Moisture conditions in external timber cladding:

field trials and their design implications

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Abstract

This thesis describes the development of technical guidance on timber facade design. The study involved a state-of-the-art review; an exposure trial of external cladding made from Sitka spruce (*Picea sitchensis)* and the production of construction details and associated information. It was undertaken because timber is an increasingly common cladding material in the UK, being used on low-rise residential buildings and for medium-rise and non-domestic buildings. The risks have, therefore, increased but this is not reflected in published guidance. Sitka spruce was used due to its availability in the UK and its similarity to Norway spruce (*P. abies*) which is widely used for cladding in Scandinavia.

The exposure trial indicated that the moisture content range in timber facades is wider than accepted. The minimum moisture content of around 10% appears to be similar for all types of timber cladding and all species. The maximum appears to vary between species according to their fibre saturation point and is influenced by construction detailing and workmanship. A preliminary model of these interactions is proposed.

From a theoretical standpoint, the moisture conditions observed in the trial mean that the (commonly quoted) mean moisture content is all but irrelevant. The mode is a more representative statistic as in most cases the data are skewed towards the fibre saturation point for the species concerned. Most detailing combinations had a moisture content near to the fibre saturation point throughout the winter. Sitka spruce is, therefore, only suitable as external cladding in the UK if preservative treated.

Around 40 construction details were produced. They integrate, for the first time, all of the performance requirements applicable to low- and medium-rise timber facades in the UK. The work’s key benefit is that the guidance arising from this study rationalises and improves facade design. Further research is, however, needed to validate the moisture content model and extend it to other timber species.

Declaration

This thesis is submitted to Edinburgh Napier University for the Degree of Doctor of Philosophy. The work described in this thesis was carried out under the supervision of Prof. Charles Fairfield and Mr Alistair Stupart. The work was undertaken in The School Engineering and the Built Environment, Edinburgh Napier University, Edinburgh. In accordance with the Regulations of Edinburgh Napier University governing the requirements for the Degree of Doctor of Philosophy, the candidate submits that the work presented in this thesis is original unless otherwise referenced within the text. The following publications were derived from the work in this thesis:

Davies, I., Stupart, A. & Choo, B.S., (2004). Timber cladding on the coastal fringe of North-west Europe. In: *Proc. 8th World Conf. on Timber Engng*, Lahti, Finland. 14 – 17 June 2004.

Davies, I., (2008). Evidence-based design of timber facades. In: *Proc. 10th World Conf. on Timber Engng*, Miyazaki, Japan. 2 – 5 June 2008.

Davies, I. & Wood, J., (2010). Exterior timber cladding: design, installation and performance. Edinburgh: arcamedia, ISBN 978-1-904320-04-3.

Davies, I., Fairfield, C., Stupart, A. & Wilson, P. Moisture conditions in timber cladding: field trial data. (Under review by *Proc. ICE, Construction Materials*).

Davies, I., Fairfield, C., Stupart, A. & Wood, J. External timber cladding: design and performance. (Under review by *The Structural Engineer*).

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Contents

Figures

CHAPTER 1

CHAPTER 2

CHAPTER 3

There are no figures in Chapter 3

CHAPTER 4

There are no figures in Chapter 4

CHAPTER 5

CHAPTER 6

CHAPTER 7

CHAPTER 8

CHAPTER 9

There are no figures in Chapter 9

APPENDIX 1

There are no figures in Appendix 1

APPENDIX 2 Defects

APPENDIX 3

There are no figures in Appendix 3

Tables

CHAPTER 6

Notation

Unless otherwise stated in the text, the symbols used in this document are listed below. Roman characters are given first followed by Greek characters. Acronyms are given after the list of symbols. The units used in this thesis are SI, or derived, units where possible.

Roman characters

A	Component quality
A_{rs}	Coefficient of variability due to variation in materials, environments and measurement
B	Design level
b	Total shrinkage
C	Workmanship
D	Days with at least 0.25 mm precipitation
D	Indoor environment
d	Shank diameter of a dowel type fixing
d_1	Edge distance of nail with no applied load
d_2	End distance of nail with no applied load
d_{init}	Initial dimension
E	Outdoor environment
f	Fibre saturation point
F	In-use conditions
G	Maintenance
h_1	Thickness at moisture content w_1
h_2	Thickness at moisture content w_2
K	Coefficient of sound absorption
$k_{climate}$	Climate parameter
k_g	Geometry parameter
k_{g1}	Contact parameter
k_{g2}	Position parameter

k_{g21}	Contacted material parameter
k_{g22}	Orientation parameter
k_{g23}	Gap parameter
k_n	Fastner parameter
k_p	Paint parameter
k_t	Thickness parameter
k_w	Width parameter
k_{wood}	Timber parameter
l_1	Initial dimension
l_d	Change in dimension
mc	Moisture content
m_{final}	Final moisture content
m_{fsp}	Fibre saturation point
m_g	Initial mass of a timber sample
m_{init}	Initial moisture content
m_o	Mass after oven drying
P	Probability
P_f	Probability of component failure
r	Pearson’s rank correlation coefficient
R	Thermal resistance
R_1	Electrical resistance
r^2	Coefficient of determination
R_{mean}	Mean value of R
S	Load
S	Shrinkage or swelling
s_1	Nail spacing perpendicular to the grain
s_2	Nail spacing parallel to the grain
SD	Standard deviation
S_{mean}	Mean value of S
s_{tan}	Tangential shrinkage or swelling coefficient
$U(y)$	Mean wind speed at height y
$u*_{ABL}$	Friction velocity

w_1	Initial moisture content
w_2	Final moisture content
x	Mean service life of test stakes divided by mean life of reference samples
Y_d	Change in moisture content
y_o	Upwind surface roughness variable

Greek characters

β	Coefficient of swelling or shrinkage
ΔH_c	Heat of combustion
κ	Von Karman constant
$\lambda_{cladding}$	Cladding parameter
λ_{fsp}	Species parameter
χ^2	Chi squared statistic

Acronyms

ACQ	Alkaline copper quaternary
ASTM	ASTM International (formerly known as the American Society for Testing And Materials)
BRE	Formerly known as the Building Research Establishment
CA	Copper azoles
CCA	Chromated-copper-arsenate
CMHC	Canada Mortgage and Housing Corporation
COST	European Cooperation in Science and Technology
CPD	EU Construction Products Directive
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CWCT	Centre for Window and Cladding Technology
DPC	Damp proof course

EC5	Eurocode 5
EMC	Equilibrium moisture content
EOTA	European Organisation for Technical Approvals
ESL	Estimated service life
ETC	External Timber Cladding in Maritime Conditions NPP project
EU	European Union
FIGRA	Fire growth rate
FR	Flame retardant
FSP	Fibre saturation point
GS	General structural grade
HRR	Heat release rate
MBD	Market and Business Development Ltd
MC	Moisture content
MOE	Modulus of elasticity
NBRI	Norwegian Building Research Establishment
NPP	EU Northern Periphery INTERREG IIIB Programme
NT	Nord Test
OSB	Oriented strand board
PCP	Pentachlorophenol
pH	Potential hydrogen scale
RH	Relative humidity
RHR	Rate of heat release
RSD	Robust Standard Details
RSL	Reference service life
S/F	Saw-falling grade
spp	Species

TDA	Timber Decking Association
TNO	Netherlands Organisation for Applied Scientific Research
TRADA	TRADA Technology (formerly the Timber Research and Development Association)
Type LR	Leach resistant flame retardant
UV	Ultraviolet
U-value	Heat transfer coefficient
VCL	Vapour control layer
WDR	Wind-driven rain
WPA	Wood Protection Association

Chapter 1

Introduction

During most of the 20th century timber facades in the UK were mainly restricted to low-rise and often low-status construction, such as social housing, occasional rural dwellings, and agricultural and forestry buildings. This has now changed. During the past 15 years timber facades have become increasingly common on mainstream housing, larger buildings and for demanding non-domestic applications such as schools, visitor centres and the like. The burgeoning interest in timber as a facade material has several implications. This thesis addresses three:

- the associated risks, such as fire spread, have increased;
- the underlying science and technology lag behind architectural practice;
- there is a growing interest in UK grown timber, but supply is fragmented.

1.1 Background

In 2001 the Scottish Executive commissioned the author to lead on the development of a policy discussion document titled *Timber Cladding in Scotland* [1]. Although little more than a well illustrated literature review, the publication attracted a lot of interest and is credited with being a key influence in the development of timber facades in the UK. One architectural practice, for example, commented [2]:

‘*… more and more of the design we are now doing with Dualchas is moving away from the white render* (sic) *slate building to using timber and tin. This was made easier for us when the Scottish Executive brought out a publication called Timber Cladding in Scotland, which demonstrates the history of timber-clad buildings in Scotland…* (and) *promotes the use of well detailed timber buildings. Our immediate response was to send a copy to our local planner …*’

The publication highlighted a number of issues and opportunities, of which the potential for using UK grown spruce as external cladding was particularly noteworthy. This led to the author being commissioned to raise the funding for, and then establish, a research project to address this topic and its wider context. In its final form the project spanned Scotland, western Norway, the Faroe Islands and Iceland; the title was *External Timber Cladding in Maritime Conditions* (ETC) [3]. Two thirds of the project budget, of almost one million euro, came from the European Union’s Northern Periphery Programme [4] with the remainder from government and industry. The research tasks were put out to tender under the supervision of a project steering group comprising the national co-funders.

In 2003 the author joined Edinburgh Napier University’s newly established Centre for Timber Engineering and secured a £125,000 contract from the project to run an exposure trial of timber cladding and, based on this, produce a manual for facade design and construction. Funding was also available to publish the manual (see Appendix 1). Other research contractors included BRE, the Norwegian Building Research Institute (NBRI) and Forest Research.

1.2 Defining the gap

During the past decade, facade engineering has emerged as a specialism; it can be defined as: ‘*the art of resolving aesthetic, environmental and structural issues to achieve the enclosure of habitable space*’ [5]. Unfortunately, facade engineers have tended to ignore timber in favour of more conventional engineering materials like concrete, steel and glass. Timber exteriors are mostly designed by architects and timber specialists working outwith the discipline of facade engineering. This split is understandable given that timber facades were until recently mostly restricted to low rise, and often low-status, buildings. Nonetheless, it has resulted in two parallel specialisms: external timber cladding design is concerned with facades made predominantly of wood, whilst facade engineering focuses on building envelopes of other materials. Consequently, the main performance standard for facades in the UK [6] largely ignores timber, whilst the guidance on timber cladding [4] [7] only covers a limited range of topics. Nowadays, timber is being used on all types of facades and so this separation is unworkable. A new approach is needed.

Facades made of timber are more complex to design and construct than those of equivalent size made of other materials such as metal or masonry. Yet, when compared to these other materials, the technical information on timber facades is very limited. Timber facades have received surprisingly little serious research attention, with the result that much of what is published is, at best, incomplete and at worst wrong. It is, therefore, not a surprise that timber cladding has, for several years, been TRADA Technology's most common continuing professional development request as well as being a frequent source of technical enquiries and expert witness contracts.

This author has had a similar experience, with enquiries and consultancy contracts spanning eight themes:

1. **Fungal decay and insect attack**. Most publications on timber facade technology review durability issues from their own national perspective without acknowledging that other approaches are possible. Timber's resistance to fungal decay is often presented as an intrinsic characteristic of the material whereas it is in reality an extrinsic phenomenon. It is, particularly in out-of-ground-contact conditions, affected by the standard of design, construction and maintenance as well as the ambient climate. Thus, for example, although wood scientists in Norway discuss the service life of timber cladding largely in terms of design-for-durability and maintenance, their equivalents in the UK tend to focus on decay resistance whilst virtually ignoring environmental control mechanisms. The relevant British Standard [8] is similarly restricted. It states that the service life of low durability timber in out-of-ground-contact conditions is around 15 years in the UK (*i.e.* it implies that decay resistance is an intrinsic material attribute) but fails to acknowledge that low durability timber can, in some circumstances, have a longer service life due to extrinsic factors such as design and maintenance.

2. **Weathering**. The recent fashion for uncoated timber cladding is resulting in a growing number of disputes where the facade has not weathered as expected. Surface coatings are one way of addressing this problem but they too have their problems as manufacturers and suppliers tend to overstate their effectiveness. Two current challenges are the growing use of so called 'ecological paints' in external conditions, and the trend towards using surface coatings as a way of preventing flame retardants being leached out. The relevant European Standard [9], and guidance documents supporting the UK's building regulations [10 ‐ 12], all fail to acknowledge leaching risks with exterior flame retardants.

3. **Dimensional change**. The most widely referenced publications on timber facades in the UK [7] [13] [14] underestimate the dimensional change that occurs in external timber or give incorrect guidance on how it is accommodated. This leads to frequent – and expensive – cladding failures. The problem is partly due to the guidance mainly focusing on the movement that occurs in indoor conditions where the moisture content of timber is only fluctuating within a narrow part of its hygroscopic region; bulk wetting is usually ignored.

4. **Corrosion**. Although the corrosion of metals by wood is well understood, this knowledge is not readily available with the result that much of the industry guidance on timber cladding is incomplete or incorrect on this subject. This is a growing problem as the corrosion risks are tending to increase due to the recent introduction of relatively corrosive cladding products such as those made from Accoya™, or impregnated with alternatives to chromated-copper-arsenate (CCA) wood preservatives.

5. **Structural robustness**. Structural engineers have recently been made responsible for certifying that timber cladding complies with Scottish Building Regulations; this is highlighting that some timber cladding on medium-rise buildings is not robust. This problem is compounded by a lack of knowledge regarding the moisture content conditions within the facade assembly; this has implications for the strength and stiffness of cladding support battens and the withdrawal capacity of fixings.

6. **Fire safety**. The fire performance of timber facades is not fully understood. This is being addressed in several countries, including Scotland, and new knowledge is

emerging. However, several issues remain unresolved or are widely misunderstood. Those of most relevance to this thesis concern cavity barrier design, the combustibility requirements for cladding near to boundaries between dwellings, eaves detailing, open jointed cladding and the service life of flame retardants in external conditions. All of these topics affect, or are affected by, the moisture conditions in timber facades.

7. **Noise**. In terraced and other multi-occupancy dwellings, the facade is subject to acoustic performance requirements wherever the external building envelope meets a separating wall or floor. Although the design of these junctions is well understood on masonry clad facades there is less knowledge of how acoustic separation is achieved in timber clad buildings. One risk is that detailing taken from masonry facades results in water entrapment when used with timber cladding.

8. **Grading**. Several sets of grading rules exist to guide timber selection for external cladding; the most commonly used in the UK is given in BS 1186-3 [14]. The criteria are typically derived from those for internal joinery (*e.g.* knot size and frequency) and do not adequately address durability and other fitness-for-purpose issues relevant to external cladding. In any case the grades are often ignored.

So long as timber facades were uncommon in the UK, this lack of reliable technical knowledge was of little importance. The UK market for timber cladding has, however, grown by at least 10 % *per annum* for over a decade and now encompasses medium-rise and non-domestic buildings as well as low-rise housing (see Chapter 3). The associated risks have, therefore, increased and so improved knowledge is urgently needed.

This problem is exacerbated by the move from prescriptive to performance-based standards and regulations. Many norms now give performance criteria for building components but no indication of how these can be delivered. In theory this role should be filled by industry codes of practice, but, although these have been published for most facade materials, none has been issued for timber. This omission may be understandable in view of the confused state of some current building regulation guidance on this topic.

Timber facades have to meet three main performance requirements in building regulations: life safety, noise reduction and durability. The building regulation guidance for timber facades in the UK has prioritised the life safety issues related to fire whilst giving less consideration to noise or durability. Indeed, the guidance contains a recurrent conflict between these requirements, with the result that moisture related issues are often overlooked.

The resultant gap can be summarised as follows:

- There is insufficient knowledge of the moisture conditions in timber facades;

- There is a lack of integration between research into the life safety, acoustics and durability of timber facades;

- There is a lack of adequate, integrated and practice-oriented technical guidance.

This gap appears to be causing a growing number of cladding failures. It may result in designers abandoning timber in favour of more predictable facade materials.

1.3 Objectives and scope of this PhD

The gap outlined above is a particular challenge for designers and manufacturers who want to use UK grown timber as external cladding. The UK does not produce enough relatively durable timber to support a major increase in supply, especially now that much UK larch seems likely to be decimated by the *Phytophthora ramorum* epidemic spreading from southwest England [15]. Accordingly, lower durability timbers, such as spruce (*Picea* spp), appear to be the main option for growth, but it is unclear how they should be used. In most of Scandinavia, Norway spruce (*Picea abies*) is the main external cladding timber (Figure 1.1); it is used without preservative treatment, except for a narrow coastal zone in western Norway and on the Faroe Islands. Scandinavians argue that the timber is suitable for this application due to its refractory nature (*i.e.* pits in the cell wall close during initial drying, thereby acting to limit the depth of subsequent preservative impregnation). Sitka spruce (*P. sitchensis*) is an equally refractory species. If this characteristic is also useful for limiting water uptake in external cladding then could one of the timber’s main limitations be turned into a benefit?

Figure 1.1 *Late 19th century timber cladding in Trondheim, Norway. Similar facades are found in most towns in western Norway; they were constructed using untreated European whitewood and redwood (Picea abies and Pinus sylvestris) These facades illustrate that durability class 3 to 5 timber in combination with elaborate detailing can achieve a long service life providing it is designed for durability and regularly maintained. Key measures include metal flashings on all horizontal projections, the avoidance of water traps, an opaque surface coating with fungicidal protection and the rapid replacement of any component that fails.*

Not all timber facade designers and suppliers are interested in UK timber. However, they do all need improved technical guidance. The objectives of this thesis are, therefore, to:

1. Investigate the extent to which UK grown Sitka spruce can be used as a facade material;

2. Generalise these results to provide new knowledge of the moisture conditions in timber cladding and their implications for construction detailing;

3. Help reconcile the conflicting performance requirements in the guidance to building regulations and thereby lay the foundation for a UK code of practice for external timber cladding.

Although focused on external timber cladding, the thesis is applicable all timber on the outside of buildings in the UK, this includes siding, rainscreen cladding, shingles and similar roof coverings, and large-section timbers such as log buildings and exposed structural frames. Many of the findings are also transferable to other temperate oceanic climates such as: western Norway, Ireland, the Faroe Islands, coastal British Columbia, southern Chile, the Falklands, and southern parts of Tasmania and New Zealand.

1.4 Research questions

The research questions are deliberately practice-oriented. They have four themes:

1. **What performance requirements are relevant to timber facades?** How do different types and designs of timber facade perform against these requirements? Do these characteristics differ from those of other facade materials?

2. **How wet does it get?** What is known about moisture conditions in timber facades? What is the intensity and duration of wetting when Sitka spruce is used on a facade? What interaction of factors influences this? Can these data be generalised?

3. **What implications does this have?** Can Sitka spruce be used as external cladding in the UK without preservative treatment? What effects will the predicted moisture

conditions have upon performance? How are these effects controlled? How can these controls be integrated with design for fire safety and noise reduction?

4. **What does this mean for facade design and construction?** What evidence-based construction details can be currently developed?

1.5 Thesis structure

Chapter 2: reviews current knowledge of moisture conditions in facades of buildings in temperate oceanic climates.

Chapter 3: outlines the market context for this research. It considers the market size and key drivers, the move to performance-based design and investigates workmanship standards.

Chapter 4: defines the performance requirements relevant to timber facades in the UK.

Chapter 5: discusses the nature and behaviour of timber as a facade material.

Chapter 6: reports on an exposure trial to investigate the interaction of factors influencing moisture conditions in external timber cladding.

Chapter 7: synthesises the findings of previous chapters to produce outline specifications and a decision support tool to guide timber facade design.

Chapter 8: develops a suite of construction details for timber cladding on low- and medium-rise buildings in the UK.

Chapter 9: gives the conclusions and recommendations for further work.

Appendix 1: gives details of publications derived from this thesis.

Appendix 2: gives examples of common cladding defects.

Appendix 3: includes a compact disc of the exposure site data.

1.6 Contribution to knowledge

Cross-disciplinary in nature, and practical in intent, the thesis is original in the sense that it:

1. Undertakes the first-large scale exposure trial of the construction detailing factors affecting moisture conditions in external timber cladding;

2. Develops a preliminary predictive model of moisture conditions in external timber cladding;

3. Synthesises these results with existing knowledge of the fire safety and acoustic performance of timber facades;

4. Uses this synthesis to inform the development of evidence-based construction details for timber clad facades that reconcile their conflicting performance requirements;

5. Provides much of the technical background from which a UK code of practice for external timber cladding can be drafted.

References

1 Davies, I., Walker, B. & Pendlebury, J. (2002). Timber cladding in Scotland. Edinburgh: ARCA Publications Ltd.

2 Dualchas Building Design (2006) [website blog]. Available: <http://www.dualchas.com/index.php/Blog/our-blog/hmtl> [Accessed 1 June 2008.]

3 Forestry Commission (2003). News release 5542: Wooden walls and Scottish weather - can they live together? [online] Available: <http://www.forestry.gov.uk/newsrele.nsf/weballbysubject/3ADA58219B57044080256C8B005A235F> [Accessed 27 October 2010.]

4 Northern Periphery Programme (2003) [website] <http://www.northernperiphery.net/> [Accessed 27 October 2010.]

5 Society of Facade Engineering. [Online Definition] [*n.d., n.l.*]: <http://www.facadeengineeringsociety.org/> [Accessed 1 July 2010.]

6 Centre for Window and Cladding Technology, (2005). Standard for systemised building envelopes. Bath, UK: University of Bath.

7 Hislop, P. (2007). External timber cladding. 2nd edition. High Wycombe, UK: TRADA Technology.

8 BS 8417:2003. Preservation of timber. Recommendations. London: BSI, 2003.

9 BS EN 14915:2006. Solid wood panelling and cladding. Characteristics, evaluation of conformity and marking. London: BSI, 2006.

10 Communities and Local Government (2006). The Building Regulations 2000, Fire safety, Approved document B, Volumes 1 & 2. London: RIBA Enterprises.

11 Scottish Building Standards Agency, (2004). Building (Scotland) Regulations 2004, Technical Handbooks. Livingston, UK: SBSA.

12 Department of the Environment for Northern Ireland, (*n.d*). Building Regulations (Northern Ireland) 1994. Technical Booklets. Belfast, UK: HMSO.

13 National Building Specification Ltd., (2006). H21 Timber weatherboarding. Newcastle upon Tyne, RIBA Enterprises.

14 BS 1186-3:1990. Timber for and workmanship in joinery. Part 3. Specification for wood trim and its fixing. London: BSI, 1990.

15 [Online archive] <http://www.forestry.gov.uk/pramorum> [Accessed 4 April 2011].

Chapter 2

Moisture

A web search on ‘leaky condo’ in early 2010 revealed over 140,000 pages, many by angry North Americans looking for someone to sue. A condominium – condo for short – is an American term for a flat in an apartment block, and the leaks in question are in the external walls of condos; they have been appearing since the mid 1980s, in and around Vancouver and Seattle, both west coast cities with temperate coastal climates. The leaks were most common with acrylic render (termed stucco in North America), but also appeared in plastic, metal, masonry and timber-clad buildings [1].

The leaky condo debacle stimulated extensive research in Canada and elsewhere, highlighting a number of contributory factors, with poor moisture management within the building envelope appearing as a common theme. As a result, much attention has been focused upon the outer layers of the building envelope, particularly the moisture conditions in the cladding and cavity [2]. The key question being how should facades be designed to minimise the risks of moisture related degradation?

2.1 Cool-temperate oceanic and island climates

This thesis is most applicable to the four regions of the world sharing a cool-temperate oceanic and island climate (Figure 2.1). Although the exact boundaries vary depending upon the indicators used to define it, this climatic zone is usually taken to comprise:

- the north west coastal fringe of Europe from Brittany up to the Lofoten Islands,
- the Pacific Northwest from the Olympic peninsula up to southern Alaska;
- Southern Chile and the Falkland Islands;
- Tasmania, southern Victoria and southern New Zealand.

In this zone, cool summers and relatively mild winters are the norm, rainfall occurs in every month, and the weather is changeable and windy. None of these characteristics is unique to the zone but, taken together, they create a distinct set of conditions found nowhere else.

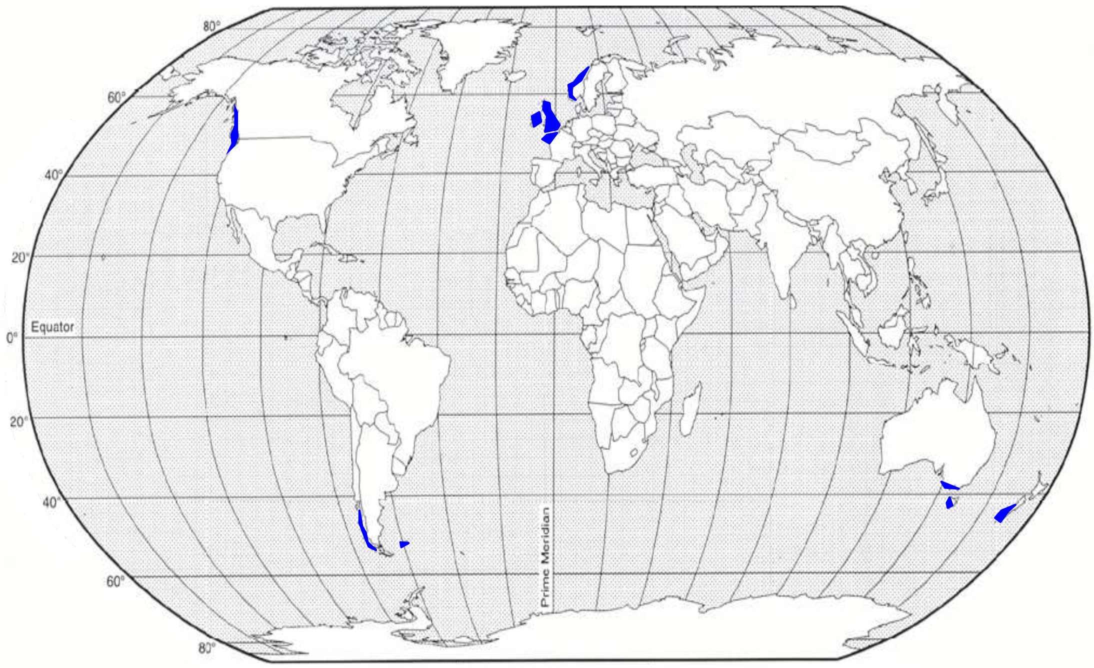


Figure 2.1 *The cool-temperate oceanic and island climate zone*

The climatic characteristics of relevance to this thesis are [3]:

- **West coasts around 40° to 70° latitude**; this zone is subject to regular storm fronts moving east along the paths of the circumpolar jet steams.

- **Oceanic climates**; the ocean has a warming effect on all four areas. The North Atlantic Current (gulf stream) has a particular impact as it pushes the temperate oceanic zone further north in Europe than would otherwise be the case. There is also a marked contrast with continental climates further inland.

- **Relatively high precipitation**; annual precipitation on the west coasts of these regions reaches over 2400 mm in many areas and up to 7000 mm in a few. Rainfall occurs throughout the year, but peaks in winter. It declines away from the coast.

- **Wind-driven rain**; the combination of wind and rain is termed wind-driven rain (WDR). The zone is exposed to frequent WDR during much of the year.

This zone does not exactly correspond to any published climate classification. The author would, however, argue that it is a justifiable category because it reflects an absolute division in timber facade technology. Timber facades in these four areas are dominated by the effects of moisture related degradation whereas those in adjacent areas are not. A survey of historic log buildings in British Columbia [4], for example, highlighted that they occurred in dry interior of the province east of the Bridge River and were absent in coastal conditions – this can be explained by log walls having a poor resistance to moisture. Similarly, leaky condos occurred near the coast but were absent in the dry interior.

2.2 Boundary layer climates

Building envelopes are a type of boundary layer climate. All such climates are dominated by energy and mass transfer processes operating on timescales of less than one day and driven by diurnal solar radiation. These fluxes also vary over an annual cycle and are influenced by storms. The effects become smaller and of shorter duration the closer one gets to the earth’s surface [5].

2.2.1 Wind

The atmosphere below 2 km is characterised by mixing and convection, and by frictional drag as the fluid atmosphere moves across the rigid earth. The bottom 10 to 50 m of the atmosphere experience intense small-scale turbulence, wind speeds decrease still further and many effects only last a few seconds. Closer still, there is a laminar boundary layer a few millimetres thick creating a buffer between the surface and the freer fluid motion above. Meteorologists model wind flow in the boundary layer over a large level surface using a logarithmic law [5]:

$$U(y) = \frac{u*_{ABL}}{\kappa} Ln\left(\frac{y + y_o}{y_o}\right) \tag{2.1}$$

where $U(y)$ is mean windspeed at height y, $u*_{ABL}$ is friction velocity, κ the Von Karman constant (0.42) and y_o is a variable reflecting upwind surface roughness. Surface roughness is often categorised using the Davenport-Wieringa classification (Table 2.1) although this is necessarily approximate and is only valid if the surface is uniform for at least 10 km upwind.

