Brickwork, Its History, Nature and Behaviour

The degradation of igneous rock in the earth's crust has produced small particles which have themselves in many cases been cemented together by the formation of crystals or by heat and pressure to form yet further rocks which have again been degraded and recomposed many times producing the immense system of sedimentary rocks and deposited calcareous structures which make up much of the accessible part of the earth's crust. Man has built with these stones and has burned calcareous and gypsum-based rock to make cements for durable mortars. For the whole of historic time man has produced a substitute for rocks in places where they were in short supply or not to be found. Dried earths initially provided this substitute and in many circumstances still do — sometimes on a large scale and for the purposes of very modern and sophisticated dwellings. But although earths can be moderately strong and stable, although they can be long-lived and although they are inert, man at a very early stage found a more durable material by firing his earths to a temperature near or at the melting point of silicon oxides.

The romantic may speculate on the discovery of the effect of fire on clays and archaeology suggests, perhaps not surprisingly, that the creation of useful earthenware in the form of utensils preceded the creation of usable solid lump material. By the discovery that clays, and compacted clays in particular, entered into an irreversible change at temperatures upwards of 785°C man created a new materials system of immense utility and incidentally of great value to his archaeological successors, for he laid down a nearly indestructible material which by style and scientific testing can yield valuable information about his activities, his life-styles and his building. Walls of brickwork have proved as durable as those of stone and since many of the crucial developing civilisations found favourable conditions in fertile river valley estuaries, brick as much as stone became the basic structural material of some of the most important emergent civilisations. Mohenjedharo and Babylon were cities of brick for the same natural reason as Venice and Amsterdam: that the necessary materials for its manufacture — wood and clay — were to hand. In many cases a stimulus may have been the lack of available stone.

A very small proportion of historic brickwork is composed of other materials; sand/lime mixtures, asphaltic compounds and molten slag cast into shape. These materials are usually specific to place and time.

It is sometimes forgotten that one essential material in the manufacture of brick — particularly historic brick — was wood, or a similar organic fuel. Depending on methods of firing the weight of fuel required might have been greater than the weight of the brick itself. Thus the labour involved in its manufacture was not simply the labour involved in handling the material as was the case with an earth block; it was perhaps as much again. This disadvantage was offset in comparison with stone by avoiding the need to quarry, shape and transport the material. In any case it must also be remembered that the same process of firing was necessary to oxidise limestone, marble or chalk and so to create lime for mortar. Gypsum mortars could be made similarly by heating although to a much lower temperature since it was only necessary to drive off the water of hydration. If the burning process was necessary to make the mortar for stone masonry it represented little change of technique to burn the brick as well.

Conservators, commonly and understandably, turn to identical materials where significant repairs are required and although they may not insist on the identical techniques of firing they are likely to go to the extent of careful analysis of sands, proportions of lime and types of earths used in the brick making in order to replicate the original materials sufficiently to provide a repair sympathetic in texture, visual quality and performance. By some demarcation of material or technique the principle of honesty in repair can be safeguarded to allow further archaeologists to identify the original work as against the repair even if records are lacking.

A major consideration in brickwork is the size and consistency of the brick itself and this has an important bearing on the ultimate quality of the work. Only in the very earliest bricks is there substantial and consistent evidence for their formation without a mould. Sun-dried bricks laid as flat slabs and trimmed by hand to minimise drying shrinkage could well be burned but even with such bricks consistency of size and shape was a natural characteristic of the product. It was a matter of both convenience in handling and the natural effects of shrinkage in drying which coincidentally produced an optimum size, with a finished dried weight in the median range of around 2 kgs.

Attempts to make larger elements could be successful but required high levels of skill in manufacture and firing. That these could be achieved on an immense scale is demonstrated by the army of terracotta, warriors slowly being exhumed, although left in situ, near Xian in Northern China. Over two millenia ago the terracotta workers of China's first united state were masters of their crafts to a degree difficult to emulate even today; but such skills were far beyond the needs of most peoples. Occasionally very large pieces of terracotta were produced as masonry and some Chinese brickwork has consistently employed components two or three times the natural weight and size of normal brickwork. They represent the largest historical deviation from general practice.

These broad optima of size and weight deriving from handlability and convenience in manufacture have tended to produce a consistency in product — roofing tiles, floor tiles and bricks — which is universal in broad terms but leaves sufficient diversity of detail for almost every type to be recognised and attributed specifically to a period or civilisation. The available techniques in manufacture and the variety of basic brick earths available, together with style and nature of handling, give such distinction to individual types of brick that they are rarely confused. As with stone and timber this diversity is a source of great visual richness in building and the eulogies over the quality of brick as it weathers have been as great as those for stone. The comparison is irrelevant beyond making the point that brick is no poor man's substitute for stone but an equivalent material, as meritorious in its own right and capable in many respects of greater diversity. It too can be carved and can also be glazed and richly coloured. Its natural textures and native colours can be manipulated in the firing and enhanced by facing. The great complexity of shapes into which it can be formed allow it to be bonded and laid in a wide variety of distinctive ways which all relate to the traditional techniques and distinctive styles historically adopted. Many historical clues lie in the making and handling of brickwork and the conservator's response will flow from his historical understanding and the analysis he will have applied to the evidence of events and changes in the life of the building.

A brick or tile, being a man made object, can provide much historic information in its own right. The type of clay used can demonstrate whether it was manufactured locally or imported. Its shape, type, size and density indicates its age, manufacturing technique and historical background. Its detailing shows whether it was intended for use in a specific part of the building, for decoration, for basework, or for mass walling. Its markings may attribute it to a manufacturer or a monarch. In the river Tigris in Iraq, the piers of a long lost bridge are built of bricks, every one of which carries the seal of Nebuchadnezzar. They provide irrefutable historic evidence of origin. Marks of wear, impact or abrasion link the brick to treatment or maltreatment during its useful life. Evidence of shaping, cutting or rubbing describe its place in the building process and the mortar which bound it betrays the origins of its sands and perhaps also the limes and cements. Together they carry the algae, fungi, lichens and plants which they have accumulated naturally and the stains, soots, and perhaps other man-made deposits reflecting events in the life of the building.

