching anchor;

After the drilling was finished, a sock containing a stainless steel reinforcement bar was inserted into each hole and cementitious grout was pumped under low pressure into the sock. Also, the sock is sufficiently permeable to permit the grout to bond to the masonry and form a structural connection.

a) b)

c) d)

Fig. 6.20 – Injection process

a) Stitching anchors with the glove on; b) Adjustment using dynamometric wrench; c) Tubes used for the injection; d) Injection process

No tension was applied to the rods other than a tightening force resulting from their adjustment using a dynamometric wrench. A slip taken from the cores was used to camouflage the strengthening bar.

Similar repairing works were developed for the connection between the spandrel walls and the arch. Four stitching anchors in each side of the arch were fixed with the purpose of linking the spandrel walls to the external voussoirs.

Repairs on Right Cutwater

The high level of damage found in the right cutwater was determinant in choosing the drastic solution of dismantling and rebuilding.

The dismantling works were preceded by the numbering of each stone that was to be removed. This was done to facilitate the repositioning.

a) b)

Fig. 6.21 – Right cutwater

a) Dismantling of the right cutwater; b) Woody vegetation.

Once this operation was done the fill material was removed and each stone was dismantled from the cutwater. The plant growth was evident and represented the main cause of the pour state of the cutwater.

Subsequently, the whole are was cleaned of vegetation and the rebuilding begun from zero. The stones were carefully elevated with the caterpillar and laid in place on a layer of mortar. The exact position of each stone was kept.

a) b)

Fig. 6.22 – Right cutwater

a), b) Rebuilding of the right cutwater.

For a better stability of the cutwater, stones in a same course were connected to each other by means of stainless steel cramps, at every three courses. The link between two consecutive courses was performed through the use of vertical stainless steel latches.

The stones that were cracked and could not be used anymore were replaced with similar stones from the region.

Fig. 6.23 – Stainless steel cramps

Removal of vegetation (biocide)

This action was carried out in two stages. The first one was to remove by hand the plants or with the help of a palette knife to scrape away the smaller plants such as algae and lichens.

Fig. 6.24 – Spraying biocide

The second stage consisted in pressure spraying a biocide substance on the whole surface of the bridge that will stop the further growth of vegetation.

Fig. 6.25 – Donim Bridge before and after the removal of vegetation

Repointing of the joints

After the vegetation was removed and the bridge was completely cleaned of any undesirable parts, the manually cleaning and repointing of the joints was performed. It was used a sand-lime mortar, designed to match as close as possible the colour of existing stone.

Fig. 6.26 – Joints repointed with sand-lime mortar matching the colour of the stones

Drainage system

The waterproofing of the filling material was done by means of BENTOFIX. This geotextile was placed on a layer of sand previously compacted and sloped to facilitate the water evacuation from the bridge deck.

a) b)

Fig. 6.26 – Drainage system

Conclusions

The masonry arch bridges have a relevant role in actual society, so much in the context of the road transportation network, as well as parts of historical heritage.

The objective of this paper was to present the most common pathologies in masonry bridges, namely: scour of foundations, splitting beneath the spandrel walls, movement of abutments, damages of the spandrel walls, infiltration of the water in the fill material, as well as the description of the associated damages and causes of their occurrence.

Works of strengthening and repair are concerned with the restoration of the stability, integrity and durability of the structure together with the bridges return to service. The deficiencies of the bridge may have been identified by inspections, assessment or the combination of both, reviewing the problems apparent on the bridge will lead to consideration of repair of the fabric of the bridge or the increase of its capacity to support load. In many instances, restoration of strength will require that new materials and new structural elements be introduced into the bridge to achieve the objective. In considering strengthening of listed structures the objective is modified by the need to preserve the outward appearance and the largest part of the original structure and should extend to the preservation of much of the original materials and workmanship as is practical. Thus it is to be expected that works will be contained within the bridge or within the materials of the bridge rather than exposed. Overall the works must be considered in the context of preserving the original bridge rather than simply providing an alternative structure and should be the minimum necessary to achieve, whilst minimising the disruption of the original fabric.

Satisfactory solutions have been developed and implemented and the structures have been returned to service. Ultimately the durability of the original structure will depend on the use of appropriate materials selected with due regard for the properties of the original materials and care in the implementation of the works.