Table 2.1 *The Davenport-Wieringa terrain roughness classification* [5]

	y_o (m)	Landscape description
1	0.0002 Sea	Open sea or lake, featureless land surface with a free fetch of several kilometres (*e.g.* tidal flat, desert)
2	0.005 Smooth	Featureless land surface with little vegetation (*e.g.* beach, fallow open country)
3	0.03 Open	Level country with low vegetation and few obstructions (*e.g.* grazing land without windbreaks, moorland, airfield runways)
4	0.10 Roughly open	Cultivated land and open country with occasional obstacles (*e.g.* farmland with low hedges and single rows of trees)
5	0.25 Rough	Recently developed cultivated landscape with high crops and scattered obstacles (*e.g.* dense shelterbelts, vineyards)
6	0.50 Very rough	Old cultivated landscape with many large obstructions separated by open space (*e.g.* farms, orchards, young forests)
7	1.0 Closed	Landscape totally covered with similar sized obstacles (*e.g.* mature forests, homogeneous villages and towns)
8	$\geq$ 2.0 Chaotic	Centres of large towns with a mix of low- and high-rise buildings, also irregular mature forests with clearings.

When a moving air mass encounters an impermeable flat roofed building set normal to the airflow, it is deflected over the top, around the sides and down the front. This creates high pressures over the windward side of the building particularly around the upper middle part of the wall where the wind is almost stopped (Figure 2.2). Pressure decreases from this point outwards. Accelerating flow near the edges of the wall can create suction particularly at sharp corners where the air flow can become separated from the building's surface. The sides, roof and lee face of a building thus experience the most pronounced suction effects. Other building shapes and orientations create variations on this pattern. Engineers have tended to calculate wind loads on buildings using a power law [5]:

$$\frac{U(y)}{U_{ref}} = \left(\frac{y}{y_{ref}} \right)^{\alpha P} \tag{2.2}$$

where $U(y)$ is a reference wind speed at height U_{ref} and αP is a power law exponent expressing terrain roughness. Whilst equation 2.1 has a physical background and theoretical derivation, equation 2.2 is empirical; the exponent being derived from measurement. The log-law and power-law do not exactly coincide. The calculation of wind loads on buildings is described in the relevant norms.

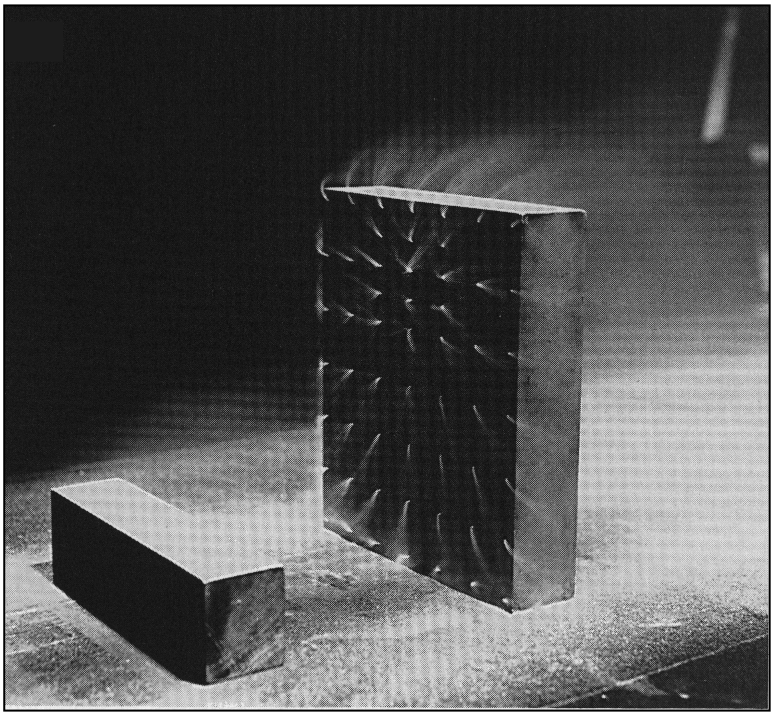


Figure 2.2 *Wind tunnel simulation of airflow around a building.* (image courtesy of BRE [5])

2.2.2 Wind-driven rain

In addition to causing structural loads, wind drives rain into the building envelope affecting water penetration and weathering. Raindrop deposition on a facade is greatest at the upper and outer edges. Contrary to most people's perception, WDR variation in the UK is not simply north-south but instead increases from southeast to northwest [6]. Areas such as Cornwall, the Lake District or western Scotland experience much higher WDR loads than London, Newcastle or Inverness.

Discussions are ongoing to develop a European WDR index, although progress has stalled due to a lack of methodological consensus. The first wind-driven rain map was produced in Norway [7], and this is in the process of being updated [8]. A wind-driven rain index has also been published for the UK [9]; it uses two calculation methods. The spell index expresses total WDR load during a continuous storm event and is, in effect, a measure of the likelihood of rain penetration through masonry. The average annual index represents short duration WDR events and is effectively a measure of the moisture content of masonry.

Because a Europe-wide WDR map was not available, the ETC project commissioned Sellers and Hale [10] to make a preliminary comparison between Scotland, Norway, the Faroes and Iceland. Their conclusions were [10 (p18)]:

> Iceland has both the lowest wind speeds and the least precipitation of the four countries, and therefore the lowest values of WDR (generally below 1 $m^2\ s^{-1}$, except in the south in the winter months). The Faroe Islands had low WDR (less than 1 $m^2\ s^{-1}$) for the three stations which recorded both precipitation and wind speed. However, these values may exceed 2 $m^2\ s^{-1}$ in inland areas where the precipitation is higher… In Norway… WDR, varies greatly across the country, with low values in the north and east, and high values in the south-west, especially in the mountainous coastal area around Bergen. Scotland experiences higher wind speeds than Norway, but the peak precipitation is similar, occurring on the west coast… WDR values in both Scotland and Norway diminish greatly away from the west coasts.

The authors developed WDR maps of Britain (Figure 2.3) calculated from long-term meteorological records as the product of mean monthly wind speed (ms^{-1}) and total monthly precipitation (m). Their method is similar to the UK annual index described above, except that WDR is calculated monthly. This was done to enable the index to be integrated with monthly temperature. The principal degradation mechanism in timber is fungal decay and it is known that this ceases if the timber is frozen and it is suppressed below around 5 ºC. Therefore, the risk of timber degradation due to moisture may be partly offset by the effect of low winter temperatures. The approach appeared promising and so monthly WDR and temperature graphs were produced for several sites in Scotland, Norway, the Faroes and Iceland (Figures 2.4 and 2.5 give some examples). If the 5 ºC threshold is valid then these figures suggest that WDR is of most concern in the Scottish Highlands between April and October.

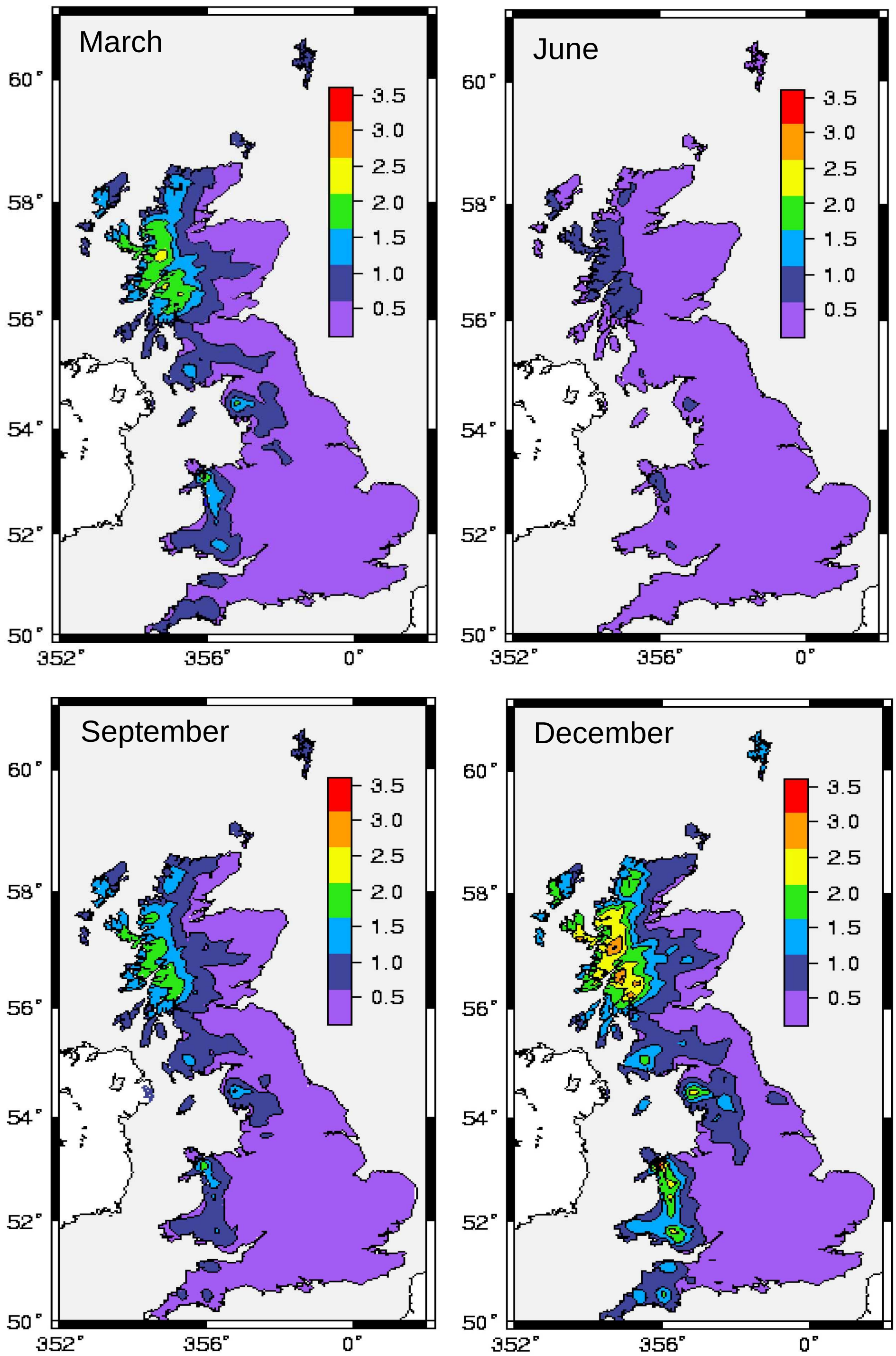


Figure 2.3 *Seasonal wind-driven rain (m^2 s^{-1}) for Britain*

(after Sellers and Hale [10])

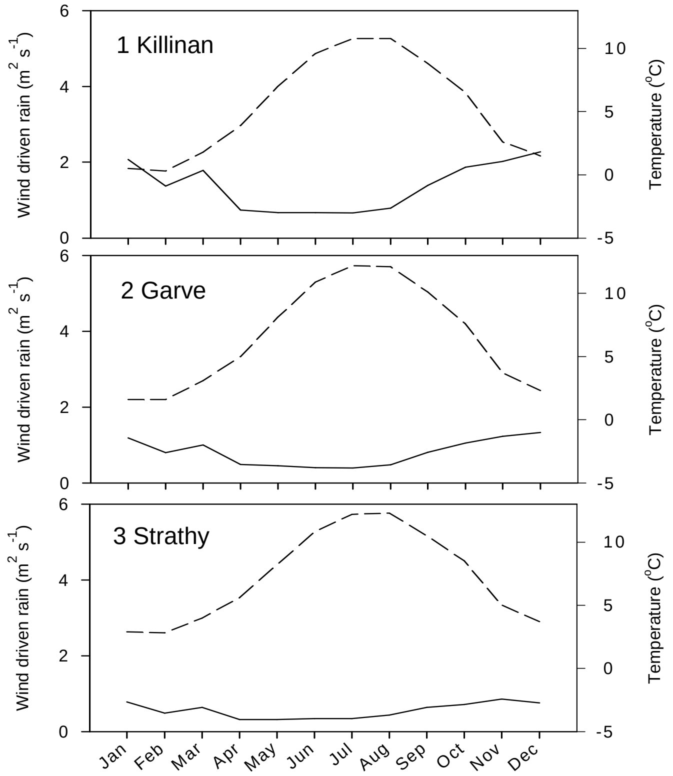


Figure 2.4 *Annual variation in WDR (solid line) and temperature (dashed line) for three sites going west to east across the Scottish Highlands.*

1: 57º 19' N, 5º 19' W
2: 57º 36' N, 4º 50' W
3: 58º 25' N, 4º 3' W

(After Sellers and Hale [10])

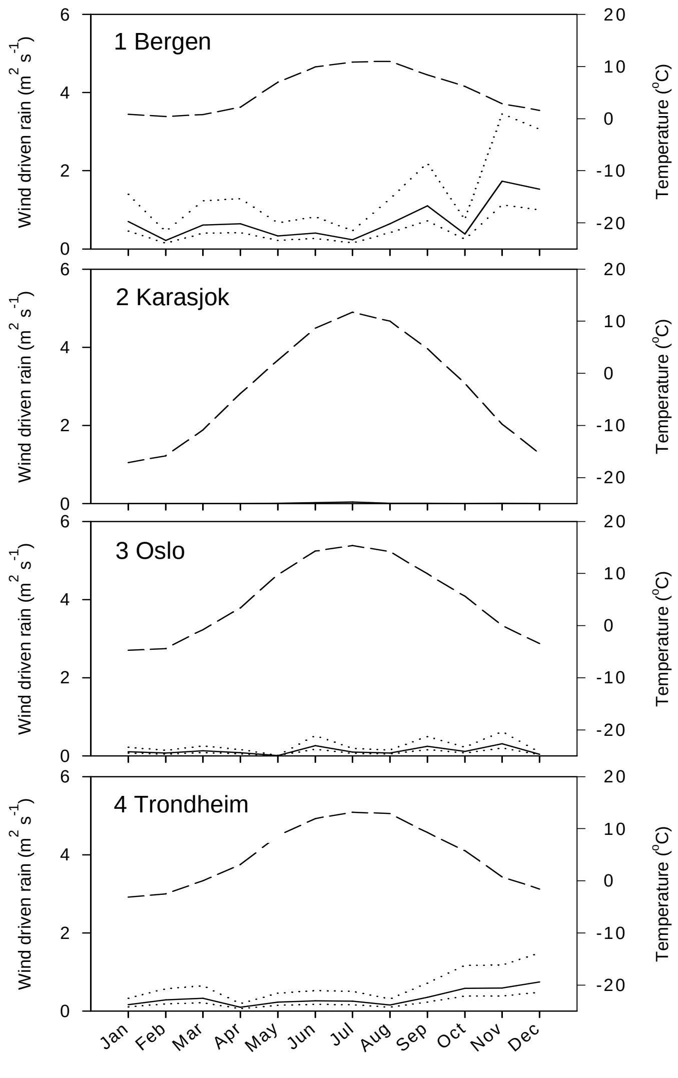


Figure 2.5 *Annual variation in WDR (solid line) and temperature (dashed line) for four sites in Norway. The dotted lines show likely variation in the data.*

1: 60º 23' N, 5º 20' E
2: 69º 28' N, 25º 30' E
3: 59º 56' N, 10º 43' E
4: 63º 25' N, 10º 26' E

(After Sellers and Hale [10])

2.2.3 Predicting WDR on walls

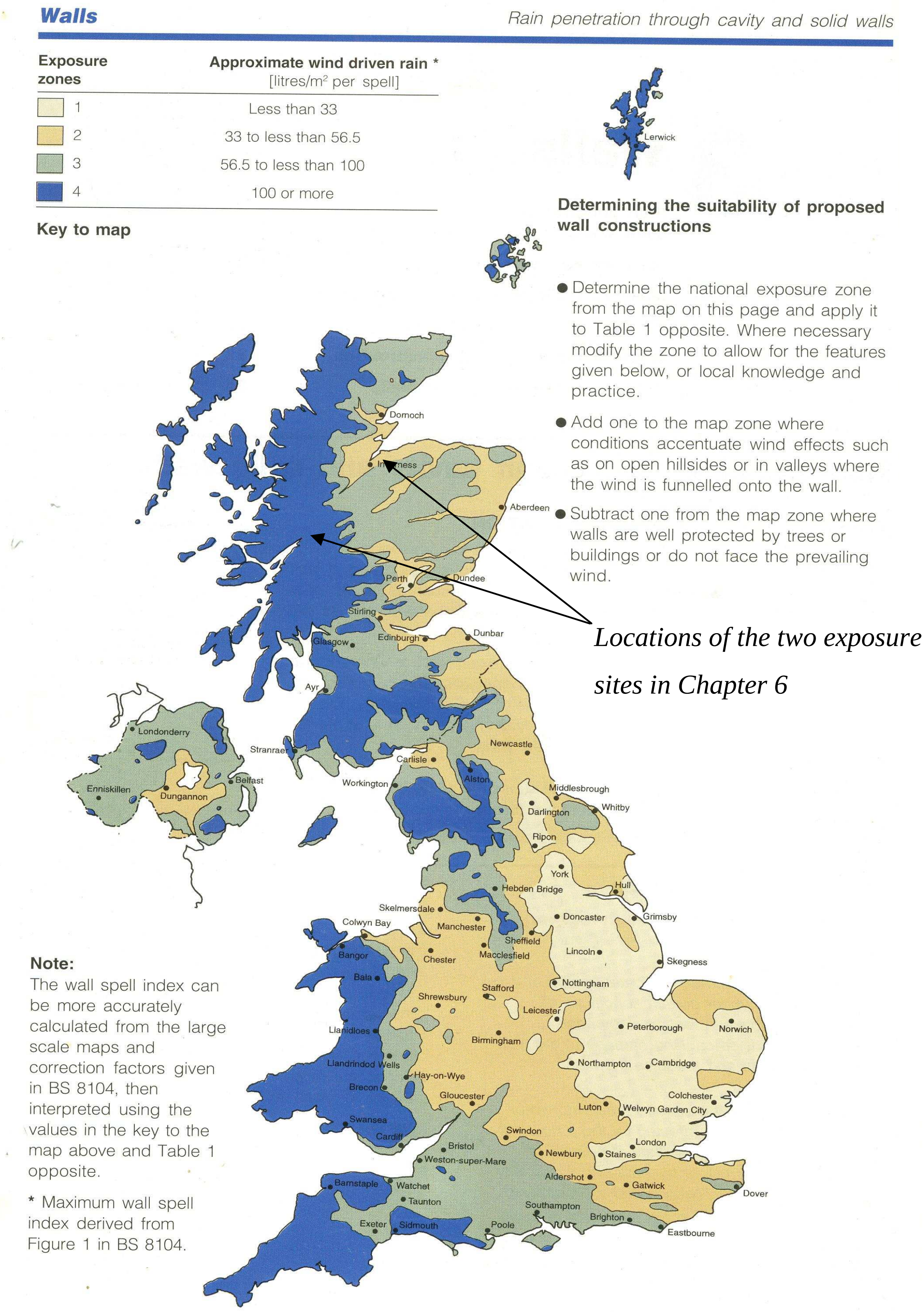
The UK index in BS 8104 [9] has been used in BRE Digest 262 [11] to define WDR exposure zones for different types of masonry wall construction (Figure 2.6). It also includes masonry cladding onto a timber-framed structure. However, because the method originated with masonry-based construction it is likely that it would need recalibration before it could be applied to cladding or insulation made from timber.

Canadian research following the leaky-condo episode provides an alternative approach. A survey of building envelope failures in coastal British Columbia [12] found a correlation between the frequency of moisture related problems and eaves width (Figure 2.7). The main guidance document produced in response to the failures [2] proposed a nomograph (Figure 2.8) which used this correlation in combination with a simplified version of the Davenport-Wieringa classification. The overhang ratio is calculated from the horizontal width of the eaves (or other projection) and its height above the lowest timber component on the facade. As with BR 262, the Canadian guidance gives recommendations for which types of cladding are suitable in each exposure category. This includes timber-based cladding. The Canadian guidance appears to be an advance on BR 262 although three issues remain unresolved:

- **Evidence**; the guidance cautions that some of the wall assemblies it discusses have not been fully tested.

- **Correlation or causation**; the relationship in Figure 2.7 may not be due to causation. This author has observed that many of the timber-clad buildings in British Columbia with large eaves date from the early 20th century and appear to be well built in contrast to the condos dating from the 1980s and 90s which have poor workmanship standards. This suggests that workmanship may be a co-factor.

- **Limitations of the classifications**; as already outlined, terrain roughness classifications only give general information on wind flow; they cannot model local effects such as wind channelling between buildings.



Exposure zones	Approximate wind driven rain * [litres/m² per spell]
1	Less than 33
2	33 to less than 56.5
3	56.5 to less than 100
4	100 or more

Key to map

Determining the suitability of proposed wall constructions

- Determine the national exposure zone from the map on this page and apply it to Table 1 opposite. Where necessary modify the zone to allow for the features given below, or local knowledge and practice.
- Add one to the map zone where conditions accentuate wind effects such as on open hillsides or in valleys where the wind is funnelled onto the wall.
- Subtract one from the map zone where walls are well protected by trees or buildings or do not face the prevailing wind.

Note:
The wall spell index can be more accurately calculated from the large scale maps and correction factors given in BS 8104, then interpreted using the values in the key to the map above and Table 1 opposite.

* Maximum wall spell index derived from Figure 1 in BS 8104.

***Figure 2.6** WDR exposure zones for masonry walls in BR 262* (map courtesy of BRE [11])

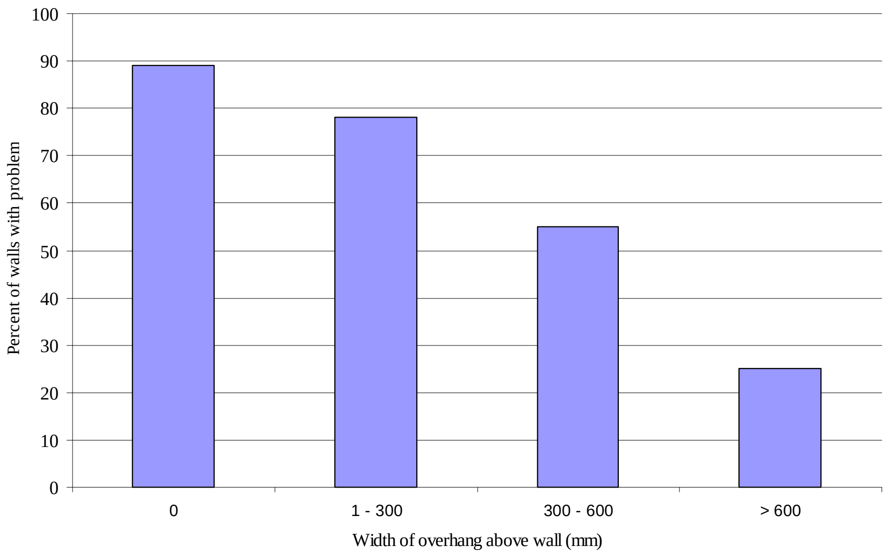


***Figure 2.7** Relationship between eaves width and occurrence of building envelope failures* (after CMHC [2])

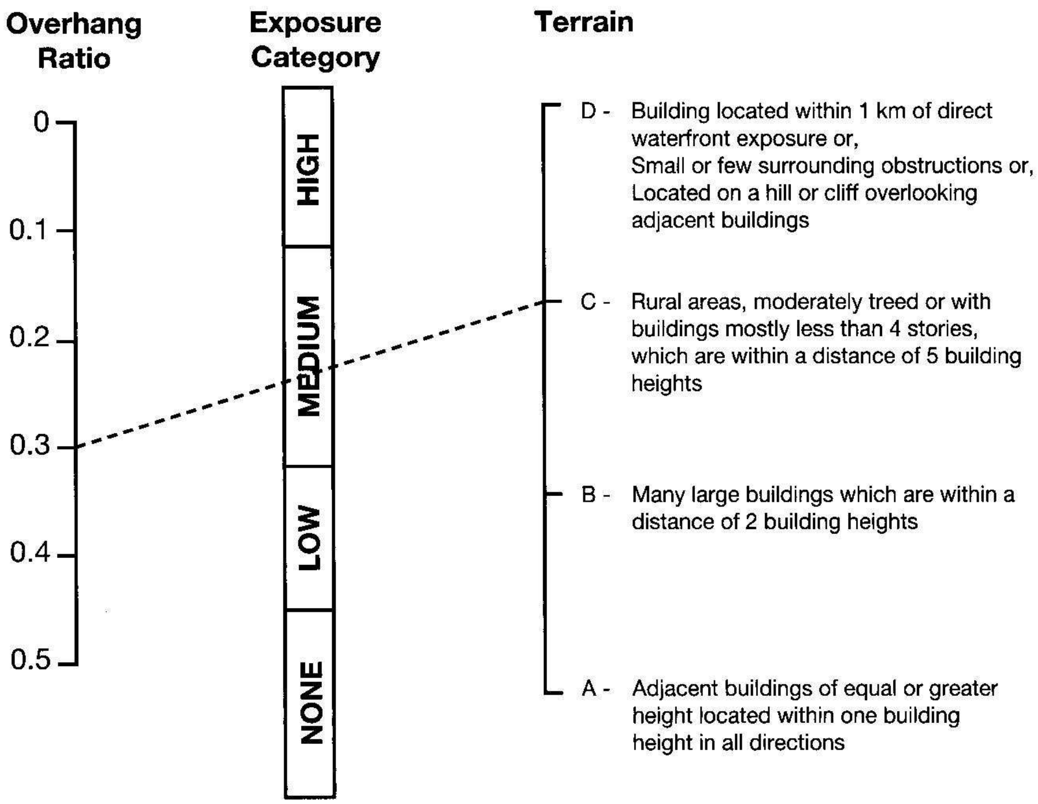


***Figure 2.8** Canadian exposure categories for timber facades* (figure courtesy of CMHC [2])

2.2.4 Heat and mass flow

The interaction between external building envelopes and the atmospheric boundary layer is mostly confined to the flow of energy or matter due to molecular exchange. Interestingly, the same basic flow relationship is found in many different materials and it applies irrespective of whether one is concerned with gaseous or liquid flow, moisture diffusion, thermal or electrical conductivity. Heat, for example, will flow from areas of high to low temperature, the flow rate being proportional to the temperature difference and the rate of molecular collisions. In its most general form this flux-gradient relationship is expressed as [5]:

$$\begin{matrix}\text{Flux of} \\ \text{an entity}\end{matrix} = \begin{matrix}\text{Ability to} \\ \text{transfer}\end{matrix} \times \begin{matrix}\text{Gradient of the} \\ \text{relevant property}\end{matrix} \qquad (2.3)$$

where flux is the rate of flow *per* unit cross-sectional area; gradient is the pressure difference *per* unit length causing the flow; and transfer ability is a constant dependent upon the type of flow involved, for example, diffusion, permeability or conductivity. This relationship was arrived at independently for different types of flow. Thus, thermal conductivity is modelled using Fourier’s law, diffusion by Fick’s first law, and permeability (fluid flow through porous media) by Darcy’s law. They all express the same general relationship, although their exact forms vary depending upon the material and transport process involved. In the case of liquid flow, Darcy’s law is expressed [13] as:

$$k = \frac{QLP}{A\,\Delta P\;P} \qquad (2.4)$$

where k is permeability, Q is the flow rate, ΔP is the pressure differential, A is the cross sectional area of the specimen and L is the specimen length in the direction of flow.

Heat and mass transfer through the building envelope can occur from the atmosphere inwards and outwards from an air mass within the building. In cool-temperate oceanic and island climates the most important consideration is usually moisture infiltration (*e.g.* water entrapment and leaks) due to wind and rain. These risks are expressed – and managed – in different ways to moisture exfiltration.

2.3 Moisture infiltration into the building envelope

Moisture can be driven into a building envelope either through openings between components, through components themselves or by a combination of these.

2.3.1 Moisture penetration

Discussion of moisture flow into building envelopes tends to be conditioned by the type of envelope material involved. Brookes [14] is typical when describing the forces acting to drive rainwater through cladding (Figure 2.9), but, in common with most other authors, discussion is based solely upon technical guidance published by the sheet metal industry.

