The Repair and Conservation of Brickwork

Brick is a coherent mass consisting largely of aluminium and calcium silicates. In physical terms it is inert and in chemical terms virtually insoluble in water. Polluted air may carry weak hydrochloric, sulphuric and hydrofluoric acids which can be damaging to brickwork.

The fundamental principles of repair are honesty, sympathy and integrity: honesty to avoid deception, sympathy to avoid visual conflict and integrity to ensure that the work is carried out with the most appropriate materials and workmanship. Reversibility is an objective much to be desired and to be achieved if possible. Invisibility may often be sought, as with the repair of paintings, furniture or pottery, subject to the evidence of repair being clear on examination.

A careful analysis of cause will have identified the faults before repairs are specified. In consequence there will normally be two concurrent and perhaps overlapping operations — the repair of damage and work to eliminate the cause of the problem. Brick is a stable and durable material and if used correctly at the outset is likely to be in need of repair or renewal at only infrequent intervals. Properly used its life should be indefinite. In perhaps the majority of instances the cause of damage to brickwork will lie outside the material itself and fall perhaps into one of the following broad categories — structural failure, plant growth, excessive water penetration and the effects of impact or other external forces.

The decay of a timber post or timber frame might transfer a major deadload on to a relatively thin brick pier or panel. A change in use from living to storage might produce much higher deadloads on a floor than those previously applied, or the rusting of inbuilt iron cramps and bars might increase the load upon a brick jamb. Faults of this nature would tend to produce an increased or eccentric vertical load whose consequence might well be to cause the brick or mortar to break down during weathering. Sometimes this phenomenon occurs parallel to the face with the result that the surface will laminate away leaving the core exposed. Replacement of the entire brick face may be justified. It is the essential effective response if the mortar has been overstressed.

The action of vegetation can be generally benign and may contribute to the visual quality. Most brickwork is subject to a series of wetting and drying cycles and moisture is frequently retained in the pores of all but the densest brick. Mortar likewise is porous and plant growth occurs intially through the microscopic ranges of algae in addition to fungi and lichens. Many varieties of leaf-bearing plant are able to establish themselves in crevices in brickwork, and with increasing decay or lack of maintenance invasive plant life can become rampant. In general terms the wetter and warmer the climate the more rapid is the process.

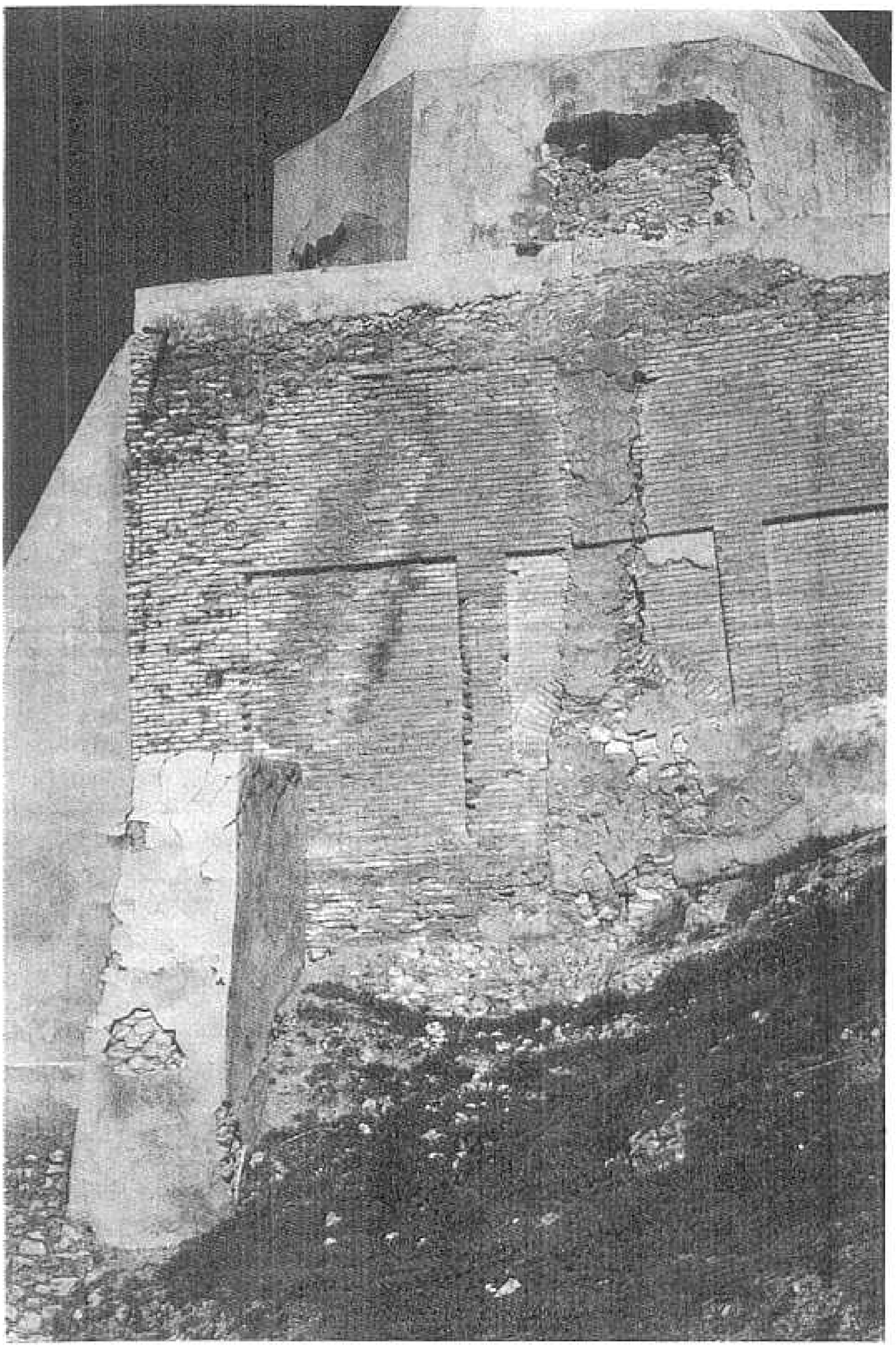
Due to the nature of mortars, brickwork generally presents a very alkaline environment during the earlier years following its construction. However, the presence of plants is immediately followed by organic decay. Photosynthesis can be based on the absorption of water and minerals from the wall itself and water, carbon and oxygen from the air. When plants, even algae die, their tissue is broken down by bacteria and fungi. Sugars and cellulose are transformed through several stages into acids and these acids neutralise the general alkaline environment of the masonry making it more suited to plant life. Plants establish themselves, penetrating the natural crevices and as they grow they expand. The expansion of plant cells under osmotic pressure can produce powerful forces at a microscopic level. As small particles are displaced by these effects the cavities become larger. Decayed material provides food. With the introduction of leaf bearing plants root systems are established. These swell under osmotic pressure creating further ruptures and the process continues until the root systems are sufficiently large to transfer the leverage of the weight and wind loadings carried on the plant stem into the wall itself. The decay is inexorable and complete failure of the masonry will follow. The conservator may interrupt this process at any point on the accelerating scale of damage. By the very nature of things such damage will be uneven, often being much more advanced towards the top of the wall where water penetration has been more severe. The removal of larger plants can be damaging to a wall structure if it is clumsily done.

