

9

Analysis of Physical Behaviour

This chapter is the introduction for the three chapters that follow. It establishes the rationale for the titles of these three chapters and draws out the common approach to analysis that is associated with understanding physical behaviour. It considers function and performance as the outcome of the physical behaviour, which, linked to the need to prevent failure, leads to the need for an explanation of how the construction responds when working under design conditions.

Visualising conditions and response

Given that a proposal for the construction has been suggested, however tentative or outlined the description, it is possible to start to think about its physical behaviour. There are three primary areas of behaviour that are of significance to the success of the building, namely:

- Behaviour creating environments
- Behaviour under load
- Behaviour over time

The analysis of physical behaviour is predominantly a technical activity, since it is undertaken after the function of the parts has been defined and after the conditions under which it has to operate have been established. It varies from an analysis of the appearance of the building in that it is not based on a social or cultural response but on a response to the condition of the physical environment. The analysis of physical behaviour must be based on an understanding of the laws of nature, the forces involved both in states of equilibrium and in the dynamic behaviour during changes in conditions.

Function and performance – a technical aim

This analysis of physical behaviour takes as its criterion for success the idea of performance.

Every part of the construction fulfils a function. It has a reason for its existence and a part to play in contributing to the function of the building as a whole. While the client or user determines the function of the whole building, the functions of the parts are determined by the chosen design concept.

Having established a design and assigned functions to a part of the construction, it is necessary to identify a level of performance. It is against these levels of performance that analysis can be undertaken and the failure modes identified. The language of performance levels will vary, but the common idea is that the performance statement must be testable. Examples would be that beams must carry load without exceeding a determined deflection, walls may have to resist the passage of heat with a specified level of insulation and no dampness should appear on any internal surfaces of the external elements of the building.

Preventing failure – a technical objective

Failure is a loss of performance. Failure follows when the response of the proposed construction does not meet performance levels. If the beam were too small or made from a material that were too elastic and had not been shaped or fixed to overcome these shortcomings, it might

deflect too much. The beam has failed to perform. If the loads were larger than predicted and the beam deflects too much, the origins of this failure are in the prediction of the design condition.

The analysis of physical behaviour requires three areas of understanding:

1. Identification of all the performance criteria
2. Careful consideration of the source and nature of the operating conditions
3. Understanding of the mode of failure of the construction responding to working conditions

This requires an ability to imagine the ways in which the construction might physically fail to achieve performance under the design conditions. The clues to this should be in the performance specification itself, for example excessive deflection in beams under loading conditions or excessive heat transfer through the walls under winter environmental conditions. It will also require a method of predicting how much deflection or heat transfer will occur to check that behaviour will remain within performance limits. The clues to this will come from visualising the internal action of the construction under these conditions in order to determine the response.

Future predictions play a part in this analysis, and this is often difficult, given the expectation of longevity for most buildings. Just establishing higher performance levels for some expected future requirements is problematic, for higher performance levels will have cost implications. Variations in conditions with time, including accidental events, need to be predicted with some probability, since designing for all imaginable circumstances also has considerable cost implications.

These considerations for the future add to the difficulties of prediction. They may be included in the brief but, if not, can be part of a technical analysis in so far as the sensitivity to error or change in conditions can be carried out. A solution that is sensitive to change may be less attractive if the future is not certain. This adds an additional dimension to the analysis. How

close to failure is the solution when under working conditions? Will small changes greatly increase the probability of failure?

This prediction of sensitivity can be part of the analysis undertaken by visualising the response of the construction under the expected conditions. Understanding of the response of the construction to the external conditions allows the estimate of behaviour under working conditions and any capacity it may have to withstand unexpected or deviant conditions.

The role of observation and science in the analysis

It is suggested that an understanding of the ways of nature is necessary to provide the descriptions and determine the behaviour, and hence the performance, of the construction.

Experience can offer direct observation of construction both during production and under working conditions. In unfortunate cases experience can offer the opportunity to observe failure. If no failure is observed in a form of construction, it can be repeated in similar conditions and be expected to achieve similar performance levels, although this observation tells us nothing about the sensitivity of the construction. If failure is observed, some explanations are necessary to determine what changes are required to achieve performance the next time. Requirements for higher performance, operating in different conditions, or a change in the construction for production for economic gain also require explanations. These explanations have to be in the form of a description of the response of the construction in resisting failure.

For those engaged in technological activity the naturally enquiring mind is likely to seek such explanations. It is possible that over the past centuries, individuals have provided their own explanations in order to develop construction in a systematic way, refining solutions and occasionally making larger leaps of understanding to new forms of construction. Whatever the scale of change, these explanations have given confidence in perusing new ideas that

would achieve performance with a limited (or at least considered) chance of failure. It is interesting to speculate whether the great cathedral builders had their own explanations to visualise behaviour.

Science provides a framework for exploring the laws and forces of nature. It provides a method of investigation from which explanations of the natural world can be verified. These explanations are useful in explaining the behaviour of construction. Science does, however, have its own language, which can be daunting to many. The knowledge derived from science has two major powers, one of explanation and one of prediction. Only the second, that of prediction, really needs to use the language of science. Explanations can be reduced to everyday language for they are only descriptions of the way the laws of nature operate. While it is the explanations that help understanding of the way in which construction may be functioning (action), prediction becomes necessary to establish a level of performance.

The approach to analysis

The analysis will be based on visualising the dynamic actions and processes involved. This will be achieved predominantly with verbal explanation or word pictures. Description of the mechanisms involved seems to offer the most widely applicable approach to understanding technology. All this can be greatly

assisted by diagrams and mathematical modelling on the one hand and by experience on the other, but both these seem to need a verbal articulation, not only for a personal understanding of behaviour but also to provide an explanation to others of the basis on which the solutions have been adopted.

The aim should be to build a picture in the mind's eye first of what the solution will physically look like (the suggestion) and second of the actions that determine the response that describes the potential failure under working conditions (the analysis). Providing a description of both physical construction and then the response to the construction against certain criteria, which if not satisfied would result in the construction being deemed to have failed, is the underlying approach used in this text.

Four basic areas have been established and need to be understood to complete an analysis:

- Conditions expected through the life of building
- Failure or loss performance
- Proposal or suggestion of the construction (components and assembly)
- Response of the proposal to the condition

The chapters that follow provide the basis for this visualisation. It involves a dialogue between the proposed construction and the response of the construction to the conditions in which it has to be built and operated in order to limit the risk of failure.

Summary

1. Performance identifies the level to which the construction has to function under the design conditions and becomes the criterion for any evaluation of success.
2. Failure is a loss of performance at some time in the service life of the building under a predicted set of conditions.
3. Failure follows the action of construction. Action is the internal response of the chosen construction under the conditions in which it has to perform.
4. Visualising the conditions under which the construction has to function and the expected response of the construction chosen provides the basis for an analysis to evaluate satisfactory performance.

10 Physical Behaviour Creating Environments

This chapter takes in turn each of the aspects of environment that are important to the well-being of individuals and their possessions in the building. These have been identified as dryness, warmth, light, acoustics, cleanliness, security and privacy. In achieving these environments the building must be seen as a system employing both active services and the passive building fabric. The overall performance requirements will depend on the severity of the external conditions and the specification for the internal working conditions. The design will have to assign the role and contribution (function and performance) of each part of the construction to the creation and maintenance of the required environment. Once the contribution to performance for any part of the construction is known, it is possible to undertake an analysis of the response of construction under the working conditions to evaluate the chance of failure. For each of the aspects of environment, the dynamic response of the proposed construction can be visualised, based on an understanding of the law of nature and hence the action or mechanisms that may lead to failure.

Aspects of environment

This chapter is concerned with the aspects of physical behaviour of the construction that ensure the internal environment required to support the activity carried out in the building. These activities require aspects of both social and physical environments to be considered to ensure the well-being of the occupants and their possessions. All aspects of the physical environment will rely on the physical behaviour of the construction to ensure a satisfactory internal environment. However, not all aspects of the social environment will require a contribution from the physical behaviour of the construction. Space and appearance is not considered in this text as a physical behaviour and has been discussed in Chapter 8. Some aspects of the social environment such as privacy and safety do rely on some physical response from the construction. In the case of safety, the physical condition may be associated with loading and will, therefore, require the analysis outlined in Chapter 11. The range of physical and social environments is given in Figure 10.1.

The building as a system

Before evaluating the behaviour of the construction it is necessary to assign functions to each part and define the required level of performance that each part has to achieve to ensure the balance of flow and transfers to create the conditions required.

A definition of the required environment does not say anything about the contribution to be made by the various parts of the building. Even when the social and physical worlds outside the building have been defined, all that has been established is the total task of modification.

Before functions can be assigned to the various parts of the building it is necessary to develop an overall view of how the required environment is to be created and maintained. There are three basic groups of technologies available to fulfil these functions:

- Passive fabric
- Active fabric
- Active services

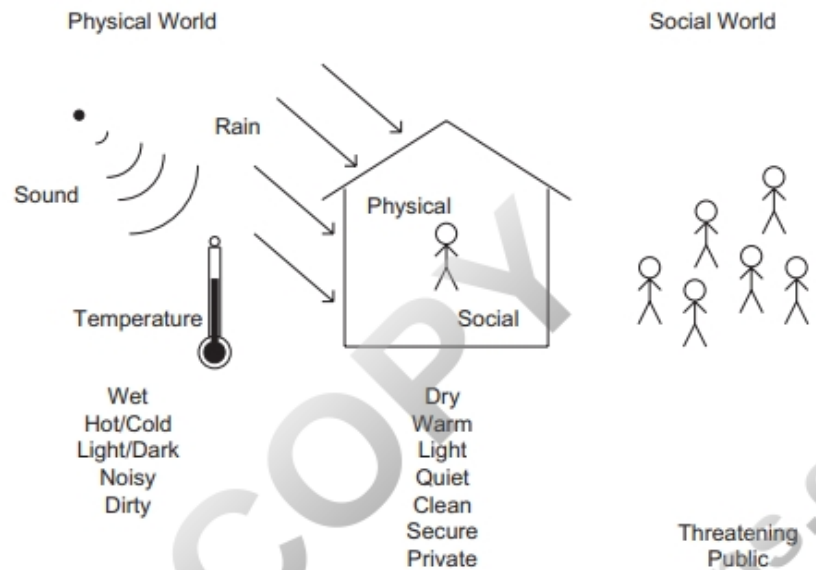


Figure 10.1 Physical and social environments.

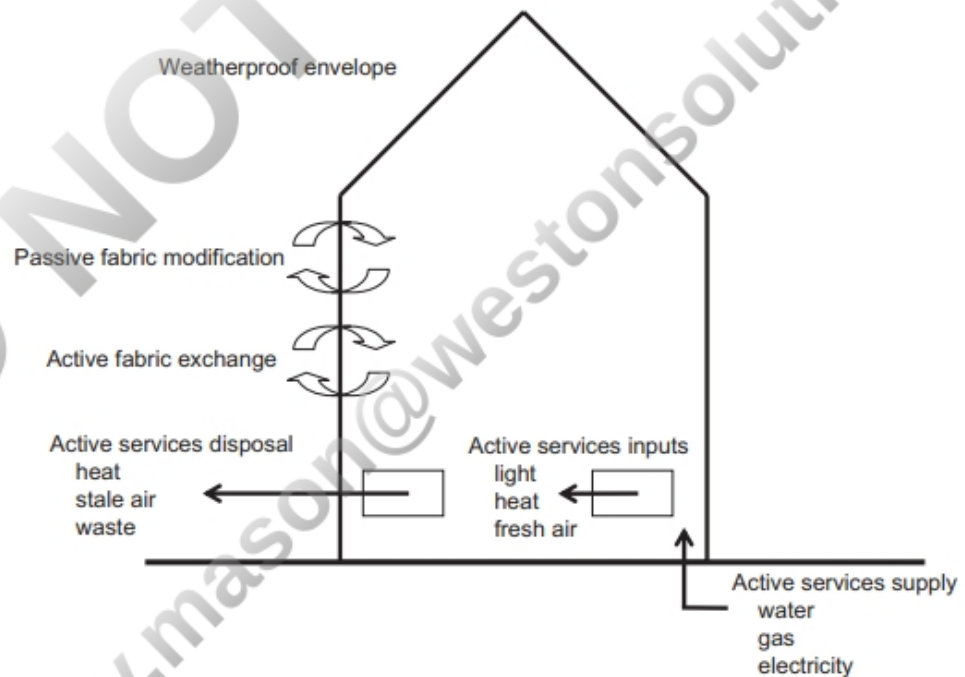


Figure 10.2
Creating internal
conditions – possible
technologies.

These are shown in Figure 10.2. It could be argued that the supply and disposal services are not all strictly environmental services, but all contribute to the provision of the active creation of the environment even though they contribute

to other operational services as well. Water, gas and electricity, for instance, are often categorised as utility services.

Many of the aspects of environment can be achieved with different combinations of these

three types of technology, for example the use of artificial lighting to supplement natural lighting provided by windows or roof lights together with the colour of walls. Decisions on this balance are influenced by initial costs, running costs, energy use and the control arrangement to be incorporated. With an increase in emphasis on the environmental impact of buildings, the combination of building design and active fabric solutions can reduce energy use from the active services.

Even when this balance between services and fabric has been established it is still possible to assign the functions of the fabric in a number of different ways. Some functions are fairly obvious, such as the roof covering's function of weatherproofing to create and maintain a dry internal environment. For others, alternatives exist. In providing a warm environment thermal insulation may be chosen to maintain temperatures in order to limit the need for heat inputs. This can become a function of either one or all of the main elements of the building, roof, walls and ground floor, each with various levels of performance contributing to that part of the strategy for maintaining internal temperature levels.

When the balance between services and fabric has been established, it is possible to start to develop details and specifications. The approach to each of the three types of technologies is different, generating a different set of decisions for each.

Passive and active fabric

Where the creation of the internal environment depends on the contribution of the fabric, the process of choice is focused directly on the variables identified in Chapter 4.

If passive fabric is to be employed then the primary concern will be for:

- The properties of the materials
- The dimensions, usually thickness
- The joints and fixings

For example, if sound transmission is being considered and mass is to be used to achieve

performance then, as will be seen later in this chapter, the density of the material will determine the thickness required, so long as the joints do not support flanking paths and the fixings provide sufficient rigidity.

Where active fabric such as windows are being used, the focus becomes the joints and fixings to ensure the operation of the moving parts. The material, shape and dimensions of the active component will be determined more by their strength and reliability in use, although they may also have a passive contribution to make that will require analysis, as suggested above. They may have to be considered for appearance, as these components are almost certainly visible.

For active fabric there will also have to be some form of control so that their effect can be brought into use when required.