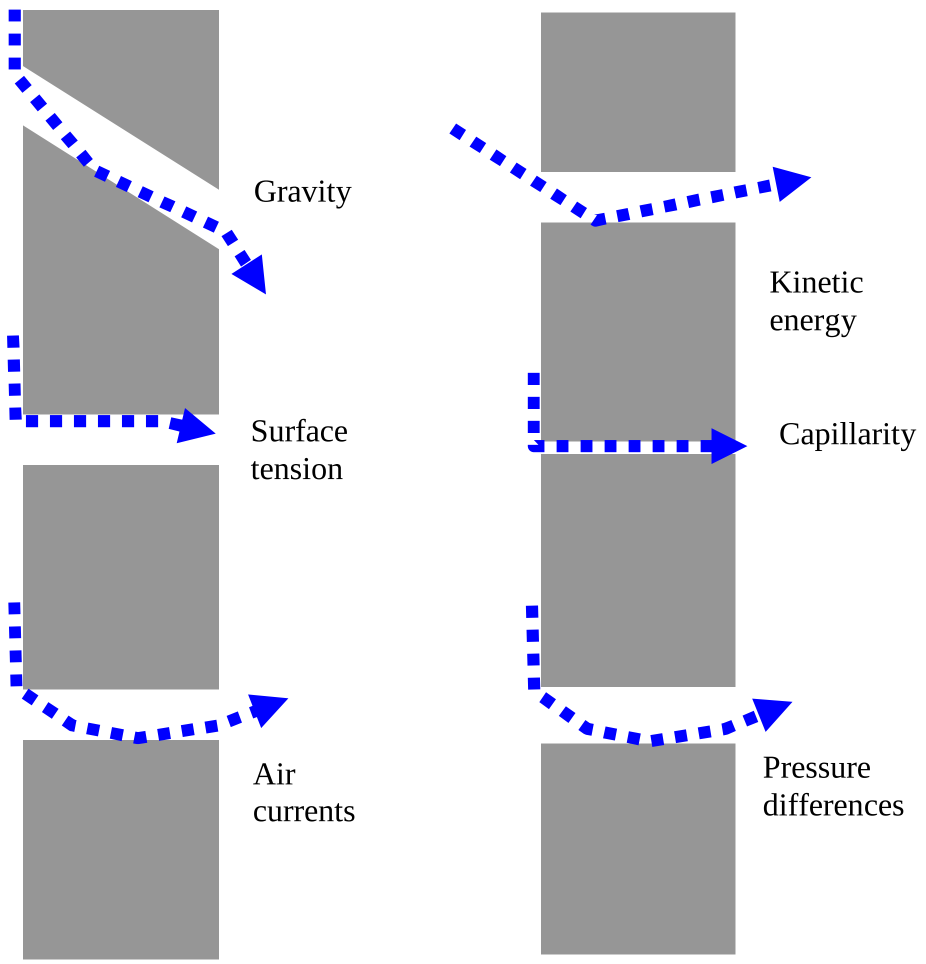


Figure 2.9 *The forces acting to drive water through an opening* (After: Brookes [14])

Whilst the processes outlined in Figure 2.9 apply to all types of facade material, they fail to acknowledge the importance of flow through porous materials and are, therefore, of limited relevance to timber. Control of rain water penetration into timber facades has to take account of moisture flow through the material itself as well as through joints.

2.3.2 Controlling rainwater penetration

Straube and Burnett [15] offer a more comprehensive discussion. They characterised the means by which moisture penetration into building envelopes from external sources can be controlled. They note that rain deposited on a wall or roof can either be:

- **Drained**; carried down the exterior surface by gravity;
- **Stored**; absorbed by capillarity or held by surface tension (pooling can also occur);
- **Transmitted**; be carried further into the building envelope by any of several mechanisms including pressure differences, splashing, bulk flow or diffusion.

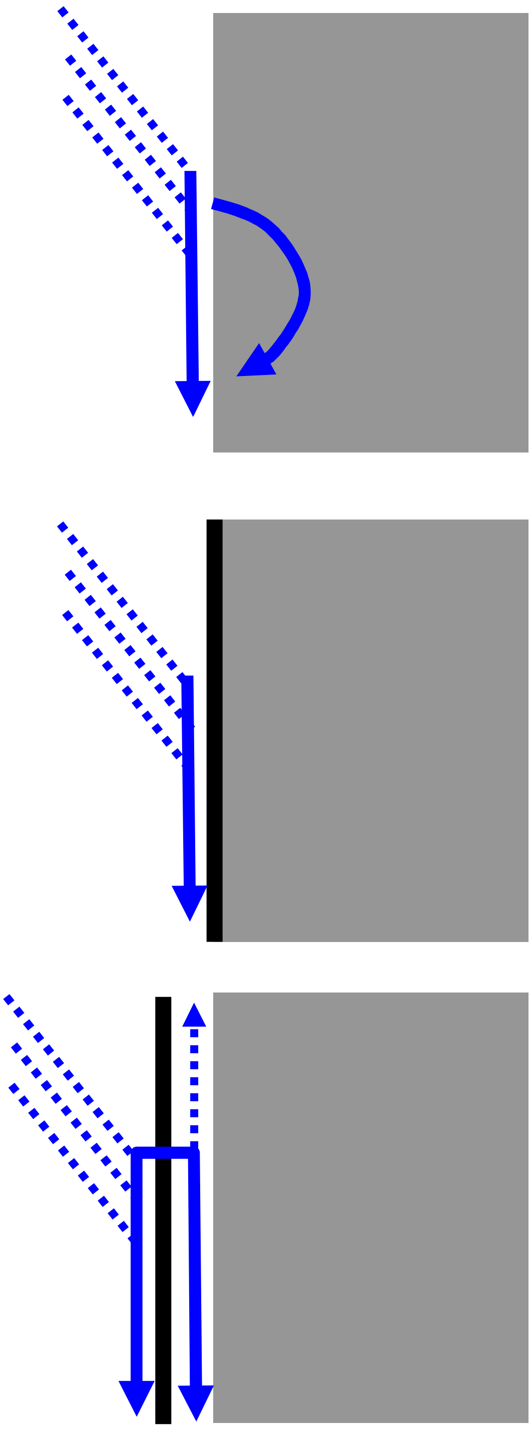
On this basis they group building envelopes into three broad categories (Figure 2.10):

- **Moisture storage**; the oldest strategy is to ensure the building envelope has sufficient storage mass to absorb all water not drained by the outer surface. Examples include solid masonry or log walls. Their performance depends on several factors including the ratio of storage capacity to rainwater load, the material's resistance to moisture related degradation, and the use of eaves and weathering courses to deflect rainwater away from the wall.

- **Face sealed**; the availability of so-called 'modern' materials and processing methods (*e.g.* rolled sheet metal, plastics, plate glass and water resistant adhesives) has stimulated interest in building envelopes where all rainwater is stopped by a watertight layer near the outer face. Acrylic render on rigid insulation is a contemporary instance, although structural glazing is probably the best example.

- **Screened and drained**; in this approach it is assumed that some rainwater will always penetrate the outer surface – the screen – and this has to be removed by drainage and ventilation before it can damage or penetrate deeper into the wall.

Some building envelopes use a hybrid approach. Modern turf roofs, for example, combine a large moisture storage capacity with a plastic water-tight layer. This thesis is mainly concerned with the screened and drained approach. This offers a considerable degree of redundancy to cope with poor workmanship, whereas the face sealed approach is less robust. Where workmanship is poor, face sealed envelopes are vulnerable to moisture penetration: a leaky-condo-in-waiting as it were.



In the massive wall approach most rainwater drains down the outer surface but some penetrates the wall where it has to be stored (without damage to the wall) until it can move back to the exterior.

In the face sealed approach a watertight outer layer is used to stop rainwater penetrating the wall.

In the screened and drained approach any rainwater that gets through the outer layer is allowed to drain and evaporate away before it can cause damage or penetrate deeper into the wall.

***Figure 2.10** Rain control strategies for building envelopes (After: Straube and Burnett* [15]*)*

2.3.3 Types of screened and drained building envelopes

Although the idea of a screen for the rain has been around for centuries, the scientific basis of this form of construction was first investigated in Norway and Canada from the late 1940s onwards [16] [17]; much literature has since accumulated although most of it is only focused on screening mechanisms relevant to non-porous materials. There are, broadly speaking, three types of screened and drained wall:

- **Siding**; the longest established type involves fixing cladding directly to the structural frame or other substrate. A similar approach is used where roof shingles are fixed to sarking boards without an intervening cavity. Any moisture penetrating the cladding is removed by evaporation to the building's interior. The approach was common on timber-clad housing in the UK until the mid-20th century and is still used on non-insulated buildings. Siding remains in use for housing in warm climates, but does not work where drying to the interior is prevented by insulation.

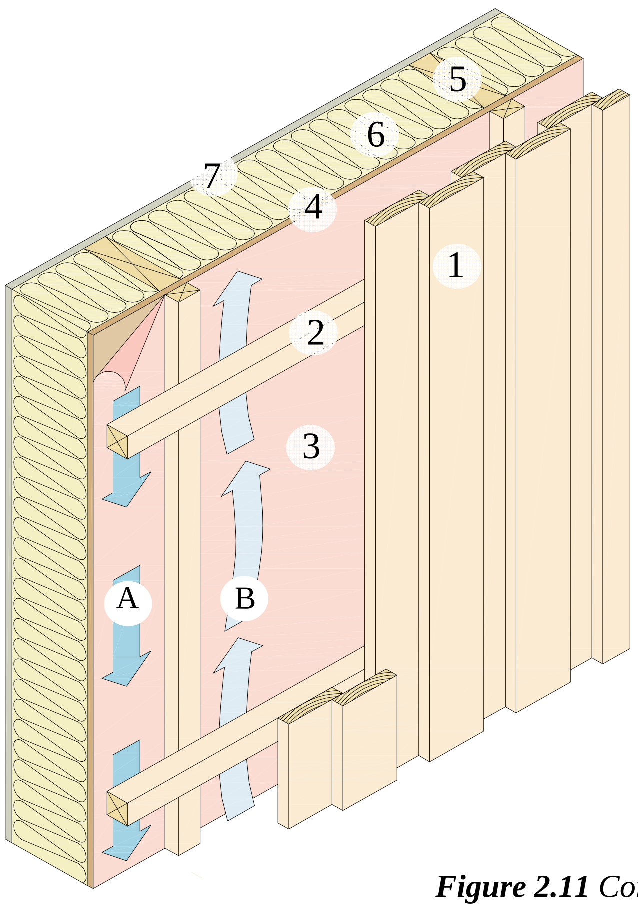
- **Rainscreen**; if cladding is prevented from drying to the interior, then a more complex layered construction is required. The cladding is separated from the substrate by a drained and, in some cases, ventilated cavity that enables drying and provides a capillarity break stopping water from migrating deeper into the wall. As a further precaution, the rear face of cavity is made of a moisture resistant material. The cavity has to be at least 6 mm wide as this is twice the distance that can be spanned by a water droplet. In practice, the cavity is usually at least 10 mm wide to allow for constructional and dimensional tolerances and other factors.

- **Pressure equalised rainscreen**; of the joint leakage forces illustrated in Figure 2.9, pressure differences between the two sides of the cladding are often the most important. In recognition of this, rainscreen cladding designs have been developed that attempt to reduce the pressure difference. They involve compartmentalised cavities in combination with sheltered joint drainage and ventilation routes sized to suit the cavity volume, and a rigid air barrier to the rear of the cavity.

Formulae have been developed [18] purporting to allow the effective vent size for pressure equalisation to be calculated. However, these can be questioned because even the most advanced systems, such as metal and glass curtain walls, achieve less than

25% pressure equalisation during field tests. Straube [19] attributes this poor performance to the near impossibility of balancing the pressure differences occurring during short duration gusts; while he observed that pressure moderation of over 90% can occur under constant wind conditions, none of the designs tested performed satisfactorily during gusts of a few seconds. He further noted that water will permeate porous walls even when perfect pressure equalisation is achieved. These walls require full provision for cavity drying irrespective of joint design or cavity compartmentation.

Pressure equalised rainscreens are therefore mainly of value where the cladding is non-porous and the cavity can be divided into relatively small compartments. Straube recommends the compartment size be no more than 1 m^2. This is only practical with folded sheet materials, castings and mouldings. In practice, therefore, rainscreen cladding is the only viable approach for timber facades over insulated walls. Figure 2.11 illustrates the components of a typical timber rainscreen in the UK. The wall build-up or terminology may differ slightly in other areas. In Scandinavia, for example, the sheathing board may be replaced with moisture resistant plasterboard.



1. *Cladding*
2. *Support battens and cavity*
3. *Breather membrane*
4. *Sheathing board*
5. *Timber frame*
6. *Insulation*
7. *Plasterboard*

A. *Drainage*
B. *Ventilation*

Figure 2.11 *Components of a typical timber–clad rainscreen wall in the UK*

2.4 Moisture exfiltration through the building envelope

At any given temperature, air can hold a specific amount of moisture as water vapour; the warmer the air the more water vapour it can hold. When a given air volume carries the maximum possible amount of water at a given temperature, it is described as being saturated. For any combination of air moisture and volume there will be a corresponding temperature at which the air becomes saturated to the point that that a drop in temperature could result in condensation. This temperature is termed the dew point. Condensation that occurs within the wall fabric is known as interstitial condensation; it can cause considerable problems if left uncontrolled [20].

2.4.1 Controlling interstitial condensation

Vapour pressure describes the partial pressure exerted by water vapour molecules in the air. In cool-temperate oceanic and island climates the vapour pressure inside a building is usually higher than that outside. This tends to drive moisture outwards through the building envelope. In these circumstances the risk of interstitial condensation can be minimised using one or more of the following techniques [21]:

- achieving low vapour pressure inside the building by, for example, room ventilation or minimising moisture emissions;
- using materials with a low vapour transmissibility near the warm side of the wall;
- using materials of high vapour transmissibility near the colder side of the wall;
- using materials with a low thermal conductivity on the colder side of the wall.

2.4.2 Approaches in the UK

The most common approach in the UK involves ensuring that the wall surface in contact with the exterior air is at least five times more permeable to water vapour than the layer at or near the inner face of the wall. A normal timber-framed wall has a relatively impermeable structural sheathing layer such as oriented strand board (OSB) at the rear face of the cavity and so this needs to have a continuous vapour control layer (VCL) near the inner leaf of the wall to maintain the 5:1 permeability ratio. The masonry cladding is ignored for the purpose of this calculation as it is the permeability of the layer behind the cavity that is at issue. The VCL is normally formed of foil-backed plasterboard or 125 μm (500 gauge) polythene.

This is not the only viable wall build-up and if, for example, the sheathing board is moved to near the inside face of the wall, then the layer facing onto the external cavity can be a relatively permeable material such as softboard insulation. In this case a thick sheathing board, such as 15 mm OSB, can act as a sufficient vapour check to maintain the 5:1 ratio and so there may not be a requirement for a VCL near the inner leaf of the wall. This type of timber frame wall build-up is known as a reverse wall and is becoming increasingly common. It is sometimes, misleadingly, called a breathing wall; in reality this term has little meaning and is best avoided. Not all sheathing boards will offer sufficient air tightness to act as a vapour check, in which case a VCL will still be required.

2.5 Cavity drainage and ventilation

In a rainscreen wall, rainwater penetrating the cladding and water vapour diffusing outwards through the wall will normally both be deposited in the cavity from where they must be able to escape. Cavity drying is, therefore, a crucial component of rainscreen cladding design.

2.5.1 Vented or ventilated?

All cavities exposed to rainwater penetration need to be drained to the exterior, many are also detailed to ensure air movement to promote evaporative drying. The requirements for cavity ventilation vary between the UK's building regulations, with those in Scotland and Northern Ireland being slightly more demanding. These differences only apply to masonry construction, however. Where timber or timber-based materials are used for any part of the cladding, support assembly or structural frame, then all of the UK's building regulation guidance documents recommend that the cavity should be 'ventilated' as opposed to 'vented'. These two terms are defined in BS 5250 [21]:

- **Vented cavity**; openings to the outside air placed so as to allow a limited, but not necessarily through, movement of air;

- **Ventilated cavity**; openings to the outside air placed so as to promote through movement of air.

The minimum requirement for a ventilated cavity is given in BS EN ISO 6946 [22]. It defines a slightly ventilated cavity as one where the gap for through ventilation is greater than 500 mm^2 *per* m length (*i.e*. equivalent to a 5 mm unobstructed gap).

It is known that the thermal resistance of a ventilated cavity is lower than if the cavity is unventilated or vented. This can impact on the overall heat transfer coefficient (U-value) of the wall. The U-value describes the rate of heat transfer through an element of construction, over a given area, under standard conditions. It is the inverse of thermal resistance. These effects are not fully understood, however. For example, BS EN ISO 6946 makes highly simplified assumptions about the effective thermal resistance of cavities depending on their ventilation conditions. It states that the thermal resistance of slightly ventilated cavities is halved relative to those with no through ventilation and that the thermal benefits of low-transmissibility breather membranes are eliminated by cavity ventilation. These assumptions have not been validated by measurements in occupied buildings. Indeed, there is surprisingly little data available about the ventilation conditions in the external wall cavities of actual houses [23].

2.5.2 Research into cavity moisture conditions

Some Scandinavian and North American research suggests that wet timber-clad walls dry faster when ventilated, whereas ventilation has little benefit if the walls are dry. A study by the Norwegian Building Research Institute, undertaken as part of the ETC project, looked at the effects of omitting the gap and two cavity ventilation gaps: 4 mm and 23 mm. The study [24] found that providing a 4 mm air gap was ensured, increasing the gap to 23 mm had no additional effect. This gap size is 20% smaller than the 5 mm minimum given in BS EN ISO 6946. The study also found that, in the absence of rain impacting on the wall, the moisture content of ventilated timber cladding was determined largely by the relative humidity of the surrounding air, whereas during rain events the moisture content can rise above the hygroscopic region (*i.e.* the moisture content is determined by a surface film of water and not by relative humidity).

In a brick-clad timber-framed wall, the cavity between the cladding and sheathing is usually about 50 mm deep whereas, in the case of timber cladding, the cavity depth varies according to the type of support assembly. Horizontal timber cladding is usually supported on simple vertical battens around 20 mm deep, whilst vertical cladding is usually fixed to 50 mm deep horizontal battens supported on thinner vertical counter-battens; the full cavity depth in this latter case is often around 70 mm. Although the cavity extends over the full height and width of the wall, documents supporting the UK's building regulations require that fire barriers be fitted to interrupt the cavity at specified locations.

Sanders [23] used a range of hygrothermal software programs to model the risks of interstitial condensation and the drying of conventional timber-framed walls in UK conditions. Other wall build-ups such as the reverse wall were not investigated. The research found that when cavity ventilation was increased from zero up to a maximum (a level beyond which there is no further change):

- If the VCL is absent, ventilating the cavity will not reduce the risk of severe interstitial condensation.

- If the VCL is incomplete, cavity ventilation behind brick cladding reduces the amount of condensation, but makes little difference if the cladding is timber.

- If the VCL is complete, there will be no interstitial condensation whether the cavity is ventilated or not.

- Wet sheathing boards behind brick cladding will dry faster if the cavity is ventilated; cavity ventilation does not have this effect behind timber cladding.

- If there is no wetting of the wall by rain, the moisture content of cladding is mainly determined by relative humidity; ventilating the cavity has little effect in these conditions.

- Cladding that has been wetted by rainfall will dry faster if the cavity is ventilated although the difference is not great.

The study concluded that, with timber-framed and -clad walls, ventilation at the base alone will be adequate in areas not exposed to high levels of driving rain, but that ventilators should be provided at the top and bottom in highly exposed areas. What constitutes a ‘high’ level was left undefined, however. The only published definition of relevance is that in BR 262 (see Figure 2.6) although, as already indicated, this may not be fully applicable to timber facades.

2.6 Moisture conditions in timber rainscreens

Few studies have been published in the UK giving long-term *in situ* data on moisture conditions in external timber cladding. Even where moisture contents are stated, there has been little attempt to explore how they fluctuate over time or the factors that drive these changes. It is therefore difficult to accurately predict the moisture take-up and loss that will occur when a particular timber species is used as external cladding in specific climate conditions. As a result, the associated moisture effects such as fungal decay or dimensional change are similarly poorly-defined.

Accurate *in situ* moisture content measurement has become increasingly feasible since suitable data-loggers became available in the mid- 1980s. Before this, moisture content was usually recorded in the form of single measurements made with hand-held moisture meters or through gravimetric testing. Many of the published moisture contents for timber cladding are, therefore, likely to be derived from short-term measurements unrepresentative of the full range of in-service conditions. Typical estimates are maximum moisture contents of around 22% on north facing facades during the winter, down to a minimum of around 10% when exposed to summer sun. The average moisture content for timber cladding is often quoted [25] as being around 16%.

2.7 Summary

This study is relevant to the four regions of the world sharing a cool-temperate oceanic and island climate. Timber facades in these four areas are dominated by the effects of moisture related deterioration whereas those in adjacent areas are not. Wind and wind-driven rain are key factors. Western Scotland experiences more intense WDR than most of western Norway.

The control of moisture in building envelopes needs to consider flow from internal and external sources. The latter is usually the main concern with timber facades in areas exposed to WDR. Most discussions of the moisture performance of facades fail to consider timber related issues.

In areas subject to WDR, timber facades are best designed as a rainscreen with a drained and ventilated cavity behind the cladding. Little research has been done into moisture conditions in timber cladding or ventilated cavities.

Datalogged exposure trails of timber cladding are needed, these should examine interactions between key variables.

References

1 Brock, L. (2005). Designing the exterior wall – an architectural guide to the vertical envelope. Hoboken, New Jersey: John Wiley & Sons.

2 Canada Mortgage and Housing Corporation (1999). Wood-frame envelopes in the coastal climate of British Columbia. Vancouver: CMHC.

3 Barry, R.G. & Chorley, J. (2003). Atmosphere, weather and climate. 8th edn. London: Routledge.

4 Clemson, D. (1974). Living with logs: British Columbia's log buildings and rail fences. Vancouver: Hancock House.

5 Oke, T.R. (1987). Boundary layer climates, 2nd edition. London: Routledge.

6 The Meteorological Office, (1989). The climate of Scotland - some facts and figures. London: HMSO.

7 Hoppestad, S. (1955). Slagregn i Norge [Driving rain in Norway, in Norwegian]. Report 13. Oslo: Norwegian Building Research Institute. [Quoted in] Nore, K., (2004). Performance based design of wooden claddings – a literature review of wooden cladding design. NBI Note 61. Oslo: Norges Byggforskningsinstitutt.

8 Rydock, J.P., Lisø, K.R., Førland, E.J., Nore, K. and Thue, J.V. (2005). A driving rain exposure index for Norway. *Bldng and Env.* 40(ii): 1450–1458.

9 BS 8104:1992. Code of practice for assessing exposure of walls to wind-driven rain. London: BSI, 1992.

10 Sellers, H. and Hale, S. (2004). External timber cladding in maritime conditions – climatic comparisons between Norway, Scotland, Faroe Islands and Iceland. Unpublished report by Forest Research. Available: <http://www.northernperiphery.net/managers/Library/Project/Publications/External/Timber/Cladding/External/Timber/Cladding/NPP/Climatic/Comparison.doc> [Accessed 1 December 2010.]

11 Stirling, C. (2002). Thermal insulation: avoiding risks. BRE Report 262. Watford, UK: BRE Press.

12 Canada Mortgage and Housing Corporation (1996). Survey of building envelope failures in the coastal climate of British Columbia. Vancouver: CMHC.

13 Dinwoodie, J.M. (2000). Timber: its nature and behaviour. 2nd edition. London: E & FN Spon.

14 Brookes, A. (1998). Cladding of buildings. 3rd edn. London: E & FN Spon.

15 Straube, J. and Burnett, F.B, (1999). A review of rain control and design strategies. *J. Thermal Insulation & Bldng Envelopes*. July 1999: 41-56.

16 Birkeland, O. (1962). Curtain walls. handbook 11B. Oslo: Norwegian Building Research Institute.

17 Garden, G.K. (1963). Rain penetration and its control. Canadian Building Digest 40. Ottawa: National Research Council of Canada.

18 Rousseau, M. Z., Poiner, G.F. and Brown, W.C. (1998). Pressure equalisation in rainscreen wall systems. Ottawa: Inst. for Research in Construction. pp. 4-5.

19 Straube, J. (2001). Pressure moderation and rain penetration control. *Proc: Int. Conf. Pressure Equalised Rainscreens: Design and Performance.* 21. Ottawa, Canada.

20 McMullan, R. (2007). Environmental science in building. 6th edition., Basingstoke, UK: Palgrave Macmillan.

21 BS 5250: 2005. Code of practice for control of condensation in buildings. London: BSI, 2005.

22 BS EN ISO 6946:2007. Building components and building elements. Thermal resistance and thermal transmittance. Calculation method. London: BSI, 2008.

23 Sanders, C.H. (2005).Ventilation of the cavities in timber framed walls. Research report. Edinburgh: Scottish Building Standards Agency, 2005. Available:<http://www.sbsa.gov.uk/archive/pdf/Web/version/of/Cavity/ventilation_Report_20_121.pdf > [Accessed 28 June 2010.]

24 Nore, K., Thue, J.V., Time, B. and Rognvik, E. (2005). Ventilated wooden claddings - a field investigation. *Proc: 7th Symp. Bldng Phys in the Nordic Countries*, Reykjavik, Iceland. pp. 617-624.

25 Hislop, P. (2007). External timber cladding. 2nd edition. High Wycombe, UK: TRADA Technology.

Chapter 3

Market

The leaky condo debacle discussed earlier is an extreme example. Nonetheless, it highlights what can happen when a rapidly growing sector of the building industry embraces new or untested technology accompanied by inadequate training and technical support. Could a similar problem be developing with timber facades in the UK? The similarities are certainly striking and include:

- A construction sector emerging from nowhere in little more than a decade;
- Knowledge gaps in the underlying science and engineering;
- Rapid technical change with a consequent lag in test development;
- Technology being transferred into the UK with no check on its suitability;
- Questionable standards of detailing and workmanship;
- Inadequate technical guidance and regulation;
- A growing number of technical enquiries and expert witness cases;
- A complex supply chain;
- Industry inaction and complacency.

This chapter addresses each of these points in turn. It combines a review of existing knowledge with two pieces of new research: an assessment of the rapidly growing market for timber facades in the UK and a survey of detailing and workmanship standards. In doing so it sets out the context within which subsequent chapters develop.

3.1 A rapidly growing market

The UK market for timber facades is frequently underestimated, poorly understood and perceived as conflicting with the marketing strategy of the timber frame industry. All of these issues appear to be related to the sector's rapid growth.

3.1.1 Market research

There is no accurate research published on the UK market for timber cladding. During the past decade, MBD were the only market research company that attempted to quantify the UK cladding sector. Their 2005 study [1] states that UK timber cladding sales during 2004 amounted to only 203,000 m^2. This figure has been widely quoted even though timber cladding suppliers regard it as a considerable underestimate The company have recently updated their research [2]; but the replacement study appears to be similarly inaccurate.

Fortunately, it is straightforward to produce a broad market estimate based on imports. Canada Wood UK [3] keeps records of the quantity of western red cedar (*Thuja plicata*) imported by the UK each year. In 2004 the volume was 36,550 m^3; of which the organisation believes 60 to 80% (22,000 to 29,000 m^3) was used as external cladding. After making allowance for machining losses and other wastage, this represents an area of at least 630,000 to 840,000 m^2 of cladding.

Discussions with suppliers suggest that imported western red cedar's UK market share was approximately 50% during 2004; in which case the total area of timber cladding sold in the UK can be estimated at 1.2 to 1.6 million m^2. The other main timbers being sold as cladding were also imported and included: Siberian larch (*Larix sibirica,* Douglas fir *(Pseudotsuga menziesii)*, and ThermoWood™ (thermally modified *Pinus sylvestris* and *Picea abies*). Preservative treatment is virtually unknown for the cladding itself but is used for support battens.

Suppliers estimate that the UK timber cladding market grew by around 10% *per annum* from 2004 to 2007 at which point it was worth approximately £30 million [4]. It has since decreased due to the construction downturn during 2008-11. Current figures are difficult to estimate due to market volatility; a few large suppliers have been bankrupted, whilst others report continued growth.

Although the market is dominated by imports, there are sawmills throughout the UK that supply local timber. The most common UK grown cladding timber is larch (*L. decidua, L. kaempferi*, and their hybrid *Larix x eurolepis*). Others include European oak (*Quercus robur* and *Q. petraea*), sweet chestnut (*Castanea sativa*), and western red cedar plus several lower durability timbers such as UK grown Douglas fir. Demand exceeds supply, although there are reservations over the quality and availability of UK timber. This will intensify if, as seems likely, the *Phytophhtora ramorum* epidemic [5] affecting Japanese larch (*L. kaempferi*) in southwest England and Wales spreads throughout the UK and to all larch species.