However, it must be recognised that if masonry can be disturbed by the removal of moderate plant growth it has already passed the point at which its mortar has failed. The general precept which should apply to the repair of brickwork damaged by plant life is that fissures and cracks penetrated by growing organisms will represent a discontinuity in the structure and the opportunity for further growth which can cause expansion within that crack. It follows that while small scale plant life is tolerable and attractive its presence is conducive to decay which will progress on an increasing scale. The sensible decision is to exclude the growth of leaf-bearing plants, however small, from wall masonry, but to take no preventive action in regard to moderate growth of fungi and lichens. Deep beds of moss or heavy growths of lichen will produce substantial amounts of organic acid with deleterious effect upon some mortars and careful judgement in maintenance will lead to a balanced policy aimed at restricting the rate of deterioration without eliminating it entirely. Most plant growth can be removed and controlled by careful hand techniques and repointing can eliminate the most direct points of damage particularly those where the plant growth and consequent deposits have penetrated past the pointing and moved down behind it. In general the use of fungicides and similar poisons is to be avoided. All such chemicals are of limited life and their principal acceptable use is to eliminate the causes of decay at one specific point in time to allow a treatment to take place as for instance where a fungal and bactericidal wash may be applied to a wall surface prior to painting or rendering.

With the advances of technology ranges of materials are available for uses which can relate to the conservation of brickwork. The areas in which they are principally employed are the control or elimination of plant and insect life, the prevention and inhibition of water movement, fixings and reinforcement and enhancement of surfaces. In addition there are techniques of control and measurement for the detection and determination of movement, loading and structural change and specialised techniques of analysis which assist in determination of age and composition.

No wise conservator will turn his back on the availability of these techniques nor upon the specialised skills of the technicians versed in them. As a general rule conservators tend rightly to turn first to traditional materials and methods, using the more exotic and modern materials and techniques only where these are demonstrably an improvement necessary or desirable because of particular circumstances. Some such interventions are totally invisible and inoffensive, some are barely visible and acceptable while the intrusion of others makes them a method of last resort.

Rising damp can be eliminated by the sequential removal of courses of brickwork, the insertion of a metal, plastic or bituminous membrane and the replacement of the brickwork with little visible effect but with dramatic changes in the moisture content of the wall and its consequent support of plant life and the decay of finishes. Alternatively brickwork can be drilled and highly fluid resins can be injected. These penetrate the porous masonry and mortars and set off to provide a waterproof barrier. Passive measures include the provision of ventilating tubes (perhaps of earthenware) into the wall to reduce the effective rise of moisture below a level at which it causes damage. Simple and sympathetic measures of this type are commendable provided that they do not disfigure the building. In some circumstances the application of a damp-proof membrane on or against the outer face of a wall below ground or water-table level can sufficiently reduce the uptake of moisture to acceptable levels, and the disfigurement of the brickwork below ground can be tolerated because it is not seen. Below ground drainage is sometimes sufficient to reduce the uptake of moisture. This may be achieved by the introduction of porous pipes at foundation level, back-filled with freely draining aggregate. On occasion the simple reduction of the area



Massive brickwork falling due to settlement in foundations. (Mosul, Iraq).

of damp ground against a wall may be sufficient to reduce the dampness in walls to acceptable levels by restoring the balance of above and below-ground exposure in a wall.

Ground levels in inhabited areas tend to rise over time, largely due to the deposition of used material. An historic building may, therefore, be wetted externally to a higher level than originally and correction of this one problem may in itself be sufficient to restore a natural and acceptable balance in the moisture content of the wall.

Water splash is another cause of disfigurement and high water content at the foot of a wall. Water discharged from a roof on to the ground will splash persistently on to the lowest courses of a wall, changing its colour and wetting it, sometimes damagingly. Likewise water-entry at the head of a wall can cause accelerated weathering and rapid decay of mortar.