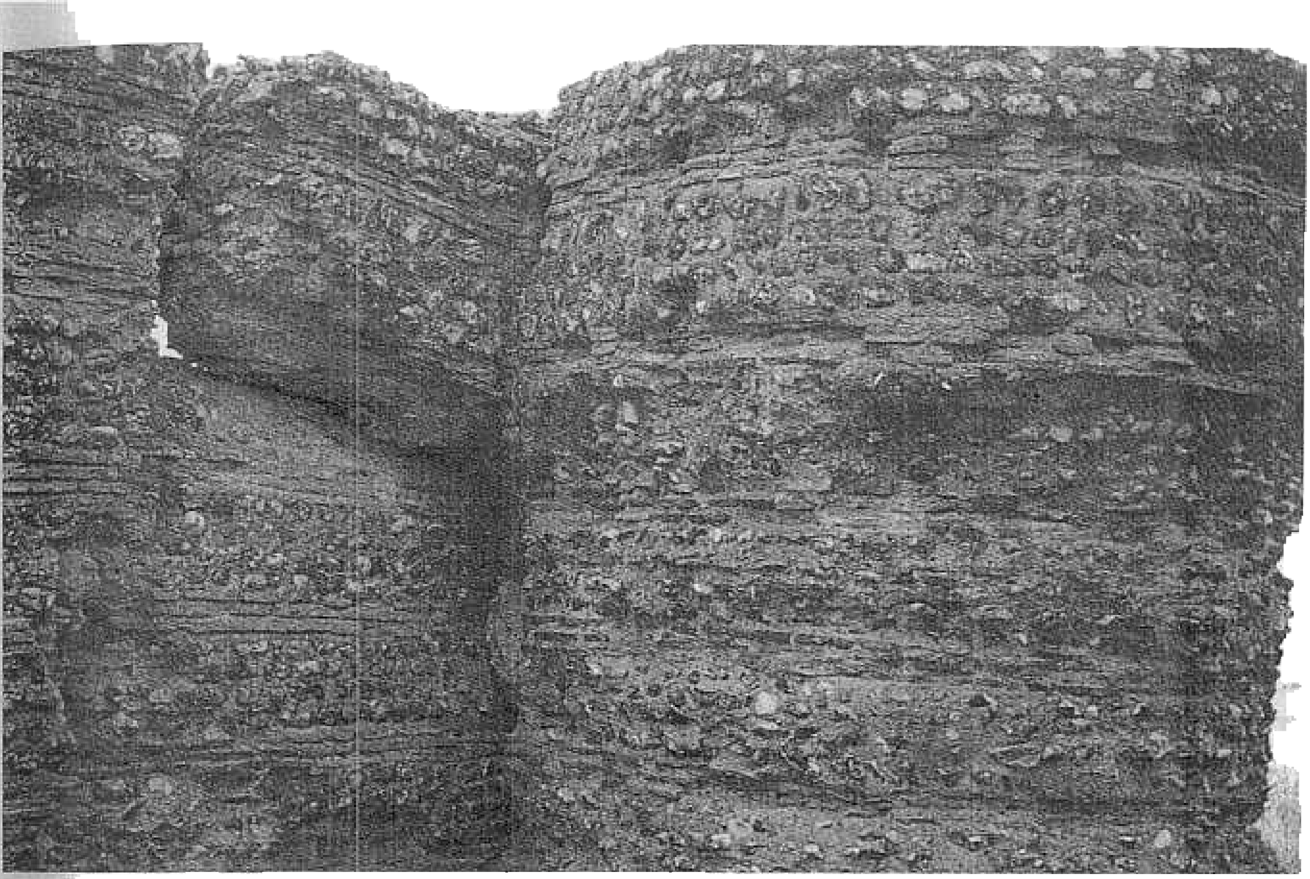
In the process of initial analysis these and features of construction play a crucial part in determining the historical circumstances and background of the building. The essential analysis will initially break down materials of brickwork and mortar into their components demonstrating their origins and the circumstances of their existence. The nature of the bonding, the variations between the forms of construction during different periods and the sequence of construction play a crucial part in understanding the history of the structure. In the great brick-built church of San Marco in Venice, pointed arcading in the narthex, thought to belong to the Gothic period, can be shown to be of very much earlier origin because it lies at the core of the structure and was overlain by 11th century work.

Bonding has always been a distinctive attribute of brick building. It is determined by traditions and practical techniques. Large, flat Roman bricks provide a very different pattern of bonding from the later smaller medieval versions of the same material. Walls where bricks are laid transversely to link two or more skins show the small or header end of bricks and these in turn form a pattern depending on their integration with the rest of the wall.

Under certain methods of firing the header face of bricks is coloured differently from the longer or stretcher face; and these faces in turn are coloured or patterned by the way in which they are set in the kiln and the nature of the heat or the way the flue gases pass them, as well as the nature of the gases themselves. A wall built with identical bricks, some of which have stretcher and some of which have header faces exposed will have a natural pattern resulting from these different colours and although such patterns may arise accidentally at first they become recognised as attractive in their own right and the laying of the bricks is exploited for the sake of the pattern that can be formed. Diaper brickwork has evolved in this way and some styles of architecture — notably Gothic Revival — have made immense play with the possibility of exploiting colour and pattern inherently available in the bricks.

The natural range of colours available in brickwork runs from near black through all variants of ochre, soft reds and browns, greys with a bluish tint deepening to almost black, buffs, russets and yellow-browns. These colours relate both the mineral content and the nature of their firing. By glazing, any colour obtainable in ceramics can be applied to brick as a fired pigmented surface. In Islamic architecture such techniques have been used to achieve brilliant and intricate colour patterns. In some instances the colour is applied only to part of the brick — perhaps a part that has been left in high relief by carving. In other cases the entire surface of the brick is coloured and the brick may be shaped to suit the colour pattern. Alternatively the design can be applied in multiple colours on the one piece of brick in which case incised lines or lines of pigment, such as managanese can be used to divide the adjoining colours.

For the most part colour is achieved simply through the exposed body of the brick but since many techniques of manufacture involved the use of sand, which adheres to the surface, after firing, the outer surface will carry an unusually high proportion of silicon oxides which may have been subject to different atmospheres and higher temperatures than



Roman bricks as coursing in flint masonry (Caister, England).

the interior of the brick, resulting in a variation in colour and texture between the outer and inner surfaces. The firing process also produces a different external surface known as the fire skin and this may be removed by exfoliation, weathering away in whole or part to reveal the inner material of the brick of perhaps different colour or texture.

The brick surfaces vary due to many other effects in firing and the presence of nodules of fuel or surplus particles introduced to achieve patterning. Wide varieties of textures, colours and patterns are achieved resulting in brindled surfaces where multi-coloured irregularies give the essential effect.

