12 Physical Behaviour Over Time

This chapter deals with the third major aspect of the physical behaviour of the construction: consideration of the analysis of deterioration, movement and wear. All these processes will happen during the life of the building and may reduce the reliability of the construction to continue its contribution to the performance of the building. Concerned with the changes that might take place with time, it considers the potential failures and the implications for maintenance and repair during the life of the building.

Reliability: renewal, maintenance, repair and disposal

The analysis of behaviour over time is about understanding possible changes that take place in the materials, components, joints and fixings that will affect the ability of the construction to perform. Changes may reduce the chance of performance the next time design conditions are experienced. The reliability of the construction is reducing. Its chance of failure under the next set of testing conditions becomes greater.

However, in most cases, construction is not just built and then demolished at the end of the life of the building. Its reliability may be dependent on interventions during its life to keep satisfactory performance. To evaluate a proposal against its reliability over time it is necessary to specify:

- How long it is intended to last before it is renewed
- What maintenance it can expect during its life
- What is the impact of failure and the ease of repair

To complete the specification it is then necessary to identify:

- How it can be dismantled
- What options there are for safe disposal

Without both the initial detailing and specification and a clear statement on these interventions in the life cycle of the construction, the proposal has not been fully evaluated.

Not all parts of the building have to last for the same length of time before renewal. Clients' and users' requirements change and, while not foreseeable in detail, they are likely to involve finishes and the division of space more than structure. It may be more economic to renew than to maintain, although this may not be desirable against sustainability criteria. It is necessary to establish as part of the analysis the client's commitment to renewal cycles and maintenance plans.

Another strategy for some parts of the building is to expect failure and renew or repair if and when this happens. For the client this has a cost burden for loss of use and in establishing an organisation of repair in the case of failure during the operation of the building.

These decisions on repair and maintenance concern all parts of the building from tap washers through decorations and roof finishes to the life cycle of the building itself, including expansion and change of use. Clients will have a view on the management of the facilities they use for their everyday operations. Decisions on value for money and sustainability are not just concerned with initial costs but the whole life cycle of the construction.

The basis of choice is therefore to understand the changes that take place over time and then consider the options for renewal, maintenance and repair to keep operational performance. Proposed construction will have to have an initial specification that should have foreseen the anticipated maintenance, with an analysis of the consequences of failure (safety, cost and disruption) and the ease of repair, with requirements for access that have to be incorporated into the design. If the client does not favour maintenance, and repairs cannot be made easily, then initial specification and detailing may have to be changed before the final choice is made.

Finally there is the consideration of dismantling and disposal which may also include decommissioning. Whether considering renewing a part or the demolition of the whole building, the ease with which it can be taken apart and the impact of disposal should be anticipated in the original specification and details. When this is seen as an economic issue it may be considered to be so far into the future that it can be ignored at the stage of initial design. However, with the increasing emphasis on sustainability with its focus on the quality of environment for future generations, dismantling and disposal can no longer be so easily dismissed at the design stage.

Basis of analysis

In the past the limited number of construction materials coupled with relatively low performance expectations allowed knowledge to build up over the years. Details were developed to protect parts from decay. Where protection was not possible, there was a greater acceptance of maintenance activities to keep the construction in good condition. The details that developed were often regional, if not local, to fully take into account the particular conditions for the locality. More than the detailing, the orientation and grouping of buildings took into account local exposure conditions, further protecting the vulnerable parts of the building from the worst ravages of the weather.

This description of the close links with experience, locality and building traditions no longer holds true for the majority of buildings erected today. This places greater emphasis on the designer's ability to undertake an analysis of behaviour of the construction with the passage of time.

There are three broad areas of analysis that have to be considered as significant to the reliability of building, each with a potential to lead to failure, invoking the need for maintenance, replacement or repair:

(1) Environmental deterioration (durability)
(2) Movement
(3) Wear

There is a need to understand their direct effects in order to undertake an analysis of the proposed solution to identify ways in which the building might become less reliable, require effort to maintain, and ultimately fail.