As a matter of general principle the coservator will not seek to eliminate moisture from brickwork, but to achieve a balance between absorption and evaporation which leaves the brickwork at all times in a stable condition of tolerable weathertightness and minimal decay. Wherever possible the simpler and more natural methods should be employed and in many instances a sequential process may be advocated, trying first the more basic methods before resorting to more sophisticated treatments only if the basic methods prove inadequate.

In some cases combinations of techniques may be appropriate. The strengthening of brickwork which has a weakened core may be allied to waterproofing by use of a cement-compatible water-proofer in the grout.

Whether used for waterproofing or for other purposes grouting introduces special problems of its own.

It has to be remembered that the stresses induced by the introduction of liquids under pressure can be substantial. A liquid exerts virtually the same pressure on every surface. Where it is rigidly contained the liquid transmits an identical pressure on all the surfaces of the container as is being exerted at the point of introduction. This is the fundamental principle on which hydraulic apparatus operates. Consequently a high pressure at the point of introduction will produce the same high pressure over the whole area of the internal cavity surfaces. Where the introduced liquid is able to penetrate behind the outer skin of a wall the pressure on the rear face of this skin at the point where the whole cavity has been filled and no more liquid can be introduced will be the pressure at the point of introduction multiplied by the area of the cavity face. The consequent force may be sufficient to increase the severance of the outer skin from the main structure and to burst it away from the building. Therefore grouting under substantial pressure should be used only where the introduced liquid has to penetrate deeply into fissures which run through strongly retained structures.

For most purposes in historic buildings the introduction of grout under a hydrostatic pressure of no more than half a metre is sufficient to provide adequate penetration.

This pressure can be achieved using tubes and funnels raised sufficiently to allow the grout to flow readily into the voids. Under such pressures the sealing required to prevent grout emerging from the cracks can be achieved by the use of clay or other simple plugging.

While such methods are effective in securing the internal stability of an historic wall structure it may be necessary to repair the visual effects of damage due to fracture under stress by the replacement of brick on the external surface. Bricks can be removed in various ways. The normal solution is to cut them out mechanically using chisels on the mortar. This will cause shock waves to run through the remainder of the structure and the consequent damage to mortar and other parts of the historic fabric may be unacceptable. An alternative method of cutting is the use of jigsaws. Short bladed mechanical masonry saws are available by which the mortar joints can be cut and any individual brick can be isolated so that it can be removed. A replacement brick can then be inserted in the pocket left. This process can be repeated across the entire length of any crack.

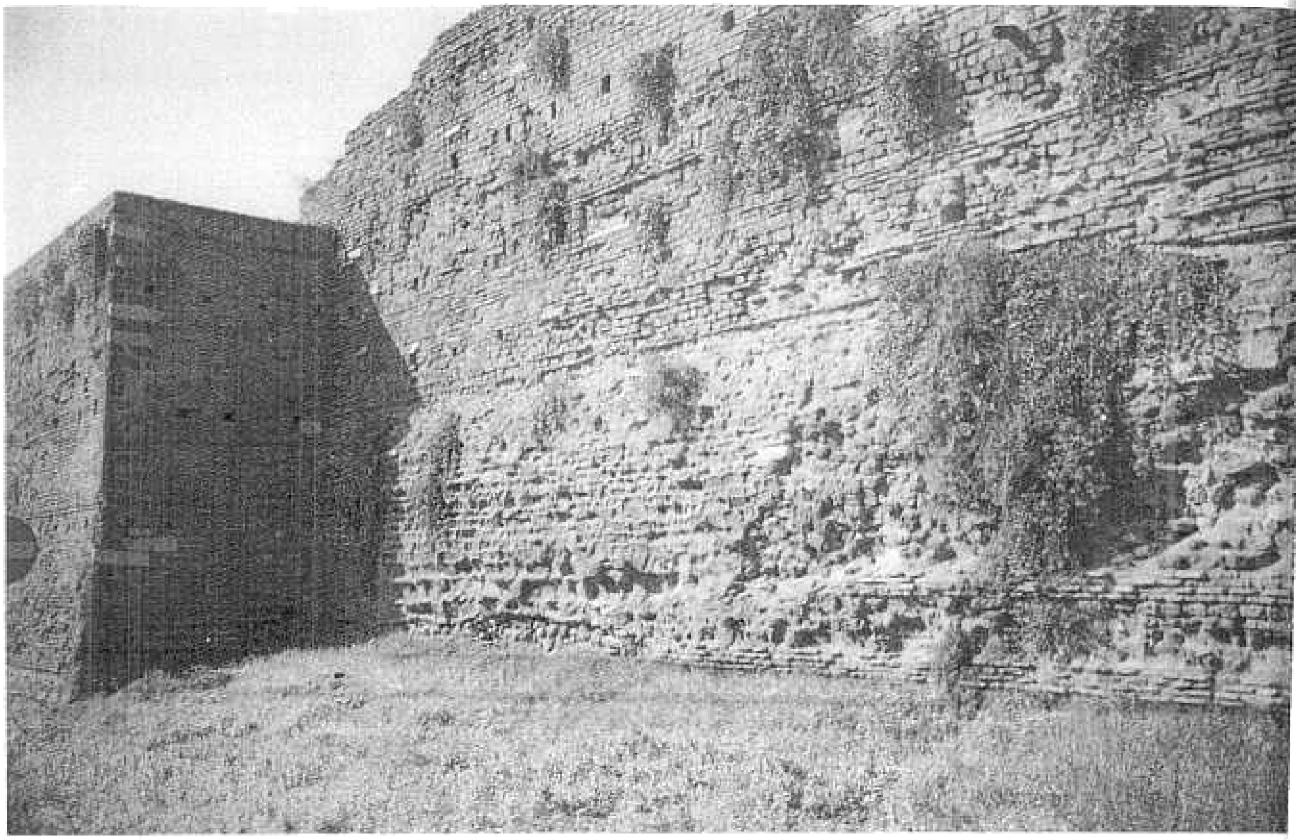
Normally alternate courses are repaired in this way as the crack is likely to pass through a perpend or vertical joint. If additional tensile strength is required flat ragged (wedge or Y shape ended) ties may be inserted behind the replacement brickwork. Such ties will normally be made of stainless steel. It is important to avoid the introduction of mild steel or wrought iron in such circumstances due to the possibility of expansion due to rusting. In more elaborate stitching repairs, holes may be drilled diagonally through mortar beds to cross the cracks. Into these holes stainless steel, phosphor bronze, glass or carbon fibre rods may be inserted in a grout or catalytic-setting resin. An interlacing pattern of such stiches can bind together a cracked section of wall and the repair will be completed by grout-filling the crack. It must be remembered that such repairs may produce a section of wall with far higher shear and tensile strength than the original structure and any further movement may then cause a parallel range of cracking beyond the reinforced area. It is, therefore, critical that the cause of the failure is remedied.