Some bricks can be uniform in colour and texture. This is particularly true of muds laid down in the large estuarial valleys, such as the Nile and the Tigris-Euphrates basin. The great river valleys in India and China likewise produce bricks which are monotone and untextured. Walls built with this type of material depend for visual stimulation on the intricacy of the patterns of bonding. These become so important that they are sometimes simulated. Some of the most elaborate Persian brickwork vaults of the post-Medieval period are not all that they seem to be: the true brickwork laid to a complex pattern of interlacing ribs is rendered over with a plaster which is subsequently incised with a pattern of brick bonding even more elaborate than that which it overlays and the whole is finally painted. Pattern making even extends to the bonding itself. Clearly the visual effect of the mortar joints depends on their size and regularity as well as on the laying of the bricks. A very precisely finished brick will produce precise joint alignments. Thick laying of mortar will expose much larger areas of generally lighter colour. The precision of a hardedged (sharp-arrised) brick often indicated a superior form of construction and the use of a brick made to fine tolerances allowed the bricklayer to set the bricks on thin mortar beds.

To achieve a similar effect with rougher bricks the deeper beds of pointing would be coloured to match the faced surface of the brick and in the face of the pointing a fine insert of white lime mortar would be placed to achieve the visual quality of a hard, thick and precise line. This technique was known in England as 'tuck pointing'. It gained prominence in the 18th and 19th centuries. Other techniques of accentuated pointing have included the insertion of small slips of coloured material — often tile or glazed tile which are compatible with the mortars and serve to obscure and protect the mortar itself. Chips of stone, brick or flint have been pressed into the joints for protection and decoration — a technique known as galleting.

The greatest skills in structural bricklaying arise in the construction of vaults, particularly those where thin, webbed shells are required, set perhaps between liernes or ribbed arches designed to break vaults into decorative panels. These panels demanded the shaping of bricks into trapezoidal wedges, polygons and other similarly complex shapes if the joints themselves were not to become dominant in the pattern. For such purposes bricks would be fired to a standard which allowed them to be carved, sawn or rubbed to shape, or perhaps a combination of all three techniques. Islamic architects from Spain to India made the greatest use of such techniques but the hand shaping of components on an extensive scale was by no means confined to the Islamic World. European builders of the 18th century were familiar with a soft brick used for building arches and known as a 'rubber' brick because of the technique of bringing it to shape which involved rubbing two bricks together or one brick against a pumice surface. Similar techniques were adopted across continental America. In medieval Europe and in Muslim countries the shaping of brick and tile by the same methods was used to provide small components which could be employed as inlay, mosaic or be assembled into decorative panels. Such brick was made with great care because of the need for consistency in texture and a density sufficient to compensate for the relatively low temperature of its firing. For this purpose the clays were refined by sieving and/or settling.

Brickmakers, tilemakers and potters use essentially the same technology but in broad terms the degree of refinement improves across the range from brick to pottery. In the intermediate range terracotta is achieved by the use of clays which have been put into suspension in agitated water and have then been allowed to settle in sequence so that the heavier particles separate out first leaving the more refined substance to be settled in a tank from which it is retrieved as a putty. The resulting material is capable of being cast into a mould or modelled by hand while green and then, having been fired, it offers the bricklayer the intended shape without further amendment or dressing. Second firings can alter the surface and can allow glazes or colours to be fixed. In Italian Renaissance Art the techniques of ceramics were used as an ultimate refinement of this process, (particularly by the Della Robbia family) for making the decorative roundels and key pieces adorning the facades of buildings.

Most terracotta, however, has tended to be used in its natural form. Some types are made by double-firing and others incorporate ground pottery or clayware. Much, but by no means all terracotta is hollowed in form to permit greater control of cracking in the drying process. The larger the piece the more essential the internal void!

Special varieties of colour approaching that of natural stone have provided scope for architectural ornament on a scale similar to that of the Chinese terracotta warriors which preceded them by two millenia. Of these the well-known English example is the Coade Stone of the 18th century, fired at high temperature from a mixture of reground ceramic or fired clay materials.

Brickwork must never be thought of in terms of bricks alone. Its behaviour is governed by the characteristics of its mortar as much as by the bricks themselves. In some instances the mortar content may exceed the weight of brickwork in a wall. Byzantine masonry is a case in point and the consequential movements of the walls and piers of the greater buildings during their construction and their subsequent flexibility under changing loads and sudden stress such as earthquake provide a wide topic of specialist study which has wider implications than the specific historical period. The behaviour of brickwork as mass masonry is, therefore, governed by the nature of the mortar as much as by the bricks themselves and any evaluation of fault or failure must look at the two materials as well as the combination in terms of an inert mass.

The mortar may be weaker than the bricks or stronger. It may adhere to the bricks or detach readily. The first step in evaluation in the nature of brickwork will, therefore, be to determine what combination of these characteristics is present and whether they are uniform throughout or across the wall surfaces and the building structure generally. Brick is not itself necessarily consistent and nor is mortar. The mortar being the common bearing material throughout the structure will, with advantage, be the weaker, with the result that strain will first appear in the mortar joints and will tend to pass through them rather than through the bricks. However, even if the mortar itself is weaker the nature and direction of extreme stress will be a determinant which may in fact induce failure in both materials and allow a crack to run through masonry in a consistent direction.

Mortar itself is inconsistent and towards the face where a pointing has been used may well be very different in composition from the core material. Likewise bricks on the face of a wall may not represent the fill at its centre where weaker bricks and rubble or even voids may produce a very different pattern of strength. Aging and salt deposition can cause a once consistent mortar to vary, being perhaps, weaker close to a surface, or conversely stronger and more brittle. In some walls a discontinuity is deliberately designed within the structure. Cavity wall construction is by no means new, but its employment dates it generally within the last hundred years. Earlier forms include brick walls in which the bricks themselves were used as cross ties. In one type (in England known as Rat Trap Bond) the outer skins are formed by bricks laid on edge. An adaptation of this idea in which a cranked and sometimes glazed brick was used to span the cavity was superseded by the provision of metal and now plastic fixings. The condition, nature and frequency of these connections affects the performance of brickwork and the transmission of loads. With the recognition of historic buildings which are sometimes no more than a generation old the performance of facing skins and detached outer skins becomes increasingly relevent to the conservation architect and architectural historian.