Durability of materials

Over time, changes take place in the properties and integrity of the materials of which components are made. This will alter their performance in the future. It should be acknowledged that some of these changes are beneficial in that they improve the durability of the materials. The weathered surface of stonework is a good example of this. This makes the material more durable. It is important to recognise this not only when specifying new building work but also when considering cleaning, maintaining or altering the building. However, many changes that take place reduce the durability of the material.

Durability of a material is dependent on the conditions to which it is subjected. Each material has specific agents of degradation or preservation. It is not possible to determine the durability of a material in a building without a clear definition of the conditions under which it will have to operate. Each material has associated agents and mechanisms that are known to degrade or preserve the materials. Either material must be chosen to survive in the expected conditions or, unless a new material is specified, some protection or preservation must be specified.

Agents and mechanisms

The mechanisms of change can be identified as taking place either within the material or at the surface. In both cases there will be a change to the internal structure of the material that is affected. This internal change can either affect the properties of the material or disrupt the internal integrity of the material, both of which result in a change in performance, most often for the worst. Changes in properties include embrittlement in plastics and fatigue in metals, while examples of internal disruption are wet rot in timber and sulphate attack in ordinary Portland cement-based materials. In each of these examples changes only occur in the presence of specific agents. Embrittlement is associated with ultra-violet light, fatigue with reversing stresses, wet rot with dampness and sulphate attack with sulphates and moisture.

These examples also serve to bring out another useful way of thinking about these agents of change. They are chemical (sulphate attack), biological (wet rot) or physical (fatigue). There is often a coincidence of conditions as in frost disruption where saturation and cold temperatures cause a change of state, not in the materials, but in the saturation water, causing a physical internal disruption of the material normally just below the surface.

Study of the major materials used in building shows that water plays a part in many of the deterioration mechanisms, as does air with its ready supply of oxygen. These components are not only significant in many biological processes but also in chemical processes, for example oxidation.

This is not perhaps surprising, for the processes of nature are dependent on decay and regeneration. Many of the materials from which we make our buildings are taken from nature and they are, therefore, part of the decay–regeneration cycle. Understanding the mechanisms and agents in this cycle becomes the key to predicting the durability of many materials and diagnosing failure.

Many of the more recently adopted materials we use are not naturally occurring but have been refined or processed. The pathways and agents of change in these cases are often to revert to their original or lower-energy states. Many processed materials have proved to be stable with time, for example glass. However, there is a tendency in some processed materials to change to lower-energy states which may not have the properties that we carefully designed into the processed materials. Many of these mechanisms also need agents, again often water and oxygen, with other chemical agents accelerating the process. The mechanism of oxidation in metals is a good example of this.

Oxidation is a surface process where the oxidised layer does not have the properties of the parent material. Oxidation of iron (rust) is recognised as reducing the life of a component. Not only does the oxidised material have a greater volume than the parent material, which increases the dimensions of the original component, but also the rust layer itself ruptures and allows the agents of oxidation to reach down to new parent material, continuing the cycle of degradation until all the material has rusted away. However, this is another example where not all changes reduce durability. Non-ferrous metals, such as aluminium and copper, oxidise, but this new surface, while of greater volume, changing the dimensions of the component, is not great enough to rupture the surface layer itself. This new oxidised layer or ‘patina’ is stable at normal temperatures and therefore protects the underlying parent material by significantly slowing down the rate of degradation. The component’s life is potentially increased.

The identification of agents associated with the mechanism of deterioration or preservation for each material is a key aspect of the analysis of the durability of a material. It involves the identification of the environment in which the material is to function.

Cycles and concentrations

Because the rate at which changes occur in materials varies with exposure to the agents of change it is necessary to project an expected pattern of exposure. The pattern must identify the frequency with which changes in concentrations of agents, which are in contact with the materials, are expected to occur. Because many deterioration mechanisms have a number of agents involved, a pattern for each has to be established so the frequency of coincidence can be identified. In frost damage, not only is the coincidence of saturation and low temperatures important, but also the frequency of the freeze–thaw cycle is crucial to the rate of deterioration. If the material remains dry at low temperatures there is no deterioration. If the material is saturated but remains frozen for long periods there is little chance of deterioration. If the material is saturated and freezes at night and thaws during the day, there is a greater chance of deterioration.