The most extensive and therefore the severest intervention possible in an historic building in such circumstances is the rebuilding of a complete section. This may be necessary where the failure is of such a nature that extensive internal reinforcement is required or where the nature of the fracturing is such as to cause the loss of considerable areas of brickwork or where the cracking is so wide that to accommodate it in perpends at the ends of replacement bricks is to produce an unacceptable pattern. then the conservator will be justified in taking down a complete section of brickwork and rebuilding it sympathetically using such original material as can be salvaged, adjusting his repair work to accommodate the movements.

In one special case particular care is required. Many historic buildings were built without an understanding of thermal movement. Long continuous brick walls move significantly under temperature change. In some climates diurnal change is sufficient to stress a wall beyond the tolerance of its mortars but the effects are more generally the effects of the difference between winter and summer temperatures. In unrestrained continuous wall structures built in lime mortar, cracking may occur regularly at intervals of between 10m and 30ms. Cracks will normally be vertical and greatest towards the top of the wall. Where the wall is perforated the cracking will occur in conjunction with the openings and may be the reason for the shattering of lintols and cills. The nature and the extent of cracking will depend greatly upon the quality of the mortar originally used. The important conclusion is however, that there is no point in undertaking repairs which restore the tensile strength of the wall at the point of fracture, unless these are necessary for other reasons such as safety, decoration or damage to other structural items. To do so simply transfers the same load to the next available weakest point and the problem will recur. Where a building has formed a natural fracture line in this way the conservator will be wise to accept this natural movement joint, rendering it as inconspicuous as may be achievable. This can sometimes be done by allowing a slip joint to exist in the brickwork, pointed up possibly with very weak mortar or with a flexible mastic matching the adjacent mortar. Where weather sealing may be required a flexible tube can be introduced behind the pointing to ensure that an air tight seal always exists. Prevention of air movement through such a crack will greatly reduce the penetration of water.

The decay of brickwork takes many forms. A sound, hard well-burned brick is virtually indestructible by natural processes but many bricks are less than well-burned. Such bricks can fall under the action of frost simply because the particles are not sufficiently well fired to adhere fully. The change in colour which occurs in brick during firing can precede the melting or partial melting of the silicon oxides and the brick may, therefore, be coloured although it is not a fully coherent piece of fired clay. Many historic buildings contain bricks which are not fully fired and the remedy is generally to cut them out and replace them with matching material. Other than for its visual merit there is no point in leaving such a brick in situ even if decorative and visually important, in conditions where it has already begun to break down. Other manufacturing faults can produce similar effects. Clay which has not been well compacted during manufacture may have left inherent fissures accentuated on drying and these discontinuities or lack of adhesion within the core of the material may not have been overcome in the firing process in which case the entry of water followed by plant growth can cause sufficient expansion to give rise to early decay.

The process of fault analysis is essentially a matter of discerning the cause of a problem or of a potential problem. The analyst who can perceive a problem before it has become a defect is in a position to avoid the loss and expense of damage by preventing its occurrence. Most prob-



Plant growth causing slow decay of ancient mortar. (Rome, Italy).

lems, however, will become apparent as defects. Generally these relate to water penetration and structural failure due to some form of overload. However, there are ranges of defects inherent in the manufacture of bricks and also in making and placing mortar.

Bricks have not always been chosen for the task in hand with the care that the conservator might have wished. Underfired and inadequately burned bricks should not be used in positions where they will be subject to heavy loading, weathering, frost action or salt impregnation and particularly in positions where they are close to the ground or placed in paving on ground which is continually wetted. They will break apart physically and require replacement with a brick chosen for its better manufacture. A brick which, while well burnt, has been the subject of physical damage before laying may fail similarly. Bricks which have been cut, perhaps on a hidden face, will fail by decrepitation as weathering and plant life follows the path of the microscopic cracking. For this reason a special (shaped) brick is always to be preferred to one cut after firing to suit its position.

During the process of firing some

bricks may inadvertently have included pieces of chalk or limestone, which, when eventually wetted, give rise to pressure in the brick which can sometimes break the fired material on a line of lamination. The effect is usually disfiguring rather than seriously dangerous. Overburning a brick during firing is unlikely to cause any defect in its usefulness other than change to a (usually) darker colour and in the more extreme cases misshapement or even fusing with adjacent bricks. Such fused bricks can sometimes be separated but physical damage results although a satisfactorily usable face may remain, and the brick should be used with care. Well chosen brick laid in a durable mortar is a very long lasting material in normal moderate climatic conditions, subject to normal structural loadings and satisfactory detailing. It is often the failure of protective detailing that causes the failure of brickwork, particularly with regard to water entry.