Through the examples of interventions presented in the chapter 5, it can be verified that several solutions exist in what concerns to the conservation and rehabilitation of masonry arch bridges. It must be emphasized that all the solutions of strengthening Donim Bridge are in agreement with the recommendations of ICOMOS.

CHAPTER 7

Introduction

7. Introduction

Europe is witnessing an increasingly frequent restoration of historical buildings used for purposes different from their original ones. Beside the well known controversial issue of the cultural property and the suitability of the project of such programs, there clearly are problems in assessing the stability of the building, both in overall plan and in the individual parts of the building.

In a large number of monuments and buildings belonging to urban nuclei, the walls are made of the so called three leaf stone masonry (two stone masonry walls with a gap between them filled with low quality mortar and small pieces of stone).

From the various wall typologies, the three-leaf walls are among the most difficult to describe in structural terms. This is due to constructional as well as structural reasons. Indeed, the term “three-leaf” covers a variety of constructional typologies, starting from walls made of two exterior leaves and a very small interior one (which may rather be described as a vertical joint), and ending to walls of a thickness bigger than one meter - in which the bearing capacity is principally ensured by the internal leaf, whereas the two external ones (usually not more than 20cm thick each) constitute the formwork, which enabled the construction process. Between those two limits, a variety of three-leaf walls may exist. In addition, the different mechanical properties of the leaves and, more important, the difficulty of describing the conditions at the interface of each two leaves renders structural modelling very complicated.

Understanding the behaviour of multiple-leaf masonry requires the knowledge of the interface response between different leaves, which mainly depends on the adhesion between them and on the geometry of the surface of reciprocal contact.

REQUIREMENTS FOR MATERIALS DESIGN

The issue regarding the study of the original (existing) materials of a historic masonry structure and the methodology for the formulation of new or repair ones was for the first time systematically tackled in (ICCROM 1982). The following fundamental requirements were identified:

- in view of the development of repair materials, or materials that may replace the in situ ones, research on new and ancient materials should be carried out in parallel. The procedure of the characterization of the existing materials is necessary for the definition of some of the properties that the new materials should have and for the understanding of their pathology;
- the new materials should be clearly characterized and very well documented;
- characterization and testing of repair materials should be standardized.

In the course of the formulation of the restoration materials, the following points should be taken into account, following the ICCROM Recommendations (ICCROM 1982):

a) Mechanical resistance,
b) Formation of dangerous by-products,
c) Behaviour with respect to water (both liquid and vapour),
d) Expansion due to heat or water,
e) Modifications due to weathering,
f) Application (which should be as simple and reliable as possible),
g) Limits of reversibility,
h) Aesthetic factors (for renderings, fillings and stuccoes)
i) Marking of materials added during conservation work (in the materials themselves or by documentation).

CHAPTER 8

Grout Dsign for Masonry

8. Grout Design for Masonry: An Overview

In the cement and concrete literature, a grout is defined as “a mixture of cementitious material and aggregate, usually fine aggregate, to which sufficient water is added to produce a pouring consistency without segregation of the constituents” (Kumar Mehta 1993). This definition describes the materials and fresh state properties of the grout, so it can be considered relatively restrictive for our purposes. A more general definition should deal with the description of the function of the grout. This option leaves open the points relative to the choice of the materials and the fresh- and hardened state properties of the mixture. Therefore, we propose the following definition:

Grout is a binder employed for the filling, homogenization, imperviousness, consolidation and/or upgrading of the mechanical properties of systems presenting pores, voids, cracks, loss of cohesion or of cohesionless systems.

Grouting materials

There exist two broad categories of materials that may be used for grouting. These are inorganic and organic binders. A short overview of all these materials is presented below.

a. Inorganic binders

This category encompasses air-hardening binders, such as hydrated lime, and hydraulic ones, which include hydraulic lime(s), ordinary Portland cement and all other types of modern cements, lime-pozzolan mixtures as well as any combination of them. Pure air-hardening binders may not be used for the consolidation of existing masonry. Indeed, hardening of hydrated lime requires the presence of carbon dioxide. It is however known that the diffusion of air at the interior of the masonry mass is a slow process. This results in a very slow hardening and, consequently, a very slow increase of the mechanical properties of this binder. As a matter of fact, hydrated lime may remain in the fresh state for a very long period. Archaeological evidence has highlighted the presence of fresh lime at the interior of masonry masses hundreds of years after their construction. Obviously, under these conditions, hydrated lime grouts cannot contribute to the repair, and even less to the strengthening, of the masonry. On the contrary, hydraulic grouts present a very interesting option for the composition of injection grouts.