It is very important to carry out this analysis of conditions very locally, in immediate contact with the material. It is very possible that even different parts of the same component are subject to very different patterns of exposure. Failure is often very localised, as with the wooden fence post rotting around ground level shown as a high-risk area in Figure 12.1. Here the patterns of concentrations of moisture, air and decay organisms are at their greatest and the cycles of change at their most frequent. This is also a good example to identify the preserving nature of some agents if their concentrations remain high but steady. The example here is water and timber. If water is constantly present, maintaining the timber in a saturated condition, it acts to preserve. The fence post buried deep in permanently wet ground does not decay. To continue the fence post example, the top of the post is also vulnerable as it is end grain that allows the water deeper into the timber, providing a pathway to high local concentrations of the decay agents.

This pattern of conditions allows an analysis of the rate of deterioration that takes place at the critical point in a component. Most materials in the building will have periods of decay and periods when little change is taking place. This may, however, in most cases be considered in the long run to be a gradual change. The changes taking place are making the component less reliable the next time the component has to operate at or near its design limits. The fence post breaks in a high wind but no worse than winds it has survived in the past.

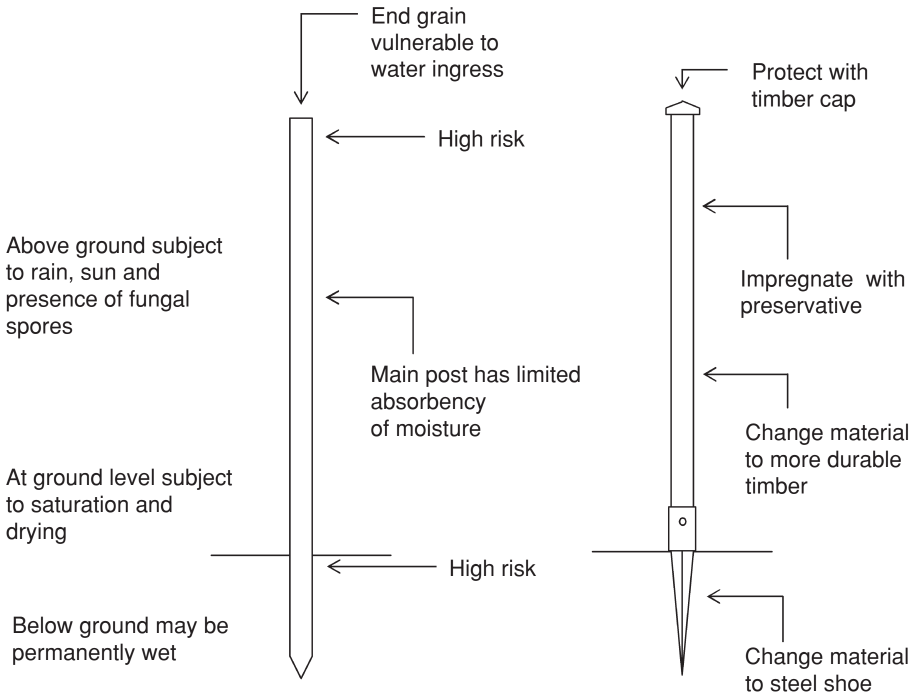

Figure 12.1 Timber fence post – deterioration and improved durability specification.

Where deterioration patterns are identified as creating a high probability of failure (or the consequences of failure are catastrophic) then consideration has to be given to changes in the suggested specification. It may be possible to protect the vulnerable parts from the agents of decay or provide some preserving process that limits the effects of the decay agents. It may be economic to change the specification of the material. In the case of the fence post the end grain at the top can be protected with a cap, the timber preserved particularly where it enters the ground or a metal shoe placed in the ground to receive the timber above the aggressive line of the ground. In this case the deterioration of the metal shoe would have to be analysed.