Mass brickwork not only receives and transmits loads; it delivers them. Where a large masonry mass is constructed with a powerful hydraulic mortar or with modern cements it may act as a single element delivering the load of its own weight and anything superimposed on it as a concentrated load at any point: in other words it may act as a gaint rock by virture of its coherence. If on the other hand the same bricks are set in a soft mortar the load is likely to be uniformly distributed and any transmitted loads, if received at specific points will be diffused rather than concentrated. This applies both to mass masonry and to non-structural panels. A panel held together by powerful cements is likely to behave as a uniform coherent object, whereas one secured by relatively weak mortar will fragment under load and collapse in small components. A mortar weaker than the bricks is unlikely to transmit to brick stresses sufficient to fracture them whereas the converse is the case with mortars stronger than the fired components. Therefore where any of these are of particular importance — pieces of moulded terracotta or historically significant bricks for instance — a weaker mortar goes some way to securing their future, provided that it does not itself induce failure of the wall.

The composition of mortars is a science on its own while their appropriate formulation in building operations remains something of an art, albeit governed by well known rules. The art lies in understanding the balance of stresses in a structure, in assessing the qualities of its components and in formulating a mixture which will achieve the best balance between longevity and strength in specific circumstances.

Historically mortars fall into four originating materials — earths, limes, gypsums and cements and these are all intermixable so that a wide range of resulting types are achieved in historic buildings. Virtually all mortars contain sand, although occasionally pure lime, pure gypsum and other exceptional materials such as bitumen have been used. Bituminous mortars — with or without sand — and modern synthetic mortars are rare and will be used only for specific properties or in specific circumstances. Earth mortars are non-setting but have by no means been confined to earth structures. In wide areas of the world burned bricks have been set in earth mortars sometimes of a calcareous nature and, therefore, being partially setting they are considered below.

The essential differences between the three forms of setting mortars relate to the chemistry of the solidification. In all cases the physical process is one of the formation of crystals which, as they grow, interlock and impact one upon the other and sometimes melt at their junctions. As a result loads will be transmitted from particle to particle and crystal to crystal in a complex structure which can never be as strong in compression as the individual crystals of which it is composed.

Gypsum (calcium sulphate) which in its purer forms is known as Plaster of Paris is found in nature in a form containing large amounts of water of crystallisation. When heated this rock, gypsum, gives off some water of crystallisation at a relatively low temperature (c. 400°C) but does not undergo a chemical change. The resulting material can be powdered and when mixed with water it reverts to the previous hydrated form, the reaction taking place quite suddenly and simultaneously in the material. As the enlarged crystals form they lock together into a solid mass which, if rigidly contained during this setting period improves upon its natural density because its expansion causes internal compression.

Comparatively the strength of the material is low and its slight water solubility is a significant defect. It has been used extensively, however, particularly in the construction of arches and vaults where the quick set allows the construction of unsupported brick arching. Its strength is always below that of brick whatever the addition of sands. While it has good adhesion to brick it has the advantage of being removable from the surface allowing the original brick to be salvaged and reused. Due to its solubility its use is more frequent in dry climates.

Lime is the material traditionally used for durable masonry particularly in damp climates. The burning of stones containing a large percentage of calcium carbonate (some limestones, some marbles and chalks) has provided the basic raw material which is normally burned in lump to allow airways for the flue gases. This also is a relatively crude process and at temperatures of about 880C°, calcium carbonate breaks down into calcium oxide and carbon dioxide which is driven off as a gas. The calcium oxide — quicklime readily recombines with water and the resulting hydroxides will form a putty or slurry which mixed with three parts of sand is the basis of most lime mortars. These mortars are stiff, plastic mixes which become stiffer as they dry and absorb from the air the carbon dioxide necessary to return the calcium hydroxides to crystalline calcium carbonate. This process takes some time depending upon temperature and mass of masonry. In very large masses of brickwork the penetration of sufficient carbon dioxide to thoroughly carbonate the masonry core may take upwards of a year during which time the material is less strong than may be required to carry the superimposed loads. An empirical understanding of this relatively slow process lay behind the modest pace of many historical building projects. The crystals of calcium carbonate tend to be slender and are susceptible to fracture. They are also very slightly water soluble depending on the PH value and the nature of the salts in solution. Frost action can fracture solidifying crystals causing loss of strength but lime mortar has the compensating advantage that in the presence of moisture and carbon dioxide in solution, crystal growth can continue. Hence the material can to some extent regain strength after crystal fracture. This means that lime forms a sufficiently soft mortar to tolerate structural change but that it can recover some of the strength lost due to physical damage and deformation.

The strength and setting characteristics of pure lime mortar are significantly changed by the presence of forms of silicon oxide, together with others such as magnesium oxide and alumina which result from the melting of sands. These cause a very much more complex crystal pattern to emerge during the setting process in which the crystal structure is not dependent upon the absorption of atmospheric carbon dioxide. These mortars are generally stronger and more durable. The effect was noticed at a very early period when Roman bricklayers mixed volcanic ash with their mortar and found that they obtained a powerful and more rapid-setting cement. They then discovered the technique of using it in bulk with the random addition of larger pieces of inert material-rock and brick — and the result was a form of concrete. Earlier concretes have been discovered (in China) but the extensive use of this material by the Romans based on their discovery of the setting qualities given by volcanic ash constitutes the first extensive structural use of the material. The discovery of its reinforcement with iron, however, as an effective structural practice, had to wait a further eighteen hundred years.

Much of the ash used by the Romans came from Pozzuolana near Naples and lime mortars with such setting characteristics tended to be known in consequences, rather incoveniently, as 'pozzuolanic' mortars. Clearly it was not feasible to transport the volcanic ash of Naples throughout even the known Roman world. A substitute was found in the use of the burned and sintered sands and clays resulting from brickmaking. Hence the addition of brick dust which was commonly used as a hardening agent in historic lime mortars. The two industries of lime burning and brickmaking provided the basis for making self-hardening mortars until relatively modern times.

In the processes of deliberate and accidental experiment that went into the making of mortars composed essentially of lime the addition of materials such as bone, clay and sands was almost inevitable and some of these experiments yielded types of material which were a preliminary to modern cements. Some of the experimentation was involuntary in the sense that limestones and to a lesser degree chalks contain materials other than calcium carbonate. They were laid down beneath the sea by the decomposition of marine life which had made use of the calcium carbonate to provide skeletal and shell structures. The immense deposits thus formed, have locked up carbon dioxide in the crystalline marine rocks of the earth's crust. When heated with sands and clays a more complex chemistry gives rise to crystal formations in which silicon, magnesium, aluminium, boron and fluorine play a role in addition to calcium; these are 'cements'.