The heads of walls in wet climates can be a serious source of weakness, particularly where exposed on both faces — chimneys even more so. Many walls have relied on coping bricks or blocks for protection and well-fired components can be effective. Many bricks used for this purpose are highly vitrified and sometimes courses of tiles are placed beneath them to provide an effective damp proof membrane. Even so the upper courses of brickwork will maintain a wetter condition than courses below and consequently will show greater signs of vegetation and decay. The introduction of a damp proof membrane can be effective and virtually invisible. If the membrane is a copper tray the effects of the copper salts can be advantageous in reducing the growth of algae on the brick below. Sheet copper, zinc and lead — all of which have been used historically as damp proof membranes — are metals which eventually tire over a long period due to the crystallisation effects which are particularly evident at points in the metal where movement continually takes place. The phenomenon is described as metal fatigue. It is unlikely to occur in embedded metal but will be found at bends, joints and junctions. Grades of stainless steel containing nickel and molybdenum are now available and are likely to give a much longer life in such circumstances. Much water entry into brickwork is attributable to the failure of sheet metal flashings, linings and gutters, which should have been replaced at or before the end of their reliably useful life.

The failure of rainwater goods is a similar and parallel cause of much distress in brickwork. Cast iron pipes which get blocked and perhaps frozen, crack. Leaking pipes and leaking gutters provide a continual point of water entry which will saturate brickwork and induce decay in the mortar. The transmission of water into other parts of the structure may be more serious and no conservator can afford to look at any one element in isolation. However the continual saturation of brickwork is sometimes readily apparent due to change of colour, weathering or the presence of plant growth, which is a sign that preventive action must be taken.

The prevention of water penetration through a wall is one of the more difficult problems of conservation. Both the inner and the outer faces of the wall may well be historically important and both surfaces may have to be retained. Nevertheless the wall may be incapable of resisting the weather and this may always have been the case from the time of its building. In some instances a later unacceptable covering may have been removed. Such a wall will become less weatherproof over a long period because continual water penetration will produce minor aquifers in the lime mortar. In such instances the conservator must choose between the drastic step of rebuilding the wall, possibly with a vertical damp proof membrane within its thickness or techniques of resin impregnation either by injection or by solvent, or coating the wall, or repointing. The historic quality of the wall may well be severely damaged by all other than the last of these techniques and pointing alone may be insufficient. Dramatic improvements can be effected by the application of water repellent materials such as silicones which are ephemeral, needing renewal on a cycle of approximately five years. Generally they have little or no visual effects; occasionally they can be thoroughly disfiguring.

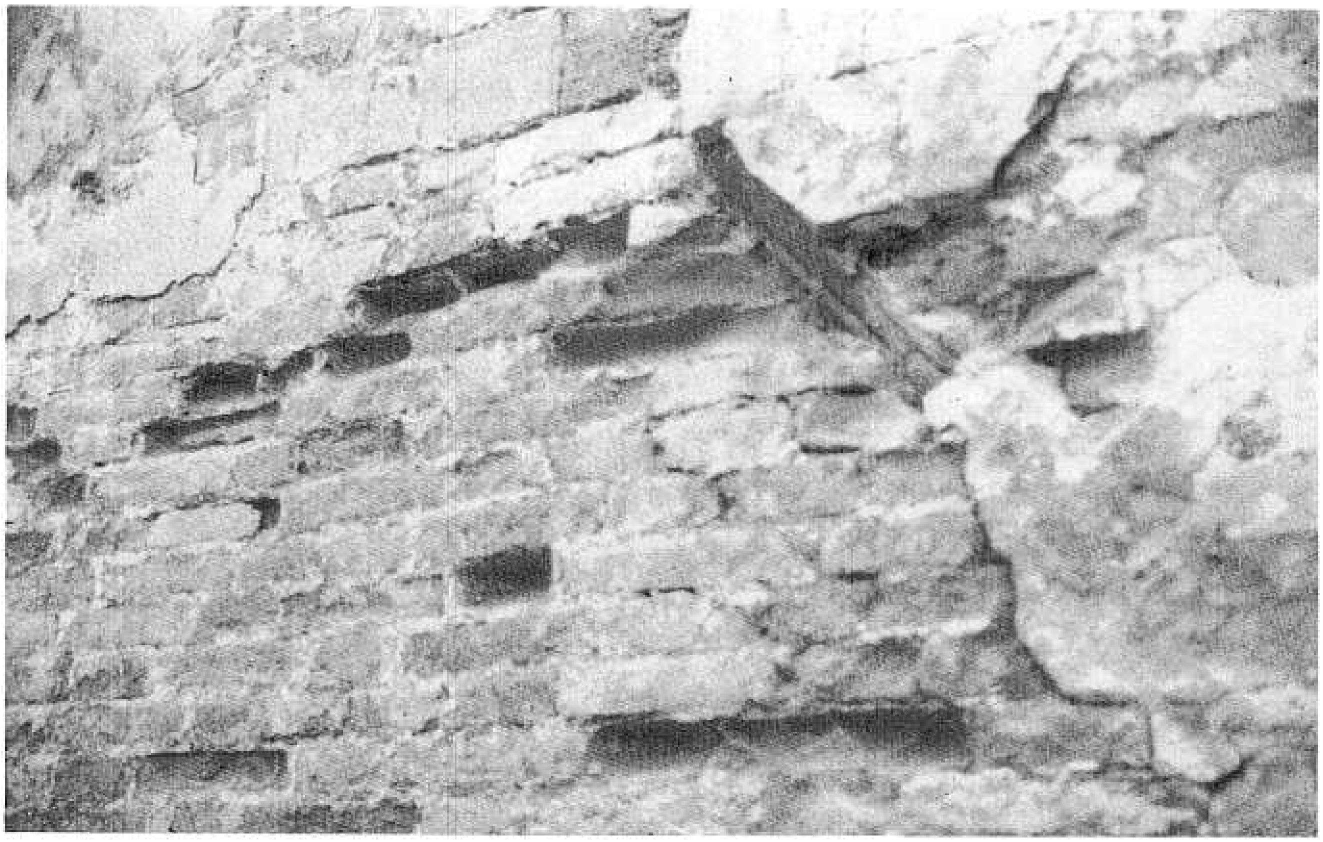
The introduction of damp proofing or damp inhibiting membranes and devices into the lower sections of walls is a subject well explored and widely practiced. The introduction of a physical barrier based on sheet metal, bitumen or plastic is technically possible in almost all types of brickwork by underpinning the structure to cut away short lengths. Sawing the mortar joints is the normal technique for such work. There are occasions when brickwork is so heavily loaded that this operation can become dangerous by overstressing the material. Resin injection of the brickwork, if well carried out, is a satisfactory alternative, although it is not always possible to be certain that every water path has been sealed.