Active services

The final choice of components and materials in services systems is not as straightforward as the direct choice that associates the specification of the fabric with the environmental conditions. Their choice has become a design discipline in its own right. They are systems within the system of the building as a whole. Figure 10.3 suggests a way of considering the active environmental systems and their integration into the overall building design.

The outlet for the services are required to link the user with either a supply or a disposal system, as shown at the bottom and top of the diagram. Taking a heating system as an example, a radiator may be provided as an outlet but has to be linked to a heat source. In this case the active distribution would be via heated water contained in pipes, most probably using a pump to provide a mechanical force. The radiators would be located in each room, probably under the windows. The boiler to provide the heat would need to be located to make fuel and flue connections plus with consideration of appearance and as a possible noise source. The pipes may be routed through the floors and either within or

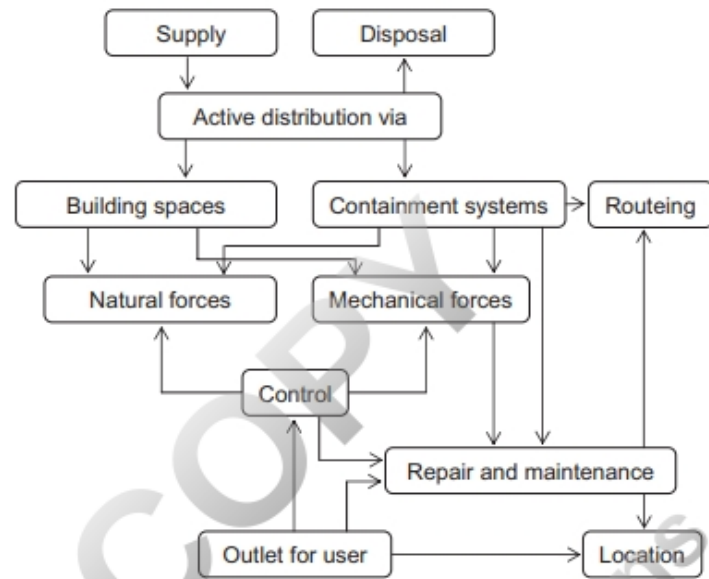


Figure 10.3 Aspects of active services systems.

on the walls of the building or through specifically designated ducts or voids. This would have to include an access point to allow for repair and maintenance. In another example, a natural ventilation system could use the building space as the distribution system, using natural forces of wind and thermal gradients to move the air from the user, to dispose stale air at high level and bring in fresh air (perhaps tempered with heating) at low level.

Figure 10.3 also shows that, like the active fabric, these active services systems require control. When the internal conditions change, some control mechanism will have to be invoked. This control can be manual, relying on the user to identify unsatisfactory conditions and then being offered some way of re-establishing the required environment. For example, opening a window as long as fresh and relatively cool air existed outside the building could control a stuffy or over-warm room. It would include leaving the occupants to switch on lights when they considered it too dark. The alternative is to devise ways of providing automatic control, such as the use of a sensor to respond when design limits are exceeded and send a signal to a part of the system, which can start a chain of events to bring the environment

back into design conditions. In the example of the heating system in the previous paragraph, this may be a room thermostat that can switch on the boiler and the pump in a central heating system when the temperature in the room (more correctly at the thermostat) falls below a predetermined limit.

Assigning environmental modification functions

Table 10.1 shows the aspects of the internal environment that may have to be created and maintained. These are each then identified with the major aspects of the external environment that will influence the achievement of modified conditions. The final two columns indicate typical functions that could be assigned to parts of the construction to achieve the modification required. For most of the aspects of modification, both passive construction and active services could be employed with different functions. For example, to create dry internal conditions it is necessary to understand patterns of precipitation, the conditions of ground water and the presence of vapour in the air. From this, waterproofing can be assigned to the fabric and water disposal to the building services.

Table 10.1 The role of fabric and services.

Internal conditions to be established	Significant aspects of the external environment	Possible functions of fabric	Possible function of services
Dry	Precipitation Ground water Vapour in air	Waterproofing Vapour control	Water disposal
Warm	Air temperature Solar gain Wind	Resisting the passage of heat Thermal mass	Heating Cooling
Light	Humidity Sun path Overcast sky	Ventilation Transmission Reflection	Room Task Mood Architectural
Acoustic	Natural sounds Pollution	Transmission Absorption	
Clean	Dirt Pathogens Fungal and plant life Animal life Air pollution	Exclusion Filtering Cleanable	Removal Filtering Disposal
Secure	Social threats Act of God Fire	Resistance Separation (barriers)	Detection Alarm
Private	Cultural and social conventions	Separation (visual and acoustic)	

Rarely does one part of the construction act alone in fulfilling one of the environmental functions and rarely does it contribute to one of the functions only. Elements of the building such as walls and roofs may contribute to many of the functions. Elements are assemblies of sub-elements, such as the external skin of a cavity wall or tiling on the roof, where a primary function is often identifiable. Choice often centres on these sub-elements, for they are normally identified with a major component or material where the focus of the functions is also often fairly clear. For example, an external wall probably plays its part in all the environmental functions. Even major sub-elements such as windows have a range of functions. Primarily for light and view, these may be used successfully for ventilation but cause problems with solar gain and security. As finer division of the sub-elements is considered, down to single components, then function is often clear. Within a wall, the damp-proof course (DPC) has a very

well-defined function of damp control. Analysis at this level has to keep sight of the function of the building as a whole, while defining the function of the components and materials of which the sub-element will be made. This division and refinement of the environmental functions is illustrated for a roof in Figure 10.4.

Assigning performance levels for environmental modification

Assigning of a function only identifies the part to be played by an element, sub-element, component or material in creating and maintaining the required environment. Assigning a performance involves defining a level of attainment. While it is unusual for a building's design to be so radical as to cause the functions to be unclear, the new demands of clients and regulations often lead to a change in performance. All the aspects required to set a performance level have already been introduced:

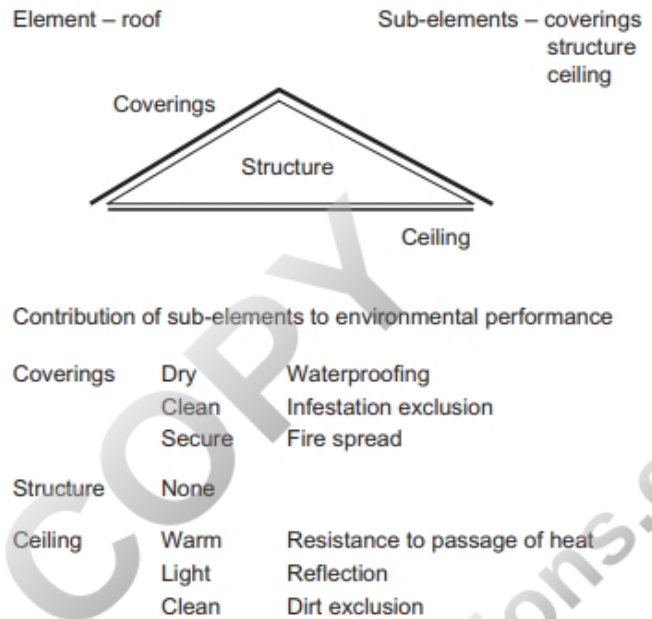


Figure 10.4 The role of sub-elements of the roof.

- The range of what will be considered normal external conditions and what extreme or accidental conditions it may be worth designing for
- The ideal internal conditions, the limits that would still be considered satisfactory and any control mechanisms that are intended to be included
- The proportion of the task of creation and maintenance of the environment to be assigned to that part of the construction

- The nature of the failure linked to performance
- Possible types of solutions
- Analysis of the response involved to achieve performance

A dynamic description of the environmental conditions to be modified and the mechanisms that determine the response of the construction to the expected environments in which it will have to operate should be carried out. This should be based on a visualisation of the flows and transfer taking place through the construction.

Thinking through the conditions

The analysis of each aspect of the internal environment will be considered in turn in the rest of this chapter. The focus will be on the analysis of the fabric, although the choice of services systems will be introduced.

Following the general format for thinking through physical behaviour established in Chapter 9, each section will consider:

- The origins and nature of the environmental conditions

The dry environment

Substances exist in a solid, liquid or gaseous state. Unlike nearly all other substances, water can exist in all these states within the normal climatic range of temperatures and pressures. This creates particular problems for buildings trying to maintain dry environments. An excess of liquid water is undesirable, but a limited quantity of gaseous water (vapour) in the air

is important for comfort, providing levels of humidity. In visualising the behaviour of construction, the possibility of a change of state has to be considered. Perhaps the most important example of this for dry environments is the change from vapour to liquid in the depositing of condensation.

As well as having an undesirable effect on health and comfort, water is a major source of deterioration of construction materials (see Chapter 12). Much detailing has the dual function of protecting the environment and the fabric of the building. In this respect, visualising the dynamic interaction between water and the construction is common to the analysis of both environmental control and durability. However, the analyses of the two need to be considered separately since different actions of the water become significant, as, for instance, in the change of state from liquid to solid with frost action, significant for durability but of little concern in considering environmental conditions.

If the requirement is for a dry interior then the clear failure can be characterised as leaks, where water enters the building through the external fabric and openings or from failure of the building services. However, much of the detailing of buildings is concerned not only with the free entry of water as leaks but also with excessive moisture in the fabric, known collectively as damp. The dividing line between these, both as observable actions and in the appropriate detailing, is often fine, so they are normally considered together.

Maintaining a dry interior (absence of dampness rather than lack of humidity) requires the control of moisture as both liquid and vapour. As a liquid, the source of water is normally external and hence the external fabric has a major functional role in damp control. As a vapour, sources are predominantly internal so both the design of the external fabric and the overall process of ventilation are used to prevent the incidence of condensation.

When considering the analysis and choice of the fabric to ensure a dry interior, it is usual to see three major threats:

- Penetrating damp
- Rising damp
- Condensation

Among others are blown light snow entering ventilated openings and subsequently thawing and leaking from water-carrying services.

To visualise the behaviour and analyse the ability of the construction to fulfil the function of damp control requires knowledge of the origins of the moisture, the forces acting on it when it comes into contact with the construction and the pathways then available for it to reach internal surfaces.

Predictive methods are available to model vapour and temperature patterns in order to assess the risk of condensation. Penetrating and rising damp assessment is still largely a matter of traditional detailing; maintaining barriers to the progress of dampness into a building by applying tried and tested methods. Testing of prototypes to wind and rain penetration is possible, particularly associated with components systems such as windows or claddings. This prototype testing is especially significant when new principles such as rain screening are applied because predicting the behaviour of water can still be a matter of trial and observation.

Each of the major threats will be considered in turn, with descriptions of behaviour, identification of pathways and of the major detailing techniques that can be employed.

Penetrating damp

Rain is the major source of water that interacts directly with the external fabric of the building, creating the possibility of penetrating damp. Three major actions can then be identified, as follows:

1. The water that comes into direct contact with the outside of the building will soak into permeable construction where pore networks form continuous capillary pathways through the material.
2. Any water running over the surface of the building is primarily influenced by gravity

moving it down the construction, but other forces also act on this surface water, particularly when it meets joints and projections. The water may be drawn into small cracks by capillary action. Wind that accompanies the rain will create pressures around the building, affecting rates of movement of the water across the surface and penetration of the fabric, particularly at open joints. Even the 'skin' formed on the surface of water exerts a force, known as surface tension, that not only holds water on the surface but also can cause it to migrate, upside-down, under horizontal surfaces beneath overhangs. Visualising this highly complex set of forces acting on water on the wetted surfaces of buildings is particularly important at the detailing of joints between components and at junctions between elements.

3. The majority of the water that falls on the surface of the construction will arrive at an edge. If it is a free edge, the water will fall off mainly under the influence of gravity. However, its behaviour at these edges will also be influenced by wind and surface tension drawing some of the water back under horizontal overhangs. It is important to make sure this water is removed from edges effectively so it does not have the chance to accumulate and soak the construction more than that expected from the original rainfall.

In reality the distinction between the first action (soaking in) and the second (surface water interacting at joints) is not so clearly defined. Most construction, such as roof tiling and brickwork, is not monolithic. It is not just one material where the properties of the material will be the only influence on the rate of soaking in. Although they may be considered as one skin, they are made up with joints, which in the case of brickwork are made with a second material: mortar. The behaviour of soaking in is now dependent not only on the permeability of the brick and the mortar but also on the reaction of the water at the joint. Some of the forces identified in the second action (interaction at joints) come into play. In fact, in brickwork with cement mortar, where drying shrinkage breaks the bond between brick and mortar to create fine capillary paths, water penetration can be observed at the joints long before it penetrates the brick itself.

The depth of penetration of the water soaking into the material depends primarily on two things: the cycle of wetting and drying and the permeability and thickness of the construction. Prolonged periods of wetting with only short periods of drying in between pose the greatest threat. If the construction is not specified thick enough, or barriers to halt penetration are not provided, moisture will appear on internal surfaces. The three basic construction forms to overcome this direct transfer through the walling material itself are shown in Figure 10.5.

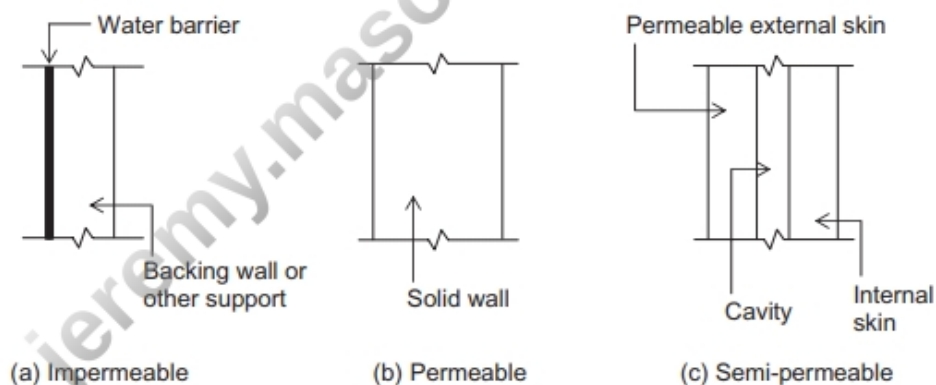


Figure 10.5 Generic forms of walls to resist penetrating damp.

All of these forms can be exploited. At the beginning of the twentieth century most house construction would have had solid walls, but by the end of the century the changes in materials, particularly the use of cement mortars (see explanation in previous paragraph), had led to the almost universal adoption of cavity construction.

The water that does not soak in or is not drawn in will move down the face of the building. If the surface is impermeable then a considerable quantity of water can accumulate. There is a danger of damp penetrating at any time when the water meets joints or projections. The expected pathway and potential quantity of water has to be visualised for each situation of joint and projection.