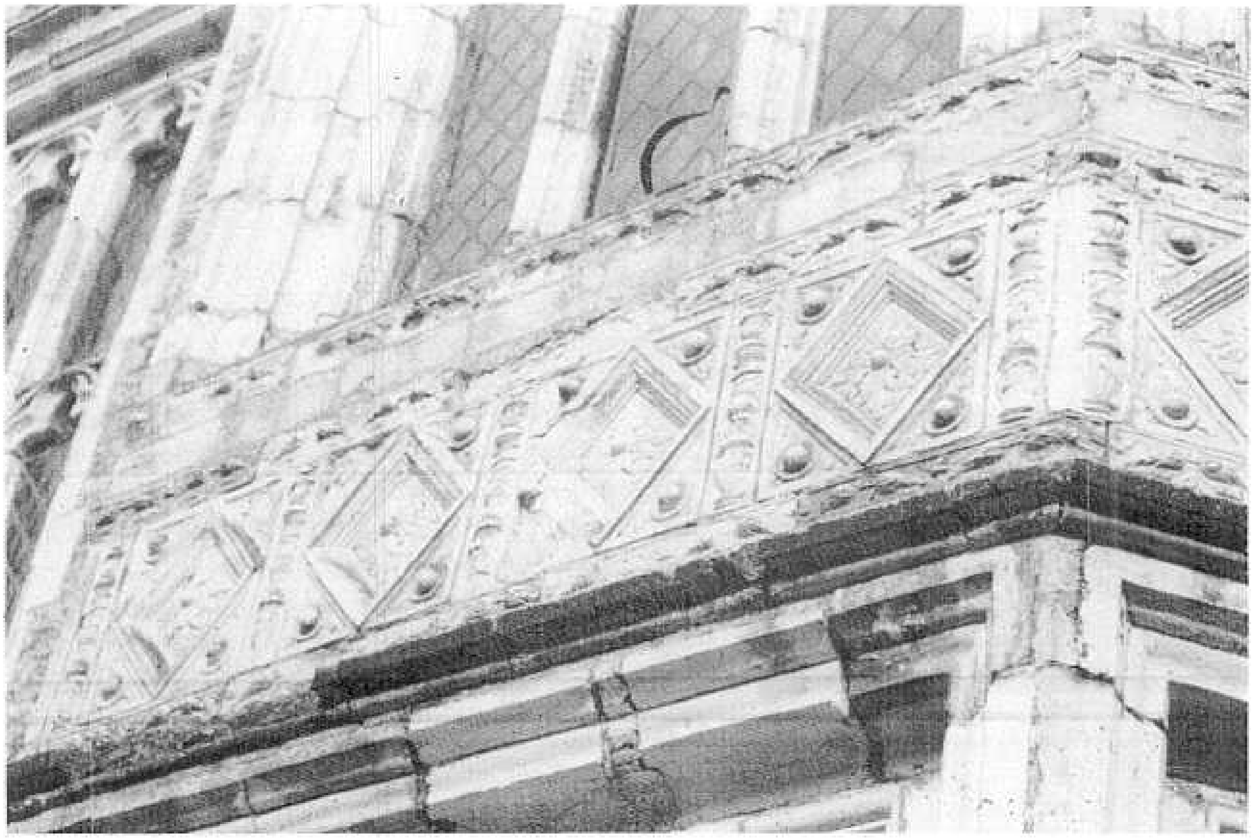
Mortars containing these materials produce a chemical 'set' and have been known as hydraulic mortars from the fact that they are able to solidify beneath water. The term is confusing and has nothing to do with the general nature of hydraulics, being the behaviour of liquids under pressure. Many historic structures are built with lime mortars that are to some degree hydraulic. In producing compatible mortars small additions of Portland or other cements may be added to lime putty to produce the same effect but yet create a mortar which can in future be distinguished, by chemical analysis, from earlier historic mortars.

The behaviour of brickwork depends as much upon mortar as upon the bricks themselves. Apart from the coherence of the structural mass which follows from mortar strengths there are a number of defects which can derive from the different natures of the materials.

In fire, brick may be unaffected. It is a material formed at high temperature and will soften or fuse only at temperatures in excess of 1200°C. Despite this the presence of water and the effects of rapid temperature change, or significant temperature differential may cause cracking, spalling or flaking, breaking down its structural coherence. Mortars are more likely to be damaged by high temperatures, gypsum and lime mortars disintegrating completely after heating to well below 1000°C. A lime mortar calcined by fire and quenched by water can disintegrate explosively, transforming a load-bearing mass instantly into rubble.

Water absorption by brick and by mortar will be different in extent and behaviour due to different porosities. Rates of evaporation will differ and hence the build-up of soluble salts will vary from one to another. Sulphates in chimney stacks and nitrates leaching up from soils may cause expansion and loss of coherence in mortars before any effect is noticed in the brick.

The effects of frost action upon brick, however, may cause crazing, loss of fireskin, spalling and decrepitation to the extent that the



Early moulded terracotta on structural brickwork. (England).

brick crumbles away leaving a reticulate pattern of hard mortar standing out to the line of the original wall-face.

Biological attack may vary, the roots of plants making deep inroads into the mortar, while the bricks themselves are unaffected. Algae and lichens, however, may find purchase on brick surfaces but be repelled by alkalinity in the mortar.

Cracking may occur in either or both as the structure is stressed by subsidence or settlement, by ground heave caused by tree roots or changes in water content. Vibration, pressures due to expansion or corrosion, alterations in loading and structural tensions will affect brickwork differently depending on the relationship between the mortar and the brick and the cohesion between the core and surface layers of the structure.

Excessive loading on a face may be induced by the failure of material in the core or by the presence of corroding iron or the failure of ties. This will be evident in the buckling of a column of brickwork or the detachment and bulging of a skin. The distress in the material may be immediately evident and failure can occur suddenly through bursting out and collapse.

Horizontal stress can be induced similarly. The common cause is the thrust of a pitched roof whose ties have failed. A tie beam built into a wall might fail through the gradual effects of rot. Such tie beams in wet brickwork may be effective initially over a long period, their restraint being achieved by fixture to a pad or plate. With the advance of decay the effectiveness of that restraint can diminish and an apparently stable and secure roof will produce outward thrust in the walls which the brickwork is not designed to resist.