The UK market for timber cladding can be split into several sectors. The most obvious division is between low-rise housing (its most common use) and larger, often non-domestic, applications. Low-rise housing divides, in turn, into private housing and buildings owned by registered social landlords. Similarly, the non-domestic sector falls into several distinct groups such as educational buildings, visitor centres, offices, *etc*. The facade height and location are also important, as the types of cladding that can be used are more restricted on walls above 18 m and near property boundaries. The use of timber facades on medium-rise and non-domestic timber facades appears to be growing, although no figures are currently available.

3.1.2 Performance benefits of timber facades

Part of the growth in popularity of timber facades is down to architectural fashion and this will certainly change. Timber facades do, however, offer a number of tangible performance benefits that should ensure their popularity even when fashion moves on. Sustainability is probably the most important perceived benefit although this is often difficult to quantify. The arguments for timber can be summarised as [6]:

- **Low environmental impact**: timber is renewable; it is available from certifiably legal and sustainable sources; and at the end of its service life timber can often be recycled or used as fuel.

- **Low embodied energy**: timber consumes less energy to produce than masonry; and can sometimes be locally sourced.

- **Low carbon:** using timber, that much of the carbon consumed during the tree's growth is locked into the fabric of the building, carbon is also stored in forest soil.

The issue of local sourcing is, however, complex. Localness is not accepted by the UK government or European Union as evidencing sustainability. This is because a localness criterion could be used as a restrictive practice, thereby increasing costs and cutting across foreign aid policies to support emerging economies [7]. The topic is discussed further in a publication by this author for Forestry Commission Scotland [8].

While sustainability can apply to all types of timber construction, timber facades bring some further gains. Timber is most often used as cladding onto a timber structural frame, in which case the main performance benefits are:

- **Few problems due to mixing construction materials.** When the structure and cladding are both made from timber the problems of differential movement are reduced [9]. Substituting masonry cladding with timber can also help minimise risks of condensation build-up within the wall, this benefit has mainly been documented by building conservation specialists [10].

- **Cost reductions.** The use of timber cladding means the 'wet trades' of bricklaying and plastering can be avoided as a joiner can erect and line out the walls. Material costs may also be reduced. The savings are typically 1 to 2 % although they have been considerably higher on some projects [11].

- **Suitability for off-site prefabrication.** Because timber cladding is relatively thin and lightweight, it is well suited to off-site prefabrication as part of a modern methods of construction approach. This is of growing importance due to several factors including health and safety, cost and declining workmanship standards.

Cladding masonry or massive timber walls brings other advantages. Although these walls have thermal mass to buffer diurnal temperature fluctuations they can be poorly insulated. Adding external insulation cuts energy demand without disrupting internal finishes. The insulation can then be clad with timber to keep it dry; this approach is long established with log buildings in Scandinavia and is increasingly being used in Finland and Germany as part of the refurbishment of concrete facades on medium-rise housing. It is uncommon in the UK at present.

3.1.3 Relationship with timber-frame construction

There is much confusion over what constitutes a timber building. In the UK the term timber frame describes a construction system where all vertical and lateral loads are transferred to the foundations through a structural framework of small section timber studs sheathed with a wood-based sheet material such as OSB. The framework is then clad with a largely non-structural skin, which can be made of several materials including masonry, rendered mesh or timber. In principle, each of these cladding materials is interchangeable. Timber frame construction is permitted up to seven storeys in the UK. Confusingly, the timber frame system is known as light frame construction in North America where the term timber frame is reserved for the large section timber structures referred to as post and beam in Europe. In most countries timber-framed buildings are also timber-clad. The UK is unusual in this respect because the popularity of timber construction is not so readily apparent: timber frame suppliers have tended to clad their houses in masonry-based materials and thus allow people to pretend that they live in a stone house. The conceit is so good that many people do not realise that it is a timber structural frame that holds up their roof.

The market share of timber-framed construction has grown throughout Britain in recent years. During 2009 about 75% of low-rise housing in Scotland was built using a timber-framed structure. The corresponding figure for England and Wales [12] stood at around 19%. For comparison, the average market share for timber-framed construction throughout the developed world was around 70%.

Many sections of the timber frame industry appear to be resistant to cladding their buildings with timber. This may be due to a perceived conflict with their marketing strategy. The difference in timber frame's market share between Scotland and the rest of Britain is often attributed to a 1983 *World in Action* television programme, which highlighted technical problems with the timber-framed homes then being built in the

UK. The programme was broadcast in England and Wales but not in Scotland. In the wake of the programme, much of the UK timber frame industry appears to have adopted a marketing strategy whereby the timber component of their buildings is not mentioned. As timber facades make further inroads into the timber frame sector then this marketing strategy may have to change.

3.2 Incomplete scientific and engineering knowledge

There surprisingly little consensus as to how the performance of timber facades should be defined or evidenced. The main engineering-based review of external cladding technology in the UK is a standard [13] published by the Centre for Window and Cladding Technology (CWCT). Most other technical publications in this field tend to base their conceptual framework upon this norm. CWCT mainly consider the performance issues affecting the so called traditional facade materials such as aluminium, glass and concrete. Accordingly, degradation of timber by moisture is virtually ignored; so too is corrosion due to organic acids, the wind resistance of a facade assembly made of boards and battens, and several other topics of central importance to timber facades.

Some of these topics are poorly understood even within the wood science community. The most obvious gaps are moisture conditions in external cladding, service life in fluctuating moisture conditions and leaching of flame retardants. This thesis mainly addresses the first of these gaps.

3.3 Rapid technical change

Timber facade technology is undergoing a period of rapid technical change driven by several underlying factors. In recent years changes in European legislation have resulted in the virtual withdrawal of CCA-based wood preservatives and solvent-based surface coatings. This in turn has stimulated growth in demand for what are termed wood modified timbers (these comprise timber products that have been chemically or thermally modified to improve their performance without the negative effects associated with traditional approaches such as wood preservation). European consumers are also influential, particularly in the growing demand for translucent surface coatings and so-called 'ecological' paints.

These changes are driving availability of many new products and technological systems: architects are embracing these with little awareness that the technology may not be transferable. Current examples include:

- Some types of German cavity barrier should only be used as part of a formal fire safety engineering approach, yet enquiries received by this author indicate they are being used on timber cladding contracts in the UK without any such precautions.

- Non-preservative treated shingles are being used in the UK even though it is known that most of these products will fail in less than 20 years in our mild and damp climate.

- German face sealed cladding is being promoted in the UK without any test data on how it performs in a wet climate. The products are made of an acrylic render onto a substrate of rigid insulation board. The lack of a cavity means that there is no redundancy to cope with poor detailing and workmanship or impact damage in use.

3.4 Inadequate technical guidance and regulation

Statutory guidance supporting building regulations is slow to respond to changes in construction practice. This is unavoidable, as the guidance has to be based on published research, which can take time to prepare. The guidance then has to go through a lengthy drafting and consultation process before approval and publication. For example, current fire regulation guidance for cladding in the UK [14 - 16] was mainly written for masonry based cladding and is not always appropriate for timber facades. This guidance assumes that the cladding material is both inorganic and non-biogenic and is, therefore, of uniform composition, non-combustible and little affected by moisture (See Chapter 5 for a more detailed discussion of this topic). The associated test procedures [17] [18] thus ignore the possibility of the cladding burning through, whilst the detailing guidance creates water traps when used for timber cladding. Similarly, the current guidance for acoustic insulation of separating walls and floor junctions [19] only mentions masonry cladding.

3.5 Poor standards of design and workmanship

It is often asserted that the standard of detailing and workmanship is poor but this is rarely quantified. The completion of Scotland's first Housing Expo [20] in August 2010 provided an unusual opportunity to survey the quality of detailing and construction of timber cladding on a selection of modern housing. Of the 51 dwellings in the Expo, 41 have wholly or partially timber clad facades, three had timber clad roofs, and one employed exposed structural timber. The buildings were designed by 26 different architectural practices and were erected by six firms of contractors. Most dwellings in the Expo were detached or semi-detached, there were three blocks of flats. Most of the cladding timber was heartwood of Siberian larch (*Larix sibirica)* or locally grown European larch (*L. decidua*).

3.5.1 Method

All timber clad walls and roofs were surveyed. The defects were listed and recorded photographically. The detailing or construction was defined as defective if it did not comply with either current best practice guidance [21 - 23], or the details being developed for this thesis. Each defect was only listed once *per* dwelling no matter how many times it occurred. That said, infrequent occurrences (*e.g.* a single over-driven nail) were ignored unless the consequences of failure were serious (*e.g.* poor cavity barriers). Appendix 2 gives examples of the defects that were recorded.

3.5.2 Results

Every timber building envelope on the site had some defects. There were an average of seven types of defect *per* dwelling. The minimum was three and the maximum ten. Table 3.1 ranks each defect by frequency of occurrence.

Table 3.1 *Frequency of occurrence of each type of timber facade defect*

Defect	Number of dwellings affected	% of dwellings affected
Poor window installation	41	100
Butt jointed boards	25	61
Silicone in joints	21	51
Nails driven too deep	21	51
Watertraps or splashzones at ducts or meter boxes	19	46
Inadequate splashzones at access ramp to door	16	39
Poor insect or vermin mesh installation	16	39
Inadequate splashzones generally	9	22
Boards nailed together	9	22
No eaves ventilation	9	22
Decking creates splashzone	8	19
Poor horizontal cavity barrier	8	19
DPC used behind timber cladding	8	19
Poor fixing details	5	12
No endgrain gaps at corners	4	9.8
Poor differential movement allowance	4	9.8
Poorly installed plywood cladding	4	9.8
Sapwood not graded out	3	7.3
Ferrous fixings in timber	3	7.3
Poor vertical cavity barrier	3	7.3
Exposed structural frame with water traps	1	2.4

3.5.3 Discussion

Only 41 dwellings were surveyed and all were part of one rapidly erected development resulting from a design competition. The sample is, therefore, of limited size and open to several uncertainties or sources of bias, including:

- The competition may have selected for defect prone designs
- The speed of erection may have produced an unusually high number of defects
- Contractors in Highland Scotland may be unusually poorly skilled

- The same contractors worked on several dwellings and so faults were repeated
- Most cladding could only be inspected from the outside and at ground level
- Flats were under represented and non-domestic buildings were missing
- The long-term impact of the defects was unquantifiable

The last point is particularly important. Although there is a broad consensus as to what constitutes a defect, the consequences can vary from minor to catastrophic. If a few boards fail, for example, they can easily be replaced, but if exposed structural timber starts to rot the costs can be considerable. Wang *et al.* [24] note that there has been little attempt to quantify the relative importance of different types of detailing problem on timber facades or elsewhere in exterior out-of-ground-contact conditions. They state that such information would be valuable. Accordingly, no attempt has been made at this stage to rank the defects by their severity, this topic is addressed in Chapter 5.

Although the survey is far from definitive, it does highlight the problems that occur. These should not be taken to mean that the quality of design and workmanship at the Expo was particularly poor; instead it is likely that the standard observed is the norm throughout the Scottish Highlands and beyond.

3.6 Enquiries and expert witness cases

Staff at TRADA Technology state that timber cladding is their most common continuing professional development request, and also a frequent source of enquiries and expert witness contracts. Enquiries and consultancy contracts at Edinburgh Napier University follow a similar trend. The technical questions span several areas: fungal decay, weathering, dimensional change, corrosion, structural robustness, fire safety, detailing, and grading. The most common expert witness contracts concern weathering, dimensional change and robustness. Scotland currently generates one or two contracts *per annum*, suggesting that the UK has ten to 20. Their consequences vary. Some involve little more than the cost of the expert witness report and some minor remedial action. Others can bankrupt the main contractor and joinery subcontractor.

3.7 Complex supply chain

The supply chain for timber-based facades is more complex than that for other facade materials. Although much of this is due to the material itself, non-material considerations also arise, including:

- **Terminology**; people in the supply chain can be confused by timber's complexity – such as the difference between hardwoods and softwoods – and the timber industry does little to overcome this. Scientists, for example, use different terminology to timber suppliers who, in turn, describe wood products and processing in a way that their customers find confusing. Redwood, for example, is a trade term that refers to different species depending upon whether the timber originates in Europe or North America. Moreover, European Redwood, (*Pinus sylvestris*) is known as Scots pine if grown in the UK. European Standard BS EN 13556 [25] brings some order to this confusion by allocating standard names to the timbers commonly used in Europe.

- **Availability**; species availability changes and new timbers are continuously being brought to market, particularly from South America. This can be challenging as authoritative information on their timber properties takes a while to be published. Suppliers often exploit this lag by making performance claims that cannot be evidenced. The current promotion of Siberian larch (*L. sibirica*) and eastern white cedar (*Thuja occidentalis*) as especially durable cladding timbers are cases in point.

- **Variability**; cladding timbers are sold with a wide variety of grading, moisture contents and dimensions. This is compounded by the published standardised specifications for timber cladding [26] [27] which omit essential information or make inaccurate statements. The grading rules in BS EN 15146, for example, are so poorly drafted as to be unusable.

Although just about acceptable in the growing construction market in the decade up to 2008, this complexity is a considerable disincentive for customers and may become an increasing problem as the recession continues.

3.8 Industry inaction and complacency

In 2002 Davies *et al.*[22] highlighted the growing need for a timber cladding association in the UK. Little has changed in the intervening years. Several meetings have been held and the Timber Decking Association (TDA) [28] has attempted, so far with little success, to expand into the gap. The main barriers are that the sector is still relatively small and fragmented when compared to those of other facade materials, such as concrete or profiled steel, and much newer than long established industries such as lead. Consequently, there is no single stakeholder who can fund a timber cladding association and insufficient incentive for a group of companies to jointly support such a venture. Thus the TDA is funded by the wood preservation industry, which has little commercial incentive to promote timber cladding, as it is rarely preservative treated. In any case, many timber cladding suppliers are not aware of the scale of technical challenges they face; nor do they have the time or technical capacity to address these problems themselves.

The net result of all of this is that every other major cladding material has an industry group and code of practice whilst timber – which is technically more complex than the others – does not. This urgently needs to change.

3.9 Summary

The science and engineering of timber facades is not fully understood. Moreover, the UK's burgeoning interest in timber facades is not adequately reflected in published market research, nor in technical guidance and training. It is, therefore, little surprise that an industry has emerged in the UK over the past decade that is designing and building timber facades of sometimes questionable quality. This needs to be addressed through improved technical knowledge and guidance before the number of timber cladding failures becomes such that the market is damaged. Such information cannot be developed in isolation, however, as it has to be compliant with other performance requirements particularly those for fire safety and acoustics. A formal code of practice is needed, therefore, needed.

References

1 Market & Business Development (2005). The UK cladding market development. Manchester, UK: MBD.

2 Market & Business Development (2010). UK external wall cladding market research report. Manchester, UK: MBD.

3 Canada Wood UK website: <http://www.canadawooduk.org/>. [Accessed 1 July 2010.]

4 Confidential memo: UK Timber Decking Association. (*n.d., n.l.*)

5 [Online archive] <http://www.forestry.gov.uk/pramorum> [Accessed 4 April 2011].

6 Read, D.J., Freer-Smith, P.H., Morison, J.I.L., Hanley, N., West, C.C. and Snowdon, P. eds. (2009). Combating climate change – a role for UK forests. An assessment of the potential of the UK's trees and woodlands to mitigate and adapt to climate change. Edinburgh: The Stationery Office.

7 Central Point of Expertise on Timber (CPET) website: <http://www.cpet.org.uk/> [Accessed 13 December 2010]

8 Davies, I. (2010). Sustainable construction timber, 2nd edition. Edinburgh: arcamedia.

9 Grantham, R. and Enjily, V., (2003). Multi-storey timber frame buildings, a design guide. BR 454. Watford, UK: BRE Bookshop.

10 Palfreyman, J. and Low, G. (2002). Studies of the domestic dry rot fungus *Serpula Lacrymans* with reference to the management of decay in buildings Edinburgh: Historic Scotland.

11 TRADA Technology (2001). Timber frame construction, 3rd edition. High Wycombe, UK: TRADA Technology.

12 UK Timber Frame Association. Market update 2009 Available: <http://www.uktfa.com/#facts-figures/4538892503> [Accessed 2 July 2010.]

13 Centre for Window and Cladding Technology (2005). Standard for systemised building envelopes. Bath, UK: University of Bath.

14 The Building (Scotland) Regulations (2004). Domestic Handbook, May 2009. Section 0.8.1. Scottish Building Standards. Livingston. UK, 2009.

15 The Building Regulations (2000). Approved Document B. Fire Safety. Vol.1 – Dwellinghouses. 2006. Department for Communities and Local Government. London, 2006.

16 The Building Regulations (Northern Ireland) (2000). Technical booklet E: 2005 - Fire safety. Department of Finance and Personnel. Belfast, 2005.

17 BS 476-20:1987. Fire tests on building materials and structures. Method for determination of the fire resistance of elements of construction (general principles). London: British Standards Institution, 1987.

18 BS 476-22:1987. Fire tests on building materials and structures. Methods for determination of the fire resistance of non-loadbearing elements of construction. London: British Standards Institution, 1987.

19 Robust Standard Details. Website: <http://www.robustdetails.com/index.php?id=12521> [Accessed 8 November 2010]

20 Scotland's Housing Expo. Website: <http://www.scotlandshousingexpo.com> [Accessed 28 September 2010].

21 Hislop, P. (2007). External timber cladding. 2nd edition. High Wycombe, UK: TRADA Technology.

22 Davies, I., Walker, B. and Pendlebury, J. (2002). Timber cladding in Scotland. Edinburgh: ARCA Publications.

23 Edvardsen, K.I. and Torjussen, L. (1997). Håndbok 45 – Trehus. [Handbook 45 – wooden house. In Norwegian] Oslo: Norges Byggforskningsinstitutt.

24 Wang, C.H., Leicester, R.H. and Nguyen, M.N. (2008). Manual No 4: Decay above ground. Highett, Victoria, Australia: Forest and Wood Products Australia.

25 BS EN 13556:2003. Round and sawn timber. Nomenclature of timbers used in Europe. London: BSI, 2003.

26 National Building Specification. (2006). H21 Timber weatherboarding. Newcastle upon Tyne: RIBA Enterprises.

27 BS EN 15146:2006. Solid softwood panelling and cladding – Machined profiles without tongue and groove. London: BSI, 2007.

28 Timber Decking Association. Website: <http://www.tda.org.uk> [Accessed 08 November 2010].

Chapter 4

Performance

Designers generally have three questions about the performance of timber facades:

- What performance requirements are relevant?
- How can these criteria be met?
- How is compliance evidenced?

Answering these questions is surprisingly difficult. This can be illustrated by comparing the European normative framework for structural engineering with those for other aspects of building performance. The requirements for structural engineering are set out in a suite of European standards known as Eurocodes. These norms have been subject to a lengthy and well resourced development process with the result that they are now accepted and are in the process of replacing national standards. The norms for non-structural building components are not as well developed. Even fire safety – which has as many life safety concerns as structural engineering – is still far from having an agreed suite of European standards. The standard for classifying reaction to fire performance [1], for example, is widely criticised [2], whilst the fire tests for cladding and cavity barriers are still being drafted. There is even less progress in areas, such as the material characteristics of timber cladding, which do not directly affect life safety. Sectoral interests, or even the views of particular individuals, can hijack the process. It is thus no surprise that the performance guidance for timber facades is in a mess.

4.1 British and European standards for timber cladding

BS 1186-3 [3] is the most widely used British standard for timber cladding. It covers a number of topics including timber durability, movement, grading and board profiles. However, the standard encompasses both internal and external cladding: seperate microclimates with different performance issues (*e.g.* movement and corrosion). Consequently, the standard has a number of errors. The recommended board profiles, for example, only suit indoor use as they cannot accommodate much movement. Similarly, the grading rules only describe those features relevant to internal trim; they give little guidance on how to ensure that timber is fit-for-purpose as external cladding.

National standards such as BS 1186-3 usually use prescriptive (do this, do that) type language which is now seen as stifling innovation and as a barrier to trade. Therefore, the European Union is in the process of introducing pan-European standards giving harmonised performance-based guidance.

The performance characteristics currently considered applicable to timber facade products are given in European Standards BS EN 13986 [4] and BS EN 14915 [5], the former covers cladding made from board products such as plywood, whilst the latter applies to solid timber. Associated standards [6] - [8] give timber grading rules and other criteria for specific types of board profile. The guidance in key European norms for reaction to fire [1], wood durability [9] [10] and preservation [11] - [13] are also highlighted. In practice, however, these norms are ignored in most of Europe because they are biased, poorly drafted and often irrelevant [14] - [16]. Two examples will suffice:

- **Softwood grading**; the softwood grades in BS EN 15146 [6] give specific rules for maritime pine (*Pinus pinaster*) but lump all other softwood timber species together. Maritime pine is mainly produced in southern France and is rarely used for external cladding, whereas timbers such as western red cedar (*Thuja plicata*) and larch (*Larix* spp.) are used for this purpose in large quantities throughout Europe. It is ludicrous to issue combined grades for popular but dissimilar cladding timbers while differentiating a minority species only of interest in part of one country. Could the fact that the committee responsible for drafting this standard was chaired by a French organisation have had something to do with it? Surely not? This author discusses some of these issues in a national commentary [17] on BS EN 975 [18] prepared for the Forestry Commission.

- **Irrelevance**; European standards for cladding repeat the error in BS 1186-3 whereby internal and external uses are combined. The norms give performance criteria for material characteristics (*e.g*. permeability and thermal conductivity) that, as discussed in Chapter 2, are irrelevant to rainscreen cladding, whilst omitting the leach resistance of flame retardants (Table 4.1). It is thus possible to have timber cladding CE marked as being fit for purpose even though its stated reaction to fire performance will leach out in less than a decade. The corrosion of fasteners by damp timber is also omitted as is any discussion of board profiles to accommodate movement. Table 4.2 gives a more complete list of the material characteristics relevant to timber facades. These are discussed further in subsequent chapters.

Because the European standards for timber cladding give little useful guidance – and much that is wrong – the relevant performance criteria have to be developed from other sources, beginning with the applicable building regulations.

4.2 Building regulations

The oldest known building regulation comes from the Babylonian Code of Hammurabi [19] a clause from which states:

> *If a builder has built a house for a man, and has not made his work sound, and the house he built has fallen, and caused the death of its owner, that builder shall be put to death*.

Although in hindsight extreme, this clause nonetheless anticipates many of the ideas underlying a performance-based approach. It is based on user need, is independent of the materials used, and gives a defined and measurable outcome. The regulations in many countries are becoming performance-based. This means that designers now have unprecedented technical freedom. At the same time the requirements they need to meet are becoming ever more complex. Although the regulations are mandatory, many are now accompanied by statutory guidance documents giving recommendations on how the requirements can be met. Designers can either follow these recommendations or develop their own solutions based on established science and engineering.

Table 4.1 *Technical characteristics for CE Marking of timber cladding*

Guidance in EN 14915		Application to the UK
Characteristic	Determination	
Reaction to fire	Many cladding products can be classified without further testing to Euroclass D-s2, d2. Other products, or those requiring higher classifications, will need testing to BS EN 13501-1	Some of the product assemblies listed do not employ rainscreen principles (and so are only suited for internal uses or where the wall is non-insulated). Some others require the rear face of the cavity to be non-combustible (Euroclass A2-s1, d0); this assembly is rarely used in the UK.
Pentachlorophenol (PCP) content	If PCP based materials are used (*e.g*. some anti sap-stain treatments) the product shall be tested to national requirements. Where the value exceeds 5×10^{-6}, this should be declared.	UK requirements are given on the Health and Safety Executive website.
Water vapour permeability	If water vapour permeability is required, characteristic values are given for various densities of timber; interpolation is possible.	In the UK, external timber cladding is normally designed as a ventilated rainscreen, in which case BS 5250 states that the cavity should be regarded as being equivalent to the outside air: vapour permeability is thus irrelevant.
Thermal conductivity	Thermal conductivity need only be determined where it is relevant.	The thermal conductivity of timber cladding is irrelevant in the UK for the reason discussed under water vapour permeability.
Natural durability	If the timber species is listed in BS EN 350-2, its natural durability shall be as given therein. Otherwise it shall be tested to BS EN 350-1.	UK guidance is the same as that given in BS EN 14915.
Preservative treatment	Products shall be defined in accordance with: BS EN 335-1 (use classes); BS EN 599-2 (preservative); BS EN 351-1 (preservative penetration & retention).	The Wood Protection Association gives standard specifications that are intended to be suitable for preservative treating most timber products to UK requirements. Cladding is described in specification C6.

Table 4.2 *Timber characteristics for cladding*

Characteristic	Comment
Density [1]	Dense timbers (> 550 kg/m^3) are preferred where vandalism is a concern
Natural durability [2]	Classes 1, 2 or 3 are recommended
Tangential shrinkage[3]	Should be considered if unseasoned timber is to be used
Movement class[4]	A low or medium movement class is recommended
Treatability[5]	If preservatives or flame retardants are used, timber should be treatable
Workability[6]	Machining and nailing characteristics must suit the cladding profile.
pH[7]	All damp timber is corrosive although the rate varies between species
Reaction to fire[8]	Low density timbers (< 400 kg/m^3) have a low reaction to fire class
Joinery grades[9]	Some cladding profiles require relatively knot free timber
Moisture content	The moisture content at the time of handover should be stated
Weathering	The appearance of different timbers varies when exposed out of doors
Fibre saturation point[10]	Defined as the moisture content at which free water leaves the cell cavity

Notes:

1) Mean density (kg/m^3) at a moisture content of 12%

2) Resistance to fungal decay as classified in BS EN 350-1

3) From green (freshly felled) to 12% moisture content

4) Dimensional change when dry timber is subject to fluctuations in atmospheric moisture.

5) Resistance to preservative treatment (4 = extremely difficult to treat)

6) Some timbers are prone to splitting and should be predrilled if fixing within 150 mm of board ends. Timber with a density over 550 kg/m^3 should always be predrilled.

7) Ferrous metals are at risk of corrosion by damp wood if the pH is less than 4.0, timber impregnated with copper based wood preservatives are also corrosive.

8) Timbers with densities below 400 kg/m^3 have a poor reaction to fire classification

9) The joinery grades are those in BS 1186-3

10) The fibre saturation point is important as it affects the maximum moisture content that cladding achieves in service

It is sometimes claimed that national building regulations are becoming – or should become – the same throughout Europe. This is not the case, as each country will continue to set its own requirements in response to local conditions such as climate, building practices or social conditions. The European Construction Products Directive (CPD) [20] and its associated harmonised standards do not impose specific performance requirements but merely set out a framework for performance specification and a common methodology for testing and verification. The CPD gives six essential requirements that buildings have to fulfil to be safe and fit for purpose. These are supported by a further requirement for durability.

The UK does not have a single set of building regulations. Instead, England and Wales are covered by one set of regulations [21] whilst Scotland and Northern Ireland each have their own [22] [23], as do the offshore Crown Protectorates of the Isle of Man [24], and the Bailiwicks of Jersey [25] and Guernsey [26]. (Building regulation may be devolved to the Welsh Assembly in the near future). There are important differences between these regulations as they have been and are developed in response to local conditions; those in Scotland and the Isle of Man tend to be more onerous than elsewhere the UK. The regulations in Scotland respond to the harsh climate (especially wind), and to social conditions (*e.g.* the high incidence of arson in parts of Glasgow), while those on the Isle of Man reflect a limited fire fighting capacity on the island.

The main building regulation criteria for timber facades in the UK are outlined in Table 4.3 and discussed further in subsequent chapters. The guidance documents supporting Scottish building regulations differ from those in the rest of the UK in that they accept component replacement as an alternative to inherent degradation resistance. The relevant clause [22] (section 0.8.1) states:

> *Materials, fittings and components used in the construction of buildings should be suitable for their purpose, correctly used or applied, and sufficiently durable, taking account of normal maintenance practices, to meet the requirements of these regulations. For example, external timber cladding for low-rise buildings that is readily accessible and replaceable need not be as durable as that which is to be used at a higher level on medium-rise buildings.*

Table 4.3 Building regulation criteria for cladding in the UK [21 – 23]

Criteria	Recommended solutions cover
Structure Cladding must:	be capable of safely sustaining all static, imposed and wind loads and transmitting them to the building's support structure
	be securely fixed to and supported by the building's structure
	accommodate, where necessary, differential movement of the cladding and building's support structure
	be of durable materials; the design life of fixings and supports being not less than that of the cladding
Fire spread Fire spread on the facade should be limited:	to nearby but non-adjoining buildings
	on external surfaces
	in cavities
Health and safety Health and safety to be ensured:	during construction, maintenance, and demolition
Noise. Building envelopes must protect against:	noise from adjoining buildings (noise from non-adjoining buildings and other external sources is controlled via the planning system and not through building regulations)
Durability and workmanship Protect against degradation from:	ground moisture
	precipitation and spray
	moisture from inside the building
	moisture from the roof
	wood destroying organisms
	corrosion

4.3 Service life

Whilst a performance-based approach to building design and regulation brings many benefits, it is complex and can be difficult to achieve in practice. A key challenge is predicting how building products will behave over time: a challenge that is of particular relevance to timber facade design.