The maintenance expectations for this specification of the fence post might include the gradual reduction of the effect of the preservative, which would have to be replenished, applied by brush some time in the future. Maintaining and/or repairing of the cap at the top of the post would be cost effective as it is easy to do. The ultimate failure may well now still be at the base of the post even with the metal shoe. If maintenance of the metal shoe is not contemplated then it may be that repair of the first few posts to fail could prolong the life of the fence, but ultimately the renewal of the whole fence would be the preferred option. Dismantling would not be problematic and neither would be the disposal of the timber as long as the preservative was not still active. It may be that at this stage the metal shoes may be cleaned, renovated and reused.

Movements in components

The term movement here refers to changes not only in position but also more generally in size or shape of the components. All buildings and their components will be subject to these movements, but, if correctly detailed, this need not lead to failure. Movements of this kind can be limited, accommodated and allowed for but cannot be eliminated. The dimensional changes are often termed inherent deviations as they occur due to the inherent properties of the materials. This is in contrast to the induced deviations that are the result of the production process and need to be considered to ensure that the initial construction will fit together, as discussed in Chapter 4.

Many movements pose little threat to the building. If they can take place freely, without impacting on adjacent construction, they will have little effect. Movements that are of concern are generally differential, where one part is moving more than another to which it is connected, or restrained, where one part is moving in one direction and meets another that cannot move (or is indeed moving to meet the first part). However, some movements need be very small to have a large effect. The shrinkage of cement mortars in brickwork breaks the bond with the brick, causing fine capillary paths leading to the potential for damp in the building, as discussed in Chapter 10, where the most common solution is to introduce a cavity to break the damp path to the inside of the building.

Much of this movement can be accommodated in the normal detailing as long as care is taken in thinking through the probability that induced deviations will not eliminate the gaps and/or that the limit of flexibility of jointing materials that allow the movements to take place freely is not exceeded. These details then have to be built with care to ensure that the expected allowance is achieved in reality. Some movements are so significant to the integrity of the construction that specific movement joints have to be designed. These may be required where structures of different heights come together with different foundation settlements. Another example is the design of large panels of brickwork where environmental changes will cause internal stress in continuous construction.

The origins of these movements can be traced to one or more of the following:

- Initial equalisation immediately after installation
- The application of loads
- Changes in environmental conditions
- Volume change associated with deterioration
- Ground subsidence

Initial equalisation movements

Many materials undergo dimensional changes early in their life while the material is developing its final properties, often through changes in temperature or exchanging moisture. These movements are normally irreversible. In processing and manufacture, many materials have to be prepared to make them workable to produce the shapes and forms required in the component. For some components made off site, at least some of these equalisation changes in dimensions take place before they are delivered. Many components, however, have not completed this change when built into the building, and for work carried out in situ all the dimensional change takes place in the final position.

Materials most often built into the building while this change in dimension is still taking place include timber, concrete and clay products such as bricks. Timber components are manufactured at moisture contents above those that will eventually be achieved in the occupied building and therefore will continue to shrink after installation. The equalisation movements in concretes, plasters and brick also include changes in moisture but in different directions. Concretes and plasters need water for setting and workability and then dry out and, therefore, like timber, shrink. Bricks that are fired and therefore very dry at the end of the manufacturing process take in moisture and therefore expand after the initial cooling shrinkage has taken place.

The important factor is often the timing of the installation. Concrete blocks laid too soon after casting will continue to shrink, causing tensile forces leading to cracking in the wall. While the majority of expansion in bricks takes place in the early weeks after firing, they continue to expand well into the initial life of the building. Some continuing expansion of brickwork should be anticipated. As brickwork normally has sufficient internal compressive strength this expansion will lead to the whole panel sliding on the damp-proof course (DPC) or cracking at short returns.

In in-situ work, all the initial equalisation takes place in position. Drying shrinkage in concrete laid in large areas such as ground floors can lead to cracking due to internal tensile forces that build up during the equalisation phase.

Loading and environmental movements

These movements are dependent on the properties of the materials and conditions experienced by those materials during the life of the building. Movements caused by loads will depend on the stress/strain relationship of the materials and on the distribution and magnitude of the loads themselves. The two major environmental agents are temperature and moisture. Nearly all materials change dimension with change in temperature. The amount of movement that takes place in a material for 1°C change in its temperature is its coefficient of linear expansion. Only permeable materials will be subject to moisture movement. Like temperature changes, the change has to take place within the material, not just in the external conditions. The amount of moisture movement that can be expected is normally quoted as a percentage of the original size.