Static electrical charges carried in rising moisture can be used to inhibit their progress by the use of converse fields across the lower sections of walls which repel the charged water. These are sometimes charged passively by the use of anodes and sometimes positively by battery circuits. However, their effectiveness has been called into question.

In wet climates rising damp will cause saturation of walls with consequential damage to finishes and associated materials such as timber. In more arid climates the higher rates of evaporation may protect the upper walls but carry salts into the brickwork with damaging results. In various circumstances metallic and ammonium nitrates, chlorides, carbonates and sulphates can reach concentrations in the surface layers of brickwork which cause failure due to expansion and the destruction of the bonds between the particles. The mechanism is the 'pressure of crystallisation' i.e. osmotic pressure within a liquid causing the ions to seek to equalise their concentration. When evaporation takes place crystals of dissolved salts form in areas of high ion concentration below the surface. As they form the concentration in the liquid is reduced by the incorporation of the salts within the crystal, where they become trapped within the forming lattice. Osmotic pressures restore the balance in the liquid and further salt molecules are drawn to the surface layers to be absorbed so repeating the process. These, with the incorporation of water of crystallisation, cause expansion in the pores breaking the bonds between particles of the material. Thereafter small physical pressures such as the impact of wind-blown sand will remove the broken fragments and the brickwork is eroded. The salts may be delivered through very mildly saline ground water, they may have originated in the vicinity of the structure from sewage deposits and the like or in the case of sulphates they may be the products of combustion deposited on the inner surface of flues and carried through the brickwork by moisture. Chimneys are particularly susceptible to this type of attack and due to higher rates of evaporation on one side than another the swelling which follows deposition of salts may cause the chimneys to lean and eventually to fall. The remedy must include the removal of the saline material and protection by the introduction of flue liners, drains and the reduction of rising damp: and it may be necessary also to reduce the volume of deposited salts in the brick. Laboratory analysis will determine the nature of these salts and their concentration.

It may be possible to remove them by processes of extended continual washing or by poulticing, that is to say by the application of an absorbant material such as an inert, wetted powder or dust held in position long enough to absorb salts. It is then removed and the operation is then repeated until the concentration of salts has been satisfactorily reduced. Poulticing may also be used to neutralise salts. A poultice impregnated with a material designed to react with the identified salt may be placed in the same way to be remvoed on completion of its work. Such treatment does not restore damaged mortar. Where the presence of excessive concentrations of salts has broken the coherence of the mortar there is no option but to take down the brickwork and rebuild it. Where bricks have been removed and cleaned they can be freed of significant concentration of salts by prolonged soaking. The bulk of the water must be allowed to drain out before they are used in rebuilding. Where a chimney stack is rebuilt advantage can be taken of the situation to construct an impervious flue using some form of flue liner. Salt glazed earthernware may be the most suitable material for the purpose. Other inert and metallic flue liners are available to suit specific purposes.

Relatively modern buildings may have been constructed using cavity walling in whole or in part. Wall ties incorporating iron may have corroded and the expansion of the iron will have damaged the mortar joints. It is not necessary to take down such walls as the removal of iron wall ties can be achieved without destruction of the brickwork. Ties can be located by metal detectors and the appropriate joint can be cut out using a carborundum disc. After the tie has been extracted a replacement can be inserted by drilling through the two walls, injecting a resin grout into the



Wind erosion completing the process of failure in under-fired bricks weakend by excessive wetting. (England).

further wall and embedding a stainless steel tie into the grout. Appropriate wall ties are manufactured for the purpose.

Bulging walls are indicative of skins of brickwork which have not been properly secured to the core or skins in which the ties have failed. Some skins of external brickwork (particularly 18th and 19th century work) are laid with a bond which provides widely spaced header bricks designed to tie back the outer skin. Differential movements between the skins can be sufficient to shear these header bricks allowing the outer skin to become detached and to bow outwards, an effect aided by the accummulation of debris in the bottom of the cavity.

Conditions of this sort may be remedied by rebuilding the outer skin with suitable ties, by drilling and the insertion of ties or by the injection of a grout with adhesive properties. Pulverised fuel ash with an emulsion of a bonding agent may be suitable. The use of substantial amounts of Portland Cement in such instances is likely to produce cement staining on the surface and should be avoided.