Other, more obscure faults, can be equally damaging. The replacement of timber flooring by kiln-dried slabs of manufactured board (an undesirable intervention in an historic building) may result in the board taking up moisture in its new position and expanding to the extent that thrusts on one wall are betrayed as cracking on flanking walls.

Changes in ground water levels in clay soils may be responsible for movements powerful enough to crack brickwork, producing apparently incongruous movements. A growing tree or a new drain might in a dry period withdraw sufficient moisture from clay benath a building to cause one corner to be inadequately supported. Many historic buildings stand on foundations too weak to withstand changes of this nature. The reduction in the support at the corner of the building might not be expressed by cracking at foundation level or in the lower parts of the wall but by a crack some distance from the affected area in the upper section of the wall but reflecting a downward movement in the foundations at the corner of the building. The position of any such crack will be controlled by any inherent weaknesses in the wall represented by door and window openings or by previous minor structural movements causing discontinuity and possible failures in longitudinal members such as wall plates or even in the weakness inherent in the scarfing of such timbers.

The action of drawing together all the relevent information is critical because only thereby can the possible causes be assembled analytically and their effects valued. Many hasty and ill-advised decisions of repair are still evident in historic buildings. Presumptions as to the causes of failure will have been made wrongly with consequent ineffective remedial action.

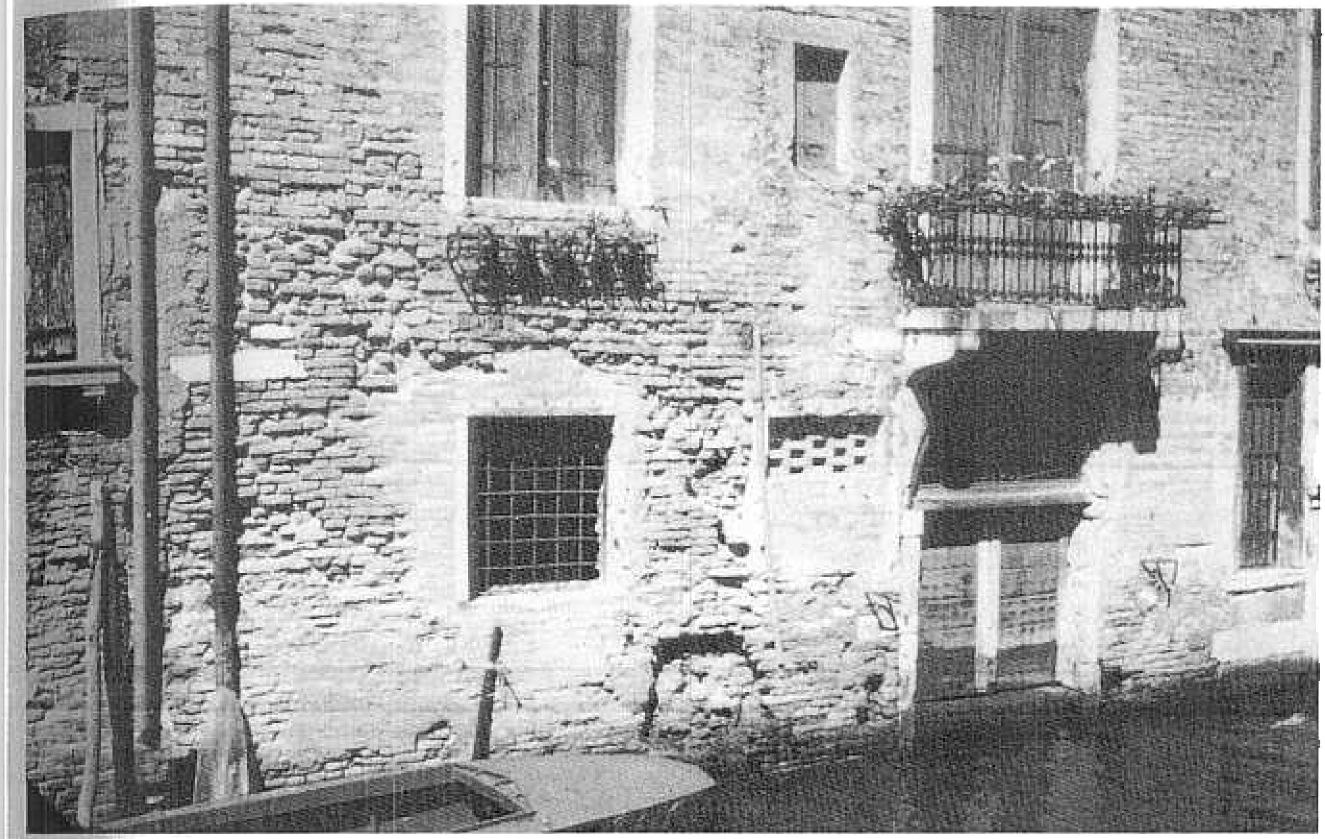
Most remedies are straightforward. A failure in a tie beam demands careful repair or renewal of that tie beam with protection against its future decay. The rusting of embedded iron demands its removal and replacement, but these two actions are in themselves insufficient. The rusting would not have occurred without water entry into the brickwork nor would the timber have decayed. It may have to be accepted that by the nature of the historic buildings construction water will always enter the brickwork and must, therefore be tolerated. In such a case an alternative material must be substituted. Wrought iron may be replaced by stainless steel or heavily hot-dipped galvanised material set in a bituminised recess. Decayed timber might be replaced by epoxy resin or with timber totally impregnated with a proofing material sufficient to ensure its longevity. A pocket might be formed in the brickwork to allow ventilation around such timber. A permanent anchor might be required to ensure the cohesion of the tie beam and the wall. The amount of water entering the wall might be found to be due to defective rainwater goods or roofing materials or perhaps the failure of leadwork or a damp proof course. Faults of this nature might call for direct remedy but additional measures might be taken. Some types of water entry might be reduced sufficiently by providing protection or by altering wind patterns and air flow by the removal or planting of trees. In some circumstances the conservator might contemplate the introduction of modern chemicals to reduce the absorption of the wall surface without interfering with evaporation and a whole series of decisions lie in the alternatives of restoring a structure to its original position as opposed to stabilising or fixing in the position it has taken up after the damaging event.