b. Organic binders

In this category, the main materials used for injection are polymer systems. An overview of these binders may be found in (Van Gemert D. 1986). They can be applied in pure form, pigmented or filled with filling materials (mainly inorganic fines). The organic component can be applied in the following forms:

- Physical system: the polymer is applied in solution, and dries through the evaporation of the solvent;
- Reactive system in solution: the solvent not involved in the formation of the polymer is added to reduce the viscosity. The dissolved active ingredient reacts with another component (hardener) and then forms a polymer, whereas the solvent evaporates;
- Active ingredient dissolved in reactive solvent: the solvent used is at the same time a reaction agent, which is incorporated in the final polymer;
- Solvent-free reactive system: in these systems, the components react directly with each other and form the polymer.

The polymer materials most used in restoration works can be categorised as follows:

Epoxy resins (EP) : they harden by polyaddition, i.e. by separation of the epoxyde groups and by addition through hardeners with active hydrogen atoms. Resin and hardener must be dosed in predefined quantities. The hardening reaction is temperature-dependent, and most epoxy resins are only reactive above 5°C. The mechanical and bonding characteristics are excellent.

Polyurethane resins (PUR) : these materials also harden through polyaddition, and as a rule they form elastic polymers. The hardening process is strongly catalysed by moisture. Through the addition of fillers, the mechanical characteristics of the elastic polymer can be varied in a wide range.

Methacrylic resins (MMA): this resin is very reactive, even at temperatures of 0°C and below. A major disadvantage is the fact that oxygen may partially inhibit the reaction, therefore special conditions are required for application.

Unsaturated polyester resins (UP) : those resins are mostly used in the field of concrete or artificial stones. They are however not alkali-resistant.

Grouting using cement or polymer-based grouts is one of the most commonly used techniques in repair and strengthening of both modern and old structures. In the case of structures belonging to the architectural heritage, the use of polymer-based grouts should be as restricted as possible, both because of the incompatibility with the old materials and because of their possibly sensitive in-time behaviour. On the contrary, cement based grouts are made of materials of well-known characteristics and more or less similar to those masonry was made of. They have, however, the disadvantages of possible efflorescence and of low penetrability into narrow cracks or voids (<2-3mm)

The main advantages of polymers are the wide range of viscosity that they offer, as well as their excellent bonding properties, which however depend on the good choice of the type of polymer to be used and the careful in situ execution of the injection (Paillère A.M. & Rizoulières Y. 1978). Thus, research on brick masonry (Binda L. & Baronio G. 1992) revealed that the resin may be absorbed by the masonry units (5-6mm penetration depth sometimes) while small cracks, that are expected to be filled, may actually remain empty. The effect on the masonry units is important, as not only the colour but also the porosity and strength properties change. In this respect, cement-polymer grouts fill cracks better but shrinkage phenomena cannot be avoided. Moreover, the resins' mechanical characteristics (modulus of elasticity, strength, creep etc.) are in general very different from those of the masonry (e.g. (Kallel A. 1986)). These differences may have a pronounced effect on the masonry behaviour under temperature variations. Thus, freeze tends to increase the stiffness and brittleness of masonry repaired by resin, whereas thaw decreases them (Binda L. & Baronio G. 1989). The main problem, however, is the decrease of the bond strength when the masonry units present wet surfaces, as is the case in historic masonry (Binda L. & Baronio G. 1992). Consequently, current masonry restoration practice and related guidelines do not recommend the use of organic binders for the repair and strengthening of masonry structures. On the contrary, the application of hydraulic binders is encouraged, due to the fact that their properties are close to those of a masonry substratum.

CHAPTER 9

Strengthening Using FRP

9. Strengthening of Masonry Using FRP

Masonry structures may need strengthening for a variety of reasons. Creep within the structure may redistribute loads such that the masonry is carrying more load over time. This may occur from increasing deformations elsewhere in the structure or from redistribution of stresses within a structural element itself. If load redistribution to masonry is combined with a reduction in decreasing strength over time can lead to failure.