The cause of bulging walls must be identified and corrected as the separation of skins and deformation are a serious cause of weakness. While differential movement between skins exposed to different conditions may be the cause there may be other profound reasons. Variations in loading, variations in foundation support and the expansion or rotting of embedded material may be indicated. Changes in soil condition and/or persistent vibration may be the root cause of the problem. Vibration, in particular is insidious and often imperceptible in its effects, causing progressive fracturing in the crystals which are the binding matrix of the mortar. Progressive weakening of the mortar can ultimately reduce it to a virtual powder and at some point during this process it loses the strength necessary to provide cohesion and adequate load bearing. The effect will be expressed by bulging or by the appearance of settlement cracks as the weakened section of wall gives way. Movement in foundations generally accompanies this problem.

Slow changes in foundation conditions may follow changes in moisture content due to drainage or tree growth/removal or perhaps be due to earth movement in unstable soils. Underpinning and piling may be necessary in which case bored rather than driven piles are more likely to be satisfactory. Sheet piling hydraulically pressed into position may be used to isolate and so firm up the subsoil without touching the building itself.

Brickwork must not produce a loading on the foundations which exceeds the capacity of the sub-soil to withstand it and foundations will, therefore, be designed with this in mind. Changes in bearing capacity can occur, however, and where they are identified additional support below ground becomes essential. The effects of piling are twofold: to carry the load further down into the subsoil with the objective of delivering it on to a wider foundation of greater bearing capacity and in the case of driven piles the effect is also of consolidation. The driving in of the pile causes the displacement of soil particles and water with the ultimate effect of increasing the density of particles in the zone into which the piles are driven. It is, therefore, possible to consolidate ground beneath foundations without achieving a physical link between the pile and the structure, although this is at the risk of transmitting energy vibrations to the brickwork and the conservator must, therefore, be satisfied that before sheet or pin piles are inserted the coherence of the brickwork is sufficient to withstand any vibrations. These can be much reduced by continuous rather than impact driving by the use of ultrasonic techniques and by the use of hydraulic buffers.

Where brickwork has been weakened the construction of buttresses is sometimes advocated. An inserted buttress can be effective only if it is locked into the historic brickwork in such a way as to receive the lateral or downward loads it is designed to resist and also only if its foundations are such as to allow it to stand without further settlement. It must not be forgotten that a buttress in addition to its own deadload will transmit applied loads as a vertical force. A buttress should, therefore, both be well founded and of minimal mass to perform its function. An over-designed buttress on inadequate foundations can accelerate or increase the deformation it is intended to cure by accentuating the pressure on the sub-soil and causing settlement.

The buttress also has significant visual impact and may be a desirable element of design or otherwise. It is usually readily identifiable as separate from the structure it supports. Perhaps the most dramatic instance of the introduction of a buttress is that built at the behest of the British Archaeologist, Gertrude Bell, against the southern wing of the great iwan at Ctesiphon, the northern wing having been brought down as a body by a flood of the River Tigris after the lower courses of brickwork had been weakened by the effects of salinity and subsequent erosion. This great flying buttress is now an established feature of the monument.

Physical movements of the ground affect structural brickwork and masonry and generally the result is cracking which is a self-evident result of the change in support.

Earthquake shock is one cause: mining subsidence or similar natural phenomena, generally classified as land slip, are others. Once satisfied that the ground has been stabilised the conservator will have to reach a decision as to whether the brickwork is to be stabilised in its deformed position, repositioned by jacking with the necessary underpinning or rebuilt. Sometimes a combination of these courses is advisable. Permanent hydraulic jacks have been developed, being known as flat-jacks. Once inserted they are pressurised to the calculated bearing pressure and their concrete filling sets off. They resemble flat metallic pads rather than conventional telescopic jacks.

An undamaged feature such as a niche may be stabilised in position if lifted, a broken arch may be reconstructed in walls left permanently out of alignment or major deformations in the structure may be accepted — the relevant cracking being filled or made good. In almost all cases there may be a temptation to incorporate additional reinforcement. This may be necessary or advisable to achieve permanent cohesion in damaged sections of brickwork and in general it will be found wise to introduce reinforcement of a tensile strength broadly in the order of the relatively modest tensile strength of the original brickwork. Controlled drilling allows the introduction of reinforcing rods and the cutting out of joints allows the introduction of perforated metal wire or rod reinforcement. It is important that any reinforcement introduced is non-rusting.

The principle of ensuring comparable strengths in the interventions in historic brickwork also guides the specifications for mortars. Bench analysis of samples will reveal the strengths of any mortars and introduced mortars should, as a general rule, be of similar nature. The conservator has the option of using several types of cement, two types of lime and other setting compounds based on ash.