4.3.1 Predictive models

Because the essential requirements in the CPD include a durability criterion, the service life of all building products being sold in the EU will eventually need to be assessed. To achieve this, predictive models are needed that allow performance to be stated in terms of failure within a specified period. Failure can be defined [27] as: '*an unacceptable difference between expected and observed performance*.' The minimum requirement for service life models is that they should be able to evaluate degradation over time taking account of any variability that occurs [28]. Although these methods originated in structural analysis [29] [30] they are beginning to be used to predict fungal decay and other failure modes affecting service life [31] [32]. The probability of component failure P_f is estimated using expressions such as:

$$P_f = A_{rs}(R_{mean}/S_{mean})^{-n} \qquad (4.1)$$

where R_{mean} and S_{mean} are the mean values of R (resistance to failure) and S (the load). A_{rs} describes the coefficients of variation due to variability in materials, environments and measurement [31].

International Standard ISO 15686-2 [32] gives a checklist for service life prediction that employs similar principles:

$$ESL = RSL * f(A,B,C,D,E,F,G) \qquad (4.2)$$

where:

ESL = estimated service life
RSL = reference service life (*i.e.* known service life of a similar product)
A = Component quality (*e.g.* natural durability, preservative treatment)
B = Design level (*e.g.* design for durability)
C = Workmanship (*e.g.* water traps)
D = Indoor environment (*e.g.* temperature, condensation)
E = Outdoor environment (*e.g.* climate, shadowing, wind driven rain)
F = In-use conditions (*e.g.* wear, impacts)
G = Maintenance (*e.g.* repair, repainting)

In practice, the factors in equation 4.2 tend to be subjective, and even where they can be quantified the data are usually lacking. The quality of components (A) probably constitutes the greatest challenge for the performance-based design of wood products in construction. The factors for design (B) and workmanship (C) are usually more predictable. The outdoor environment (E) is, to some extent, material neutral although the influence of moisture on wood-based materials needs special attention [33].

The estimated service life depends upon a product's use and service conditions. Thus, while optimum durability is always needed, this does not mean that maximum resistance to degradation is essential in all cases: it just has to be fit for the purpose intended. Service life prediction is reviewed in Hovde and Moser [33] and its application to timber is evaluated by European COST E37 network [34]. The final report concluded that service life prediction for timber products must deal with four issues: characterisation of materials and components, characterisation of the environment, knowledge of biodegradation mechanisms and use of reliable test methods. Other studies [35] - 44] have addressed these issues, of which recent work at CSIRO [37] - [44] is the most comprehensive. This Australian work quantified the effect of maintenance in such a way that it can be included within predictive models. It used factors similar to equation 4.1 to describe the conditions applicable to a particular type of component. For each component type and location, degradation is assumed to proceed at a uniform rate subject to a lag effect to take account of maintenance. Australia was the first country to propose a performance based-standard for timber durability [45].

4.3.2 Service life of timber facades

So, how long should a building component such as timber cladding last? Guidance on this is given in several documents [46] [47]. Table 4.4 is typical; it gives the criteria used in preparing European technical approvals and standards [46]. In this thesis it is assumed that Table 4.4 applies to timber facades. The 'normal' category refers to buildings such as houses and offices, whilst 'long' applies to monumental buildings and the like. Accordingly, where timber is used to clad a normal building it should have a service life of 25 years assuming the owner is then prepared to repair or replace the cladding '*with some effort*'. If this assumption is not appropriate then all materials and products should be designed for a 50 year service life. Alternatively, particular components could be designed to be easily replaceable should the need arise.

Table 4.4 *Working life assumptions in EOTA Guidance Document* [46]

Assumed working life of construction works (years)		Working life of construction products to be assumed in European technical approvals and standards (years)		
		Category		
Category	Years	Repairable or easily replaceable	Repairable or replaceable with some effort	Not repairable or replaceable easily or with some effort
Short	10	10	10	10
Medium	25	10	25	25
Normal	50	10	25	50
Long	100	10	25	100

4.4 The need for performance guidance on timber facades

Although performance-based design brings more freedom than a prescriptive approach, it also puts increasing responsibility on the designer. Whilst this is true of all building design, work with timber, especially in emerging areas such as facade engineering, is particularly affected. This raises a question: as British and European standards become performance-based – and therefore solution independent – where can guidance be found on how components are put together? In normal circumstances this information is to be found in codes of practice [48]. Although UK codes of practice are already published for most types of cladding, nothing has been issued specifically for timber. A few topics are covered in BS 5534 [49], which covers all types of slate, tile and shingle cladding on both walls and roofs but more information is needed. In view of the burgeoning interest in timber facades in the UK, this gap needs to be filled as soon as possible. This thesis is intended to inform progress in this area since any discussion of the topic has to be founded upon an understanding of the distinctive nature and behaviour of timber as a facade material.

4.5 Summary

The performance-based approach to building design and regulation is becoming increasingly common. In Europe it is incorporated into the Construction Products Directive, which sets six essential requirements for construction products. The requirements are, in turn, incorporated into mandatory technical specifications for products; these include a suite of norms covering external timber cladding. The timber cladding norms are currently ignored, while this is not in itself illegal, it does create a gap as compliance with the CPD still has to be evidenced. The service life of timber facades are difficult to predict. The main problem being a lack of long term in-service data to inform the models. Service life targets for timber facades exist although little useful guidance is published on how these can be achieved. A UK code of practice for timber cladding is urgently needed.

References

1 BS EN 13501-1:2007+A1:2009. Fire classification of construction products and building elements. Classification using test data from reaction to fire tests. London: BSI, 2009.

2 Brannigan,V.M. (2008) The Regulation of Technological Innovation: The Special Problem of Fire Safety Standards. In: Carvel, R., ed. Proc. Symp. Fire & Building Safety in the Single European Market. 12 November 2008, Edinburgh. Edinburgh: University of Edinburgh. pp 20-33.

3 BS 1186-3:1990. Timber for and workmanship in joinery. Part 3. Specification for wood trim and its fixing. London: BSI, 1990.

4 BS EN 13986:2004. Wood-based panels for use in construction - characteristics, evaluation of conformity and marking. London: BSI, 2005.

5 BS EN 14915:2006. Solid wood panelling and cladding - Characteristics, evaluation of conformity and marking. London: BSI, 2006.

6 BS EN 15146:2006. Solid softwood panelling and cladding – Machined profiles without tongue and groove. London: BSI, 2007.

7 BS EN 14519:2005. Solid softwood panelling and cladding – Softwood machined profiles with tongue and groove. London: BSI, 2006.

8 BS EN 14951:2006. Solid hardwood panelling and cladding – Machined profiles elements. London: BSI, 2006.

9 BS EN 350-2:1994. Durability of wood and wood-based products. Natural durability of solid wood. Guide to natural durability and treatability of selected wood species of importance in Europe. London: British Standards Institution, 1994.

10 BS EN 350-1:1994. Durability of wood and wood-based products. Natural durability of solid wood. Guide to the principles of testing and classification of natural durability of wood. London: British Standards Institution, 1994.

11 BS EN 335-1:2006. Durability of wood and wood-based products. Definitions of use classes. General. London: BSI, 2006.

12 BS EN 599-1:1997. Durability of wood and wood-based products. Performance of preservatives as determined by biological tests. Specification according to hazard class. London: BSI, 1997.

13 BS EN 351-1:1996. Durability of wood and wood-based products. Preservative-treated solid wood. Classification of preservative penetration and retention. London: British Standards Institute, 1996.

14 Health and Safety Executive (2010). *Non-agricultural pesticides approved under: The Control of Pesticides Regulations 1986 (as amended)*. [online] Available at: <http://www.hse.gov.uk/biocides/copr/approved.htm> [Accessed 10 July 2010.]

15 BS 5250:2005. Code of practice for control of condensation in buildings. London: BSI, 2005.

16 Wood Protection Association. WPA manual: Industrial wood preservation specification and practice 2007. [Compact Disc]. Castleford, West Yorkshire, UK: Wood Protection Association, 2007.

17 Davies, I. & Watt, G. (2005). Making the grade: a guide to appearance grading UK grown hardwood timber. Edinburgh: Arcamedia.

18 BS EN 975-1:1995. Sawn timber – appearance grading of hardwoods. Part 1: oak and beech. London: British Standards Institute, 1995.

19 Code of Hammurabi [stone slab], Louvre Museum, Paris. c. 1790 BC. [Quoted in] Brannigan,V.M. (2008). The Regulation of Technological Innovation: The Special Problem of Fire Safety Standards In: Carvel, R., ed. Proc. Symp. Fire & Building Safety in the Single European Market. 12 November 2008, Edinburgh. Edinburgh: University of Edinburgh. p. 27.

20 Council Directive 89/106/EEC of 21 December 1988 on the approximation of laws, regulations and administrative provisions of the Member States relating to construction products (OJ L 40, 11.2.1989, p.12). Brussels: European Commission.

21 Department for Communities and Local Government (2006). The Building Regulations, 2000 (as ammended). London: DCLG.

22 Scottish Building Standards Agency (2004). Building (Scotland) Regulations 2004. Livingston, UK: SBSA.

23 Department of Finance and Personnel (2005). The Building Regulations (Northern Ireland), 2000. Belfast: DFP.

24 Department of Local Government and Environment (2007). The Building Control Act 1991, Statutory Doc. No 153/07. Douglas, Isle of Man: DLGE.

25 Minister for Planning and Environment (2007). States of Jersey. The Building Bye-Laws (Jersey) 2007. St Helier, Jersey: Planning and Environment.

26 Environment Department (2008). Guernsey Statutory Instruments. The Building Regulations 1992 (as amended). St Peter Port, Guernsey: Environment Dept.

27 Leonards, G.A. (1982). Investigation of Structural Failures. *Proc. Am. Soc. Civ. Engrs. J. Geotech. Engng. Div.* 108(2): 185 – 246.

28 Englund, F., Van Acker, J. and Rapp, A. (2008). Performance Classification: a strategy for wooden products. *Proc. of Cost Action E37 Final Conference*, Bordeaux, 28 - 30 Sept. 2008.

29 Ditlevson, O. and Madsen, H.O. (1980). Discussion of "Optimal reliability by fast convolution". *Proc. Am. Soc. Civ. Engrs. J. Engng. Mech. Div.* 106(3):579.

30 Elingwood, B., Galambos, T.V., MacGregor, J.G. and Cornell, C.A. (1980). Development of a probability based load criterion for American National Standard A58: NBS Special Publication 577. Washington, D.C.: National Bureau of Standards.

31 Wang, C.H., Leicester, R.H. and Nguyen, M.N. (2008). Manual No 12: Equations for Use in Timber Life. Highelt, Victoria: Forest and Wood Products Australia.

32 ISO 15686-2:2001. Building and Constructed Assets - Service Life Planning - Part 2: Service life prediction procedures. Geneva: International Organization for Standardization, 2001.

33 Hovde, P.J. and Moser, K. (2004). CIB Publication 294: Performance based methods for service life prediction - State of the Art Reports Part A & Part B. [online] Available at: <http://cibworld.xs4all.nl/dl/publications/Pub294.pdf> [Accessed 20 June 2010].

34 COST E37 final report: < http://www.cost.esf.org/domains_actions/fps/Actions/E37 > [Accessed 8 May 2011]

35 Masters, L.W., ed. (1985). Problems in service life prediction of building and construction materials. NATO ASI Series E, *No.* 95. Lancaster: Martinus Nijhoff.

36 Scheffer, T.C. (1971). A climate index for estimating potential for decay in wood structures above ground. *For. Prod. J.* 21(10): 25-31.

37 Wang, C.H., Leicester, R.H. & Nguyen, M.N. (2008). Manual No. 3: Decay in ground contact. Highelt, Victoria: Forest and Wood Products Australia.

38 Wang, C.H., Leicester, R.H. and Nguyen, M.N. (2008) Manual No. 4: Decay above ground. Highelt, Victoria: Forest and Wood Products Australia.

39 Nguyen, M.N., Leicester, R.H. and Wang, C.H. (2008). Manual No. 5: Atmospheric corrosion of fasteners in timber structures. Highelt, Victoria: Forest and Wood Products Australia.

40 Nguyen, M.N., Leicester, R.H., and Wang, C.H. (2008). Manual No. 6: Embedded corrosion of fasteners in timber structures. Highelt, Victoria: Forest and Wood Products Australia.

41 Nguyen, M.N., Leicester, R.H. and Wang, C.H. (2008). Manual No. 7: Marine borer attack. Highelt, Victoria: Forest and Wood Products Australia.

42 Leicester, R.H., Wang, C.H. and Nguyen, M.N. (2008). Manual No. 8: Termite attack. Highelt, Victoria: Forest and Wood Products Australia.

43 Nguyen, M.N., Leicester, R.H. and Wang, C.H. (2008). Manual No. 9: Service life models for timber structures protected in building envelope. Highelt, Victoria: Forest and Wood Products Australia.

44 Wang, C.H., Leicester, R.H. and Nguyen, M.N. (2008). Manual No. 11: Equations for use in a service life design guide. Highelt, Victoria: Forest and Wood Products Australia.

45 Nguyen, M.N., Leicester, R.H., Wang, C.H. and Foliente, G.C. (2008). A draft proposal for AS1720.5 timber service life design code. Highelt, Victoria: Forest and Wood Products Australia.

46 EOTA (1999). Assumption of working life of constructional products in guidelines for European technical approval, European technical approvals and harmonized Standards. EOTA guidance document 002. Brussels: European Organization for Technical Approval.

47 CSA S478-1995. Guideline on durability in buildings. Ottawa: Canadian Standards Association, 1995.

48 PD 6612:2004. Guidance on the preparation of codes of practice for building. London: BSI, 2004.

49 BS 5534:2003. Code of practice for slating and tiling (including shingles). London: BSI, 2003.

Chapter 5

Timber

Many architects and engineers go through their education, or even their career, without engaging with timber in any detail. Most textbooks on engineering materials are equally silent on this subject. Although performance-based design is supposed to be material-independent, designers who are only versed in the so called ‘traditional’ construction materials sometimes give insufficient consideration to the properties of timber.

Timber is a distinctive facade material as it is both organic (composed of carbon based compounds with at least one C-H bond) and biogenic (derived from living organisms). Most facade materials are inorganic and non-biogenic (Table 1). Particles will move within and between the groups listed in Table 1 driven by the interplay of two thermodynamic quantities, entropy change (ΔS) and enthalpy change (ΔH). Entropy is the measure of energy dispersal, in effect the degree of molecular disorder. Enthalpy is a measure of heat flow at constant pressure. The type of particle movement depends upon whether entropy and enthalpy work in concert or are opposed (Table 2). Types 1 and 3 are important in this chapter. Type 1 are oxidation reactions (they involve electron loss), whereas Type 3 are reduction reactions (they involve electron gain). The two are always coupled as oxidation-reduction (redox) reactions where electrons are cycled between reactants. Redox reactions include the photosynthesis and combustion (or decay) of timber and the smelting and rusting of iron.

Organic compounds hold large amounts of energy in their chemical bonds, are thermodynamically unstable and, given the right conditions (see Table 2), revert to a more stable form, releasing energy during the process. They tend to have low melting and boiling points, high combustibility, low solubility in water, poor electrically conductivity and covalent bonding. Inorganic materials, by contrast, are more thermodynamically stable. They usually have a high melting and boiling point, are difficult to ignite, highly soluble in water, electrical conductive and their bonds are often ionic [1].

Biogenic materials can be categorised depending upon whether they originate, directly or indirectly, from living organisms or from other sources. Those coming directly from life processes (*e.g.* wood, leather) tend to be non-uniform whereas the others (*e.g.* oil, plastic) are more uniform. Organic-biogenic materials share a further characteristic: moisture sensitivity.

Timber, therefore, has three defining characteristics as a facade material:

- sensitivity to moisture;
- combustibility;
- non-uniform composition.

None of these characteristics is a barrier to using timber externally – far from it. The differences between wood and other mainstream construction materials do, however, tend to be manifested through two different approaches to facade design (Table 3). Most published accounts of rainwater penetration through cladding, for example, focus on leakage through the joints between impermeable sheet materials but fail to consider moisture flow through the cladding itself; this can be a significant route for moisture penetration though timber facades. Similarly, most discussions of facade corrosion address atmospheric and galvanic mechanisms but omit the effect of organic acids.

Where no references are provided in this chapter, the text is based on a few key publications namely: Dinwoodie [2]; Drysdale [3]; Eaton and Hale [4]; Skarr [5]; Siau [6]; Tsoumis [7], and Zabel and Morrell [8].

Table 5.1 *Organic and inorganic compounds, biogenic and non-biogenic materials* (After: Railsback, [9])

Materials Compounds		Biogenic		Non-biogenic
		Directly biogenic	Transformed biogenic	
Organic compounds (C-H bonds)	Carbon based	Most living tissue (e.g. carbohydrates fats proteins) and their remains (e.g. wood, leather, cotton, paper, food)	Fossilised biogenic materials (e.g. coal, oil) and their derivatives (e.g. petrol, natural gas, plastics, paint)	Methane in or from the mantle. Carbon bearing amino acids and other molecules in meteorites
Inorganic compounds (no C-H bonds)	Carbon based	Teeth and bones of calcium Tests, shells or skeletons of calcite (e.g. brachiopod shells, Paleozoic coral) Tests, shells or skeletons of aragonite (e.g. mollusc shells, modern corals)	Atmospheric carbon dioxide and bicarbonate in water from combustion of organic remains or fossil fuels Charcoal and soot Calcited aragonite Limestone, marble Lime, cement	Atmospheric carbon dioxide and bicarbonate in water from weathering of rocks or combustion of non-biogenic organic materials Calcite in sandstones and limestones Diamond and graphite
	No carbon	Skeletons or tests of opalline silica (e.g. tests of diatoms, skeletons of many sponges) Phosphatic shells or skeletons	Sedimentary chert Phosphorite sediments	Silicates in igneous and metamorphic rocks. Most silicates in sandstones Most other minerals (e.g. iron ore) and their derivates (e.g. iron)

Table 5.2 *Spontaneity of a chemical or biological process* (After Kolz et al. [10])

Type	Enthalpy change in a system $\Delta H°_{sys}$	Entropy change in a system $\Delta S°_{sys}$	Spontaneity	Examples
1	Exothermic $\Delta H°_{sys} < 0$	Less order $\Delta S°_{sys} > 0$	Spontaneous under all conditions $\Delta S°_{univ} > 0$	Oxidation processes such as combustion, fungal decay, corrosion or weathering of stone
2	Exothermic $\Delta H°_{sys} < 0$	More order $\Delta S°_{sys} < 0$	Depends on relative magnitudes of ΔH and ΔS. Most favourable at lower temperatures.	Ammonia formation
3	Endothermic $\Delta H°_{sys} > 0$	Less order $\Delta S°_{sys} > 0$	Depends on relative magnitudes of ΔH and ΔS. Most favourable at higher temperatures.	Reduction processes such as iron smelting or photosynthesis
4	Endothermic $\Delta H°_{sys} > 0$	More order $\Delta S°_{sys} < 0$	Not spontaneous under any conditions $\Delta S°_{univ} < 0$	

__Table 5.3__ Material issues affecting facade design in temperate climates

Degradation type	Timber facades	Non-timber facades
Moisture infiltration	Through both joints and the material.	Mainly through joints, leakage through porous materials (*e.g.* brick) can occur.
Biodeterioation	Fungal decay and insect attack in damp timber.	Little affected by biodeterioation.
Weathering	Photo-degradation followed by fungal staining. Splitting and erosion also occur. Flame retardants and preservatives can leach out.	Stone is mainly affected by oxidation and erosion. Fungal and pollution staining can occur. Plastics are photo-degraded.
Dimensional change	Mainly wetting/drying induced swelling/shrinkage.	Mainly thermal expansion/contraction.
Corrosion	Embedded corrosion by organic acids predominates. Other corrosion mechanisms occur in some circumstances.	Atmospheric and galvanic corrosion predominate. Other corrosion mechanisms occur in some circumstances.
Loss of robustness	Most mechanical properties reduce as dry timber gains moisture.	Little affected by moisture.
Frost	Non-problematic.	Problematic with sedimentary rock.
Fire	Structural fire performance is time dependent. Good structural performance in fully-developed fires due to development of insulating char layer. Surface flame spread problematic.	Structural fire performance is temperature dependent. Metals and plastics soften or melt in fully-developed fires; concretes spall. Surface flame spread less problematic (except for plastics).

5.1 Non-uniformity

The non-uniformity of timber is manifested in two ways; it is heterogeneous (*i.e.* composed of different materials) and anisotropic (*i.e.* its properties vary in different directions). Both affect its performance as a facade material.

5.1.1 Heterogeneity

The heterogeneity of timber is manifested in several ways, of which the differences between sapwood and heartwood, and the presence of knots, are generally the most important from a facade designer's perspective.

5.1.1.1 Heartwood and sapwood

In a growing tree the sapwood contains living cells and is used for moving and storing metabolic compounds. As the tree increases in girth the inner sapwood progressively converts to heartwood. This zone does not contain living cells; its role is to provide structural support. These different roles mean that the heartwood and sapwood usually have very different material properties. Heartwood is often distinguishable from sapwood by its darker colour.

In the living tree, sapwood is more resistant to degradation by wood-destroying organisms (biodeterioration) than the heartwood: this is mainly due to its moisture content being too high to permit fungal attack. Heartwood, being drier, is at risk of biodeterioration and many tree species combat this by depositing toxic substances in their heartwood as a defence mechanism. After a tree has died and its moisture content starts to drop, the relative biodeterioration resistance of heartwood and sapwood reverses because the latter does not usually contain these toxic extractives and so has little natural resistance to wood-destroying organisms. Some tree species, such as birch, are relatively short-lived and so do not need to have heartwood that is resistant to biodeterioration. By contrast, other species such as European oak (*Quercus* spp.) and many tropical hardwoods are very long-lived or are exposed to particularly aggressive wood-destroying organisms and so require their heartwood to be resistant – this is termed natural durability. These differences in the ecological strategy of different tree species largely explain the variation in biodeterioration resistance between species [11] [12].

The properties of the heartwood may also vary to some extent. In many species the inner heartwood around the pith tends to have inferior timber properties compared with the outer mature heartwood. This zone is termed juvenile wood and is generally assumed to comprise the inner 10 - 15 growth rings (Figure 5.1) forming a continuous core up the full height of the stem. Juvenile wood tends to be weaker and less dimensionally stable than mature heartwood and may also have a lower resistance to wood-destroying organisms. Much of the variation in material properties occurring within a timber species is attributable to inter-tree differences in the ratio of juvenile wood to mature heartwood. This can be due to several factors including age and growth conditions [13]. These issues are discussed further in a study, led by this author, for the Forestry Commission [14].

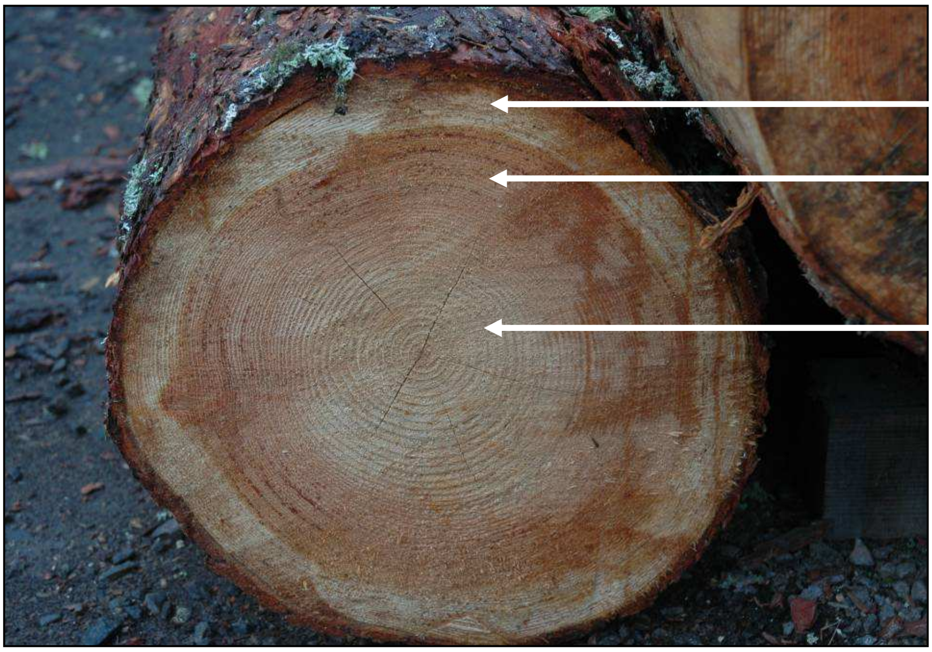


Figure 5.1 *A butt log of European larch showing a change in colour and working properties at around the 15th growth ring*

5.1.1.2 Knots and other features

Wood usually contains knots and other deviations from a regular pattern of growth rings. Their occurrence depends upon growth conditions and genetic factors. Knots are the remains of side branches that become enclosed in the tree bole as it increased in girth. If the branch was alive when enclosed it is termed a live (or intergrown) knot, whereas if the branch had ceased to be alive the resultant knot is known as a dead (or non-intergrown) knot. Dead knots can loosen and fall out; they may also contain areas degraded by fungal decay. Knots do not directly affect the decay resistance of timber but they may create water traps thereby indirectly reducing its service life. Knots and other grain deviations do, however, affect other timber characteristics of importance for external cladding; the most important being strength and stiffness, stability, machining and nailing. Appearance is also affected and so very knotty timber tends to be rejected for many cladding applications. Much of the popularity of Siberian larch (*Larix sibirica*) and imported western red cedar (*Thuga plicata*) is attributable to these timbers being sourced from old-growth forests where the wood is largely knot free. If knots or other defects are present, a few cladding suppliers grade them out or offer a choice of appearance grades. Some cladding suppliers are beginning to go further by cutting out defects (defect cutting) and then finger-jointing the sections of clear timber back together.

5.1.2 Anisotropy

It is possible to distinguish three directional axes within a piece of timber (Figure 5.2). The radial axis describes a section from the centre of a log outwards in a radial direction. The tangential axis describes a section tangential to the growth rings. The transverse axis follows a cross-section across a log, perpendicular to its length. It is also useful to refer to the longitudinal direction along the length of the log. Timber behaves differently in each of these directions. Although this anisotropy can seem quite abstract it becomes particularly important when dimensional change due to moisture is considered and it also affects other characteristics such as decay resistance and structural robustness.

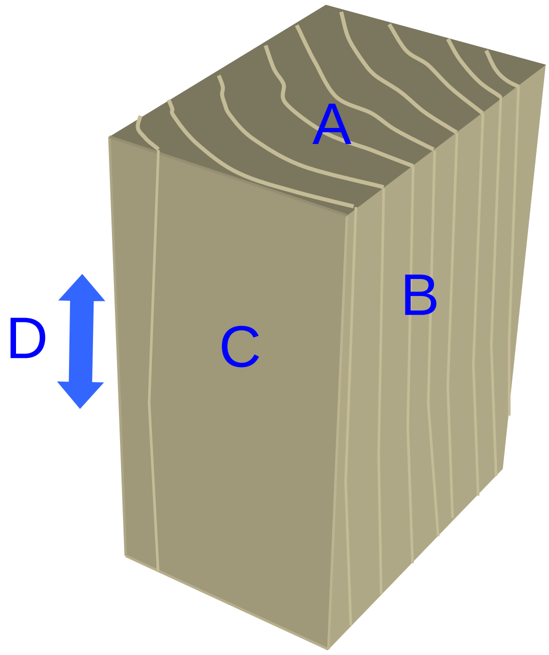


Figure 5.2 *Sketch of a block of wood showing (A) transverse, (B) radial, and (C) tangential surfaces, along with (D) the longitudinal direction.*

5.2 The cell wall

Wood, like all living organisms, is made up of cells. The living cell consists of an outer wall that encloses a cavity (the lumen) containing various structures concerned with the organism's metabolism. Much of timber's lack of uniformity is due to the structure and composition of the cell wall and to cell orientation.

5.2.1 Cell wall composition

The chemical composition of timber from all wood species is similar; in the oven dry (OD) condition it comprises 49% to 50 % carbon, 6% hydrogen, and 44% to 45% oxygen. There is also a small mineral component, termed ash, usually comprising calcium, potassium and magnesium. The ash content is generally between 0.2% and 1% of the OD weight of wood [15].