The action of capillarity at a filled joint has already been identified between the brick and its mortar if the bond breaks and fine hairline cracks are formed. This is the scale at which the mechanisms have to be visualised. Pathways through the fabric are often very fine and tortuous, with damp appearing on the inside, some distance from its entry on the outside. Other joints are open with no filling material. If these joints are narrow, they may support capillarity if a fine continuous open gap is formed. However, two other forces will assist water penetration at gaps or joints: gravity and wind. These may be significant even where the gap size would not support capillarity. Not only may wind change the surface water's move-

ment directly, but also the pressures that it builds up around the building may blow water through joints or even pump water up behind detailing, such as flashings.

Two other forces that may act on the water when at joints or projections are kinetic and surface tension. Kinetic energy is present in the falling rain. It is the force that causes it to bounce on hitting the surface, so apparently sheltered areas may become wet. Kinetic effects are relatively weak, but surface tension has the potential to cause problems at overhangs and projections. On the underside of projections, which may also be considered to be sheltered from wetting, surface tension will hold water on the underside of the projection where it will migrate towards an apparently protected joint and enter from below the projection. The basic forces acting at joints are shown in Table 10.2.

Penetration at joints can be aggravated when they occur at projections such as sills. Water will collect on the top surfaces of a projection, causing high levels of soaking or additional water to be drawn in through joints. Identification of the damp pathways and the detailing of damp-proofing at the sill of a window are shown in Figure 10.6. This figure illustrates the use of jointing materials (putty), filled joints (water bar), barriers (DPC) and, on the underside of the sill, the simple device of the groove or drip detail. In the drip the water collects and gains sufficient mass to break the surface tension

Table 10.2 Forces potentially assisting water to enter at joints.

Force	Direction of action	Effect
Capillarity	Any	Water travels through fine cracks and pore networks
Gravity	Downwards	Water enters any opening or crack with downward path
Pressure differences	Any	Above ground wind ● Driving rain ● Holding water in joint ● Moving towards lower pressure ● Pumping behind flashings
Kinetic	Rebound	Water pressure below water table in ground
Surface tension	Any surface	Localised to area of impact Movement at underside of projections Holds film of water on surface and on ledges

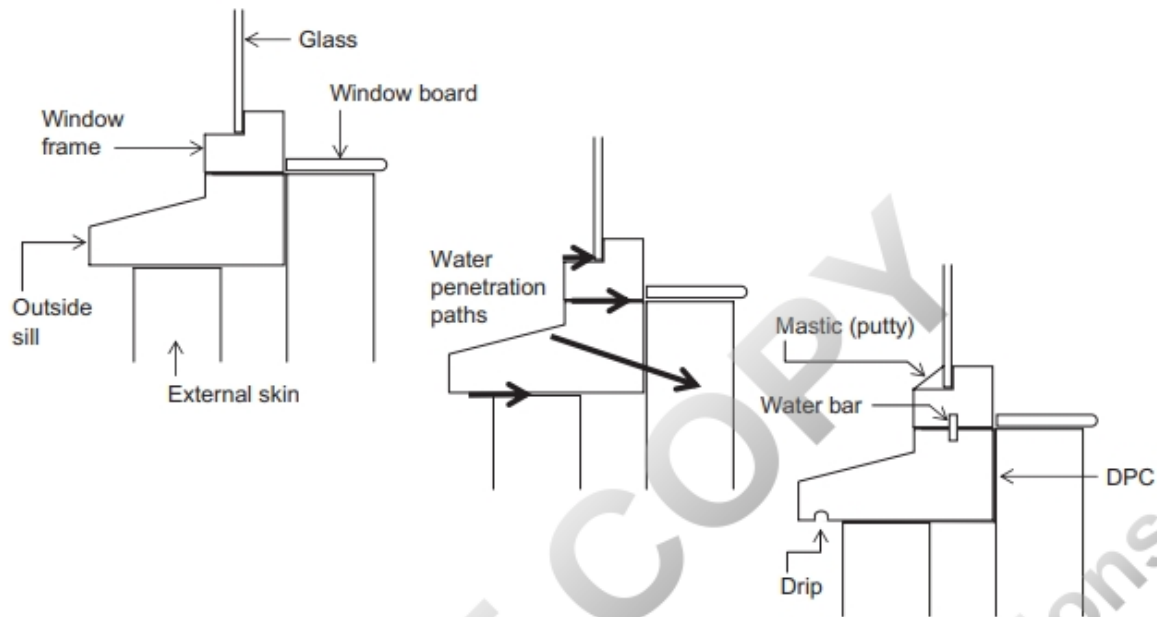


Figure 10.6 Pathways and details to resist damp penetration at sills.

when droplets fall from the underside before reaching the joint under the sill.

The distinction between absorption from prolonged wetting and direct penetration through joints and projections has particular importance when thinking about aspects of external climate and rainfall in a particular locality. Any building subject to heavy, driving rain may need to be detailed differently to one subjected to prolonged drizzle. The total average annual rainfall may be the same.

Finally, it is necessary to consider the water that is shed from the building, particularly where the roof discharges water at the top of walls. If not intercepted, gravity will take it towards the ground. It is not a direct threat if it falls directly to the ground, but it may fall or be blown onto the surface of the construction, soaking materials to an extent not envisaged by direct exposure to the rain itself. If it reaches the ground without contact with the construction, it may still splash (kinetic forces) onto the fabric at ground level and increase wetting and soaking of materials close to, but above, the ground. The rest of the water reaching the ground will either directly soak into the

ground or collect and flow away on any flat, hard surfaces. Intercepting this water at the edge of the roof is normally the function of gutters and drains.

Rising damp

The threat from rising damp is ever present in temperate climates. Moisture is found in the ground at virtually all times of the year. While the greatest threat may be during wet periods when the moisture content of the soil will be high, the moisture persists in all but the surface layers, even in dry periods. This is even above the water table. If a building is built below the water table, and comparatively few are, then the building is under an additional threat of water pressure assisting entry through the fabric of the building.

The major action associated with rising damp, as the name implies, is a transfer of moisture up into the building against the pull of gravity. The water travels through the fine network of connected pores in permeable materials by capillary action. This rise within the pore system in the materials can reach

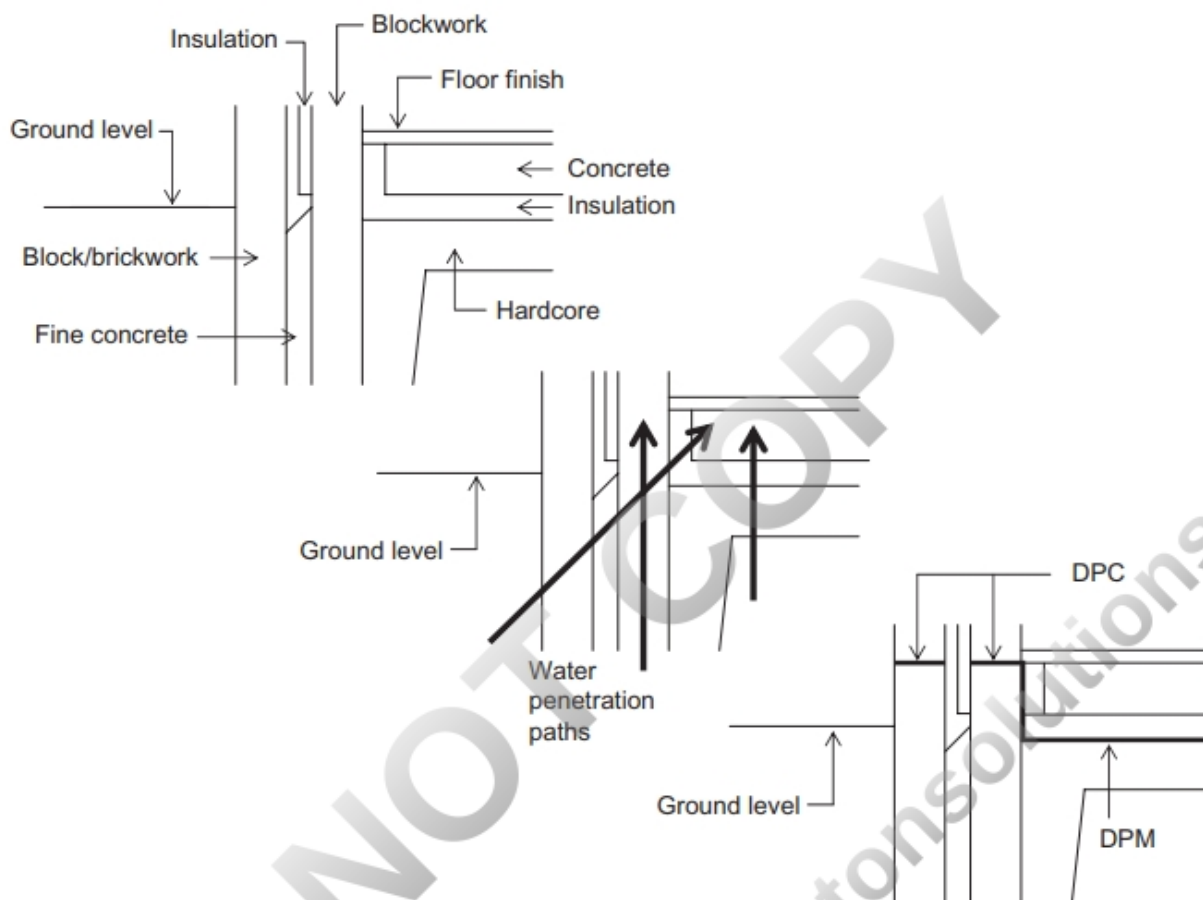


Figure 10.7 Pathways and details to resist rising damp.

considerable height above the source of the moisture in the ground.

It is not normally economic to use anything other than permeable materials for the major components below ground. The usual detailing solution is to provide an impermeable barrier known as a damp-proof course (DPC) in walls and damp-proof membrane (DPM) in floors. Identification of the damp pathways and the detailing of damp-proofing at the junction of the ground floor and the external wall of a house are shown in Figure 10.7.

The detailing and care in construction to ensure continuity within and between these damp-proof barriers become extremely important. Given that the major action is capillarity, which by definition exploits the finest path-

ways, this indicates that any lack of care in detailing or assembly can have a disproportionate effect. Once damp-proofing is breached, the materials on the dry side absorb the moisture and transfer of the moisture will continue to internal surfaces.

Condensation

The descriptions so far have been of the possible pathways threatening a dry interior, essentially from outside, through the fabric. This is, however, not the only source of internal dampness. Primary among other sources is condensation. The moisture for condensation does not enter the building as water but as vapour, and most is generated within the building through

everyday activities. This vapour not only comes from cooking and bathing but also is generated by the act of breathing, leaving almost all activities as generators of vapour which, as a gas, is carried away by any process of ventilation occurring in the building.

Vapour is not a threat to the dryness of the environment (although excessive vapour causing high humidity can be uncomfortable); as long as all the vapour can be held in the air it causes no damp problems. There is, however, a limit as to how much vapour can be held in the air, dependent on a number of factors, primarily temperature. If vapour increases at constant temperature or temperature decreases with constant vapour the result may be condensation or the appearance of liquid water. This is most commonly seen on the internal surfaces of window glass, which will probably have one of the lowest surface temperatures in the room. Another vulnerable area is at the internal corners between wall and ceiling and behind furniture where ventilation has least effect. Here the surface temperature may be higher but so will the vapour concentrations. As these surfaces, unlike the window glass, are permeable the condensation will soak in and the first sign of a problem may be mould growth.

The temperature at which condensation occurs varies depending on the quantity of vapour in the air. The less vapour in the air, the lower the temperature at which condensation first occurs. The temperature at which condensation will occur for a given air–vapour mix is called the dew point temperature, where the air is said to be 100% saturated or to have a relative humidity of 100%. If the temperature continues to fall (or more vapour tries to enter the air), more condensation will be produced, as the air can be no more than 100% saturated with vapour.

As well as occurring on surfaces, condensation can be a problem within the materials themselves. Most of the materials of which construction is made are not only water permeable but also gas (and therefore vapour) permeable. The two are, however, not directly related. Gas permeability of a material is a different

property to water permeability. When air inside the building is warm, it is probably holding more vapour than cold air outside. This difference is sufficient to cause vapour from inside to migrate through the construction towards the outside. As it is warm on the inside and cold on the outside, heat will also be flowing out across the construction, the temperature of each layer of material becoming colder towards the outside. This drop in temperature becomes particularly large across any insulation. Insulation material does not normally hold up the vapour being transferred, so this may create the conditions for condensation to occur within the construction. Because it happens inside the materials, it is known as interstitial condensation.

Water is now present within the construction. If vapour continues to flow and temperatures remain low, the quantity of condensate increases. The presence of water within the materials may threaten the durability of the materials and may change other properties on which the function is depending: principally their insulation and air permeability values. Depending on the detailing and where the condensation occurs, it may create dampness on the internal wall. This will depend on there being a pathway for the condensate water back towards the inside face of the construction. Similar forces and mechanisms create these pathways, as discussed in penetrating dampness. The water will travel in capillary paths within porous materials or through cracks. Gravity will work on the water (hardly at all on the vapour), draining it through the construction where it may find a pathway in.

If it does not find its way into the building it will, like absorbed rain, have to dry out from the outside surface, where wind, rising temperatures and the sun will dry the surface, creating the conditions for a migration of absorbed water to the surface or to evaporate it back to vapour. This may be a slow process and condensate can remain within the construction for considerable periods.

Detailing, including the position of the insulating layer along with ventilation and vapour

control layers, can limit the risk of condensation and this is discussed in the section on the warm environment that follows.

The warm environment

In temperate or cold climates it is natural to see the function of the building as creating and maintaining a warm environment. In warm or hot climates the function may be characterised as providing a cool environment and this will lead to very different strategies and will therefore need a different analysis to the one described here. In hot climates thermal mass and white exteriors are likely to be employed rather than insulation, which is common in temperate climates. This section will focus on the temperate climate winter heating condition, although the summer condition will also be considered.

Feeling warm is not just a case of the air temperature. It is dependent on radiant effects, cooling air movement (draughts or breeze) and humidity.

Radiant effects are a process by which heat is lost (or gained) from the body by radiant exchange. This is independent of air temperature and only requires a cold (or hot) surface to be in direct line with the individual (or another object) for heat to be exchanged.

Areas of glazing can be associated with these effects. The rate of radiant exchange is proportional to the temperature difference, and this is likely to become large if the glazing itself is directly exposed to sunlight (heat gain) or a clear winter night sky (heat loss). It is likely to be uncomfortable if activities have to be carried out too close to the glazing. Under these circumstances some form of shading, blinds or curtains may have to be used, either externally to keep the surface at air temperature or internally to cut out any direct radiant exposure from the surface to the individual. Placing warm radiators beneath cool windows will also help mediate the radiant exchange experienced by the individual if the temperature of the cool glazing is not too extreme. Working very close

to a radiator can also be uncomfortable due to radiant exchange.