The timing of movements caused by environmental and loading conditions can be seen to be associated with two phases that may overlap in time. The first phase takes place predominantly during construction and in the early stages of occupation, where the movements are usually not reversible. These are taking place at the same time as many of the equalisation processes and are initially associated with loading. Structural members are gradually loaded (dead and imposed) as the building is constructed and during the initial phase of occupation. This loading increases stresses that increase strains, causing the distortions discussed in Chapter 11.

In addition, the temperature and moisture conditions can be very different during construction depending predominantly on the time of year. This determines not only how quickly equalisation processes take place but also the size of components at the time when adjacent construction is installed.

Once the building is occupied most of the loading is completed, but the internal conditions are now being established for the first time. This will move the temperature and moisture to working conditions and during this period more dimensional changes will be taking place. Not all strains from the applied loads take place immediately. While settlements in non-cohesive soils will take place as the loads are applied, consolidation in clay soils may take years to complete, meaning that not all foundation settlement is experienced in the initial loading period. Some materials, including concrete and timber, exhibit creep. This is a continuing strain under constant sustained load. The rate of strain decreases with time but can manifest problems some years after the construction of the building. This period could cover the first few years of occupation.

The second phase in which movements may take place covers the rest of the life of the building, after the first few years of occupation. These movements are usually reversible. Most of the equalisation process will have taken place.

The effects of environmental changes in moisture and temperature on external materials become significant in this second phase. Exposed areas can experience wide variations in temperature. In temperate climates these are not so acute on a daily basis but are experienced in the annual cycle of the seasons. While air temperature varies from summer to winter, materials exposed to the radiant effects of the clear sky experience the greatest surface variation. Midday summer sun can raise the temperature of surfaces, particular if dark in colour, to temperatures of 60°C. Conversely, clear night skies in winter will reduce temperatures of surfaces directly exposed to the sky to −20°C, again particularly if dark in colour. This potential 80°C difference will significantly alter the dimensions of many of the common materials used externally on buildings. Particularly vulnerable are continuous roof coverings, leading to the specification of white-coloured protection to limit the temperatures experienced by the roof covering itself.

External materials also experience wide changes in moisture, from prolonged periods of sunshine to extended periods of rain. Perhaps this is most often noticed in timber doors that ‘stick’ in wet weather. The materials affected, which have to be permeable to absorb the moisture, fall into two categories: rigid internal structures and elastic internal structures. These are broadly ceramics such as brick and concrete and organic materials, predominantly timber, respectively. Ceramics are subject to relatively small changes, while timber is subject to significantly larger changes. Timber shrinks and expands differently in different direction to the grain, changes being greatest across the grain.

Interior components are subject to less variation in temperature and moisture unless the activity undertaken in the building creates variations in these environmental conditions and no specific measures such as ventilation are taken to limit the areas affected. It should not, however, be assumed that all internal components will remain stable. Windowsills are particularly vulnerable to sunshine through the glass, raising their temperature, and fittings associated with heating systems will be subject to wide changes in temperature. Pipes should be able to move freely where they pass through the construction or they may ‘creak’ as the movement takes place.

Movements due to temperature and moisture changes only take place if the changes occur within the material, not just at the surface. However, surface changes can create internal stress as the surface tries to change but is restrained by the mass of the material. This image of layers of construction expanding and contracting at different rates is particularly important if layers of different materials are to be bonded together to act as a composite. If thermal expansion properties are significantly different then changes in temperature from those at the time of bonding will create bending stresses in the materials and shear stresses along the bonded surfaces. This is also true for moisture changes. Materials bonded together that get wet can suffer similar stresses to those suggested by temperature changes if their moisture movement characteristics are significantly different.

Volume change associated with deterioration

In considering durability earlier in this chapter, some of the changes were in the properties of the materials, but some involved changes in volume. They were mainly associated with the chemical changes, such as sulphate attack or corrosion, but would also include frost disruption. These changes in volume not only create the potential to disrupt the component itself but also have a potential to create additional stress in adjacent components with which they are in contact. An example of this is the attaching of stonework using iron fixings that rust.