The cell wall comprises three main polymeric components: cellulose forms the skeleton, hemicelluloses the matrix and lignin acts to bind the other components together, thereby giving rigidity to the cell wall. In addition, wood contains extractives (substances extraneous to the wood structure which can be extracted using solvents). The relative proportions of these components vary between hardwoods and softwoods and as a result of the analytical procedure used. Typical values (on a dry mass basis) are:

- Cellulose: 40% to 47% in both hardwoods and softwoods,
- Hemicelluloses: 20% in softwoods, 25% to 35% in hardwoods,
- Lignin: 25% to 35% in softwoods, 17% to 35% in hardwoods
- Extractives: temperate species 1% to 10% but up to 20% in tropical hardwoods

The cell wall is made up of a number of layers (Figures 5.4 and 5.5). Of these, the S_2 layer is the thickest comprising around 80% of the cell wall thickness in softwoods whilst the corresponding figure in hardwoods can be around 50%. It contains 30 to 50 lamellae, each around 60 to 70 μm in thickness.

The nature and composition of the cell wall components are as follows:

- **Cellulose**; occurs as long filaments formed from glucose ($C_6H_{12}O_6$), the number of units (degree of polymerisation) varies but is typically around 2000 to 10,000. The empirical formula for cellulose is $(C_6H_{12}O_4)_n$ where n is the degree of polymerisation. Glucose occurs in either of two forms depending upon the position of the –OH groups. Starch is formed from α-glucose, whilst β-glucose is the main wall building component of timber. In β-glucose the molecules are able to align themselves into chain-like bundles termed microfibrils. When the microfibrils are evenly ordered they are termed crystalline cellulose, whilst areas of uneven ordering are known as amorphous cellulose. About half of the cellulose is crystalline. Amorphous cellulose is hygroscopic whilst crystalline is not. This means that the microfibrils have different moisture properties depending upon how they are ordered. When water permeates between the chains in the S_2 layer it forces them apart, causing transverse swelling. There is little dimensional change in the longitudinal direction.

- **Hemicelluloses**; the hemicelluloses are also carbohydrates but are formed from different sugar units to cellulose. Hemicelluloses have similar hygroscopicity to amorphous cellulose, indeed this property seems to be related to the amount of hemicelluloses present in the wood. High density wood appears to be correlated with a low amount of hemicelluloses; so too is wood with thin cell walls.

- **Lignin**; chemically dissimilar to the other two structural components of wood, lignin consists of large amorphous molecules formed from complex phenolic polymers. It gives stiffness to the cell wall. Lignin is less hygroscopic than amorphous cellulose and the hemicelluloses.

- **Extractives**; these compounds vary considerably between wood species. They include: starches, resins, fats, salts and tannins. Some extractives such as the starches are associated with the tree's metabolism, whilst others are toxic to wood destroying organisms and function to protect the heartwood from biodeterioation.

The relative proportions of cellulose, the hemicelluloses and lignin varies across the cell wall. A typical distribution for hardwood species is given in Figure 5.3.

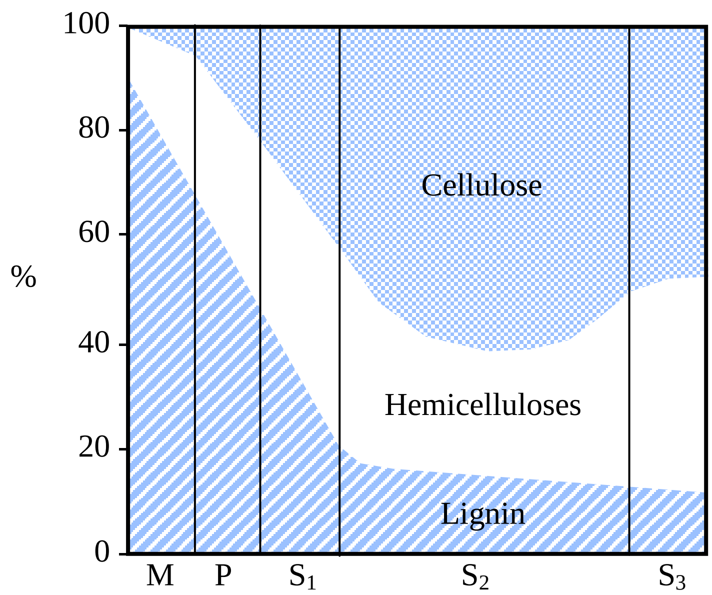


Figure 5.3 *Relative distribution of cellulose, hemicelluloses and lignin in the cell wall of a hardwood. M: middle lamella, P: primary wall,* S_1 *to* S_3*: layers of the secondary wall.* (after: Faln, A. [15])

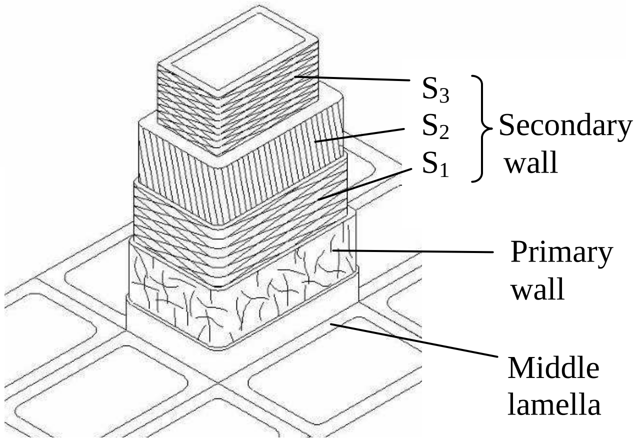


Figure 5.4 *(Above) Diagram of the cell wall structure in wood. The various layers are illustrated including the* S_2 *which has the microfibrils running almost vertically.*

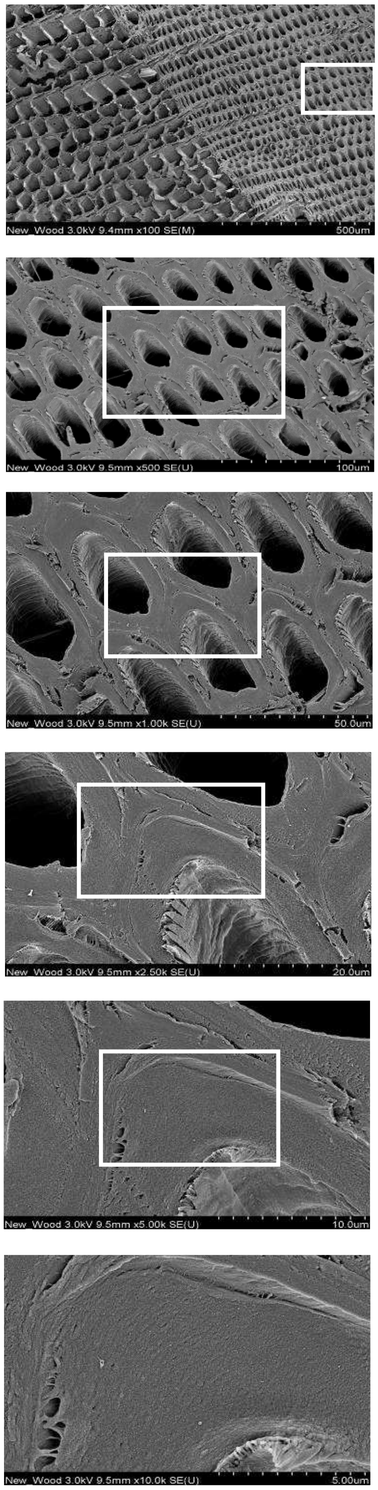


Figure 5.5 *(Left) This sequence of scanning electron microscope images shows a transverse section of European larch being progressively magnified from ×100 to ×10,000. The white rectangles show the area that is enlarged in the next image. The top image in the sequence shows the boundary between low density earlywood and high density latewood across one growth ring. This transition is visible with the naked eye. In the bottom two images the thick* S_2 *layer can be seen. The sample was prepared by dehydration followed by splutter-deposition of a conductive coating of gold particles.*

5.2.2 Wood density

Density is defined as the mass *per* unit volume of a specimen. From a construction viewpoint it is one of the most significant characteristics of timber as it affects strength, stiffness and most other mechanical properties. The density of timber depends upon the amount of substance present and also the presence of moisture and extractives. If the extractives content is high these substances have to be removed before density is determined. Moisture in timber increases the mass of the sample and causes it to swell. Therefore, both mass and volume must be measured at the same gravimetric moisture content. These parameters are usually determined at an oven-dry moisture content (effectively zero). In Europe, density is frequently quoted at a moisture content of 12% as this level is commonly encountered in use. The density of timber varies both between species and within a species. The density of the cell wall is, however, similar at about 1500 kg m^{-3}. It therefore follows that wood density is determined by the ratio between the amount of cell wall (nearly constant) and lumen (variable).

5.2.3 Natural durability

Timber species can be classified according to the natural durability of their heartwood. BS EN 350-1 [16] defines natural durability as: '*The inherent resistance of wood to attack by wood-destroying organisms*' and gives durability classifications for each of the main types of wood-destroying organism. These classifications do not describe intrinsic material properties. Instead they are extrinsic and can only give a relative ranking based on the particular conditions of the test; timber species can have slightly different durability rankings depending upon the test conditions. Consequently, the service life of timber of a particular durability class will tend to vary according to the exposure conditions [17] - [19]. Table 5.4 gives the European classification of natural durability against fungal decay given in BS EN 350-1 and is based on BS EN 252 [20]. This classification is based upon decay resistance in ground contact conditions. All sapwood of all species is assigned to the lowest natural durability classification. Sapwood should be removed wherever a timber is being used for its inherent biodeterioation resistance. Biodeterioation is not inevitable, however, as in most cases it depends on the moisture content of the timber. All timber – even sapwood – can last for centuries if it is kept dry.

Table 5.4 *European classification of natural durability against fungal decay* [16]

Durability class	Description	Results of field tests expressed as x*
1	Very durable	$x > 5.0$
2	Durable	$3.0 < x \leq 5.0$
3	Moderately durable	$2.0 < x \leq 3.0$
4	Slightly durable	$1.2 < x \leq 2.0$
5	Not durable	$x \leq 1.2$

$$\text{* x value} = \frac{\text{Average life of test stakes}}{\text{Average life of the most durable set of reference stakes}}$$

5.3 Moisture sensitivity

Facades are constantly exposed to fluctuating moisture conditions and so the relationship between wood and water tends to dominate much of timber facade design. It is only a slight overstatement to say that much of timber facade design is about the management – and sometimes even the celebration – of moisture effects (Figure 5.6). Most failures in timber facades, and timber buildings generally, are caused by water: either the timber was installed at the wrong moisture content for its intended use, or it became wetter in service than was allowed for in the design.

Figure 5.6 *Celebration of moisture effects: the location and detailing of this timber clad building in Dublin has created a wide variation in microclimate conditions and correspondingly wide range of weathering effects. This was done in full knowledge of the likely consequences – it was an aesthetic decision. The timber was European oak (Quercus* spp.*).*

5.3.1 Moisture content

The moisture content of a piece of timber is defined as the mass of moisture in the sample expressed as a percentage of its mass when fully dry. It can be measured in several ways of which the most accurate is the oven-dry (or gravimetric) method. To do this the wood sample in question is weighed, fully dried, and then weighed again. If this is done using standardised procedures [21], the moisture content (*w*) can be calculated as:

$$w = \frac{p_g - p_o}{p_o} \times 100\% \qquad (5.1)$$

where p_g is the timber sample's initial mass and p_o is its mass after oven drying. The oven dry method is impractical for rapid measurements on site and so electric moisture meters are often used instead; these are normally hand-held although automatic data-loggers for connection to permanent installations are also available. These meters do not measure moisture content directly but instead use some electrical property that varies according to the mass of water in the timber. At moisture contents between 6% and 25%, a measurement accuracy of ± 2% can be achieved using these meters [22] providing the procedure follows standard practices [23] [24]. This is sufficient for most building science purposes. The meters become less accurate outside this range.

5.3.2 Fibre saturation point

When freshly felled, the moisture content of timber can, depending upon species and other factors, vary from below 30% to over 200%. In this condition, timber is described as being green or unseasoned. Timber holds liquid water in two forms: free and bound. Free water is present in the cavities between and within the cells whilst bound water is chemically bonded into the cell wall. Green timber contains both free and bound water. As this timber is dried, the free water is removed first until a condition is reached where all water has gone from the cavities but the cell walls remain saturated. This is termed the fibre saturation point (FSP). Further drying involves removal of bound water from the cell wall. The term fibre saturation point is somewhat confusing because it implies a specific moisture content whereas in reality the FSP is a more of a zone of moisture content in which liquid water finally disappears from the surface of the cell wall. This occurs in most timbers at approximately 28% ≤ FSP ≤ 32%. although in a few species the FSP can be as low as 19% or up to around 40%. Moreover, the FSP is not an exact concept and so varies slightly depending upon how it is defined and measured. Nonetheless, the key point is that most timber properties are stable at high moisture contents but they tend to change as the moisture content drops below FSP. Beyond this point, for example, timber starts to shrink and its strength increases. The FSP can usefully be thought of as a narrow zone of moisture contents below which timber properties start to change.

5.3.3 Equilibrium moisture content

In addition to free and bound water, timber also contains water vapour and this becomes important below the FSP. Timber is hygroscopic – it will absorb atmospheric moisture if it is drier than the surrounding environment and will give up moisture when wetter – and so for any combination of vapour pressure and atmospheric temperature there is, in principle, a corresponding moisture content below the FSP at which there is no inward or outward diffusion of water vapour from the cell wall. This is known as the equilibrium moisture content (EMC). A stable EMC is rarely achieved in practice because most timber inside buildings is exposed to some degree of climate fluctuation. Nonetheless, an approximate value can be predicted. Timber in a centrally heated room, for example, may attain an EMC of 9% to 13% in European conditions.

5.3.4 Sorption

The graph relating the EMC of wood to its ambient relative humidity at a constant temperature is known as a sorption isotherm (Figure 5.7). The isotherm obtained when wood is losing moisture (desorption) does not coincide with that for moisture gain (adsorption). This hysteretic lag effect occurs in many materials. It means that the equilibrium moisture content of wood is influenced by temperature, relative humidity and by its immediate history. At any given temperature there are three main sorption isotherms for wood:

- The initial desorption isotherm as the wood dries from a green condition
- The absorption isotherm as the wood takes up moisture after drying
- The secondary desorption isotherm as the wood redries.

The initial desorption isotherm is everywhere wetter at points between zero and its peak moisture content, whereas the absorption isotherm is always the driest (boundary conditions excepted). These isotherms are the border equilibrium conditions. Most wood in service fluctuates between these curves, creating what is known as an intermediate isotherm; this occurs when sorption is reversed, the transition between curves is smooth. Sorption is affected by both chemical and physical factors.

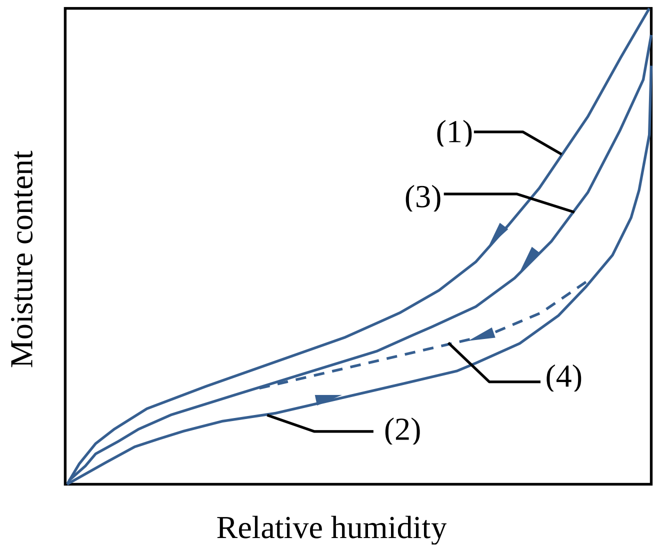


Figure 5.7 *Schematic diagrams of the sorption isotherms for wood: (1) initial desorption isotherm, (2) absorption isotherm, (3) secondary desorption isotherm, (4) intermediate isotherm (After: Siau* [6]*).*

The physical and chemical basis of sorption in wood was reviewed by Salmén [25] who suggests that water sorbed by wood polymers is bound onto their polar groups, namely, the hydroxyls (-OH), the carboxyls (-COOH), and sulfonic acid (…S(=O_2)-OH). Most sorbed water is bound onto the –OH groups in the amorphous regions of the cellulose fibres and by hemicelluloses in the microfibrils. Unlike the crystalline areas, amorphous cellulose has free absorption sites available and so the amount of sorbed water is determined by the fibre’s chemical composition. Physical adsorption is similar to condensation although the heat of adsorption is higher than the heat of condensation. By contrast the heat of adsorption for chemical adsorption tends to be larger and is similar to a chemical reaction. Physical sorption is thus readily reversible whereas chemical adsorption is not. Adsorption equilibrium occurs when the number of molecules arriving on a surface is balanced by the number leaving. Ahlgren [26] reviewed the types of physical sorption isotherm found in a range of materials (Figure 5.8). Type 2 is applicable to timber and most other porous materials.

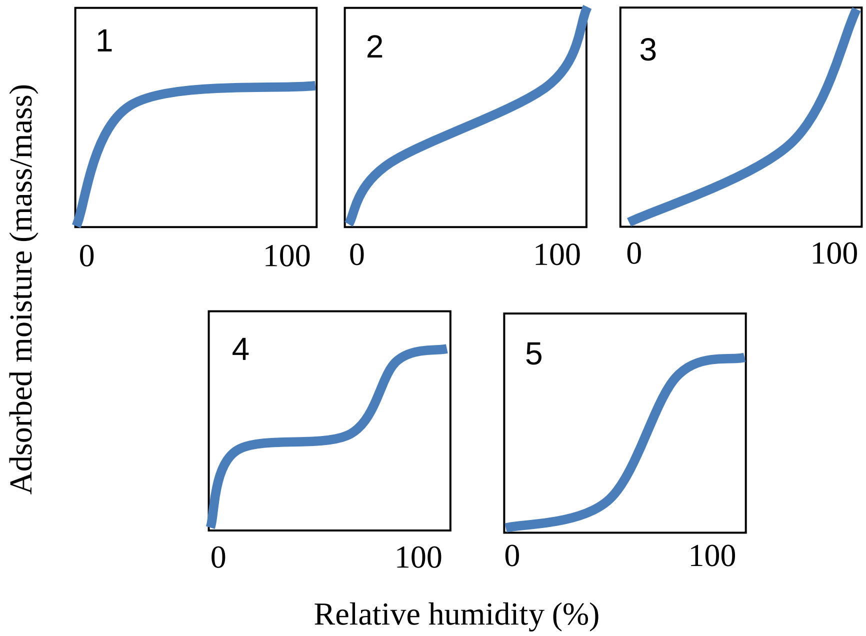


Figure 5.8 *The five types of adsorption isotherm (after: Ahlgren* [26]*)*

The moisture fixation mechanisms in wood vary in response to the RH. At relative humidities below around 10% it is assumed that water molecules are adsorbed as a single layer. The mechanism appears to be some kind of chemisorption with the result that the bound water is difficult to remove. As the relative humidity increases to up to about RH 30% to 50 % moisture fixation changes to multilayer adsorption; this occurs at a wood moisture content of 6% to 15%. As the moisture content approaches 20% the adsorbed water molecules tend to cluster and are drawn into the timber by capillary suction. Osmotic binding may occur at RH values near 100%. The sorption isotherm is only defined for RH values up to 98% as it is impossible in practice to measure at higher values. The zone in which the sorption isotherm is valid is known as the hygroscopic region and sorbed water at an equilibrium moisture content with the surrounding temperature and RH (below 98%) is termed hygroscopic moisture.

The concept of an equilibrium moisture content is only partly applicable to timber that is used externally because the component is exposed to periods of precipitation. If the timber surface is coated with a film of rainwater, this is equivalent to an RH of 100% placing the timber outwith its hygroscopic region. The upper moisture content of external timber is therefore likely to be influenced by the degree of wetting due to sustained contact with liquid water and by the FSP of the species concerned. As already indicated the moisture content at fibre saturation varies between species.

The minimum moisture content attained by external timber is easier to predict. Although the moisture content at FSP varies between species; this is not the case at low moisture contents. Tests at TNO [27] indicated that all wood species attain an EMC of around 5% at 20% RH, and 11% at 60% RH. The authors argue that this relatively constant relationship corresponds to the so-called Langmuir type of sorption [28] characteristic of many porous materials. At RH values above 60% the sorption isotherm varies between species (Figure 5.9) this is believed to be due to differences in the encrustation of the cell wall with extractives. Tropical hardwoods tend to have fibres heavily encrusted with phenolic compounds resulting in a low FSP and high natural durability. As the RH on a hot summer day in the UK is often in the region of 50% to 60% this would mean that the minimum EMC for external timber is 9% to 12% assuming the dry period lasts long enough for equilibrium to occur.

Sorption in wood is discussed through the techniques of classical thermodynamics, although the wood-water system is not fully reversible. The process of water vapour absorption is exothermic due to the heat of sorption being released. Conversely, water desorption is endothermic as energy is required to drive the process. Sorbed water in the cell wall is thus analogous to the frozen phase of water because it has a lower enthalpy than liquid water.

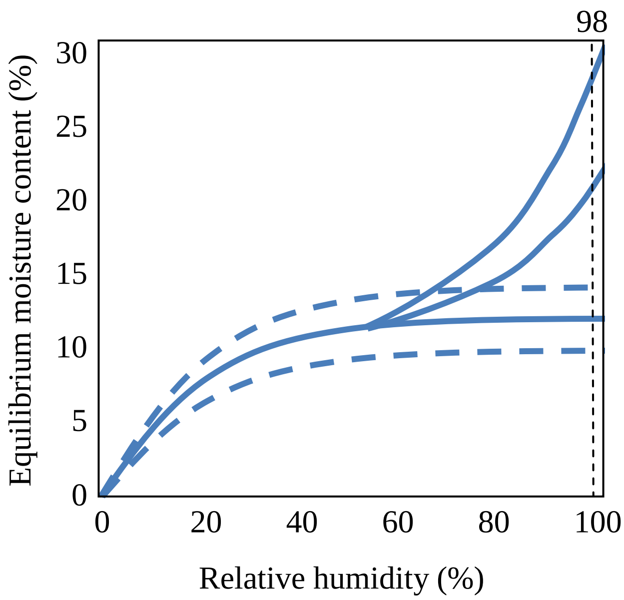


Figure 5.9 *Adsorption isotherms for wood. The path for 0% - 60% RH is constant for all timber species (subject to normal variance) and is believed to be due to the mono- and bimolecular bound water. The path from 60% - 98% RH is due to poly-molecular adsorption. The curvature varies depending upon the degree of cell wall encrustation* [27].

5.4 Fungal decay and insect attack

Although timber can last for centuries in dry conditions, it is at risk of degradation from a range of organisms if it becomes wet for extended periods. Wood-destroying fungi and insects are the main threats in the UK. Fortunately these risks are manageable with suitable materials, design, construction and maintenance. For virtually all timber species, there is no risk of fungal decay if timber is dried to, and then maintained at, a moisture content below 22%. The risk of insect attack in the UK is also relatively minor at these low moisture contents.

5.4.1 Fungal decay

Wood-destroying fungi have several physiological requirements, all of which must be satisfied for colonisation to occur:

- **A digestible substrate:** unable to photosynthesise carbon themselves, fungi need a digestible carbon-based substrate. Wood-destroying fungi can readily assimilate some carbon sources, such as soluble sugars, and produce enzymes that break down the structural components of timber (cellulose, hemicelluloses and lignin) into carbon. Fungi also require minerals and other substances, particularly nitrogen.

- **Temperature:** fungal decay rates increase with temperature until some metabolic reaction becomes limiting. Although a few fungal species can tolerate temperatures below 0 °C or above 50 °C, most have growth limits between 5 °C to 45 °C and an optimum of 15 °C to 35 °C. Fungi become dormant below their minimum threshold temperature and are killed if high temperatures are sustained.

- **Moisture and oxygen availability:** the optimum moisture content for most fungi is 40% to 80%. Moisture affects decay fungi both at low availability, where it limits enzyme activity, and at high levels, where lack of oxygen is a factor when more than 80% of the void volume of timber is water-filled. Decay cannot start until the timber moisture content is high enough for a film of water to form on the cell wall; fungi are thus unable to grow in wood with a moisture content below the FSP. Dry rot (*Serpula lacramens*) is believed to be capable of moving moisture from damp to dry conditions but is not found in external timber in the UK due its intolerance of wind and desiccation. At the upper threshold, fungi need oxygen for respiration and so are unable to grow in saturated timber. As the moisture content of wood increases above the FSP, water replaces air in the cell voids. The void volume varies inversely with density and so the upper moisture limit for decay is lower in high density species.

- **Acidity or alkalinity (pH):** the optimum pH for fungal decay is generally between 3 and 6. Most timber species have a pH within this range.

- **Absence of inhibitory substances:** many timbers contain extractives that inhibit fungal decay. Product manufacturers can also introduce inhibitors as a means of timber preservation. These substances delay the onset of decay but, providing other physiological conditions are met, it will still occur eventually.

Of these requirements, moisture, temperature and oxygen availability are principally environmental and their interaction can be used to describe a decay threshold diagram as shown in Figure 5.10 [29]. In principle, fungal decay in wood can be controlled by creating conditions outside these environmental parameters: conditions that are too hot, cold, wet or dry for the organism involved. Practical application of this technique includes timber being stored in ponds to prevent decay, or the elimination of a dry rot outbreak by heating the whole fabric of the affected building. Moisture content is usually the easiest parameter to control.

The lower moisture content threshold was first proposed by Cartwright and Findley [30] who concluded that the practical moisture content limit to prevent decay was in the region of 22%. This value includes virtually all timber species and allows for inaccuracies in moisture measurement. They further advised that a safety margin should be applied, resulting in the now widely accepted moisture content threshold of 20%, below which it is assumed that timber is immune from fungal decay. At 20 °C most softwood timbers attain this moisture content when the relative humidity is above 85%.

Whilst the 20% rule is a useful approximation, the duration of wetting is also important. Short periods at or above the FSP cannot support fungal decay; spores can germinate in a few minutes, but if the moisture content then falls below the FSP, the organism will be destroyed or become dormant. For an attack to be sustained, the timber has to be damp for an extended period. One frequently cited study [31] has put the threshold as being at least three days *per* month, with the decay rate increasing as the damp period is extended. The practical implication of this is that the intensity of rainfall tends to be less important than its duration. Regular wetting of timber is generally a greater problem than short intense storms. The speed of drying thus becomes significant and the ratio between wetting and drying times is therefore an indicator of decay risk. The time factor is dependent upon temperature as colonisation can occur more rapidly at 15 °C to 35 °C (the decay optimum) than at lower temperatures. Most decay fungi cannot colonise timber below 5 °C no matter what the moisture content. Although environmental control should be the first line of defence against fungal attack, such measures are not always suitable. Additional wood protection is needed in such cases and the options are discussed in chapter 7.