With forewarning – usually the appearance of cracks – masonry can be strengthened. Once of the earliest methods of strengthening was to place a heated flat iron bar across the damaged area and bolt it to solid material on the other side. On cooling, the contraction of the bar would compress the damaged masonry, placing the bars in tension but leaving residual strength to resist any increase in load.

An advantage of fibre reinforced polymers (FRP's) is their high durability in moist environments. The materials do need to be protected from ultraviolet light which causes enbrittlement of most of polymer matrices currently in use. The FRP's therefore need to be completely hidden inside a masonry assemblage, or coated with paint. Improved resins are being developed such that even this concern may be alleviated over the next few years. The fibres in interest are Carbon (CFRP), Glass (GFRP) or Aramid (AFRP). The materials are produced either in the form of bars, with the fibres parallel to the longitudinal axis of the bar, or sheets. In the latter, there can be a predominance of fibre orientation in one direction if that is desirable for the project at hand. GFRP can also be moulded in the form of a mesh. The latter can be used to replace at least the upper steel mat in a bridge deck.

The advantages of using such products are several: very low weight, corrosion immunity, high tensile strength and low thermal expansion coefficient. On the contrary, their up-to-failure linear elastic behaviour does not allow to base the ductility of the system on the plastic behaviour of the strengthening material itself. However, the possibility of binding or warping structural elements made of brittle materials (like masonry) allows, in most cases, to avoid the collapse of the structure and so assure the pursued safety conditions. The strength and stiffness of a structure can be increased with very little increase in mass, distinctly advantageous from the seismic perspective. Moreover, despite their still high cost, the somewhat easiness of execution of the intervention, even in difficult operative conditions, allows a wide range of possible applications in several situations of damage. Anyway, despite their diffusion, specific models and design recommendations for masonry structures, both at local and global levels, are not available yet and some aspects of their behaviour still need to be deeply investigated.

CHAPTER 10

Mechanical Behaviour of Three Leaf Masonry

10. Mechanical Behaviour of Three-Leaf Walls

From the various wall typologies, the three-leaf walls are among the most difficult to describe in structural terms. This is due to constructional as well as structural reasons. Indeed, the term “three-leaf” covers a variety of constructional typologies, starting from walls made of two exterior leaves and a very small interior one (which may rather be described as a vertical joint), and ending to walls of a thickness bigger than one meter - in which the bearing capacity is principally ensured by the internal leaf, whereas the two external ones (usually not more than 20cm thick each) constitute the formwork, which enabled the construction process. Between those two limits, a variety of three-leaf walls may exist. In addition, the different mechanical properties of the leaves and, more important, the difficulty of describing the conditions at the interface of each two leaves renders structural modelling very complicated. The interface between two adjacent leaves determines whether there exists a “collaboration” between them and, in structural terms, whether a load transfer between them is possible through shear mechanisms, as their stiffnesses are generally different. Load transfer is then dependent on the cohesion and friction angle that characterize the interface between the leaves.

The causes of the main structural problems of those walls are: (i) the weakness of the internal layer, (ii) the deterioration of the mortar in the external joints and (iii) the lacking of the connection among the whytes. As a consequence, they are very sensitive to brittle collapse mechanisms, which usually happen, both under vertical and horizontal loads, by the detachment of the layers and out-of-plane expulsions.

It was found that, even if the internal leaf is weak, it still participates in load-bearing to a limited extent. Two phases of structural response were recognized, the first corresponding to the behaviour of the inner leaf in an elastic way and the second corresponding to its behaviour after « yield ». The overall performance of the wall depends on the infill behaviour during this second phase. The failure of the infill was caused by formation of cone- or wedge-shaped shear planes, whose geometry depends on the material stiffness. The outer shells also sustain load, this being reflected in their failure mode which is of bending type. The load-bearing capacity increases linearly with an increase of the internal leaf’s thickness.