Air movement will come from ventilation, where if the rate of airflow is too high a cooling effect will be felt by evaporation from the skin. This will be discussed in the section on ventilation below. High humidity reduces the efficiency of skin-cooling evaporation, making us feel less comfortable in high air temperatures even with high air flow rates.

The function of the passive fabric of the building in maintaining a warm environment within the building is complementary to the function of the active environmental services systems. It is necessary to see any thermal design to be integrated between the fabric, heating and ventilation arrangements of the building. This strategic decision is also concerned with issues of energy use, clean air and running and maintenance costs. Whatever the overall contribution in each case the fabric will fulfil the same function, only the level of performance will vary.

In a temperate climate, the usual initial concern is the loss of heat through the fabric of the building under winter heating conditions. The more heat that is lost through the fabric by transfer and ventilation, the more heat has to be provided by the heating system. This reflects the wider concern associated with energy consumption and running costs. There is also increasing concern with larger commercial building regarding cooling in summer, dealing with high internal heat gains and reducing solar gain so that less cooling is required. The role of the fabric under these conditions is different from the winter heat retention role. This will, for instance, require greater rates of ventilation, the use of shading on the external face and exploiting thermal capacity rather than lower ventilation rates and insulation of the building skin required for winter conditions.

To consider the external skin of the building it is necessary to understand how the construction responds when a temperature difference exists on either side of a wall, roof or floor. The fabric will almost certainly consist of various layers performing different functions,

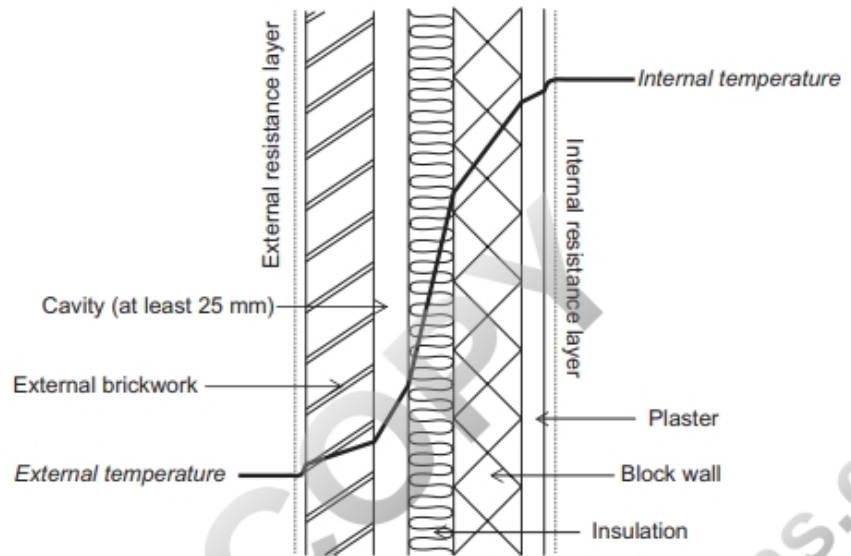


Figure 10.8 Typical temperature drop across insulated cavity wall.

only one of which may specifically be to enhance thermal performance. However, it is the behaviour of the fabric as a whole that needs to be considered.

It is possible to visualise the materials and layers of construction from the point of view of either ease with which they transmit heat or the resistance they offer to the passage of heat. Generally the description that follows will think in terms of layers offering resistance. The function is resisting the passage of heat. Layers with high resistance have materials normally thought of as insulating materials.

The simple view of fabric heat loss

The simplest view of heat loss through the fabric considers the system of inputs and loss to be in equilibrium. It assumes the temperature on each side to be constant and the rate of transfer to have reached steady state. It also assumes that all heat moves directly through the fabric from one surface to the other. The transfer of heat through the fabric is, under these circumstances, dependent on the resistance to heat transfer offered by the layers of the materials chosen, including any cavities, plus the layers of still air held at the surfaces of the construction.

Steady state is the simplest way to visualise the heat flowing through the construction and it illustrates the fundamental influence of the construction. Given a temperature difference on either side of the fabric, heat will flow from the high to the low temperature. The quantity of heat that passes through the fabric, in a given time, the rate of heat flow, will depend on the resistance of the layers, including surface air layers and cavities of air. The greater the resistance of the whole construction, the less heat passes per unit of time. It is not possible under steady state for more heat to be flowing through one layer than another.

The second influence of having layers with different resistances is the way in which the temperature changes across the construction from the warm to the cool side. This is dependent on the relative resistance of each layer. This is illustrated in Figure 10.8. Layers contributing a large proportion of the resistance to heat flow (the insulation) will experience a large proportion of the temperature drop across the construction as a whole.

Not only is steady state the easiest way to visualise heat flow, but once the resistance of each layer is established it is the simplest condition for which to provide calculations. The rate of heat loss is expressed as a function of the

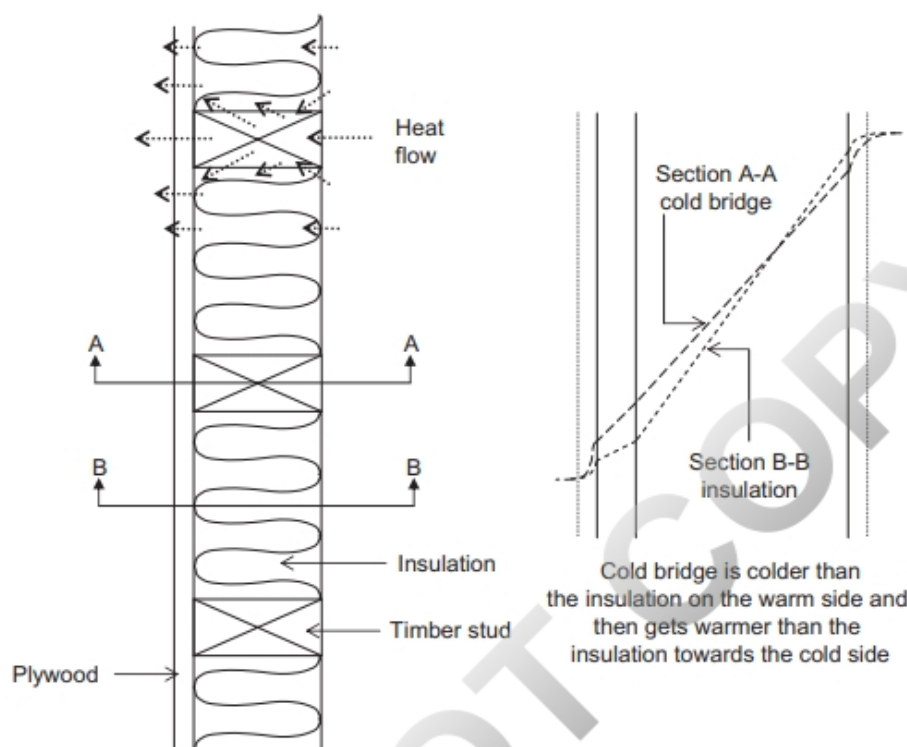


Figure 10.9 Effect of studs as cold bridge in timber frame wall panel.

whole construction, combining the effect of all the layers into one figure representing the transmittance of the complete construction. This is a single transmittance value known as the U value.

Heat loss calculated in such a way is, however, based on a description of behaviour that is rarely observed in practice. While the internal temperature may be relatively constant, the external temperature throughout a heating season will vary a great deal. Deciding on a design condition for external temperature becomes crucial to the value of the estimates provided by such calculations. Chosen too low and heating systems will be over-designed for most of the heating season, while chosen too high and conditions of comfort may not be achieved for a large proportion of the days when heating is required. Current design practice in the UK is to take 0°C as the external design temperature.

The accuracy of any estimates calculated in this way is sensitive not only to the choice of

design conditions but also to detailing. The assumption was made that all heat moves directly through the fabric from one surface to the other. If the resisting layers remain continuous over a large area, this assumption is reasonable. However, whenever the layers are interrupted by structure or openings this assumption must be questioned.

Cold bridging

Figure 10.9 illustrates the effect on heat flow through construction where the studs in a timber framed wall panel do not provide a single layer. The studs are said to be providing a cold bridge by the diversion of the heat so it does not pass directly from one side to the other. This will also occur at junctions of floors and around window openings. Heat will flow naturally towards the lower temperature, distorting the temperature profile. This thermal bridging has the effect of losing more than a simple heat loss calculation would suggest.

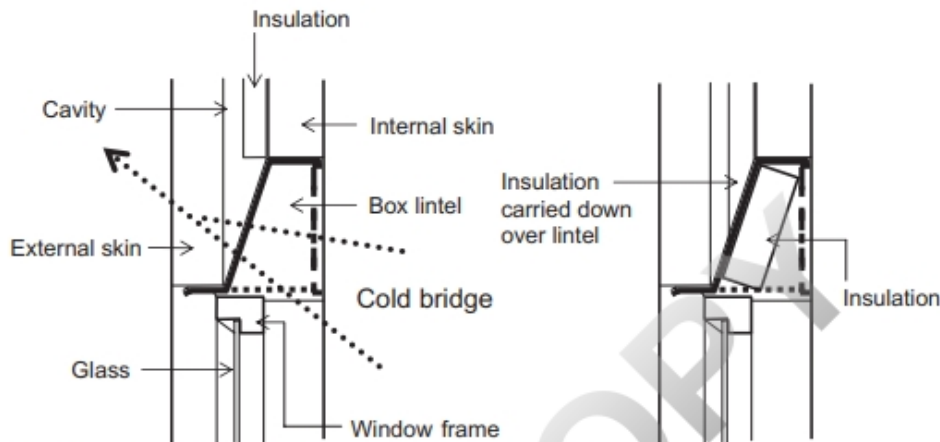


Figure 10.10 Cold bridge and details to reduce heat loss at window head.

Hence where a building has little continuous high resisting fabric with frequent penetrations or openings, the detailing to reduce this effect needs to be considered. The potential bridge at the head of a window and the detailing to minimise the effect are shown in Figure 10.10.

Non-steady-state heat exchange, capacity and diffusivity

While a building is being heated, the internal temperature will be relatively constant. The outside temperature will vary much more, even on a daily cycle. Not only does this involve the air temperature but also surface temperatures will be directly affected by radiant exchange by direct exposure to the sun (gain) and to clear night-time skies (loss). Surfaces, particularly if dark in colour, will absorb heat if directly exposed to the sun and lose heat if directly exposed to a clear winter night sky. Surface temperatures can by this mechanism reach values significantly different from air temperatures.

Buildings may not be continuously heated. Intermittent heating may be necessary to match the occupation pattern. Under these circumstances both internal and external temperatures are changing, often in the opposite direction, with internal temperatures rising just as external temperatures are falling.

In order to visualise this dynamic thermal behaviour it is necessary to think about how rapidly the temperature profile in the fabric changes in response to temperature changes at the surface. The thermal properties of the materials and thickness of each layer will determine the speed with which the fabric will respond. This needs not only a measure of resistance or insulation value of the layers but also one of thermal capacity. Capacity is a measure of the amount of heat necessary to create a given rise in the temperature of the material (or for the heat to be given up during an equivalent fall in temperature). The rate at which the temperature within the layers changes will be quick when there is little resistance to heat flow and little thermal capacity. With increasing resistance or capacity of the layers, changes in temperature within the materials will be slower. This measure of the speed at which the internal temperature profile changes is a function of both resistance and capacity and is known as thermal diffusivity. Generally, materials offering high resistance are low density with large volumes of air entrapped in the materials, while high thermal capacity materials have higher density and hence a lower resistance to heat flow.

Analysis of response and capacity becomes more important than insulation in climates where the large changes occur between night

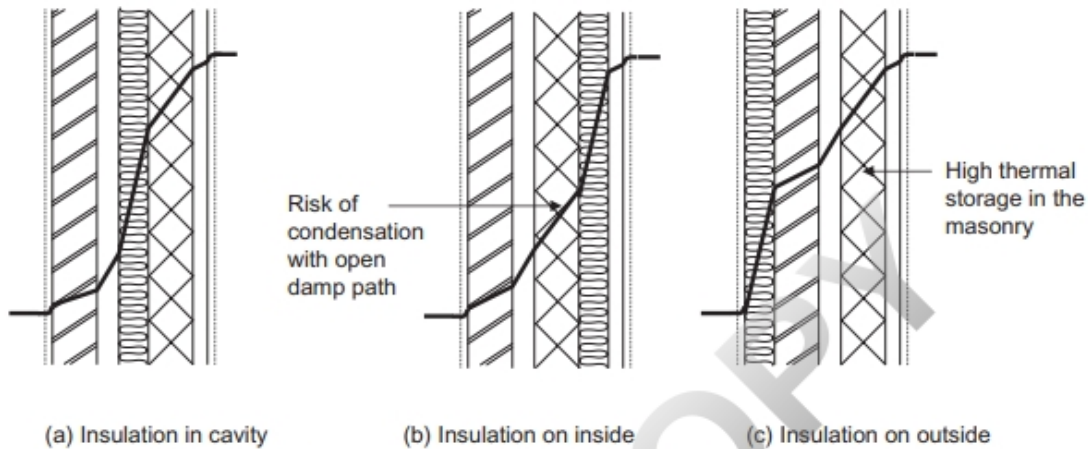


Figure 10.11 Temperature gradient with position of insulation in cavity wall.

and day, such as in desert areas, rather than between summer and winter, as in temperate climates. Hence, heavier, thermally massive materials are used. This is similar to the summer cooling designs in temperate climates where the fabric is used to store the heat generated during the day, which is then purged at night.

Analysis of response is also important where buildings have to be heated for short periods, when thermally light building may be appropriate. Another strategy would be to have a heating system that was chosen with radiant heaters that heat the individual directly without heating the air so that the fabric has little role to play in feeling warm other than reducing draughts.

Position of the insulation

When only considering heat loss and taking the simple view of steady state conditions, the position of the high-resisting, insulation layer is of no consequence. When the behaviour of the fabric is being analysed for any purpose where temperature profile or response time is important, the position of the relative resistance offered by each layer may become significant.

If the insulating layers are near to the inside of the building (warm side) then the outside layers will have a smaller temperature rise in order to achieve steady state. In these

circumstances not only is steady state approached relatively quickly but also there is little heat stored in the fabric even if constructed with relatively high thermal capacity materials. Often more significant is when the insulating layer is on the warm side, in which case there is an increased risk of condensation with the lower temperatures that arise on the cold side of the construction.

Figure 10.11 shows the temperature profile for walls with the insulating layer in different positions. The converse is, therefore, that insulation on the cold side reduces condensation risk but may increase warm-up periods where intermittent heating is required.

If the condensation risk is high then additional detailing will be required. This will normally take the form of either a vapour control layer or the ventilation of cavities to take away the vapour migrating across the construction. Ventilation can be particularly effective in roof construction.