Ground movement, settlement and subsidence

The ground is subject to two types of movement: settlement and subsidence. Settlement is the result of loading and moisture changes in the soil and therefore its analysis is the same as that for loading and environmental changes of any other part of the building.

In assessing the consequences of settlement it is important to remember that it is the overall flexibility of a building that determines the amount of settlement it can sustain without distress. Brick structures in cement mortar can take less differential settlement without cracking than brick in lime mortar. Frames with pin joints can take more differential settlement than continuous structures without a redistribution of stress that may cause failure.

To assess settlement, soils are often characterised as cohesive and non-cohesive, representing the clays and the granular soils respectively. This is a useful distinction when considering movements in the soil carrying the building. Under loading conditions, clay takes considerable time (sometimes years) to compress (the action is consolidation) and even then may be subject to creep. Granular soils compress (predominant action compaction) almost immediately the load is applied and do not change unless the loading is changed.

Clay soils undergo high volume changes with changes in moisture, not a characteristic of granular soils. Processes of desiccation in clays include seasonal drying of soil in the summer and removal of moisture by vegetation, particularly trees. These movements can be very large and very powerful. Not only will a drying and therefore shrinking clay cause additional settlement but also clay taking up moisture will heave with sufficient power to lift the building. Generally, foundations should be established sufficiently deep to be below any chance of these movements affecting the support of the building. Piles may need to be sleeved as heaving clay will grip the pile and lift the whole pile with the building on top of it.

The freezing of water within the structure of the soil can also cause heave in some soils, typically silts, chalk, fine silty sands and some lean clay. Foundations should, therefore, be placed below the frost line in these soils (unless building on permafrost, a condition found in some cold regions of the world).

Increasingly buildings are being built on ground that is neither cohesive nor granular as defined by geologically laid down material. Landfill, be it from excavation, demolition or domestic waste, is creating new development sites. This material is highly variable and cannot be easily generalised. It may have been well laid with some measure of compaction or it may have been just tipped. The engineering properties of such materials have to be carefully investigated before foundation decisions are taken. Taking deep foundations through the fill, ‘floating’ the building on a raft or improving the ground to allow shallow foundation in the fill may represent the economic answers. This will depend not only on ground conditions but also on the building structure, taking into account the scale of development and the flexibility of the construction.

Subsidence causing a loss of support to the soil acting as the foundations can occur with geological changes or from human activity. Geological changes can be deep, such as earthquakes, which, while a real threat in some parts of the world, are not a design consideration in many others. Geological processes can also be surface actions, with slope stability being a particular threat to buildings. Natural slopes can become unstable in extreme weather conditions, but man-made slopes created as part of the development process can also become unstable, threatening the support to foundations. If slopes have to be steep, then retaining walls may have to be built to protect the buildings at both the top and bottom of the slope.

Mining activity gives a particular subsidence problem. When some mine workings are abandoned they may collapse, causing a lowering of the ground surface in a wave behind the collapsing galleries of the mine. Buildings that exist as the wave passes are vulnerable, but after it has passed, new development is less threatened. Shafts and swallow holes (natural shafts which open up in limestone areas) can also pose a threat and site investigation and a search of the geological and mining records are essential in areas known to be active.

Movement and detailing

Movements occur because of changes in shape, size or position of the materials and components that may or may not in themselves create any damage. The possibility for damage often lies in the detailing; the way the parts are connected and fixed. As soon as parts are connected or touching then there is the potential for the movement or its effects to be transferred. If the detailing allows the movement to take place freely then only the component itself need be considered. If no such freedom can be identified in the detailing then the movement will be restrained and force will develop between the moving and restraining components. This force may move adjacent components or may induce stresses that distort parts that are still held in position; finally it may induce stresses sufficient to crack or break components or the fixing between materials.

Estimating possible movements in a particular material or component is, therefore, only the start of any analysis. It becomes necessary to be clear on the details to identify free and restrained movements.