The study of the influence of the infill's strength and stiffness revealed a linear correlation of those two properties to the compressive strength of the specimens. The infill stiffness was found to affect more the strength of masonry wallets than its strength. The study of the evolution of the horizontal deformations shows that their value remains low until the beginning of the second phase, which corresponds, as previously mentioned, to the end of the elastic behaviour of the infill material. After this point, horizontal deformations increase disproportionately to the load increase. They are due to the creation of shear failure planes inside the infill material, which cause high horizontal pressures on the external leaves. The specimen collapse is caused through bending failure of one of the two external leaves.

In their research work (Binda L. 1991), (Binda L. 1993), (Binda L. 1994), (Anzani A. 1998), the authors have recognized the complexity and the variety of patterns of three-leaf walls and have insisted on the thorough understanding of the constructional details as the basis for modeling. A first effort for modeling three-leaf walls was done by limiting the issue to the examination of two constructional configurations considered as limits. In the first, the leaves are horizontally connected by high stiffness elements (such as stone blocks), which do not significantly deform in flexure and which distribute the loads to the external leaves. In this case, the important mechanism to be accounted for, is the vertical deformation of the leaves. The type and nature of the connections at the interfaces among leaves is not taken into account. The second configuration consists in the absence of connectors and the existence of vertical joints, which actually form the interface between adjacent leaves. The vertical load distribution depends on the properties of these joints, mainly characterized by their bond properties to the adjacent masonry units.

Those configurations are then analyzed, assuming that the materials' behaviour is linear elastic, and a simple mathematical model for the evaluation of the masonry load-bearing capacity is then developed (Binda L. 1991). It was shown that the presence of stiff transversal elements could successfully distribute the vertical loads to the leaves; in this case, shear stresses along the interfaces between leaves can be disregarded. In the absence of such stiff horizontal elements, when a perfect bond can be assumed between the leaves, a system of self-equilibrated stresses normal to the joints' plane are introduced. These stresses represent a kind of normal bond and ensure the contact between the leaves. It is then possible to calculate the internal force N(x) transferred to the exterior leaves at a distance x from the top. If a weak bond is present, then strengthening of the interface is required, through grouting for example. This ensures the development of the self-equilibrated stresses along the interface and render possible the load distribution among leaves. Despite these advances in the development of models, the authors recognize the need for experimental investigation of the weak joints, in order to determine realistic valuesfor e.g. the joints' modulus of shearing required by the developed formulae. However, the authors provide a first description of the way a grout functions at the interior of a three-leaf wall and put at the center of the mix design problematic – even if not clearly stated – its bond strength rather than other mechanical properties.

The aforementioned models were considering perfectly bonded vertical joints along the whole height of the masonry cross-section. This situation, however, does not occur in historic masonry and it is very difficult to proceed to assumptions regarding the actual bond strength among vertical leaves in case of a weak vertical joint.

These works were based on the hypothesis of elastic-brittle behaviour of the masonry materials, which is in fact not exact. Under increasing load, the system develops an inelastic behaviour, which affects the developing stresses, displacements and strains. Further research focused on the study of bond strength between mortars and masonry units (Binda L. 1994). Tests with a setup similar to the one used by (Binda L. 1993), showed that, in the case of a weak joint without interlocking of masonry units, it is the bond strength between the units and the vertical joint mortar and not the compressive strength of the units that is controlling the compressive strength of specimens. Further study has led to the following remarks regarding the structural behaviour of the tested models : When there are no stresses normal to the vertical joint (in other words, there is no confinement of the wall), the joint behaviour can be considered elastic-softening ; it may be represented as a bi-linear law, increasing up to a peak value and then decreasing.

The aforementioned researches dealt with the study of thre-leaf and two-leaf masonries. They highlighted the difficulty of constructing representative specimens for laboratory testing, which explains the limited literature on the subject. Moreover, they confirmed the inelastic behaviour and potential of this type of masonry which, if disregarded, leads to very conservative evaluations of the masonry load-bearing capacity and to the need of sometimes useless or overdimensioned interventions. To the centre of attention was for the first time put the bond strength of the vertical joints, which unite two adjacent leaves. Indeed, it was shown that, when « strong » vertical connections exist, then loads are transferred mainly by a compression-flexural mechanism. This situation, however, corresponds to a well-built wall. In the absence of a sufficient number of such connections and the presence only of such « weak » vertical joints, then the transfer of the vertical loads from one leaf to the others occurs through shear stresses. If the main function of a grout is to « glue » the various leaves together, then design should focus on the maximisation of the bond and tensile grout strength, rather than other mechanical properties.