These lines of argument must be carried through from the point of identification of all possible faults and weaknesses to the stage where an adequate range of precautionary and protective measures have been taken and the faults affecting the brickwork have been corrected. At this point the damage to the brickwork itself will be considered and the evaluation based on minimum intervention will be translated into action. In some instances no action will be necessary. The visible effect of the damage may be accepted as an historic incident in itself which can be allowed to survive as representing an event in the history of the building. Provided that the fracture is not disfiguring or an inducement to further failure or decay this argument may be acceptable.

Minimal intervention might be seen as the simple pointing up of a fracture with no attempt to restore structural continuity in a circumstance where this was of no importance. The merit of this action might be that no further opportunity would be left for weather penetration and that the pointing up in itself would act as a telltale allowing future development of the failure to be monitored.

These minimal interventions are of virtually no structural effect and therefore are applicable where the conservator is satisfied that additional strength or recovery of the original strength is unimportant.

The depth and nature of internal cracking and failure is frequently not evident in historic structures. Thick walls may well be composed of weak or minimal mortars and loose fill in the core. A wall which may appear to be perfectly sound can be opened up to reveal substantial loss of material. This removal of weak mortars by insects and the leaching out of poor and decayed mortars by water flow can produce significant internal voids. These may be detected by experimental boring and by the introduction of water under modest hydrostatic pressure. Some water will be taken up by absorption into the internal brickwork but the immediate acceptance of substantial volumes of water can indicate the extent of major internal voids. The emergence of water elsewhere is a further indication of the continuity of these voids and internal



Decay of brickwork due to excessive moisture. (Venice, Italy).

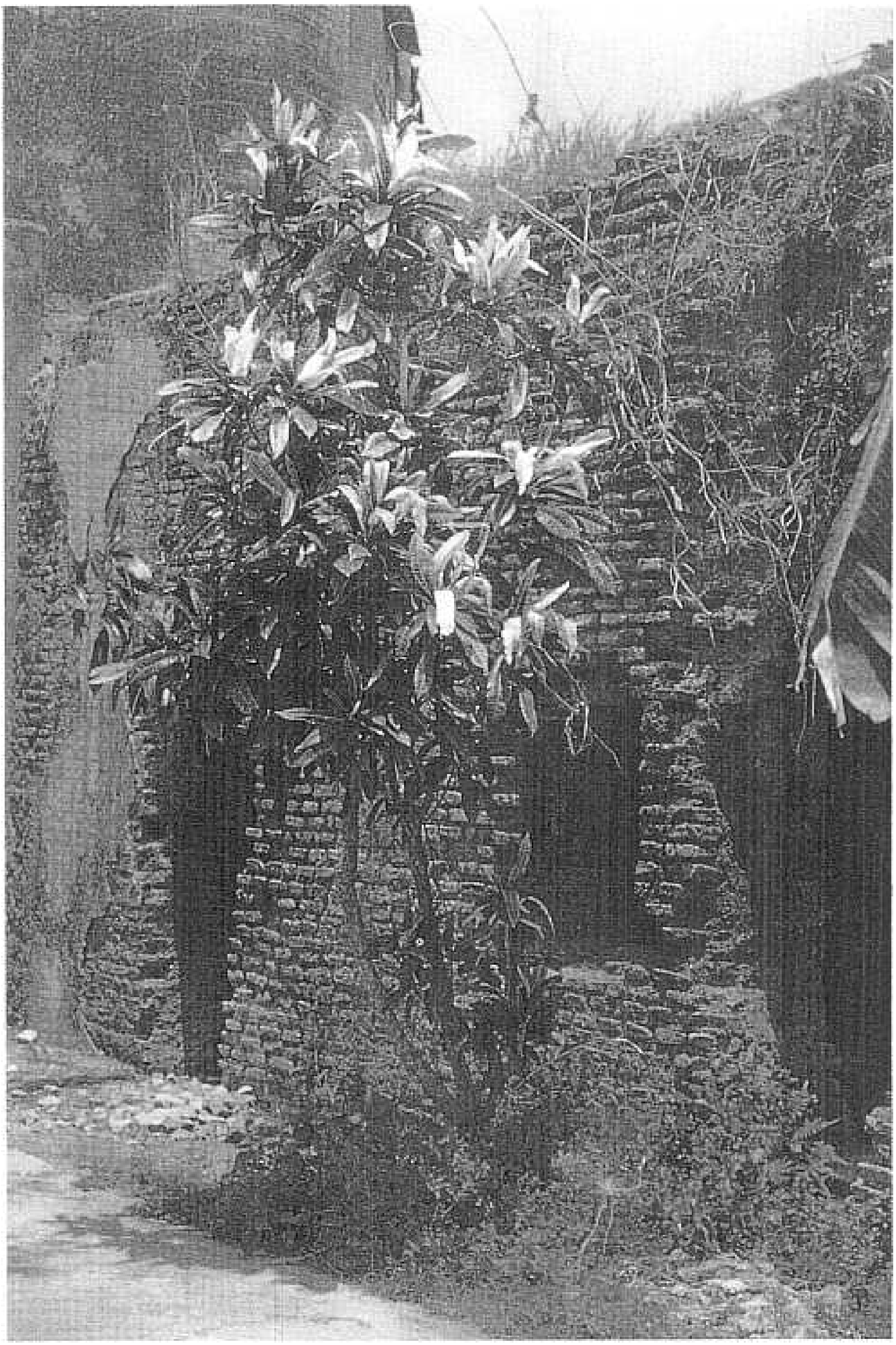
weakness. A direct solution to this problem is the introduction of grout. The grout should be of a mortar which will set to a strength and density compatible with the mortars in the wall. This may argue for the use of lime or for another material such as pulverised fuel ash — P.F.A. This ash is the residue of the high-temperature combustion of coal in fluid-bed burning, and the location of coal-burning power stations is likely to determine its availability. A slurry produced with P.F.A has considerable penetrating power due to the spherical nature of the particles. Additional strength may be provided by the introduction of lime and/or Portland cement in judicious quantity. The material should always be introduced to a damp masonry and, therefore, the initial flow should be of water unless the wall is already saturated or very well wetted.