Ventilation

Maintaining a warm environment is affected not only by the choice and detailing of the fabric but also by the amount of ventilation. The direct loss of warm air from a room under winter conditions accounts for a significant proportion of the heat loss. Ventilation involves air

exchange and therefore airflow. If the speed of this airflow becomes too great, it can be called a draught, increasing heat loss from the body so we no longer accept the environment as being warm even if the air temperature has not changed. Under summer conditions the increased speed of airflow may be called a breeze and is welcomed in order to maintain a comfortable thermal environment. In temperate climates, ventilation is the main means of maintaining a comfortable thermal environment under summer conditions. Air conditioning, being expensive to install and having high running costs, is restricted to a limited range of buildings in these climatic zones.

Ventilation, however, is not just a consideration for maintaining a thermal environment. It also plays its part in two other functions. First, it removes water vapour, which reduces the risk of condensation and hence dampness in the building. Second, it removes stale air, maintaining a clean environment, keeping down the level of airborne pollutants and odours to a safe and comfortable level. This will be covered in the section on the clean environment, for there is no doubt that an exchange of air is necessary within buildings, and some means of achieving a controlled level of ventilation has to be considered.

For ventilation to take place it is necessary to have two conditions. There needs to be a pressure difference to move the air and the presence of openings to let air in and let air out. This assumes a supply of air that is suitable to replace

the air in the building. If this is not the case then cleaning by filters or dehumidifying may be necessary, but this will not be considered here.

The need for a pressure difference and openings is true for both natural and mechanical systems. The way they are provided and the means of control are, however, very different. They may be hybrid approaches, the simplest of which is mechanical extraction to increase (or at least control) the pressure difference in order to dictate the exit opening but leaving the fabric to provide the inlet openings. Even with a full mechanical system, the fabric must be detailed and built so it is not too leaky, as this could influence the performance of the mechanical system.

The part played by the fabric in the provision of ventilation is one of providing openings. These are not only those specified for this purpose such as air bricks or chimneys but also the cracks that are present around opening windows and doors. Sealing these cracks with draught excluders is often seen as a cost-effective way of saving heat. This may be true, but it may also exclude a level of ventilation necessary to maintain a dry and healthy environment. Windows with draught seals should be provided with some other ventilation process such as trickle vents if there is a danger of low ventilation rates in the building.

Pressure differences created by the wind occur naturally around buildings. Typical pressure distributions around a building are shown in Figure 10.12. Air will enter any openings on

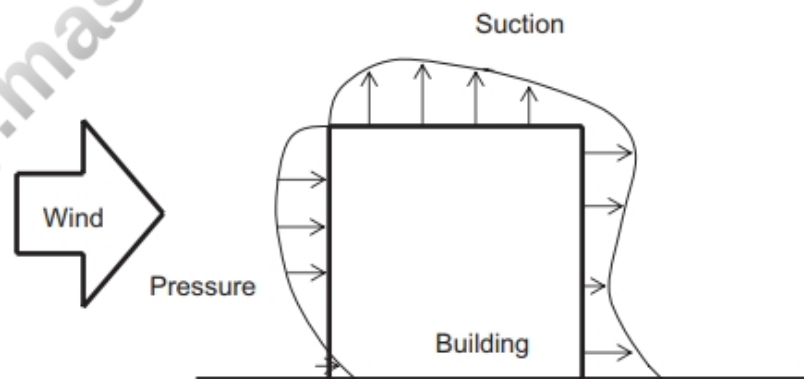


Figure 10.12 Typical wind pressures around buildings.

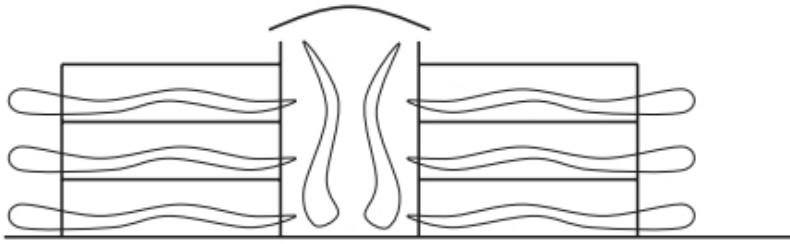


Figure 10.13 Natural ventilation using atrium or internal street.

the side of the building experiencing positive pressure and be drawn out from the side with negative pressure.

A second process that can be harnessed to create natural ventilation is the stack effect. This does not induce a cross flow of air but a vertical air movement. It relies on a temperature difference with warm air at the bottom and cooler air above, but it will be assisted by wind if the upper opening is in a negative pressure and the lower opening in a positive pressure region on the outside of the building.

Since the primary force inducing natural ventilation is the wind, it is clear that control has to use openings in the fabric and that this control will have to account for a variety of conditions experienced locally by the building. Local conditions can be highly modified by adjacent buildings, which may have a profound effect on the levels of ventilation achieved in practice.

Visualising these processes demands an analysis of wind pressure and temperature differentials as well as the pattern of opening provided by the fabric. These can be highly complex and particular to an individual building. Mathematical modelling, wind tunnel and salt bath trials can be used to inform this process of visualisation for building using natural ventilation. This can be a major strategy in this important area of the building's performance as it can greatly reduce the energy use in a building.

The design of the building as a whole has to be considered in order to harness the forces in natural ventilation. One way this can be achieved is with the use of the atrium or street (generally an atrium along the length of the building). The basic design and the natural ven-

tilation forces are shown in Figure 10.13. This design can also take full advantage of natural lighting, again reducing energy use throughout the life of the building.

The light environment

To fulfil the majority of its functions the enclosure of a building will almost certainly use materials that do not transmit light. This means that if the user is to make use of natural light, specific consideration will have to be given to getting light into the building. Since most buildings are occupied during the hours of both daylight and night-time, provision has to be made for artificial lighting as well as natural lighting. These two may be separate in that the building is to be designed to operate during the day without the use of artificial light. Alternatively there may be an element of permanent artificial supplementary lighting for daytime activity. This does have considerable running cost and energy implications as well as considerations for the consistency of level and quality of lighting provided. One further issue in lighting is that, over and above providing general levels of light, there may be a need for the provision of task lighting or dramatic or mood illumination, which may also be provided by either artificial or natural lighting, depending on circumstances.

Natural lighting

The simplest way to allow light into a building is to leave empty openings in the external enclosure, but this is unlikely to be satisfactory given

the other functions of the walls and roof. The materials available for enclosure that transmit light are limited, being primarily glass and plastics. Increasing the thickness of these glazing materials reduces the amount of light transmitted, limiting them to relatively thin sheet applications.

These materials will have limited strength and are therefore unlikely to be able to carry structural loads from the building, although they will have to carry wind loads to the structure. They will most often be framed to provide the strength required. As single sheets, the glazing materials will transmit heat easily, giving high heat loss in winter and high gain in summer and will provide limited sound resistance. At the same time they must remain waterproof and are often used to control ventilation by providing sections which can be opened. They may have limited ability to provide security and privacy.

These components, such as windows and roof lights, become sub-elements of walls and roofs of which they form a part. They have to contribute to the performance of the element as a whole, but it has to be accepted that they will have different performance levels. These components may also be made of very different materials from the fabric that surrounds them, and the detailing of the fixings and jointing to the main enclosure materials has to be thought through independently and yet be complementary with the consideration of the elements as a whole.

In addition to all these considerations the size and shape of windows has a significant effect on the appearance of a building. They are an integral part of most styles of architecture, often playing a major part in giving the style its distinctive character.

Against this background it is clear that the solution to providing natural light may often be a compromise with the other functions of the building. Its own importance in function and design terms varies greatly, depending on the use of the building and the designer's interpretation of its importance to the design. The use of multi-layers of glass or plastic components is

now common and recent development in materials has given these multi-layer transparent components improved thermal and sound performance and even strength and fire-enhanced properties to help security functions.

What is clear is that the energy use in electrical artificial lighting is high and therefore the provision of high-quality natural light can play a large part in achieving sustainable development.

Source of natural lighting

Being dependent on the sun, the quality, intensity and time during the day when natural light is available are highly variable. These vary with latitude and with orientation. In the northern hemisphere light from the south is generally brighter than from the north. It does, however, vary in intensity, often causing uncomfortable or disabling glare rather than even illumination. Light from the north is more consistent and reliable but colder and rarely dramatic. This made it suitable for factories and warehouses where roof lights on the steep pitch of the characteristic saw-tooth roof-line were orientated to face north. For other purposes, variety and qualities of brightness and warmth may be more appropriate, which, with some control for glare, is best provided from the south.

Natural light also varies with the time of year and the weather conditions. The hours of daylight vary with the seasons, and the light levels and the angles from which the sun can be directly viewed will vary. This will give a quality of light that varies with the seasons but also means that shading may have to be variable to match the angle and direction of the sun. The cloud cover affects the quality of the light. The highest level of light is available with no clouds covering the sun, whereas storm clouds can all but eliminate the light, creating near-night conditions during the day.

With all this variety it is unlikely that performance levels can be assured throughout the year. Bright light may need to be shaded, while storm clouds may dictate that artificial light is needed during the day. This variety is greater

in temperate rather than in hotter climates, where the sun is more predictable and remains higher in the sky. In buildings designed for these hot climates windows may be small and/or be permanently shaded by shutters or verandas facing the main path of the sun.

A variety of natural light is not necessarily undesirable. Changing levels of intensity and colour give information about outside conditions. They keep occupants in touch with natural conditions, marking the passing of the natural cycles of the day and the seasons. In addition the light received brings with it a view from outside. Windows, and perhaps to a lesser extent roof lights, allow occupants to look outside to see what is going on. In many cases, landscape (or cityscape) can be designed to provide spaces seen as visual extensions to the internal space. This gives vistas and panoramas that enhance the activity for which the building is designed. The increased cost of offices on upper floors of skyscrapers and penthouse suites is based in some measure on the view they provide.

Despite the technical difficulties of providing the performance of the enclosure where lighting openings are to be included, and the probable additional capital and running costs, windows and roof lights are judged to be good value (if not essential) in the provision of views, light and the influence they have on the appearance of the building. This makes the technical challenges particularly acute.

Penetration of natural light to internal spaces

Given the prevailing external lighting conditions, the quality and quantity of light reaching the internal space are controlled by the size and shape of the openings, the opacity of the glazing material and the shading or other control mechanisms provided. The proportion of light then available penetrating into the space depends upon the area and shape of the room, both its width and depth. Lighting levels reduce with increasing distance from the windows, but penetration can be enhanced by the careful choice

of shape and position of the openings, particularly the height of the head of the window.

Lighting levels from natural light are also influenced by reflections from objects or surfaces, particularly towards the back of the room. Surfaces that are shiny or light in colour will reflect a greater amount of light, raising the level of light at the working surface. In the same way as it is possible to provide shade from the direct glare of the sun at the window it is possible to provide reflectors to enhance the levels of light incident at working positions within the room.

Predicting lighting levels from natural lighting is now well established. Data on the external conditions and calculations that take window shape, depth of room and the reflection of surfaces into account are available to predict the level and reliability of natural lighting into a building.

Artificial lighting

For any building that is to be in use after dark the need for artificial lighting is clear. The provision of this lighting will assume that there is no light available from outside. Windows left uncovered will then act to transmit the internally generated light out and the view will then be available from the outside of the inside, affecting privacy and security. Heat loss will also increase as the temperature falls at night-time. Given these circumstances, curtains or blinds become associated with window design.

After dark, not only is lighting for internal spaces lost but also the exterior of the building loses its illumination. This has implications for its appearance and for security. These two may require different types of lighting. They may need different levels of lighting, colour and modelling requirements. However these are resolved, there is often a need to provide sources of artificial lighting outside as well as inside the building.

If levels of natural lighting are assessed to be inadequate in the daytime then artificial lighting may be seen as a solution, even during the day. This is particularly a problem in deep

building where the middle of the space is some distance from the external walls. In single-storey buildings (or the top floor of a multi-storey building) this can be solved with roof lighting. In very deep multi-storey building the use of light wells or atria can bring light to a central space, making light available to areas some distance from the outward-facing walls. In other circumstances artificial lighting will have to be used, although this has energy and running cost implications over the lifetime of the building.

For many buildings the daytime use of artificial lighting is only associated with limited periods when the external conditions are poor. In these cases the lighting designed for night-time use may be switched on. However, even if general lighting levels with natural lighting are satisfactory, specific task lighting may still be required and provided by artificial sources.

Sources and control of artificial lighting

The source of natural light is the sun, often obscured by cloud, so its quantity (level of illumination) and quality (colour, warmth, etc.) are variable dependent upon the time of day and the seasons of the year. With artificial light sources, the parameters of quantity and quality can be chosen. Since the case for artificial lighting also has to consider energy consumption, it is important to be able to identify the energy use for a given output since this also varies greatly between the different sources.

The demands made for lighting both internally and externally vary greatly and hence a wide range of sources has been developed. Originally powered by oil or gas, artificial lighting is now almost exclusively powered by electricity. The initial characteristic of the light is governed by the way the electrical power is converted into light. Whether the light is generated by the incandescence of a solid material such as tungsten halogen lamps or the excitation of a gas such as the fluorescent tubes, it is this conversion process that determines the basic colour and the power consumption of the source.

This light can then be harnessed to best effect by the fitting and positioning of mounted units. Directional spot lights get their power and colour from the light source, but their directional capacity comes from the way they are housed and even focused, with lenses to minimise scatter, as with theatrical lighting. Colour can also be added to white light with filters. For general lighting, the fluorescent tube, mounted in a reflective box, or luminaires with a diffuser on the front to give an even light with limited glare and then mounted in the ceiling at relatively regular spacing provide an overall level of illumination with some control over colour with the choice of tube.

More general control over individual rooms or sections of large areas is achieved by switching the electricity on or off or dimming to reduce the level of light emitted. In many situations this control can be manual by providing switches for the occupants to operate. For energy saving, some level of automation should be considered. Often based on movement sensors to identify occupants, automatic switching will turn off lights when rooms are not being used and turn them on again when people return. This might have to be set to leave low levels of illumination if safety might be compromised. Light level sensors can be used to switch on lights as levels of natural lighting reduce. It is particularly effective to bring in banks of lighting parallel to the windows to supplement the natural lighting at the back of the room without using lights close to the windows where natural lighting is still satisfactory.

As with natural sources, artificial light received at a point in a room is not just in a direct line from the source but also arrives from reflections from surfaces. The strength of these reflections is dependent on how close the surface is to the source and on the texture and colour of the surface itself. This can be used either to increase the level of illumination (quantity) or to create effect (quality) when used in conjunction with the source, its housing and its mounting position.