CHAPTER 11

Design and Construction

11. Design and Construction of the Test Specimens

The specimens are 0.60 m wide, 1.10 m high and 0.30 m thick. In particular, the thickness was given by the average value detected for existing walls, whereas width and height were chosen with regard to their influence in compressive tests procedures. The two external leaves, approximately 11 cm thick each, consists of rough-shaped granite blocks having the highest dimension of about 18 cm, arranged in horizontal courses, with mortar joints having thickness varying from 1 to 3 cm. The internal core, about 9 cm thick, has been built with mortar and granite scabblings (derived from the rough-shaping of the stones), poured into not compacted layers between the two external leaves, so that a certain amount of voids was created. The thickness ratio between external and internal leaves (1:0.78).

The walls were characterized by a proportion of 68% of stones, 22-17% of mortar and 10-15% of voids. Such percentage of voids is in agreement with real values detected in a group of walls defined as with high probability injectable (Binda et al. 1999). Therefore, the panels were dimensioned with a percentage of voids and a thickness ratio such that the effects of the injections will make clear, but being however sufficiently representative of real walls, as obtained by the deep analysis of the literature cases.

Before grouting, a series of injection holes have been drilled with a diameter of 3 to 4 cm spaced about 35cm. Such holes distribution was arranged to assure the complete injection of the voids and to check the diffusion of the grout during the intervention.

The holes were executed through corresponding mortar joints, where possible; otherwise the stone blocks, that were quite workable, were directly bored.

Subsequently, RFP bars and plastic tubes (9 mm internal diameter, 12 mm external) have been introduced and sealed into each hole.

The grouts have been injected under low pressure (around 0.5 atm) into the hoses starting from the bottom of the walls, even if keeping the pressure constant was a noticeable difficulty encountered. The lateral sections have not been sealed and some small outflows were noticed.

The main scope of the technique is the improvement of the connection between the leaves and the consequent reduction of the transversal deformations.
The transversal tying of walls, strongly reduce vertical and transversal strains at the peak stress. In particular, the transversal strain, thanks to the restraint effect of the ties, showed an average reduction, compared to the case of the unstrengthened walls, of about the 50% at the peak stress, and of about the 90% at the same stress level.

As expectable, the walls consolidated by injection combined to other techniques have reached good values both for compressive strength and modulus of elasticity. Therefore, simple or combined injections can be considered as the most effective strengthening technique for such typology of walls. Nevertheless, it is worth to mention that the combined techniques play an important role in improving the global behaviour of the walls, raising one another their own effects and allowing an enhancement of the feasibility in the execution phase (in fact, the highest performances have been obtained for the wall strengthened by the “integrated intervention”, that is by all the three techniques).

CONCLUSIONS

There is significant potential for the application of FRP’s in the masonry industry, both in new construction and for rehabilitation. FRP’s can improve not just the strength capacity of the material, but also the ability to resist crack propagation and retain structural integrity through increased toughness. Specially designed FRP connectors, which again have higher toughness in maintaining integrity in the structure need to be developed for masonry. For both new and rehabilitated masonry, the ranges of conditions under which the currently observed modes of failure occur, need to be elucidated: simple analytic methods need to be developed for codification. The range of testing needs to be increased to determine if yet unknown modes of failure might occur. In some instances, the actual sequence of failure requires clarification. Lastly there are serviceability issues which have received little attention to date but should be investigated. Since so little has been done, but what has been investigated shows exciting promise, further work is needed to explore the many possibilities of improving the performance of masonry, both new and old, under seismic loading.

The injection of grouts has revealed to be the most effective in raising the ultimate load capacity of the walls and in improving the brittle mechanism of failure of the non consolidated walls. Moreover, increments of the modulus of elasticity still compatible with the existing structures have been detected, but with significant reductions of the transversal dilation. No significant differences in the ultimate strength have been detected for the different types of the used grouts.

Injecting and transversal tying have revealed their efficiency mostly in terms of reduction of deformations. Nevertheless, the best performances can be ascribed to the walls strengthened with combined techniques, especially when injections are involved in.

Finally, particular attention has to be paid to significant parameters and critical aspects of the single phases of the intervention techniques, in order to identify correct design and execution procedures.

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