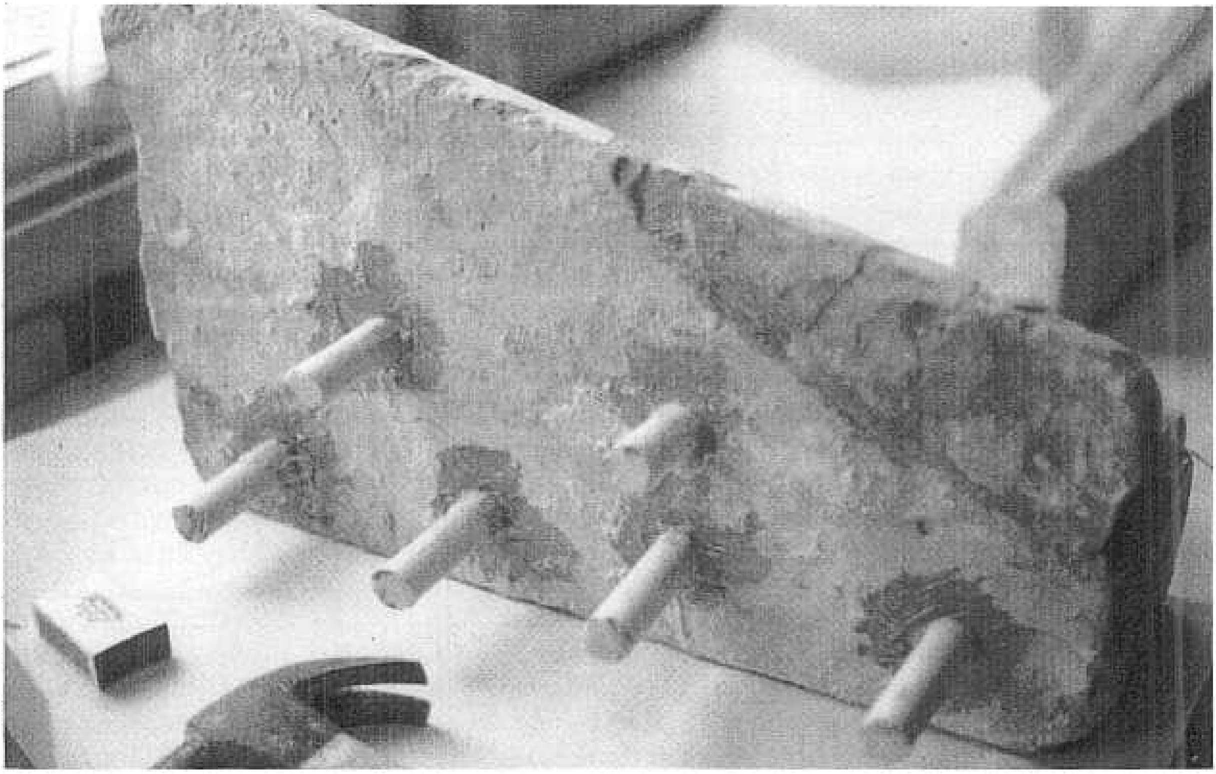
Portland Cement tends to be grey in colour, hard and brittle when set and is capable of leaching through brickwork to cause a grey bloom. The strongest mix usually allowable is 1:3. Cement to sand. Mixes can be as weak as 1:10, yet still provide a strong and rigid mortar. Portland Cement can be used as a trace material in lime putty to provide a set and to differentiate mortars used in repair from traditional mortars. However, in a building originally built using lime the introduction of anything beyond traces of Portland Cement is undesirable. Many more recent historic buildings were built with cements, and initial analysis of the mortar is important prior to a decision as to the mix to be used.

Mortars have coefficients of thermal expansion which differ from those of fired earths. A strong cement mortar may expand as much as one third faster than brick and produce high local stresses in consequence. This is a particular danger in pointing. Where cement is to be used and sulphates may be present a sulphate resisting cement is to be recommended. The efficacy of a sulphate resisting cement depends upon the availability in the cement of an excess of material which will react with the free sulphates with which it comes into contact. In effect this surplus is a sacrificial element which can be taken up without diminishing the strength of the mortar or concrete. If the entire surplus is taken up the cement is weakened as any other cement would be. It is, therefore, important to know the extent of the sulphates in the building.

Where it is necessary to achieve colour matches white cements are available. These are made from carefully selected raw materials which eliminate the grey colours deriving from normal clays. Kaolin is extensively used in the production of white cements. They are sometimes used to provide a mortar which simulates an historic lime mortar but with higher standards of strength. All cement mortars can be gauged with hydrated lime by as much as twice the volume of cement. The effect is to produce a weaker and more pliable mortar which to some extent avoids the defect of brittleness. A cement:hydrated lime:sand mortar in a ratio of 1:2:4 provides a strong mortar comparable to that used in most recent historic buildings. Reducing the ratio of cement by up to half provides a more flexible mortar often used to match historic lime mortars. This is not good practice however. Lime mortars should always be matched in the same material.

Lime putty, unlike hydrated lime, has not been dried after slaking and, therefore, has not been exposed to the air. It sets by combination with carbon dioxide more slowly than a cement and produces a weaker mortar. It is mixed with sand in a standard ratio of 1:3 by volume with little variation in proporation. The addition of brick dust, pulverised fuel ash or cement causes an hydraulic set which produces rigid brickwork more quickly and, therefore, allows work to proceed faster. Where such materials are introduced the volume of sand is reduced proportionately.

Gypsum cements are principally employed in the formation of plaster other than in arid climates. They respond well to combination with finer sands and produce a hard white mortar which unlike other cements expands on setting. Gypsum mortars are weak. Often used neat



Repaired brick dowelled for structural bonding to similar brick. (England).

their sand content may be twice to four times the volume of the gypsum. Fine sands are to be preferred.

The choice of sands is significant in relation to the colour, texture and strength of finished mortars. Historically ash and brick dust are regular constituents of mortars. The strongest combinations of sands provide a gradation across the size range from some 2 mm down to .1 mm with the largest proportion in the upper range. Sands should be free of significant amounts of clay which diminishes the performance of mortars with no consequent advantage.

Sharp sands are those in which the components have been fractured but have not been so subject to weathering that the arisses and edges are rounded away. Sands which are the product of sustained erosion tend to be softened on these edges and are generally known as soft sands. Material of this type is significantly less strong with a given ratio of cement but has the advantage of being very workable. The combinations of colour, strength, workability, rate of setting and resistance to erosion must all govern the judgement of the conservator in selecting the most suitable to form the mortar for an historic wall whose qualities he has identified. When any novel situation or unfamiliar combination is encountered, tests and samples should be made and allowed to harden before the mix is finally approved.