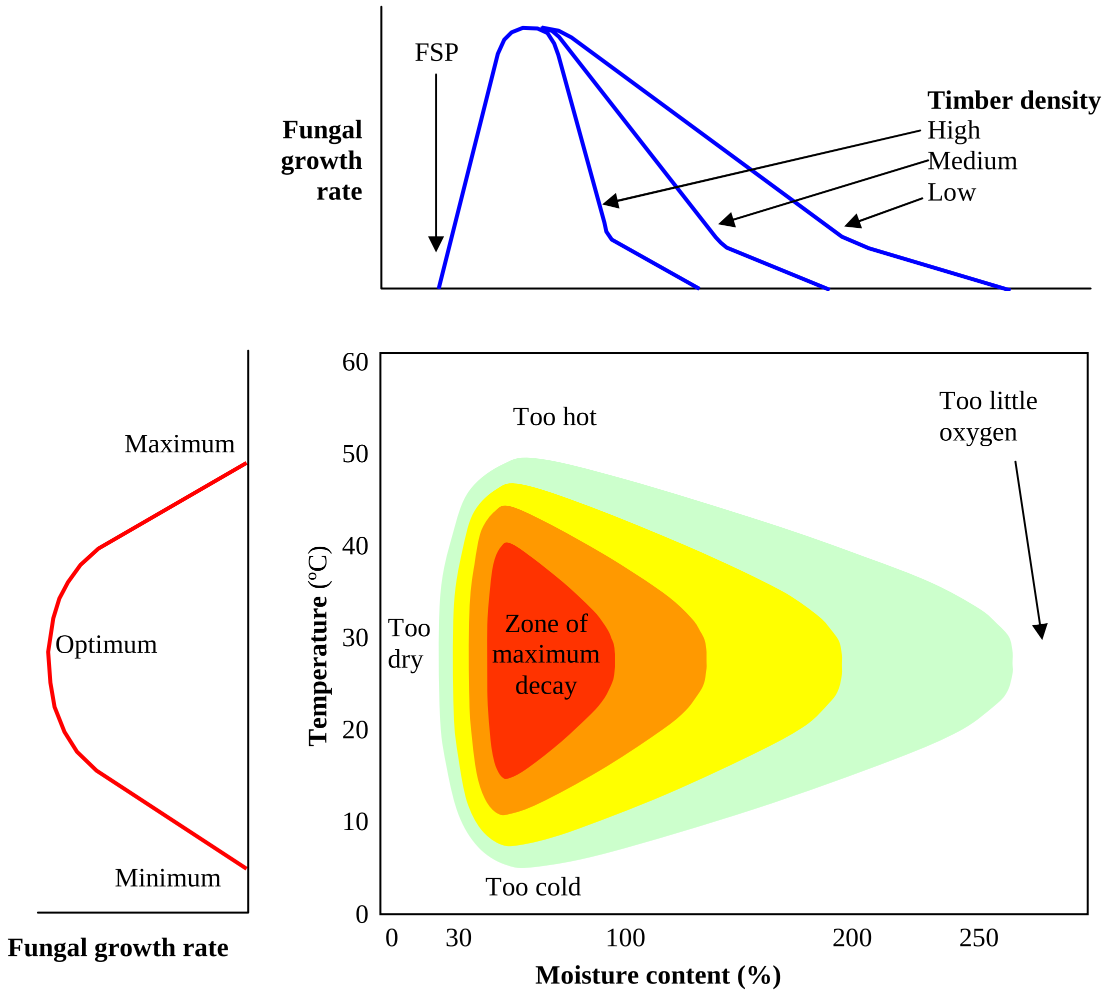


Figure 5.10 *Idealised environmental parameters for fungal decay in wood (after: Tronstad [29],* Raynor and Boddy [12]*)*

Wood-destroying fungi are classified into three groups [32] (Table 5.5), each of which has a slightly different environmental requirement or characteristic biodeterioation. Brown rot and white rot are the most common causes of wood decay, with soft rot generally only occurring in situations where the other types are inhibited by, for example, preservative-treated timber or low temperatures. Not all fungi that colonise wood will cause decay: some will simply stain the timber without breaking it down. Stain fungi are considered below under weathering.

Table 5.5 *Types of wood destroying fungi (after Schwarze et al.* [32]*)*

Brown rot		
Host	Mostly softwoods	
Degradation	Cellulose and hemicelluloses	
Consistency	Fragile, powdery brown, with cubic cracking	
Strength	Drastic reduction in bending & impact strength	
Examples	Dry rot *serpula lacyrmans* (internal timber only in the UK) Wet rots: *Coniophora puteana & C. marmorata* (hardwoods & softwoods, often confused with dry rot) *Dacrymyces stillatus* (hardwoods & softwoods, common on external joinery)	
White rot		
	Simultaneous rot	Selective delignification
Host	Mostly hardwoods	Hardwoods and softwoods
Degradation	Cellulose, lignin and hemicelluloses	Lignin and hemicelluloses are attacked first, then cellulose
Consistency	Brittle fracture	Ductile fracture
Strength	Great reduction in impact bending strength	Slight increase in impact bending strength
Examples	*Phellinus contiguous* (hardwoods & softwoods, common on external joinery)	
Soft rot		
Host	Hardwoods and softwoods	
Degradation	Cellulose, hemicelluloses & lignin	
Consistency	Brittle fracture	
Strength	Between brown and white rot, high stiffness, brittle fracture.	

Ecologists use the concept of an ecological strategy to describe how species inhabit their environment and interact with other organisms. A key descriptor is r-K selection. An r-selected strategy involves an ephemeral life form, whilst in a K-selected strategy the individuals are longer lived. In fungi, the adoption of either strategy is related to the interaction of three environmental determinants: stress, competition and disturbance. Environmental stress limits biomass production for most organisms in the community. The incidence of competitor organisms can reduce resource availability. Disturbance can make new resources available for exploitation by either destroying resident biomass or enriching the habitat. Fungi have three primary behaviour strategies in response to these determinants (Figure 5.11) [33] - [37]:

- **Ruderal**, ephemeral, often only capable of using easily assimilated resources, rapid and sometimes total commitment to reproduction;
- **Combative**, long-lived, capable of defending resources, possibly rapid growth and spore germination, slow or intermittent reproduction, good enzymatic competence;
- **Stress tolerant**, persistent where stress conditions are maintained, but subject to replacement if stress is alleviated, good enzymatic competence.

Although these strategies, and their combinations, allow behaviour at a particular time to be characterised, they cannot be used more widely. This is because behaviour may change in different circumstances or during the organism's life cycle. In any case the descriptions are only relative and so organisms may be characterised differently in different habitats [12].

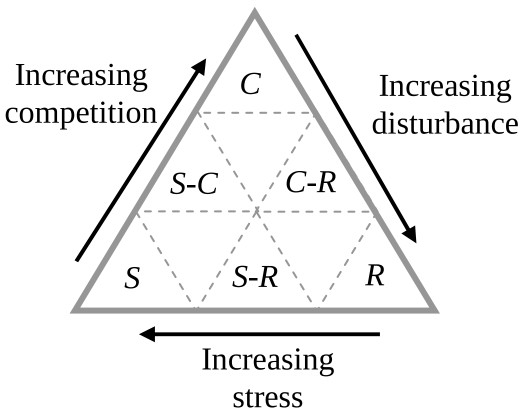


Figure 5.11 *Primary and secondary strategies of fungi due to the relative importance of competition, stress and disturbance. Primary: C, combative; S, stress-tolerant; R, ruderal. Secondary: C-R, combative ruderal; S-R, Stress-tolerant ruderal; S-C, stress-tolerant combative. After: Grime 1977* [33] *and Cooke and Raynor* [37].

5.4.2 Insect attack

Timber can be colonised by larvae of several beetle species. The problem is acute in warm climates and absent in very northern or southern locations. The species capable of colonising external cladding in the UK are given in Table 5.6. Others such as pin-hole borers (*Platypodidae* spp. *Scolytidae* spp. and *Lymexylidae* spp.), forest longhorn beetles (*Cerambycidae* spp.) and wood wasps (*Urocerus gigas*) occur in logs but cannot colonise dry timber. Identification guidance is given in Bravey *et al*. The common furniture beetle (*Anobium punctatum*) is the main threat in the UK as it is the only locally-occurring insect that regularly attacks timber below the FSP. Both softwoods and hardwoods can be affected, although not all species are susceptible. Damage is normally restricted to sapwood, but heartwood can be colonised if rot is present. In the wild, *A. punctatum* is a forest-floor species and so the optimum moisture content for the larvae is 18% to 30%; similar to the conditions in a fallen branch. The larvae can survive at moisture contents down to 12%, although the colony will tend to die out.

Table 5.6 *Insects commonly or infrequently seen in external cladding in the UK* [38]

Insect species	Type of timber		Comments
	Hardwoods	Softwoods	
Main insect species that can infest external cladding in service in the UK			
Woodworm *Anobium punctatum*	✓	✓	Sapwood only, unless rot is present in which case heartwood as well. MC over 18% but can survive for a period down to 12%.
Insect species that occasionally infest external cladding in the UK			
Lyctus powderpost beetles *Lyctus brunneus* & *L. linearis*	✓		Restricted to sapwood of ring porous hardwoods (*e.g*. oak). Thus not seen in cladding unless sapwood is present.
Leafcutter bees *(Magachile* spp.) and solitary wasps (*Carbro* spp.)	✓	✓	Decayed exterior wood including fencing, windows and cladding. Rare
Sawfly *Ametastegia glabrata*		✓	Sapwood and heartwood of external timber. Can infest durable timber and preservative treated timber. Rare.
Insect species that cannot infest cladding in the UK but which may already be present in the timber when it is felled or imported – will die out			
Jewel beetles, family *Buprestidae* several species		✓	North American timbers particularly western red cedar. Larvae may survive in dry timber for several years but cannot re-infest dry timber.

5.4.3 Effects of climate

The environmental parameters outlined above assume varying levels of importance in different geographical locations. In sub-arctic areas, minimum temperature is the limiting factor for much of the year although lack of moisture is also an issue. In deserts, a lack of moisture is the main controlling factor, although the upper temperature threshold can also be important. In temperate climates low temperatures can be the dominant factor in the winter whilst water availability is more important during the rest of the year [12].

Regional climate is not the only environmental factor: microclimate is also important. In Europe, the occurrence of wood-destroying organisms in buildings is outlined in European Standards BS EN 335 Parts 1 to 3 [38] - 40], which groups timber products into five 'use classes' reflecting their moisture conditions and associated biodeterioation risk. External joinery such as cladding is assigned to use class 3: a microclimate in which the timber is frequently, but not permanently, at a moisture content where it is liable to attack by fungi (Table 5.7). The use class system was revised in 2006. Before this revision, the classes were termed 'hazard classes' but this was seen as being too alarmist. The revision introduced sub-classes in use classes 3, 4, and 5 to reflect variations in microclimate or the occurrence of particular biological agents. The practical application of these sub-classes is not yet clear, however, with some people arguing that the presence of a surface coating on external timber is sufficient to change the sub-class from 3.1 to 3.2. Others point to the likelihood that coatings will not be maintained as evidence that class 3.1 should only applied in conditions where the wall is well protected by physical features such as wide eaves. These issues are still poorly understood. In any case, the use class system applies throughout Europe and necessarily involves a degree of approximation. In Mediterranean and sub-tropical climates, for example, it is argued that thin cladding tends to perform best as it dries out quickly whereas thick boards tend to split thereby creating water traps (Figure 5.11) [41]. In Scandinavia, by contrast, thick boards are sometimes recommended because they are believed to be more stable and, as a consequence, reduce the risk of water entrapment (Figure 5.12) [42]. This topic has not been properly investigated. In some countries the effect of these local factors is described in national standards. The use class system should not be confused with the service classes given in Eurocode 5 [43]. Although the two systems are superficially similar they are designed for different purposes and cannot be combined. The service classes are discussed in section 5.8.1.3.

Table 5.7 *Use classes for wood products in Europe (after: BS EN 335 parts 1 and 2, [38] [39])*

Use class	General service condition and sub-class where relevant	Moisture content	Biological agents [a]			
			Fungi	Beetles	Termites	Marine borers
1	Interior and covered, *e.g.* internal joinery	Maximum 20 %	-	U[b]	L[f]	-
2	Interior or covered, *e.g.* timber in external timber-frame walls, slating laths.	Occasionally > 20 %	U[c]	U[b]	L[f]	-
3	3.1 Exterior, above ground, protected from wetting, by *e.g.* large eaves [h]	Occasionally > 20 %	U[c]	U[b]	L[f]	-
	3.2 Exterior, above ground, unprotected from wetting, *e.g.* cladding, windows [h]	Frequently > 20 %	U[c]	U[b]	L[f]	-
4	4.1 Exterior, in ground contactor fresh water	Predominantly or permanently > 20 %	U[d]	U[b]	L[f]	-
	4.2 Exterior in ground (severe) or fresh water	Permanently > 20 %	U[d]	U[b]	L[f]	-
5	In salt water	Permanently > 20 %	U[d]	U[be]	L[e]	U[g]
U = universally present in Europe; L = locally present in Europe						
It may not be necessary to protect against all biological agents as they may not be present or significant in all conditions or locations. A higher use class may be assigned if timber is likely to be wet due to *e.g.* design faults or poor workmanship.						
[a] Due to local variation in occurrence and the need for targeted prescription, sub-classifications of biological agents is possible. [b] The risk of attack can be insignificant in some geographical locations [c] Both disfiguring & decay fungi occur [d] Disfiguring & decay fungi occur plus soft rot [e] The above-water portion can be exposed to wood boring insects including termites [f] If termites are locally present the use class is given the suffix T (*e.g.* 3.1T) [g] Use class 5 is split into 3 sub-classes depending on the type of marine borer: 5A = *Teredinids* and *Limnoria* 5B = as A + creosote tolerant *Limnora* 5C = as B + *Pholads*. [h] Some publications interpret sub-class 3.1 as referring to coated timber and sub-class 3.2 to uncoated.						

Figure 5.12 *Thin cladding timbers are preferred in Mediterranean or sub-tropical climates. It is argued that they dry out quickly after wetting and thereby have a low decay risk. (Obi, Japan)*

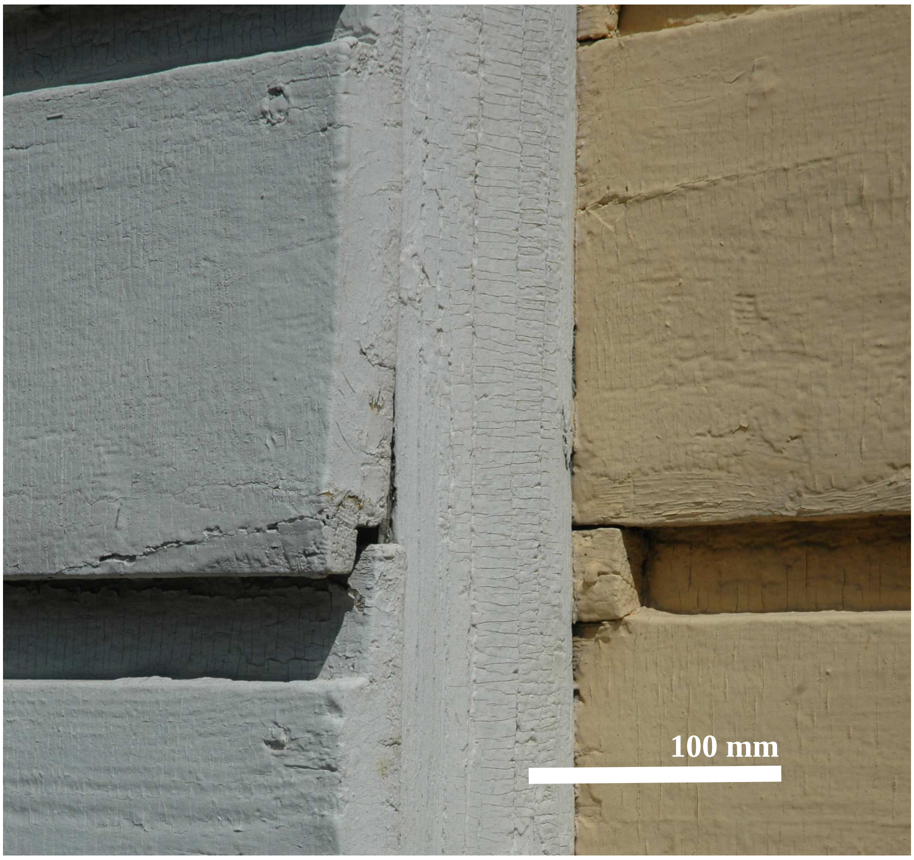


Figure 5.13 *Thick cladding timbers are traditional in Finland where it is argued that they are stable and thereby resistant to water accumulation due to splitting.*

5.4.4 Assessing biodeterioation risks in use class 3

Natural durability is often discussed as if it is an intrinsic material characteristic whereas it is simply a statement of performance under specific test conditions. Being an extrinsic phenomenon, natural durability statements should be used with caution. Although there are extensive test data on timber durability, much is from laboratory and short-term exposure trials which experience has shown to be poorly correlated with performance under some in-service conditions. Part of the difficulty is that these tests are derived from use class 4 conditions and do not adequately model the effects of intermittent wetting and drying. It is therefore likely that a new exposure trial procedure – known as a double layer test – will be adopted for assessing natural durability in use class 3 [44]. This method will not, however, do away with the need for product specific exposure trial tests such as those discussed in the next chapter. This topic is reviewed in Råberg *et al*. and Van Acker *et al* [45] [46].

5.4.5 Decay indexes

There have been several attempts to express the regional importance of these factors using various forms of fungal decay index. Three of these are discussed below although a note of caution should be sounded. All of these models are derived, at least in part, from historical climate data. They have a predictive role where environmental conditions are similar from year to year but their future accuracy can be questioned in the light of climate change.

5.4.5.1 The Scheffer index

The earliest model of fungal decay in out of ground contact conditions is the Scheffer Index [31] developed during the 1960s and based upon temperature and rainfall data. It assumes a linear relationship between mean monthly temperature (T) and decay with a lower threshold of 2 °C below which decay ceases. For rainfall, it uses the number of days (D) with at least 0.25 mm of precipitation. Rainfall of fewer than three days *per* month is discounted. Converted to metric units, it becomes:

$$Climate\ index = \frac{\sum_{Jan}^{Dec}\left[(T-2)(D-3)\right]}{16.7} \qquad (5.2)$$

The divisor is chosen to give a score below 100 for most of the United States. The index ranges from below 35 (virtually no decay) in parts of the American southwest, through to 70 - 130 (rapid decay) in the southeast and a small part of the Pacific northwest. Tropical areas such as north west Brazil score around 300.

5.4.5.2 The European Climate Index

Work is ongoing on an index for Europe based on the Scheffer model. It appears that the decay rate increases slightly from continental climates to western coastal conditions, and from north to south. Expressed on the Scheffer scale, the decay rate in most of western Europe is 50 to 80 [47].

5.4.5.3 The Timber Life index

The Scheffer Index has its limitations and so other models have been developed. Australian researchers have developed the most advanced model to date [48]. It is one of a series of engineering-based degradation models developed through the Timber Life programme [49]. These models assume that once the relevant preconditions have been met, fungal decay (or any other degradation) develops at a uniform rate for the location and timber concerned. Maintenance can remove the preconditions for a time, thereby introducing a lag effect. But, once maintenance ceases degradation will proceed at the original rate. Although this model appears to allow the service life of timber in use class 3 to be estimated, it is currently only applicable to Australian conditions and would need to be recalibrated for other climates. One difficulty is that the Australian natural durability classification is different to Europe. It is known that natural durability rankings are only relative and can change in different durability classes. This is not currently reflected in BS EN 350-2 [50] although work by Rapp and Augusta [18] is addressing the issue. The Australian research has produced different natural durability classifications for in ground and out of ground contact. Table 5.8 compares the current

European and Australian classifications using timber species common to both documents.

Table 5.8 *Durability classes against fungi* [48] [50]

Common name	Botanical name	Australian durability classes		European durability classes in use class 4
		Hazard class 3	Hazard class 4	
Western red cedar (US)	*Thuja plicata*	2	3	2
Douglas fir (US)	*Pseudotsuga menziesii*	4	4	3
Hemlock	*Tsuga heterophylla*	4	4	4
Jarrah	*Eucalyptus marginata*	2	2	1
Keruing	*Dipterocarpus* spp.	3	3	3*
Meranti, dark red	*Shorea* spp.	3	4	2 - 4*
Meranti, light red	*Shorea* spp.	2	4	3 - 4*
American white oak	*Quercus* spp.	3	4	2 - 3*
Radiata pine	*Pinus radiata*	4	4	4 - 5*
Burmese teak	*Tectona gradis*	1	2	1

* Variable, depending upon growth rate and other factors

It is known that durability classes of some species in Table 5.5 are variable whilst others (*e.g.* teak and western red cedar) may be changing due to a shift from old growth to plantation origin. In which case, the differences between the two classifications can probably be explained, although more work would be needed to confirm this. It is, however, reasonable to assume that the durability classes in BS EN 350-2 broadly equate to Australian durability classes for hazard class 4.

The Australian index predicts the decay rate using a range of biological factors expressed as:

$$Decay\ rate = k_{wood}k_{climate}k_pk_tk_wk_nk_g \tag{5.3}$$

where k_{wood} describes the timber species and type (heartwood, sapwood, preservative treated); $k_{climate}$ is a climate parameter; k_p is a parameter for paint; k_t is a thickness parameter; k_w is a width parameter reflecting the risk of splitting; k_n is a fastener parameter and k_g is a parameter for component geometry.

The wood parameter (k_{wood}) quantifies the effect of different natural durability classes. Converted to the European natural durability classification it is expressed as:

$$k_{wood} = \begin{cases} 0.50 & \text{Class 1} \\ 0.62 & \text{Class 2} \\ 1.14 & \text{Class 3} \\ 2.20 & \text{Class 4} \\ 6.52 & \text{Class 5 \& sapwood} \end{cases} \tag{5.4}$$

Australia spans a wider range of climate conditions than Europe and this necessitated the country being split into four decay zones. Different zones were also devised for in-ground and out-of-ground conditions:

- In-ground hazard zone B describes the Australian dry-temperate zone that virtually encircles the desert interior. It is broadly equivalent to European use class 4.

- Out-of-ground hazard zone C describes the Australian east coast temperate zone, it excludes some dry-temperate areas. It is broadly equivalent to European use class 3.

Climate parameter $k_{climate}$ = 0.65 is used for hazard zone C and comes closest to describing use class 3 conditions in Western Europe.

The paint parameter is set at k_p = 1.0 for unpainted timber, while the effect of paint timber is quantified differently for each natural durability class:

$$k_p = \begin{cases} 3.5 & \text{Class 1} \\ 2.0 & \text{Class 2} \\ 1.5 & \text{Class 3} \\ 1.1 & \text{Class 4} \\ 1.1 & \text{Class 5 \& sapwood} \end{cases} \tag{5.5}$$

The thickness parameter is set at k_t = 1.0 for timber in contact with other timber but if the component is not in contact:

$$k_t = \begin{cases} 1 & t \geq 20 \text{ mm} \\ 0.5 & t < 20 \text{ mm} \end{cases} \tag{5.6}$$

The width parameter ranges from k_w = 1.0 for a 50 mm wide board up to k_w = 1.5 for a 200 mm wide board according to the expression:

$$k_w = \frac{w}{300} + \frac{5}{6} \tag{5.7}$$

The connection parameter is set at $k_n = 2$ where there is a connector and $k_n = 1$ where there is not. These parameter values are very provisional

The geometry parameter is expressed as:

$$k_g = k_{g1}\, k_{g2} \tag{5.8}$$

where k_{g1} is a contact factor and k_{g2} is a position parameter. The contact factor depends on if the assessed surface is in contact with other components or not:

$$k_{g1} = \begin{cases} 0.3 & \text{Non-contact surface} \\ 0.6 & \text{Flat contact} \\ 1.0 & \text{Embedded contact} \end{cases} \tag{5.9}$$

The position parameter for non contact surfaces takes account of orientation and the effect of shelter and exposure to sun. For vertical members the values are:

$$k_{g2} = \begin{cases} 6.0 & \text{Top flat} \\ 5.0 & \text{Top sloping} \\ 2.0 & \text{Facing south} \\ 1.5 & \text{Facing north} \\ 1.5 & \text{Facing east} \\ 2.0 & \text{Facing west} \end{cases} \tag{5.10}$$

The values for north and south are reversed from those for Australia. The effect of differences in sunlight exposure between the UK and Australia cannot yet be estimated.

The position parameter for contact surfaces takes account of the type of contact material and the size and location of gaps. It is expressed as:

$$k_{g2} = k_{g21}\, k_{g22}\, k_{g23} \tag{5.11}$$

where k_{g21} is the contacted material, k_{g22} is the orientation and k_{g23} is the gap. Parameter values for the type of contacted material are:

$$k_{g21} = \begin{cases} 1.0 & \text{Porous material (\textit{e.g.} wood, concrete)} \\ 0.7 & \text{Non-porous material (\textit{e.g.} steel, plastic DPC)} \end{cases} \tag{5.12}$$

Where members are end jointed, if is the gap is ≤ 1.0 mm, $k_{g23} = 2.0$, while if the gap is ≥ 2.5, $k_{g23} = 2.0$. Intermediate values are calculated as:

$$k_{g23} = \frac{3.7}{1.5} - \frac{0.7}{1.5} \times (\text{gap size}) \tag{5.13}$$

The index is based on three types of test, in-ground stakes, vertical boards, and L-joints. With vertical boards, for example, researchers examined the effect of water traps at the top and bottom edge and at a saw cut; decay at the bottom edge was around three times faster than at the other two locations (Figures 5.14 and 5.15). The L-joint samples with a surface coating test tended to decay around 25% more slowly than those without a coating (Figure 5.16). Test samples within the European climate index appear to be performing in a similar fashion but this has not been quantified yet.

Although at first sight the Australian work seems comprehensive this is not yet the case. The researchers also note that the impact of construction detailing has not yet been fully addressed in the model. Cladding is poorly described, for example, and so the model cannot in its current form be used to predict the service life of timber facades. Table 5.6 compares the Australian performance-based service life predictions with the prescriptive estimates in BS 8417 [19]. In most cases the use class 3 service life estimates in BS 8417 fall within the upper half of the Australian hazard zone C predictions for fencing and pergolas but have less correspondence with the equivalent estimates for decking. Similarly, the UK estimates for service life in use class 4 broadly correspond with the Australian predictions for square posts; the exception being Jarrah *(Eucalyptus marginata)* but this can probably be explained by differences in relative durability rankings (Table 5.9). It is therefore plausible to assume that the Australian performance based estimates for hazard class 3 can be used to make very provisional predictions of the service life of external cladding in the UK.

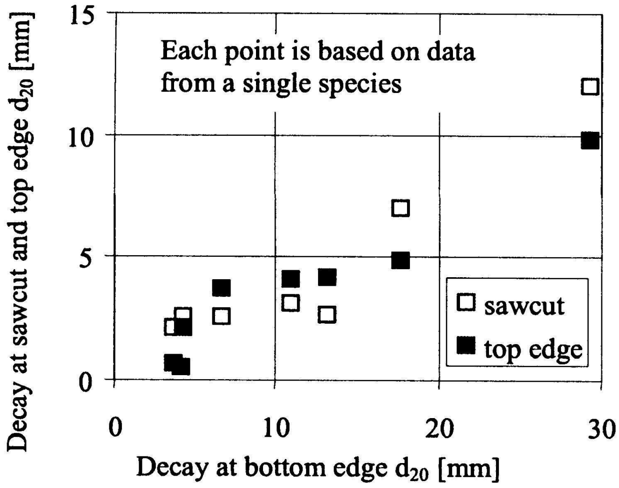


Figure 5.14 Extrapolated 50 percentile value for 20 year decay of non-preservative treated species in the vertical boards (see Figure 5.13) comparison between decay zones. (From: Leicester et al. [48])

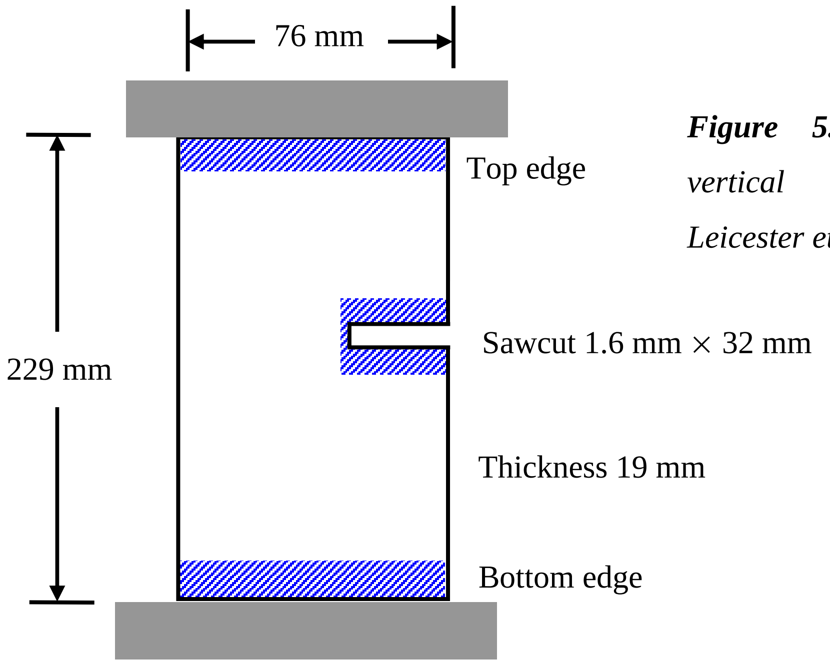


Figure 5.15 Design of the vertical board test (After: Leicester et al [48].)