Emulsions of long chain polymers such as polyvinyl acetate are now available and sold for the purpose of providing adhesion between mortars and brickwork. Their longevity is not yet proven but such bonding agents can have a place in grouting and seem to offer the advantage that they minimise the leaching out of calcium salts and consequent surface staining. If introduced in high dilution — e.g. a ratio from 1:15 up to 1:30, emulsion: water in the wetting agent and included in similar dilution in the mix they provide a method of strengthening and stabilising the core of an historic wall without disturbance to the face. Grout may be introduced under pressure for the purpose of gap and crack filling. If mechanical pressure is used the conservator must be satisfied that the internal pressure created will not increase the cracking, burst out the surface of the wall or have other weakening or damaging effects. High pressure grouting is usually suitable only where cracking has occurred in rigid structural brickwork. All surface orifices must be sealed before application of the grout.

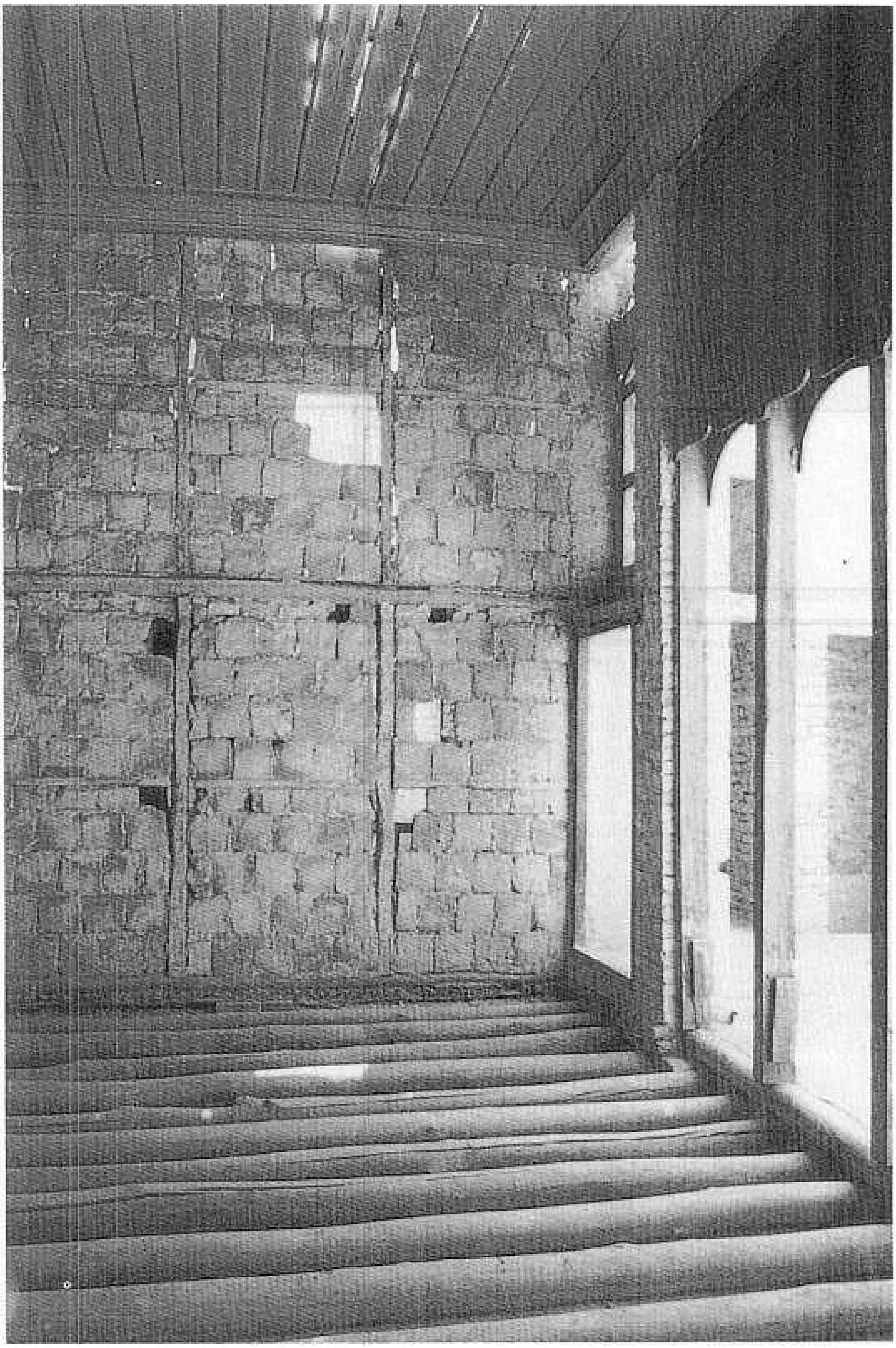
It is to be remembered that strain may be the result of stresses due to temperature, thermal movement, frost action and direct pressures such as earthquake and physical impact. It can also be due to erosion. Stresses give rise to strains (i.e. physical movements) and where these exceed the tolerance of the material, rupture takes place. The resultant cracks are clearly visible and represent a structural discontinuity which it may be necessary to correct. The nature of the discontinuity will be symptomatic of the nature of the brickwork and the type of load or other stress laid upon it. Air movement can also induce stress by wind loading and the abrasion of structures by windborne particles is at times a crucial cause of failure. The continual erosion by wind blown particles of surfaces damaged by the salt laden rising damp can be an astonishingly rapid cause of destruction to major brick monuments whose upper structures have remained intact and virtually undamaged while their supporting walls are eroded at ground level to the point where the entire structure topples.

Water can damage brickwork by dissolving mortars, by dissolving limes and other products of the initial burning in the bricks themselves, by erosion — in particular by the freeze-thawing cycle — and by supporting plant life which generates root expansion and decays induced by organic acids. These latter are some of the most insidious forms of decay and are responsible for the slow degradation of even well-burned brick. Perpetually damp brickwork may be entirely stable in itself but may present to other materials, such as adjacent timber, a serious source of decay and for this reason corrective measures will have to be applied. Cut or physically damaged bricks are very much more susceptible to decay, particularly in wetted and exposed conditions than those which remain whole.

In analysing the reasons for decay before taking any corrective action the first stage is to understand the precise nature of the brickwork and its components. The second stage is to understand the loads, pressures and forces which have acted upon it during its lifetime and the third is to know clearly and precisely what force or form of erosion has caused it to fail or might cause it to do so. In the majority of cases several forces will be at work each of which could cause a failure in due course. Only with the completion of an all-embracing analysis can a permanent repair be specified with full confidence.



Decay of brickwork due to plant growth. (Sonargon, Bangladesh).



Thin timber-framing whose failure will cause brick panels to fall apart. (An Najaf, Iraq).