The predictive methods and the data available for the sources concerning the levels of

general illumination are well developed. Both predictive models and data on reflective surfaces and the manufacturers' values for the sources and the luminaires are freely available and reliable. Even predictions of loss of efficiency with time, energy usage and heat generation are possible with the current data available. Architectural lighting and effect or mood lighting are less susceptible to calculation and need a measure of imagination, but some calculation and computer modelling can give clues to comparative effects especially in terms of power and the interpretation of light and shade for soft or dramatic effects.

The acoustic environment

Sound can be considered either as wanted or as unwanted noise. Sound that is wanted can be enhanced or degraded by the fabric of the building, particularly by the finishing and the shape of the room in which the listener is located. Most wanted sound is generated within the space occupied by the listener, most often associated with talking or music. Some wanted sound comes from outside the room. Often sounds from the natural environment need not be totally eliminated since they bring an awareness of the wider world and even pleasure. Like a view or the changing quality of natural light from a window, they limit any sense of isolation that can be psychologically undesirable. Very low background noise conditions the ear so it picks up small noises that become intrusive. The lack of any external sound can also be disturbing as sound is used to identify threats. In modern building the possibility of natural threats is now supplemented by a number of alarm systems provided within the building and it is necessary for these to be heard by all the occupants. Fire and intruders alarms are the most obvious and these must be audible in all parts of the building when activated.

An increasing number of modern sounds are now considered unwanted. They are categorised as pollution and as such are now being given much attention in reduction at source, but

this still often leaves excessive noise that has to be reduced through careful choice of materials and detailing of the construction.

Characteristics of sound

Sound has two characteristics as identified by the ear: frequency (pitch) and loudness. Frequency determines how high or low we perceive the sound to be. If too high or low, it becomes inaudible to humans, although some pets can hear higher frequencies, and some low-frequency sound does affect other organs in the body and causes discomfort, but these sounds are very rare. Combinations of frequencies can be harmonious, as in music, or carry information, as with speech. Groups of frequencies that are disharmonies or carry no information are often called noise and, while useful as alarm signals, are generally considered undesirable.

Loudness is associated with volume. Because it has energy or power, it has the capacity to cause pain if it excites the mechanism in the ear to excessive movement. At the other end of the scale, quiet noise can be irritating, since it is frustrating if you think it is carrying information that you cannot obtain, or it is continuous and begins to intrude on your consciousness.

All sound, whether wanted or unwanted, reaches the ear through vibrations set up in the air around us. These vibrations from an airborne sound can also travel through the construction, and hence the provision of a barrier will only modify and not eliminate noise. Further, impact sound created by striking the construction itself, such as footsteps on a floor, will create a sound not only within the room but also transmitted to other areas by the direct connection of the structure and fabric of the construction. The transmission of the sound around the walls and floors directly between source and listener is by means of flanking paths. These noise sources and transmission paths are shown in Figure 10.14. In addition, mechanical plant has the potential to create noise, and this can be passed through the building via the services duct and pipework systems.

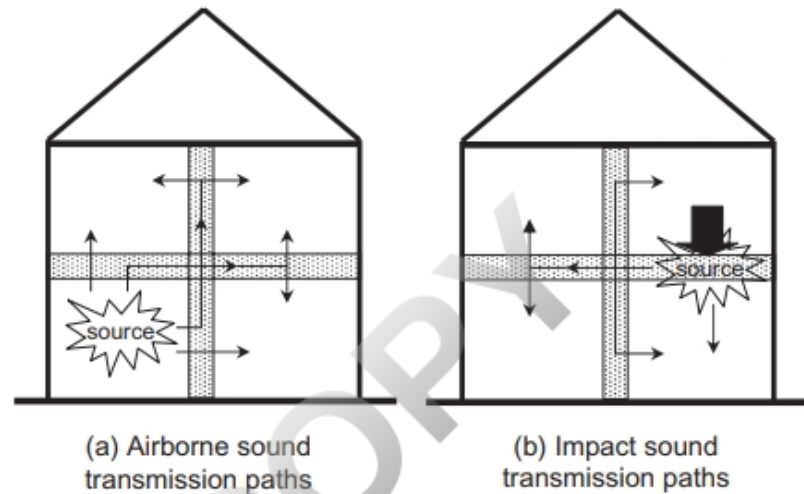


Figure 10.14 Sound source and transmission paths.

Sound created within the space

The sound will travel out from the source and there will be a natural decay of its power as it moves away. If in a direct line with the source, the listener will receive the sound directly. The sound will continue through the air in the room, striking other objects and eventually the floor, walls and ceiling that make up the room. Sound reaching openings in the floor, walls and ceilings will pass straight through. The sound that strikes objects or the surfaces in the room will be partly absorbed and partly reflected, depending on the nature of the surface itself. The reflected component will return into the room, where it may be received with a reduction in power and fractionally later than receiving sound direct from the source. These reflections will continue to be heard by the listener until the power in the reflection is too low to be audible. The quality of the sound is, therefore, highly dependent on the acoustic (absorption and reflection) characteristic of the objects in the room and the surfaces. However, since the sound loses power with distance, and takes time to return as a reflection, the size and shape of the room are also important. The time each individual sound takes to decay to become inaudible is known as the reverberation time. With highly reflective surfaces in a large room reverberation times will be increased.

For both speech and music it is important to have a quiet background; little or no noise from outside the room and little or no generation of sound within the room other than either the speech or music. For both it is necessary to have a good strong direct path from source to listener, but for reflections and reverberation time the requirements for speech and music are very different. For speech a strong early reflection reinforces the sound, but later reflections interfere with the clarity of the separate sounds. Reverberations as low as a twentieth of a second are required. For music it is the later reflections that enhance the sound, enveloping the listener in the sound field. Now reverberations of one to two seconds are required. This enveloping also requires the room to have a certain volume to maintain a smooth and prolonged decay of the sound.

There is one other phenomenon that can occur if a sustained sound with a dominant low frequency is coincident with the dimensions of the room. This is most likely to arise from vibrations from outside the room, which will be considered later, but the characteristic is associated with the room itself. If the room dimension is a function of the frequency (wavelength) of the sound, a standing wave may be generated sustaining that frequency.

It is clear that the major influence the construction can have over the quality of the room

acoustics is associated with the reflection/absorption of the finishes, having taken into account the influence, particularly absorption, of the objects (including the listener) in the room. In general terms, hard, flat surfaces are highly reflective. As the surface becomes progressively softer and more textured, absorption is increased. Soft, fissured or even re-entrant surfaces are sound-absorbent as the energy in the vibrating air becomes dissipated within the cavities of the irregular surface.

Airborne sound made outside the space

Increasingly, airborne sound is unwanted, but, as has already been pointed out, total sound isolation may not be a sensible performance requirement. The sound will move out from the source as before. If it were in the open air it would be modified by wind and other atmospheric disturbances, but no such disturbance would be experienced if the sound were created in another room. The sound is again going to be influenced by objects it meets, being either absorbed or deflected, but at some point it will impinge on the dividing construction, such as walls and floors.

An opening in the construction will not change the sound; it will enter (or leave) the room unaffected. It is important to appreciate the significance of the size of openings in transmitting sound. Small openings have a large effect, considerably reducing the sound reduction performance of a barrier, however well detailed.

The walls and floors of the building will act as a barrier to sound. The construction will reduce the loudness but not equally for all frequencies. The action of the construction in reducing the noise is two-fold: it dampens the vibrations due mainly to the mass of the construction and it isolates the vibrations if discontinuities (layers of resilient materials or cavities) can be introduced in the detailing. Hence the overall performance of a wall, floor or roof in attenuating sound will depend on the openings, mass and discontinuities and any sound-absorbent materials in the cavities.

Sound will also be carried deeper into the building by other elements attached to the initial barrier along flanking paths, making edge detailing particularly important. Figure 10.15 shows possible soundproofing details for a timber joisted floor, illustrating how mass, discontinuities including abortion in cavities and edge details can be integrated into a basic structural floor.

Care has to be exercised in assessing the performance of cavities. If the cavity is too small it has little effect as the vibration energy is transferred directly across the cavity. This is known as acoustic coupling. It happens in standard double-glazing, where the gap between the glass panes is small and therefore the soundproofing effect is almost entirely due to the additional mass of the second pane of glass. For cavities to be effective they have to be approaching 200 mm or larger.

While the potential sound reduction lies in the basic construction of the floor or wall, the part played by edge conditions and flanking paths means that the actual transmission loss when the building is in use may be less. Transmission loss of the proposed construction can be measured in the laboratory to provide a sound reduction index R_w normally between the frequencies of 30 and 315 Hz. A value of 40 dB reduction will render loud talking inaudible. This value helps to select appropriate specification, but these laboratory-based values may not be achieved when incorporated into the final construction on site, depending on the detailing and any variability arising from the site operations. It is possible to measure on-site performance, where the transmission loss R'_w will be quoted.

Sound generated by striking the fabric or from mechanical services

Sound is created by directly setting up vibrations in the construction itself. These vibrations will be much stronger than those set up by airborne sound reaching the fabric of the building. Flanking paths created by continuity between elements of structure and fabric are important

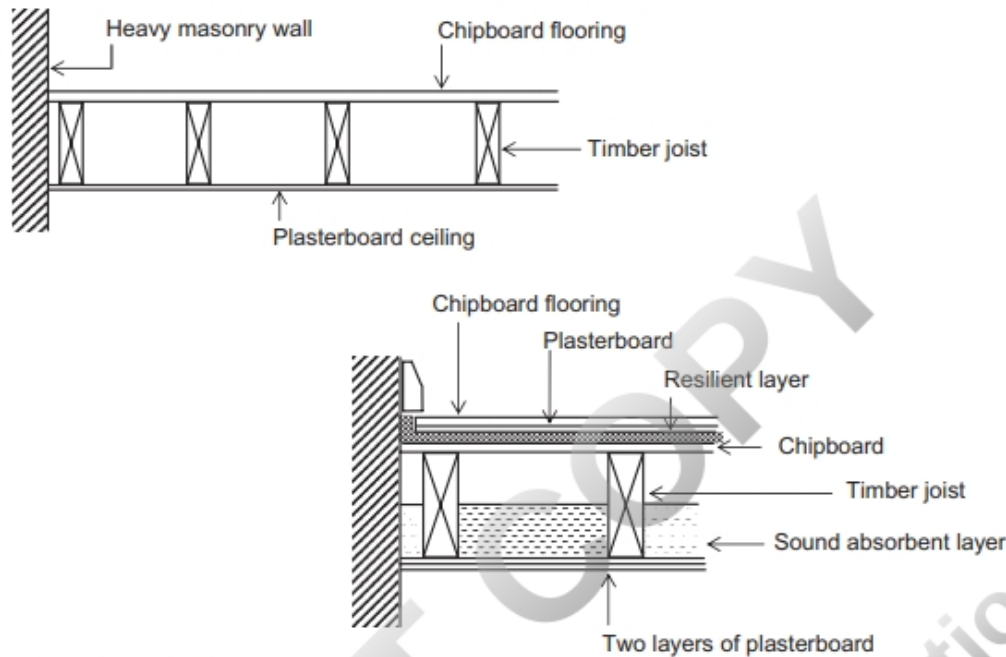


Figure 10.15 Timber joisted floor and details to provide sound proofing.

since if the vibrations can travel across junctions between elements and via joints and fixings the noise will penetrate deeper into the building. Mass will again play its part in damping the sound, but rigidity and natural vibration or resonance of the components sympathetic to the frequency of the noise may become important. Discontinuities and edge detailing are particularly effective in limiting the transmissions of these sounds.

Striking hard surfaces creates the greatest sound, not only in the room but also in setting up vibrations throughout the structure. Soft surfaces dampen the original impact and absorb the airborne sound that results.

There are particular problems associated with the pumps and fans of the services. The continuous rotation generates noise, but the movement of the rotation may also set up continuous vibrations in the construction to which it is attached. This may be the fabric of the building supporting the pump or fan or it may be the pipe- and ductwork to which it is attached. Isolation or discontinuities have to be used to

mount the pumps and fans and connect them to the distribution system.

Methods of prediction

Definitions of a comfortable acoustic environment are well established for a wide range of activity including spaces with both general and specific acoustic demands (e.g. offices and concert halls). There is a great deal of empirical measurement of the characteristics of the materials commonly used in construction, and predictive calculations based on theory can utilise these values to predict performance in a wide variety of circumstances. Modelling, originally physical but increasingly on the computer, can be used in the design of specific spaces.

For the predictions to be fulfilled much care is necessary in the design detailing and the production phase. Identifying isolation discontinuities and in particular edge fixings to elements of the construction are of prime importance. During site operations, fixings and edge details need particular care. Gaps at junctions and the

rigidity of connections can be crucial in achieving acoustic performance.

The clean environment

As with all aspects of environmental performance it is necessary to be clear about what activities are being carried out in which part of the building. Acceptable standards of cleanliness will have to be defined for the occupants but may also have to be considered for the materials and equipment to be housed and used within the building. For all these aspects of the activity, cleanliness will have to be defined against two complementary sets of criteria: those that would be detrimental to health or operational requirements and conditions that would be socially defined as unacceptable.

The socially defined criteria for cleanliness may not be detrimental to health or operational efficiency. They will, however, contribute to the social and psychological health of the occupants. The distinction between the health of occupants and the efficiency of operations is also important. Definitions of cleanliness will have to be identified against ideals of hygiene, the control of pathogens harmful to life or health. They will also have to be defined for the materials stored and equipment operated in the building. Levels of dust and dirt may not be detrimental to life but may interfere with the operation of equipment.

Another way of considering cleanliness is to identify the possible undesirable components of the environment as physical, biological or chemical. The term 'clean' is most associated with the absence of dust or dirt. These particles will be of various sizes and possible composition. They may be inert minerals but are also likely to include matter of biological origins (dead skin cells). They may also be chemically reactive if associated with, say, industrial waste. Particles are most commonly associated with surfaces but can be suspended in the air. The air, however, also carries other potentially undesirable components. Gases can mix with the air and odours can be carried in the air. The

source of both gases and odours can be either natural or manufactured, and while some can be a health hazard, some are only a nuisance. Some gases, such as carbon monoxide produced from faulty heaters or the burning of fossil fuels, have an immediate deadly effect, while the naturally occurring gas of radon from some ground conditions only shows its effect after many years. Other gases such as methane and carbon dioxide from the degradation processes in the ground such as landfill sites that are now being used for development are not just a health hazard but also introduce the safety risk of explosion. In addition to particles, gases and odours, it is now possible to detect appreciable amounts of electromagnetic flux, the long-term health effects of which are still under investigation.

It is clear that surfaces and the air are two major areas of concern in providing a clean environment. Water is also a medium that has to be clean. Once it has entered the building at an appropriate quality, avoiding cross-contamination becomes a priority in the design of the water distribution systems.