The first part of the analysis of details involves estimating the possible position of the parts when incorporated into the building. This cannot be assumed to be the position shown on the drawing. Each operation on site can only be achieved within certain dimensional limits associated with induced deviation. The exact position within these limits cannot be known at the time of specification. It can only be assumed that construction will be achieved somewhere within the extremes of these allowable tolerances.

Movements take place from this initial installed position. Equalisation changes that have not taken place at the time of installation will cause movement, loading as it is applied will cause movement, environmental changes may induce movements and later deterioration may create a change in dimensions, again causing movement. Not all of these will always be cumulative. Expansions may tend to cancel out shrinkage, as with concrete where operational thermal expansions are really greater than equalisation drying shrinkages. The shrinkage in concrete may, however, aggravate other details such as in the connection of a clay brick façade, which will tend to expand while the concrete frame will almost certainly shorten by both concrete curing and subsequent loading (including creep). The form of a movement joint to accommodate these movements while remaining weatherproof is shown in Figure 12.2.

If this analysis predicts failure then modification needs to be made to the specification or the detailing. Materials with different properties may have to be considered. Protection for the conditions creating the movements could be considered. However, the most appropriate option may be the redesign of joints or connections to accommodate the movement, allowing it to take place in a controlled way where the detailing can include gaps or materials capable of taking the movements without loss of performance.

Wear of components

The section on movement has concentrated on the changes in dimension, shape and position that occur in components when loading and environmental conditions change. Wear is also

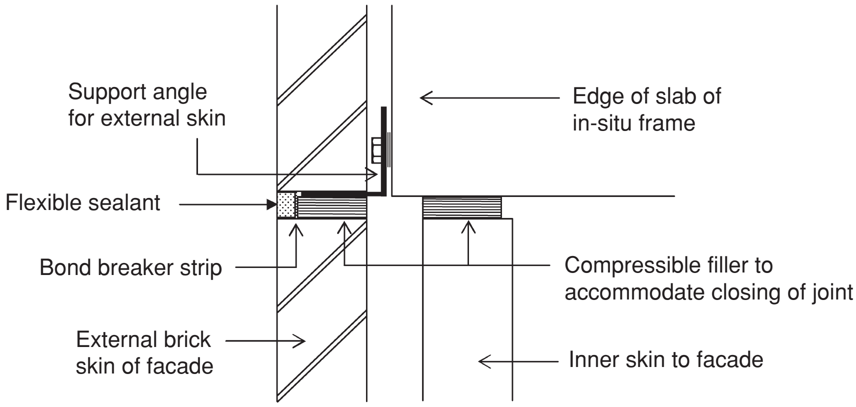

Figure 12.2 Brick façade on reinforced concrete frame – detail of movement joints.

the result of movement, but in this case in parts that are designed to move, such as hinges or moveable partition tracks. Wear is not determined by the conditions to which the components are exposed but by the frequency of operation. It is only a small part of the analysis of most construction because the majority of building construction is concerned with passive performance.

Wear is more of a consideration in services where moving parts are often associated with motors and machines that are part of services systems. Here the possibility of loss of performance at some future date requires access to remove and replace parts or even replace the whole unit. This has to be considered in the design of the building as well as the design of the parts themselves.

Summary

(1) During the life of the building, changes occur in the materials and components that affect the reliability of the construction to perform the next time it is tested under its design conditions.
(2) The three broad changes that might bring about a loss of reliability and failure are environmental deterioration (durability), movements and wear.
(3) Environmental agents causing deterioration are specific to each material, and therefore it is necessary to determine the concentration and frequency of these agents in the environments associated with the specific components of the building, often very localised to one vulnerable part of the detail.
(4) Movements, or changes in shape, size or position of components, can be caused by initial equalisation processes following installation as well as the loading and environmental conditions of temperature and moisture changes that may take place during the life of the building. Movements in the ground then require a separate understanding associated with subsidence, which is in addition to the loading and moisture changes that cause settlement.
(5) Wear takes place in parts designed to move and is, therefore, more significant in services design where provision has to be made for replacement of parts or whole units.
(6) Not all these changes lead to failure. Distress in the building leading to loss of performance will depend on the detailing limiting deterioration and accommodating movements.