Surfaces, air and water are all open to inspection. Occupants and equipment come into contact with them. However, within the construction or in unused or not often visited spaces there is the possibility of infestation. Varying in size from cracks in the construction to whole loft spaces, there exists the potential for infestations of animal and plant life. Infestations of insects, rodents or birds are all possible, as are bacteria in some locations. Plant life is most likely to be mould or other fungal growth, as these often do not need light to maintain growth.

Infestations of this type not only are undesirable against the notion of a clean building but also can be harmful to the fabric of the building itself. Control of these infestations is important for the durability of the construction as well as maintaining a clean environment for the occupants and the operations of the building.

It is, therefore, necessary to undertake an analysis of the air in the building, the surfaces of the construction visible and in contact with the operations in the building and the infesta-

tion potential of the construction and unused spaces in the building.

Clean air

It has long been recognised that particles in the air, particularly from smoke, result in a high incidence of respiratory disease as well as making surfaces, including clothes and skin, dirty. Similarly it is recognised that dampness in the air is not desirable and that limits to humidity are sensible. Although not as much of a problem as foreseen by early medical predictions, some disease is carried in the air, although often associated with water droplets suspended in the air, and breathed in with the air itself. Smell is another component of the air that, if allowed to concentrate, can become unpleasant, although it is not really a health hazard in itself. It is now being recognised that very low levels of chemical and ion (radiation) concentrations in the air can also be injurious to long-term health or have a low-level debilitating influence. The full implications of many of these are not yet understood and hence safe levels have not yet been established. It appears, however, that as we 'clean' our environment we improve health but then become susceptible to thresholds of other components in the environment that then redefine our levels of performance.

This general process of demanding new levels of cleanliness has also been true where the activity in the building has been manufacturing. This can be seen at its most obvious in the electronics industry, where some processes are now housed in areas called clean rooms.

Clean air is maintained primarily through ventilation. Most harmful components carried by the air are generated from within the building itself and the process is one of replacing the contaminated air with 'fresh' air from outside. Increasingly the air outside also contains contaminants and, therefore, some measure of processing of either the stale internal air or the incoming outside air has to be undertaken. Typically this is the process of filtration with a variety of processes used for physical, chemical and even biological cleansing.

The process of ventilation, both natural and mechanical, has been described earlier in this chapter. The necessity of a pressure difference and openings to create the air movement is the same, but the rates of ventilation may be significantly different. It is necessary to identify not only the types of contaminants but also the rates at which they build up and the threshold levels at which the air is to be considered no longer clean. Like all aspects of the clean environment, the performance level of clean is not absolute. There are only acceptable levels or thresholds of contaminants, many of which cannot be detected by sight or smell and require monitoring in other ways. Traditional methods of leaving the occupants to open windows when the room becomes stuffy will still be satisfactory in many situations. However, contaminants such as radon are tasteless and odourless and therefore have to be detected by other means. As a gas from the ground, its control will require gas-proof layers similar to the damp-proofing discussed earlier in this chapter.

Cleanable surfaces

The specification of surfaces is not that they shall be clean, for all new materials are clean. The requirement is that they shall be cleanable. This demands that the nature of contaminants must be known, as must the means that will be used to clean them. It is possible to speculate that the widespread use of fitted carpets has been dependent on the invention and affordability of the vacuum cleaner.

Taking the lifetime cost to the user of a surface, it is more than likely that more will be spent on cleaning a surface than on its initial purchase. In the domestic situation, reducing the time needed for cleaning may be seen as quality of life; to a commercial undertaking this will inevitably mean money.

The method of cleaning will be dependent on the contaminant. It is possible that some cleaning agents may be aggressive to some materials and these will have to be excluded from any possible specifications. Much cleaning associated with hygiene will be water based and

hence impervious surfaces will have to be specified. The specification of surfaces with respect to cleanliness will only fail if they cannot be cleaned in the manner prescribed. Lack of cleaning in use does not constitute a failure of the specification.

Infestation

Many infestations are unpleasant rather than a threat to health. Infestations occur where either plant or animal life breeds and lives within the fabric or within voids created by the detailing or within the furniture and stored items, particularly food. The scale of infestation and the size of the animals vary considerably, as does any definition of what might be unacceptable. Generally, in the developed world, very low levels of infestation are tolerated. Performance specifications would wish to exclude the larger animals such as birds, mice and rats and most forms of insects. Some life sharing a building is, however, inevitable. What is shelter to us provides shelter to many other life forms unless the choice of material and detailing preclude them.

The first line of defence with animals (including insects) is exclusion of the mature adult. Although this is possible with animals and larger insects, it is often not possible with the smaller species and bacteria. In the case of plant life it is the seeds or spores that have to be excluded, and this can prove very difficult. Openings that lead to internal, dry cavities have to be detailed and constructed with care to ensure minimum dimensions to exclude adults. Larger openings have to be protected with screens where infestation is possible.

If exclusion is not an option the key to stopping infestation is to understand the life cycle of the potential infester and the conditions necessary to sustain each stage of its life. Removing food sources may deter an infestation, but for most infesters it is only shelter and protection that they gain from the use of the building, which allows them to breed and hence establish an infestation. If it is difficult to limit the conditions suitable for habitation, positively injurious conditions to the health of the infester may have

to be created. While this may be part of the specification, as with wood preservatives, it is more likely to be arranged by the user during occupation of the building.

So far, infestations and breeding patterns have been considered. In some cases it is necessary to exclude adults from the actual rooms, not because they would cause an infestation but because they would be a nuisance or health hazard in themselves. This would include flying insects, either disease carrying or able to inflict injury. Similar detailing is necessary, although this may be contrary to requirements for ventilation.

Our knowledge of the animals and plants that are likely to seek shelter within our building is well developed and much traditional detailing takes the elimination of infestation into account. However, we have to be ever vigilant in that poor detailing or poor construction may lead to colonisation and infestation.

The safe environment

The need for safety in a building arises from the perception of a threat. Understanding the nature of the threat determines the performance required of the construction, the nature of failure and hence the choice of materials and detailing. Threats can be seen as arising from natural events, fire and from within society, where they are associated with security.

Natural threats

Many of the natural threats have been discussed in other sections of the text. For example, infestation and the presence of landfill gases such as methane are discussed in the section on maintaining a clean environment. They were seen as a direct threat to health rather than to safety, although clearly some safety measures are designed to prevent injury and damage to health. This distinction is arguable, but this text has chosen to discuss these health issues with the general requirements for a clean environment. Irrespective of how the distinction is

made, the choice of materials and detailing will be the same, and these were discussed in the previous section and so will not be covered again.

Natural threats not yet discussed come from what is often termed an act of God. It includes the natural extremes of climate, such as high winds and excessive snowfall, and other natural occurrences, such as earthquakes. This threat can be identified with the performance of stability and strength. These natural threats exert forces that the structure and fabric have to withstand without failure. Processes of structural analysis and design are now well established, even though the natural forces involved are often complex and dynamic. The dynamic nature of the forces means the solutions may have to be carefully worked out in terms of the response of the structure and fabric of the building. This is discussed in Chapter 11.

An extreme of climate is flooding. Practical steps that can be taken to hold back water inundation in the choice of construction fabric are limited. Infrastructure projects in coastal and river defences for low-lying areas may limit this threat. Often location and the initial choice of levels for the development are the most effective measures to take against this threat.

The threat of fire

Fire can be a natural threat, but its probability is much higher in the built environment than in the natural environment. The source of most fires in building comes from the activity within the building or a malfunction of the services, particularly electrical. It is also associated with the possible threats from society itself when associated with arson. However it starts, it is seen as a major safety issue in the built environment and its analysis concerns the whole building. It has an influence on most aspects of the construction. There is now much regulation concerning fire safety design and this shows the level of threat that is perceived in modern buildings. Fire is a major threat to life, but there is

also a financial implication in the destruction of the property, and therefore the design of a building often takes both into account.

Many of the requirements for construction are now laid down in codes, standards and regulations. When operating with any highly codified rules, it may be difficult to apply them to new design ideas. There becomes a need to return to an engineering approach. This has always been difficult given the complex environment of a fire, but computerised modelling can help in the evaluation.

Whether making choices by using published standards or by fire engineering techniques, there is a need to understand the progress of a fire in a building in order to make informed choices.

Like any environmental design, it is necessary first to understand the conditions in which the construction has to perform. The progress of a fire in an enclosed space follows a fairly consistent pattern. This is shown in the typical fire curve illustrated in Figure 10.16.

For a fire to start at all there has to be combustible material (fuel), oxygen and an ignition source. Fire in a building is really a series of fires starting at various time intervals in each room and each following the basic development on the fire curve. Fire in each space requires ignition and then the amount and type of fuel and the rate of supply of oxygen will determine its progress.

In order to understand how fire grows and spreads, it is important to remember that heat can be transferred by conduction, convection and radiation, and each will be involved to a greater or lesser extent depending on how well the fire is developed. These transfer processes are important in both the growth of the fire in each space and the generation of the ignition source for the spread to other parts of the building.

It is also important to know that the objects and materials that combust give off not only smoke but also flammable volatiles, such as gases, which burn in the presence of oxygen, generating flames. This adds greatly to the heat evolution.

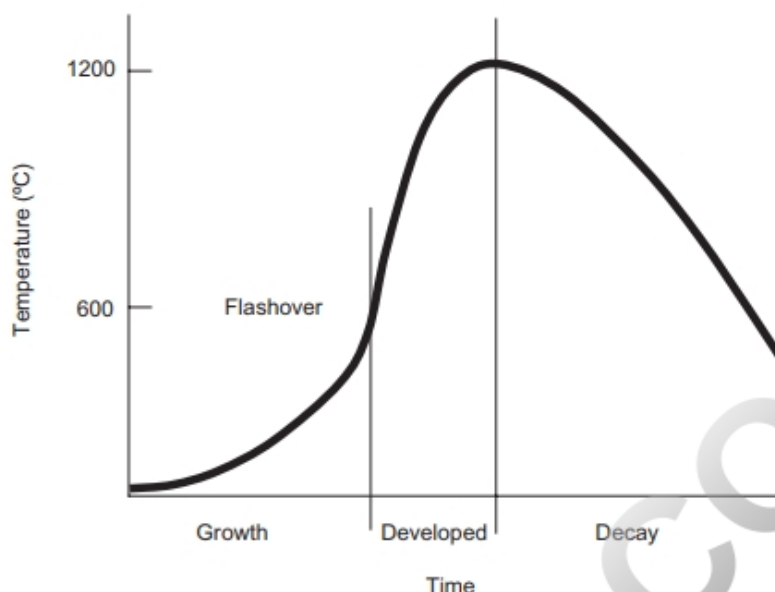


Figure 10.16 Typical fire time-temperature curve.

Fires normally start small. Only objects in contact with the original ignition source start to burn. Gases, heat and smoke will be given off. These will rise in convection currents, heating other possible fuel sources, which start to give off gases, and these all collect under the ceiling, where the surface area of this flammable material becomes much greater. If there is still oxygen to support the fire, when the flames reach the ceiling and the temperature is great enough the gases will ignite. The resulting increase in radiant heat will now cause ignition in most of the remaining flammable objects and materials (particularly surfaces or linings) in a very short space of time. This point occurs at around 600°C and is known as flashover; the fire is then fully developed. If there is insufficient oxygen the gases will not ignite, but the objects that are on fire will continue to smoulder and give off heat. The introduction of oxygen as the door is opened will cause the sudden ignition of the gases, causing the phenomenon known as backdraft.

The temperature in the space now rises rapidly and the potential for the fire to spread becomes much greater. Containing the fire at this point depends on the fire resistance of the

elements such as walls, floors and the building structure.

By following the development of the fire as described in this way it is possible to identify the technical solutions that could be used to make sure people escape and that the integrity of the building is maintained throughout the fire.

Fire prevention

It is clear that the best defence against fire is to prevent ignition. Identifying the possible sources of ignition and isolating them from a significant supply of fuel will accomplish this. If the activities or processes undertaken in the building produce heat, they should be carefully designed so as to be isolated some distance from any combustible material. These can often be easily identified as heat-producing appliances and flues. Minimum distance of timber components from flues is a good example of fire prevention. However, another major threat is the malfunctioning of any energy distribution services such as electricity and gas. Malfunctioning electrical systems are a common cause of fires. If the electrical current arcs it provides a direct

source of ignition at high temperature, causing immediate ignition of surrounding fittings or construction. In extreme risk areas, low-voltage electrical supply may be specified to minimise the risk of electrical fires.

Ignition from accidental sources such as discarded cigarettes is difficult to control by strategies involving the choice and detailing of the construction. However, treating fabrics with fire retardants has had major success in limiting the start of fires from such accidental sources.

Fire detection and escape

If a fire does start then there should be a maximum chance of it being dealt with in the initial phase of the time-temperature curve. This involves early detection and fast extinguishing. These two functions are most often associated with the services provided in a building. Both detection and alarm can be either manual or automatic. The simplest means of detection and alarm that has been used is the provision of a bell (or triangle) to be rung by hand by the person who detects the fire. Alarm may still rely on an individual activating a building-wide alarm system automatically by breaking a glass disc in front of the alarm switch. Increasingly an automatic detection system will be specified using heat and smoke detectors to set off the alarms.

Having detected the fire and raised the alarm, two activities have to be considered together: the evacuation of the people and the provision for fire-fighting.

Given that the fire has been detected during the growth phase indicated on the time-temperature curve, heat will still be relatively low, although smoke may build up very quickly. If the fuel is chemically complex, the smoke may be acrid or even toxic. Escape has to be a priority. The majority of deaths in fires are from asphyxiation by hot smoke rather than burns due to the heat.

However, with very early detection it is possible to smother a small fire. Traditionally this would have been done with manually applied

material such as sand or a fire-blanket, but nowadays a fire extinguisher would be used. There is a link here with the operational management of the building. The contents of all extinguishers are not the same. Products of water, foam, powders and CO₂ are available for different types of fire; clearly water should not be used on electrical fires or even fat fires. If initial fire-fighting equipment is to be provided then personnel have to be trained in its use and the equipment checked regularly.

Automatic initial extinguishing can be achieved with sprinkler systems (or their gas equivalents as long as evacuation can be achieved first). These include a detection system that automatically releases the extinguishing medium, water in the case of sprinklers. In sprinklers each sprinkler head is its own detector (heat expands a liquid in a glass stopper which breaks and allows water to escape from that head only), so extinguishing can be as local or widespread as the fire. Even if the system does not extinguish the fire, it gains valuable time in that it considerably reduces the production of both heat and smoke, prolonging the initial phase on the time-temperature curve and the opportunities for escape. It does, however, require a large volume of water if the control is expected to be widespread as in large open warehouses. Here the public water supply may not be able to deliver at the required rate. Large storage tanks with pumps may have to be provided to maintain flow should the sprinklers ever have to be used.

As soon as detection and alarm have been established evacuation should commence. Again, the link between construction provision and occupation management is very clear. The design of the building must provide the means of escape, while it is the responsibility of the occupation management to ensure that the routes are known and maintained unobstructed.

The design of the building for means of escape is initially a case of planning routes and determining the size of these to ensure a speedy and panic-free evacuation. Everybody should perceive that they have an equal chance of

escape. Initially anybody in the space in which the fire starts has to escape. They have to be able to move to areas that are on the escape routes directly linked to the evacuation point. Here they may meet people from an as yet unaffected part of the building also heading for the evacuation point. While most of these escape routes will utilise the everyday corridors and stairs, additional provision is often necessary due to the fact that everybody would be using them at the same time. It is also necessary to provide alternative directions of escape so individuals do not have to go through the fire to reach evacuation points. The distances and size of these routes have been determined empirically and are now provided in codes and regulations, but computerised modelling can also provide predictions of behaviour in these early stages of evacuation.

These escape routes need protection. They need protection from heat and smoke if escape is to be effected. This protection will be provided primarily in the choice of materials and detailing of the construction that encases the route and ultimately in the stability of the structure of the building itself. In order to think about the properties of the material chosen and the appropriate detailing it is necessary to see how a fire spreads from its initial ignition to other parts of the building.

Building fabric fire performance

Fire development and fire spread are the two areas where the fabric of the building makes most of its contribution to fire design. The floor, wall and ceiling coverings, or linings, influence the development of the fire, and then fire resistance of the elements, both structural and non-structural, influences the spread. The role of the fabric can be identified as significant in the following two broad areas:

1. Lining materials
2. Fire-resistant elements
 - Internal wall and floors
 - Structural members
 - External walls and roofs

While linings are significant in the initial stages of the growth of a fire, within each space the fire-resistant elements are important as fire barriers and maintaining structural stability. Fire barriers also slow the spread of smoke within the building and, in some cases such as compartment walls and floors and in protected shafts, contain the fire within sections of the building. In the design of party walls and external facades the aim is to ensure that the fire does not spread to adjacent property. Structural integrity needs to be maintained throughout the fire, where the question of its potential performance in any rebuilding might be considered.

Fire performance of linings

The choice of linings can affect the time available for escape by slowing down the growth of the fire, but they may also contribute toxic gases and/or flammable volatiles, which may add to flashover gases or create hot droplets that may be a source of ignition. The properties of the materials for fire performance for the linings to the floors, walls and ceilings can now be identified. Combustibility, surface spread of flame and fire propagation all indicate how quickly, if at all, the lining will assist the development of the fire. Smoke and droplet (burning particles) tests along with measurements of contribution to flashover gases give a complete picture to evaluate the choice of lining against fire performance criteria.

Fire resistance of elements

Having chosen materials for the linings, the next concern is the spread of smoke to escape routes and the fire igniting material outside the room. Controlling spread is the role of the fire-resistant elements. Performance is not just dependent on materials' properties but the design of the whole element, be it wall, floor or structural components. This is recognised in that while we talk about lining materials we also talk about the fire resistance of elements. Whole assemblies have to be tested, including all the detailing, joints and fixings (and loading

for structural elements), for a performance rating for fire resistance.

Fire-resistant elements may have the role of a barrier to smoke and fire and/or be a part of the building structure, the collapse of which would not only allow the spread of fire but also cause physical danger to occupants escaping and members of the rescue services.

There are three ways a fire-resistant element could fail and allow a fire to spread:

- Resistance to collapse (stability)
- Resistance to fire penetration (integrity)
- Resistance to the transfer of excessive heat (insulation)

The stability of a structural element may be affected if the fire reduces its load-carrying capacity to the point where the element collapses under the load it has to carry at that stage in the fire. The integrity of a barrier may be lost if the element cracks, shatters or just burns away. This includes jointing materials that may burn or melt, or fixings that fail under the influence of the fire. The insulation of a barrier must be sufficient to keep the other side of the element from reaching temperatures that will cause ignition. More correctly, 'insulation' should be seen as heat diffusion. High thermal mass or endothermic reactions (chemical changes that absorb heat from the fire) will have a similar effect of maintaining the other side at temperatures below ignition for the duration of the fire, even though in thermal resistance terms the material of the element may be considered a poor insulator.

Internal walls and floors can contain fire and smoke to control the spread of a fire. Not all of these barriers need the same degree of resistance to the passage of fire, even within the same building. The performance requirements will depend on two factors. First, the nature of the occupancy including the total number of people in each area and their mobility at the time at which they have to use the escape routes. This will determine the actual time it will take to evacuate everybody to safety. Second is an estimate of the speed of growth and ultimate ferocity of the fire as it follows the pattern illustrated

in the time-temperature curve. This will determine safe evacuation periods.

Another consideration that will determine the fire resistance of elements is the size and configuration of the building. In order to limit the fire resistance requirements for individual elements it is possible to design the whole building as a number of fire compartments separated by compartment walls and floors designed to contain the fire completely. While the specification of these elements may be particularly onerous, the elements themselves do reduce the demands on the other elements inside the compartment as the risk to both people and property is significantly reduced.

Fire may spread more easily at openings in the floors and walls acting as fire-resistant elements if not correctly detailed. Openings are potential breaches in the integrity or insulation of the element. Two types of opening can be identified: doors (and opening windows) and spaces for services to pass from one area to another.

Doors need particular attention, as they have to contain both heat and smoke from escape routes. Not only must the door itself have properties of integrity and insulation but also the gap around the door is particularly vulnerable in spreading the fire to the outer surface of the door. The dimension of the closing edges and the coverage offered by the rebate become a particular aspect of detailing. Closing edges on double doors may have to be fitted with intumescent strips. These materials expand on heating, sealing gaps and ensuring integrity and offering an insulating layer against heat transfer.

The small spaces created around the services passing through walls and floors need to be filled, or stopped, with a fire-resistant material to maintain the integrity of the element.

The services are in fact often carried in voids either above the ceiling or below the floor. The convenience of these voids is that the services may pass unhindered above or below the rooms independent of the partitions between rooms. In fire design these are known as cavities and have the potential to spread smoke and fire

rapidly to other parts of the building. There is a need to provide barriers in these cavities to prevent the spread of both smoke and fire. These cavities should not extend across compartment walls or through compartment floors.

Another danger is spread via vertical shafts. These shafts are provided in buildings for circulation (stairs and lifts) and for services. Once breached by fire, they will act as flues and transmit heat, smoke and volatile gases to higher floors very quickly. The fire resistance of these shafts becomes an important aspect of the fire design. Protected shafts between compartments have to have walls with high resistance ratings and the openings such as doors and service entry points have to be fully protected. Since the stairs are probably escape routes, preventing the intrusion of smoke may be a major performance requirement, possibly by the introduction of positive pressure.

So effective are vertical shafts and cavities that even the cavities in cavity wall construction provide a pathway for the rapid spread of fire to higher floors. This leads to the need to provide barriers in these cavities if the internal skin has limited fire resistance.

As well as establishing barriers to control the fire it is necessary to ensure that the structure of a building does not collapse or damage the barriers for the duration of the fire. There may also be some consideration of the integrity of the structure at the end of the fire for its use in any rebuilding work.

Structural materials in fire

Elevated temperatures change the properties of many materials, including strength, so stability of load-carrying elements may be lost without any apparent physical fire damage to the element. It is necessary to understand that structural sections exposed to fire may not burn, but the rise in temperature may cause expansion and/or a significant loss of strength. The section may deflect and even collapse, as it is no longer strong enough to carry the loads.

The mechanisms are different for the major structural materials. Steel has a high thermal

conductivity and low thermal capacity, which leads to a rapid rise in the temperature when exposed to fire. There is, therefore, a rapid loss of strength as steel has lost something like 50% of its yield strength at 600°C, well within the temperatures reached in a building fire. Steel can be fire engineered but is usually protected from the heat. Casing or spraying the steel with either an insulating material or a material that can absorb the heat can achieve this. Absorbing can be achieved by either high thermal capacity or endothermic reactions, where chemical changes in the materials use the heat of the fire. These casings and spray-applied materials must remain attached and not crack during the fire. Other strategies that have been used include filling the structure with water to absorb the heat or putting the structure on the outside of the building, but these options have not gained widespread application.

Reinforced concrete has a high thermal capacity so, unless the sections are thin, the rise in heat during a fire is slow other than near the surface. If the surface cracks or spalls, or if the steel reinforcement that is near the surface is allowed to gain heat, the section may fail. This focuses attention on the concrete providing cover to the reinforcement. The aggregates in the concrete and the depth of cover are the specification items of significance to the fire resistance of reinforced concrete.

Timber has a completely different mechanism associated with achieving fire performance. Timber burns, but the charred products of combustion remain attached to the section and insulate the unburnt timber from oxygen and heat. Burning slows considerably as the fire progresses. If unprotected structural timber is specified oversize to account for a charred layer, the timber will carry the load for the duration of the fire but will need to be replaced in any rebuilding.

Fire performance of external elements

Having specified internal barriers and the structure so that they perform during a fire, there remains one other major threat. If the fire

breaches the external envelope, it not only will gain a source of oxygen but also may spread between adjacent properties. There are two ways that this spread between properties could happen. The first is spread along external surfaces to adjacent buildings, particularly along roof surfaces. The second is directly from areas of the facade breached by the fire. While spread along external surfaces implies that the buildings are connected, breaches in the facade imply a distance to the adjacent building. If this space between the buildings is large enough, the risk of spread is eliminated altogether. Up to this point, at least some of the facade must act as a fire-resistant element. The closer the buildings are together, the greater the area that must be fire-resistant. The codes and regulations give guidance on how much unprotected area can be allowed against notional boundaries between buildings.

Specification of fire resistance

All these performance requirements need to be specified in terms of time. There remains the problem that while evacuation can be established in real time the actual time an element will hold back the fire depends on the ferocity of the fire. For comparable performance between elements, testing must use a standard fire, one with a predetermined time-temperature curve. Hence the times quoted for fire resistance are not real time but standard test times. The required fire resistance has to be chosen by taking into account both the required evacuation real time and the ferocity of the fire defined by its time-temperature curve.

Fire-fighting provision

There remains one other area of consideration for the design of the building, that of the provision for fire-fighting by the professional fire service. Earlier discussion covered the provision of equipment for fighting the fire by the occupants early in its development. Once a fire starts to develop, this equipment has limited value. It becomes necessary to give access and

provide services such as hose reels, wet and dry risers and foam inlets for the use of the fire brigade. This will require consideration to be given to the access of fire appliances into the grounds of the building and, possibly, on large buildings, even specialised personnel access in the provision, for example, of fire lifts. Like so much fire provision, this is a matter for initial design, but it also has to be managed 24 hours a day for the life of the building.

Threats from within society

Some threats come from the society within which the building is designed to operate. Like the natural threats (acts of God) and fire, they are threats to both person and property. In most politically stable societies direct threats to the person from strangers are relatively low unless associated with a threat to property. These threats are most usually associated with crime, possibly including the extreme of terrorism. They are characterised by the means individuals are willing to use to act out the threat. These are complex sociological problems and it has been suggested that the quality of the built environment can play its part in reducing the threat as well as providing defence against it.

The nature of the threat is highly dependent on the activity to be housed in the building. For the most part it is concerned with the intrusion of an external threat, but there are situations where the threat is being housed (e.g. prisons) and the risk is to the activities being carried on outside the building.

Whichever of these is the case, the approach to design is likely to follow that identified for fire: deterrent or prevention, followed by detection and alarm, followed by the provision of resistance to the forces of the threat in order to limit injury to persons and damage to property. Unlike fire, however, the perpetrator of the threat has reasoning and therefore defining any set pattern of attack is difficult. For instance, there is for each perpetrator a fear of detection and an assessment of the risk of being caught.

Assessing the threat involves assessing determination and the means the perpetrator is

willing to use. Petty crime against households may be deterred by the provision of good locks and simple common-sense occupation management to stop opportunistic crime. The determination to burgle any specific property is low and the means that will be used will not involve large forces. At the other end of the scale, terrorism is characterised by having specific targets, high levels of determination and access to considerable force to inflict the damage necessary to breach the defences offered by the fabric and structure of the building. An interesting third example would be a cat burglar, who may target specific objects, plan and execute the intrusion with great determination but operate with very little force. Devising strategies and the performance of the construction solutions chosen is dependent upon understanding the mind and means of the perpetrator.

Personal accident

The main focus of the analysis of a safe environment has been the possibility of external threats, but there is also the need to reduce the risk of personal accident while using the building under normal operational conditions. The evaluation of the potential for accidents in the building is the same as the approach taken to health and safety on construction sites. It starts with the identification of hazards and an assessment of the potential to do harm. When the chance of an incident causing harm is established, the risk can be assigned. In the operation of most buildings safety equipment is not acceptable, so the hazards should be eliminated in the design. This determines much of the dimensioning and detailing of ramps, staircases, balustrades and handrails. Safety issues are implicit in specifying fixings for fittings where failure during use would cause harm. Another example is specifying floor finishes that are not likely to become slippery when wet. In addition to reducing the risk of personal accident, materials should not

be chosen that might be injurious to long-term health.

The private environment

The origins of the requirements for privacy are the conventions of society. Unlike safety, the needs do not arise from the existence of a threat but from a sense of what is right and wrong, what is acceptable or unacceptable social behaviour and organisation. To understand the needs of privacy it is necessary to understand the ways of the society itself and the beliefs of its people.

The concept of the family dictates much about the form of dwellings. Management style and organisational structures will determine much about the form of commercial buildings. This is linked to the concern for image and status, which was considered an aspect of appearance but is associated with other aspects of the performance of the division between spaces to carry out separate activities.

The feeling of privacy comes not from the absence of the sense of impending physical danger but from the close proximity of others invading so-called personal space, even if no physical barriers exist in a room. However, social convention often requires physical separation, involving limiting the attention of others seeing or hearing or in any way being aware of the activity associated with the use of that space.

As such, the major requirements for privacy are acoustic and/or visual separation. The need for privacy adds to the performance requirements of the enclosing elements of the building. Although predominantly walls, it includes the construction of floors, ceilings and service distribution routes, where cross-talk can be a problem.

The analysis and evaluation of the performance of visual separation needs no complex theory or testing other than that of direct observation. Predicting acoustic performance is less direct and has been considered earlier in this chapter.

Summary

1. The aspects of the environment that need to be considered have been presented as dryness, warmth, light, acoustics, cleanliness, safety and privacy. The analysis of these seven areas is the focus of this chapter.
2. The building is a system of active services and passive fabric whose role and contribution (function and performance) is decided in the design.
3. For each of the aspects to be considered it is necessary to have a dynamic description of both the external conditions and the response of the construction to those conditions.
4. Each aspect of the environment that could lead to failure in the proposed construction must be analysed to ensure the performance of the whole.