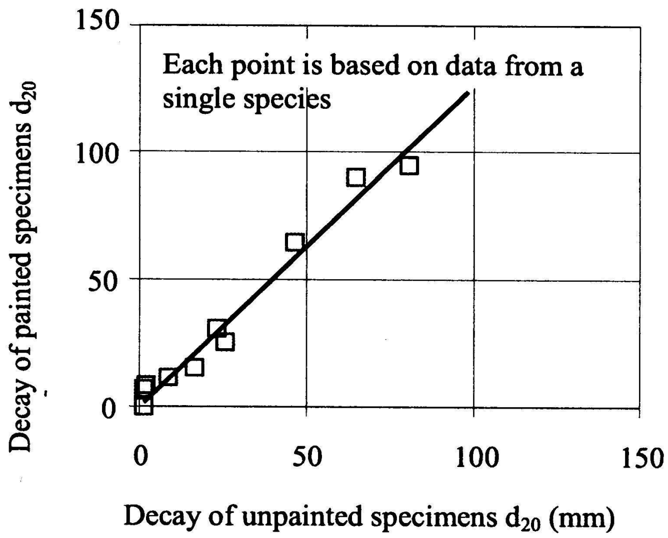


Figure 5.16 Extrapolated mean value for 20 year decay of non-preservative treated species measured using an L-joint test; comparison between coated and uncoated samples. (From: Leicester et al. [48])

Table 5.9 Service life estimates in UK and Australian guidance [19] [48]

Common name *Botanical name*	Australian performance based service life estimates * (years) Hazard class 3 Hazard zone C			Australian performance based service life estimates ** (years) Hazard class 4 Hazard zone B		UK prescriptive service life estimates (years)	
	Fencing	Pergolas	Decking	Round pole	Square post	Use class 3	Use class 4
Western red cedar (US) *Thuja plicata*	35 - 80	25 - 40	35 - 50	25 - 40	15 - 25	60	15
Douglas fir (US) *Pseudotsuga menziesii*	10 - 25	8 - 15	10 - 15	-	-	30	-
Hemlock *Tsuga heterophylla*	10 - 25	8 - 15	10 - 15	-	-	15	-
Jarrah *Eucalyptus marginata*	35 - 80	25 - 40	35 - 50	25 - 40	15 - 25	> 60	60
Keruing *Dipterocarpus* spp.	20 - 45	15 - 25	20 - 25	-	-	30	-
Meranti dark red *Shorea* spp.	20 - 45	15 - 25	20 - 25	-	-	15 - 60	-
Meranti light red *Shorea* spp.	35 - 80	25 - 40	35 - 50	25 - 40	15 - 25	30 - 60	-
American white oak *Quercus* spp.	20 - 45	15 - 25	20 - 25	-	-	30 - 60	-
Radiata pine *Pinus radiata*	10 - 25	8 - 15	10 - 15	-	-	≤ 15	-
Burmese teak *Tectona gradis*	4 - 90	30 - 50	45 - 60	45 - 80	30 - 50	> 60	60

* Depends upon component geometry
** Depends upon diameter or section

5.5 Weathering

All external building materials change with time: metals corrode, masonry erodes, plastic becomes brittle, wood rots. Eventually these processes can result in the disintegration of the facade material but, before this; there is a period of ageing – of weathering – where the surface appearance changes in often unpredictable ways. These processes condition the way we view buildings, and our expectations of how, and for how long, a facade will resist the effects of its environment. In the UK people tend to have a consistent set of expectations about how masonry-based materials will age. Yet they often lack a corresponding appreciation of timber. By contrast, in countries such as Norway where wooden facades are commonplace, people have more of a shared language for using timber externally; it is not controversial.

All uncoated timber, irrespective of species, eventually weathers to various shades of grey when exposed out of doors. If the effect is uniform it may be described as 'silver-grey' and is even, misleadingly, compared to the green patina that forms on copper. Leaving a timber facade to weather naturally can minimise maintenance costs, but in many cases the resultant finish can have unexpected and variable characteristics. Often this is viewed as being cheap or drab and in this respect uncoated timber facades have much in common with those of mass concrete. The challenge for facade designers is to pre-empt reaction against the current generation of uncoated timber cladding by the use of careful design and construction.

5.5.1 Main weathering processes on wood

When wood is exposed out of doors without a protective coating, the surface undergoes changes to its appearance and texture (Figure 5.17). Weathering of wood should not be confused with fungal decay, which results from extended periods of excess moisture allowing wood-destroying fungi to colonise and degrade the timber. Nor is it a purely physical process driven by ultraviolet (UV) light. Although the physical, chemical and biological processes involved in weathering of timber are understood [51] - [54] their interaction in specific cases is difficult to predict. The normal weathering sequence in the UK is as follows although not all these stages appear in every case.

1. **Oxidation**: as timber dries, extractives accumulate on the surface where they oxidise to a brown stain (this is similar to the cut surface of an apple turning brown). The effect is usually short-lived, as rainwater will remove the extractives, although it can persist where the timber is protected. Leached extractives are often deposited as temporary brown stains on surfaces exposed to runoff from the facade. These effects vary but can be pronounced, particularly in oak and sweet chestnut.

2. **Photo-degradation**: the visible and UV components of sunlight both act to photo-degrade lignin at the timber's surface to produce organic acids and other compounds which are then leached away leaving the fibrous cellulose and hemicelluloses largely intact. The depth affected is up to 0.5 mm. Weathered timber surfaces tend to roughen as the fibres are exposed (Figure 5.18).

3. **Staining**: the greying of damp wood is generally due to the presence of stain fungi; *Aureobasidium pullulans* is particularly important in temperate climates. The hyphae of these fungi are pigmented and they tend to refract visible light, accordingly the timber surface appears grey. Refraction varies depending upon the surface moisture content and so weathered timber is always darkest when wet. Under favourable conditions, *A. pullulans* grows on the surface of many materials. Its ecological requirements are modest, the main condition being the occasional supply of water. On weathered timber, the organism lives off lignin breakdown products leached down the surface. It can colonise timber surfaces after less than a year's weathering though the rate depends upon water availability – the effects are most pronounced on upward facing surfaces and those exposed to wind channelling, splashing or high relative humidity (Figures 5.19 to 5.22). Stain fungi such as *A. pullulans* also colonise weathered timber under coatings (Figure 5.23).

4. **Splitting**: repeated movement of the timber due to moisture content fluctuation may lead to surface cracks. These vary according to the timber's characteristics and how the board is fixed to the wall. Experience in Scandinavia [55] suggests that the risk of splitting is minimised if boards are positioned so that the side of the board nearest the pith faces outwards. Some UK publications claim otherwise, although this appears to be based on a misreading of Scandinavian advice.

5. **Erosion**: the surface of external timber will slowly be worn away due to a combination of photo-degradation, mechanical abrasion by wind blown particles and biodeterioation. The rate varies depending upon the site conditions and timber density.

Figure 5.17 *Weathering of timber is rarely uniform as it depends on a complex interaction of factors. This photograph shows cladding made of European oak (Quercus spp.) at Henley River and Rowing Museum. On the bottom left the oxidised surface of the cladding has been protected from leaching by the projecting canopy. On the right side the cladding has been photo-degraded and the resultant breakdown products are, given sufficient moisture, supporting the growth of stain fungi turning the timber surface grey. All of the right hand side is equally exposed to UV light. The variation in grey staining appears to be due to differences in moisture availability affecting the growth rate of stain fungi.*

Figure 5.18 *Fibres being exposed as the timber surface weathers.*

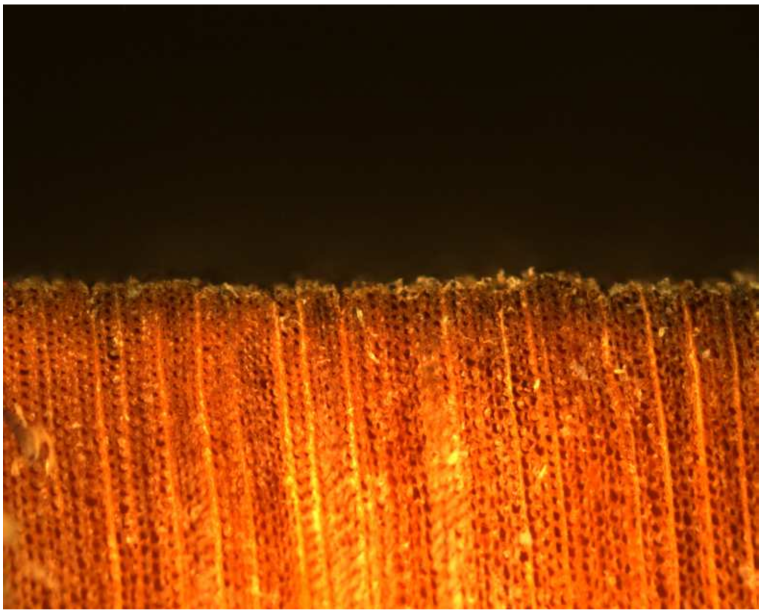


Figure 5.19 *This light microscope image (×5) of a section through a piece of weathered larch illustrates how the grey staining is mainly a surface effect.*

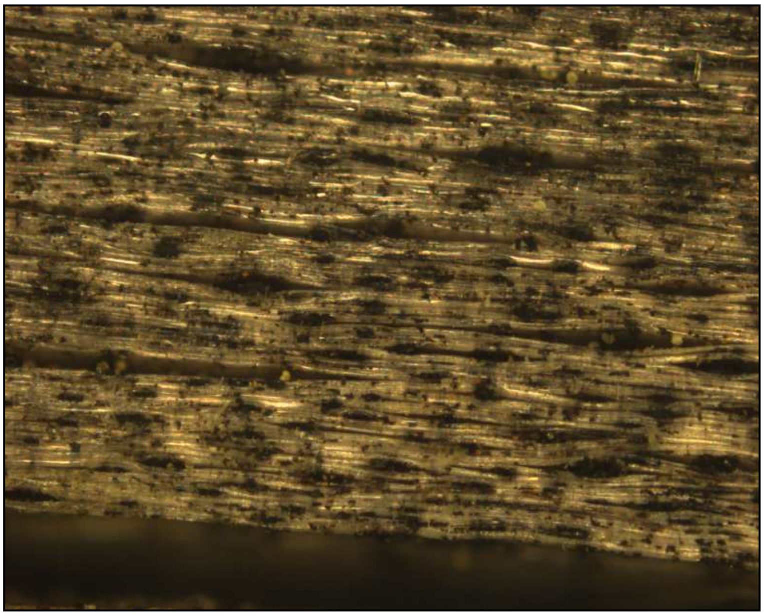


Figure 5.20 *Light microscope image (×5) of the surface of a Douglas fir board after 18 months weathering. The dark grey areas are fungal staining on the surface.*
(Photo courtesy of Victoria Sharratt)

Figure 5.21 *This oak cladding at Henley-on-Thames has stained in a uniform manner due to its sheltered humid site*

Figure 5.22 *This western red cedar cladding in Aberdeenshire has been exposed to wind-driven rain at the gable while the three side panels have been sheltered. This variation in wetting has resulted in marked differences in fungal staining.*

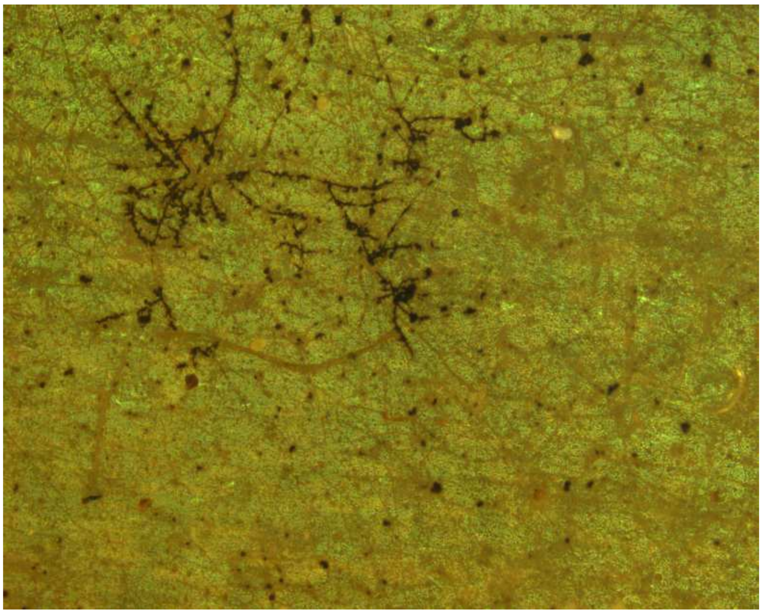


Figure 5.23 *Florescence light microscope image (×5) through an exterior varnish. The grey lines are fungal mycelium growing between the coating and wood substrate. (Photo courtesy of Victoria Sharratt)*

5.5.2 Other weathering effects

Although weathered timber generally turns some shade of grey due to colonisation by stain fungi, other organisms can also affect surface appearance. The most important of these in UK conditions are algae, wasps, slugs and lichen.

Algal growth on timber cladding usually first appears in areas exposed to rainwater run-off (*e.g*. below leaking gutters). The growth rate increases with moisture availability and is limited by drying or erosion. Algae require higher moisture contents than stain fungi. The most frequent species is the common subaerial green algae (*Desmococcus olivaceus*) [56] [57] which occurs on shaded or polluted timber not colonised by lichen.

Wasps harvest photo-degraded timber to build their nests (Figure 5.24), whilst slugs eat algae. In both cases the effect is that light coloured irregular lines appear on the grey or green surface of the wood.

Many lichen species can colonise external timber though their speed of growth is slow (Figure 5.25). Most species are sensitive to pollution and consequently are rarely seen in urban areas. In unpolluted locations, however, their growth can be extensive. Although lichen growth appears to have little detrimental effect on the timber substrate, the owners of many of the recently completed timber clad country homes in western Britain may come to take a different view. Lichen growth on timber facades has not been investigated. Indeed the whole topic of non-fungal growths on external timber has received little research attention.

Figure 5.24 *Wasp harvesting photo-degraded timber*

Figure 5.25 *Lichen growth on a 25 year old larch gate near Inverness*

5.5.3 Factors influencing weathering

Weathering of timber is affected by a number of factors particularly the site characteristics and the species used.

5.5.3.1 Building location and design

In areas of high rainfall some timber facades can turn grey in only a few months whilst in dry locations this process is generally slower. Walls facing south-west tend to experience relatively fast weathering. North-facing walls tend to weather uniformly as do facades on humid sites.

The form and shape of a building strongly influences the impact of wind-driven rain upon it. Buildings without eaves tend to experience their highest moisture loads near the top of the facade, particularly at outer corners [58]. This may result in those areas staining faster than other parts of the wall. Eaves shelter the upper part of the wall, though the effect depends upon the ratio of wall height to depth of the eaves projection. An overhang ratio of at least 4:1 is required before the entire wall is sheltered [59]. Projections such as eaves can cause uneven weathering immediately below that point, however, because extractive staining persists and photo-degradation is prevented in the area sheltered by the projection. Projections can also cause splashing, which in turn leads to localised staining. Projections and splash-zones are therefore an important influence on weathering.

5.5.3.2 Timber species, modification and preservatives

Although all timber species turn grey when exposed to a combination of sunlight and moisture, some tend to be more predictable than others. Whilst the influence of species is usually less important than a building's form and detailing, a number of general points can be made.

If timber is to be left uncoated to weather naturally, it is normal practice for the heartwood of a relatively durable timber species to be used. Low durability timbers will turn grey but, because these species have little resistance to fungal decay, a surface coating is usually applied in an attempt to keep their moisture content as low as possible. In the UK it is normally assumed that the heartwood of durability class 3 (*i.e*. moderately durable) timbers can be used externally without a coating although a durability class 2 or 1 species (*i.e.* durable or very durable) will tend to have a longer service life [19]. Density is also important. Low density timbers such as western red cedar (*Thuja plicata*) are prone to more rapid erosion than denser timbers and so it may be prudent to avoid these species wherever wind blown particles are a risk.

Some timbers species are particularly prone to staining. Oak (Q*uercus* spp.) and sweet chestnut (*Castanea sativa*) are well known for their rapid and variable weathering response. The effect is most pronounced in the first few years. In contrast, many tropical hardwood species and imported western red cedar tend to weather uniformly unless affected by differential wetting due to either orientation or the design of the facade.

Some chemically-modified timbers such as Accoya™ are also very prone to staining, whereas most thermally-modified timbers tend to stain more uniformly. These effects are not fully understood. Preservative-treated timber contains a fungicide and this reduces the speed and variability of colonisation of wood surfaces by stain fungi. The preservatives used for external applications often impart a green or brown colouration to the timber, which although fading over time, may not be visually acceptable in all cases.

5.5.4 Anticipating or responding to weathering

Although weathering tests are published for surface coatings, and for external flame retardants (see below), there is no standardised weathering test for timber itself. It is unlikely such a test will be developed as the phenomenon is so variable and because there is little commercial incentive to do so.

In some cases the effects of differential weathering can add to the architectural effect of the timber facade. This approach was pioneered by Louis Kahn in the United States who used uncoated teak on the facades of several buildings. Kahn’s aesthetic accommodates the effects of weathering; whilst many modernist buildings might be considered to have aged poorly and become outwardly shabby, the bleaching and streaks on Kahn’s facades are not so obtrusive and indeed are regarded by many as complementing their appearance [60]. It should, however, be cautioned that Kahn was mostly working in relatively dry North American climates where the degree of weathering is generally not so pronounced as that experienced by external timber facades in temperate oceanic conditions such as the UK. Kahn's aesthetic is, in some respects, reminiscent of the celebration of diversity and transience evident in traditional Japanese construction. The concept is termed 侘 寂 (wabi sabi) which is typically defined as the flawed beauty or simple wisdom inherent in natural objects [61]. Timber facades in Japan can experience very pronounced and rapid weathering due to their warm, wet climate; many of their traditional timber buildings celebrate this effect.

Weathering of exposed timber is unavoidable. There is no surface coating that will preserve the original colour of timber indefinitely. Attempts to prevent weathering by applying a water-repellent oil or clear varnish coating generally result in patchy grey or black staining of the timber. This is because stain fungi can develop under the coating where their hyphae turn the wood substrate grey (Figure 5.23). Coating the timber with a fungicide can slow down the onset of weathering although it will still occur eventually. Consequently, weathering effects can either be accepted, in all their unpredictability, or, if this is not appropriate, the main alternative option is to apply a pigmented surface coating before, or immediately after, the cladding is installed. The most durable external timber coatings employ a fungicidal primer.

A number of techniques are occasionally used to 'pre-weather' timber. Their success is variable and some can be quite expensive. It is possible to char external timber to simulate a uniform weathered appearance, an effect that is easier to achieve with low density timbers. 'Weathering stains' provide a cheaper and more controllable option: they use either grey pigments or involve a chemical change to the wood's surface. In each case the effect is to induce a temporary greying of the timber, but this will disappear after a few years. Several proprietary products are available to simulate the effect of weathering (although vague claims made about their ability to 'protect' the timber should be ignored). Often the easiest way to simulate the effect of weathering is to use a readily available ferric sulphate solution, as is occasionally done in Norway. The temporary staining caused by extractives can easily be removed with a 5 - 10 % solution of oxalic acid bleach. The grey stain caused by colonisation by *Aureobasidium pullulans* can also be removed by bleaching but this does not remove the photo-degraded timber: sanding the surface is the only option for this. Oxalic acid can also be used to remove any blue-black markings caused by ferrous metal corrosion. It is, however, preferable to avoid corrosion occurring in the first place.

5.6 Dimensional change

Timber changes size in response to changes in moisture content. Temperature will also affect the dimensions of a wood sample, although not to the same extent as moisture.

Below the FSP, timber shrinks as the cell walls dry out (*i.e.* bound water is removed) and swells as the cell walls gain moisture. At moisture contents above the FSP, the cell walls are fully saturated and so changes in moisture content have no effect on size. For any given species, the magnitude of shrinkage and swelling within the hygroscopic zone is approximately in proportion to the volume of water lost or gained (desorbed or adsorbed) by the cell wall. By convention, dimensional change due to initial drying of the timber is often referred to as shrinkage while subsequent changes due to moisture fluctuation in service are known as movement. Shrinkage and movement values are quoted separately as the former are greater than the latter. These dimensional changes are anistropic. Changes in the longitudinal direction are minimal and can usually be ignored. The changes are greater in a radial direction and greater still in a tangential direction. Designers and builders normally have no control over whether the timber they are using is radially or tangentially cut, in which case it is prudent to assume that the larger (tangential) values apply.

Moisture in the cell wall is held by hydrogen bonding. The bonds are mainly to the hemicelluloses and the hydroxyl groups in the amorphous cellulose. These components contract as water is removed from the cell wall. The lack of longitudinal change is mainly due to the orientation of microfibrils in the S_2 layer: these fibres shrink and swell across their width but not their length [62]. The difference between dimensional changes in the radial and tangential axes is not fully explained. The most common explanation is the presence of ray cells which are believed to have a radial restraining effect. These dimensional changes in wood can be influenced by several factors including extractives content, permeability, density and microfibril angle. Juvenile wood is relatively unstable as it is associated with changes in microfibril angles.

5.6.1 Shrinkage

In Europe, shrinkage values for different timber species are conventionally given for a moisture content reduction from the FSP down to 12%. American literature often quotes shrinkage values from the FSP down to ‘oven dry’. The extent of shrinkage varies both between trees and within a tree. The published shrinkage coefficients are necessarily approximate. Shrinkage values are only applicable to timber facades where green (i.e. unseasoned) timber is used. In such cases the moisture content ranges quoted in the literature may not be relevant and so intermediary shrinkage values need to be interpolated. This can be done algebraically but it is usually more convenient to interpolate graphically by representing the shrinkage curve as a straight line and then reading off the percentage dimensional change that occurs as the timber dries from FSP down to the target moisture content (Figure 5.26).

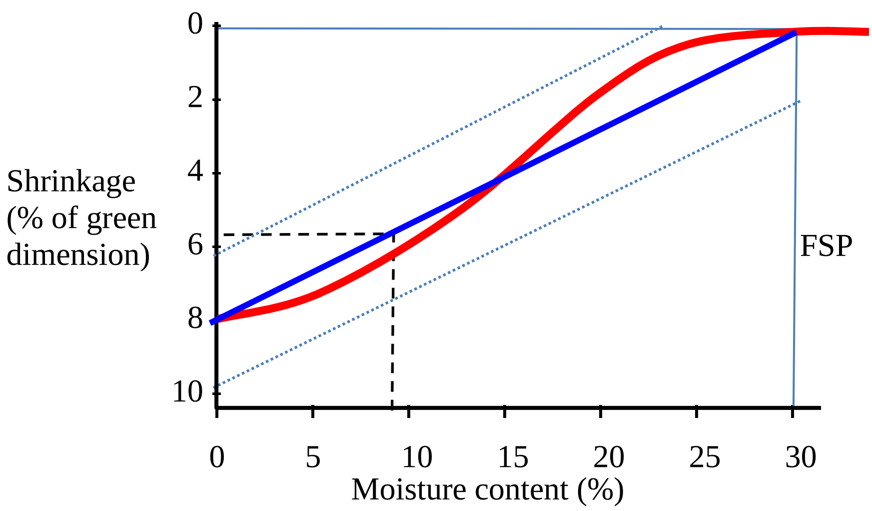


Figure 5.26 *Graphical interpolation of shrinkage at a specific moisture content*

Actual shrinkage curve (often not available in practice)

Linerised shrinkage values (taken from published shrinkage coefficients)

Interpolation of shrinkage at a specific moisture content

5.6.2 Movement

Most construction timber is used where it will not be exposed to precipitation. In which case, providing it has been dried to near its EMC, designers do not need to concern themselves with shrinkage and instead need only to consider movement in-use due to ongoing fluctuations in moisture content within the hygroscopic zone. The extent of these fluctuations can usually be predicted and so BS EN 942 [63] gives in-service moisture content values for most joinery applications (Table 5.10).

Table 5.10 *Moisture content of solid timber in in-service climates in Europe* [63]

Category	Sub-category based on in-service climate	Moisture content (%)
External joinery		12 - 19
Internal joinery	In unheated buildings	12 - 16
	In buildings heated to 12 - 21 °C	9 - 13
	In buildings heated to over 21 °C	6 - 10

Movement values have been derived by measuring the dimensional changes occurring when timber in equilibrium with air at an RH of 60% is moved to air where the RH is 90%; the temperature in both cases being 25 °C. For most softwood timber species this equates to a moisture content fluctuation between approximately 21% and 12%, although due to the hysteresis effect already outlined there are slight differences depending on whether the timber is gaining or losing moisture. The movement value for most commercial timbers is known and, for any given species, the relationship between movement and moisture is approximately linear and can be estimated from several formulae.

Hoffmeyer gives what is probably the most elegant formulation [64]:

$$h_2 = h_1\left[1 + \frac{\beta}{100}\left(\left|w_2 - w_1\right|\right)\right] \tag{5.14}$$

where h_1 and h_2 are the thickness dimensions at moisture contents w_1 and w_2 respectively. β is the coefficient of swelling (positive) or shrinkage (negative) taken from the literature.

Brown [65] gives an easily understood but cumbersome formula which, with minor adjustments for clarity, can be stated as:

$$S = \frac{(m_{init} - m_{final})d_{init}}{\left(\frac{m_{fsp}}{S_{\tan}} - m_{fsp}\right) + m_{init}} \tag{5. 15}$$

where is S shrinkage or swelling, m_{init} is initial moisture content, m_{final} is final moisture content, d_{init} is initial moisture content, m_{fsp} is the fibre saturation point, and S_{tan} is the tangential shrinkage or swelling coefficient from FSP to oven dry.

The movement characteristics of timber species are often expressed in relative terms using three movement classes (Table 5.11) [66] [67]. Timbers with a medium or low classification are suitable for most cladding applications though a small movement class is usually selected for tongued and grooved profiles, boards over 150 mm wide or any design where dimensional change is difficult to accommodate. Large movement species can also be used as cladding providing that the detailing can accommodate the dimensional changes that will occur. Unlike timber used inside buildings, cladding timber is exposed to both bulk wetting and intense drying. The resultant moisture content is thus likely to be wider in range than the 12% to 21% used as the basis of movement class definitions. The implications of this are discussed in later chapters.

Table 5.11 *Movement classes of timber (After: Hislop* [67])

Movement class	**Across grain dimensional chance due to moisture fluctuation in service**
Small	1% for every 5% change in moisture content
Medium	1% for every 4% change in moisture content
Large	1% for every 3% change in moisture content

5.7 Corrosion

Virtually all timber facades use metal fastenings and many have metallic flashings and support brackets as well. If these are degraded by corrosion, the building's appearance will be affected and the attachment of the cladding to the wall may be compromised. Corrosion can be defined as *'the destructive attack of a metal by chemical or electrochemical reaction with its environment.'*[68]. This definition excludes physical deterioration and all non-metallic degradation. Rust is the corrosion of iron and its alloys to produce hydrous ferric oxides; non-ferrous metals corrode but do not rust. Although dry timber is not corrosive, all timbers pose a corrosion risk if they become wet. Some species are especially corrosive, as are particular flame retardant and wood preservation treatments. Coastal environments are also a problem. The corrosion of metals by wood is controllable providing it is considered at the outset. Corrosion is therefore an important topic in timber facade design.

There are numerous types of corrosion although they all share five characteristics:

1. Ions are involved and need a medium to move within (this is usually water);
2. Oxygen is involved and has to be available;
3. The metal has to be willing to donate electrons to start the process;
4. A new material is formed which may be reactive or can protect the original metal;
5. Corrosion proceeds through a series of steps that all require a driving force.

Where metals are surrounded by dry air, a direct reaction occurs to form an oxide film on the metal's surface. As it thickens, the film prevents contact with the air and thereby prevents further oxidation. By contrast, most types of corrosion occur when a metal surface is wet; this aqueous medium makes the process more destructive [69]. Uniform (or atmospheric) corrosion occurs over most of the exposed surface of a metal; the rate is steady and often predictable. It is generally easy to control by making the material thick enough to function for its projected service life or by coating the surface with a non-conducting paint or by use of a sacrificial coating. The rate increases in corrosive atmospheres, such as near the coast, where control measures require a metal relatively high on the electrochemical series such as 316 grade austenitic stainless steel.

5.7.1 Corrosion of metals by wood

Wood is inherently corrosive and can be made more so by processing. Unlike most corrosive materials, wood contains acetic acid; this is volatile and in a poorly ventilated space wood can corrode adjacent metals even though there is no physical contact. In immersed conditions, large electrolytic cells can form. Corrosion of metals by wood can therefore arise in three areas [70]:

1. in poorly ventilated containers, by vapour corrosion without physical contact;
2. at points of physical contact in immersed structures, particularly seawater; large scale galvanic mechanisms predominate;
3. at points of physical contact in land-based structures, through attack by wood acids and chemicals such as some flame retardants or preservatives.

The first is mainly restricted to where corrosive timbers such as oak are used to make museum cases; it is not a concern with external timber and so will not be considered further here; nor will corrosion in immersed structures.

5.7.2 Corrosion mechanisms

Where there is contact between wood and metal in atmospheric conditions, corrosion can take place due to several micro-electrolytic mechanisms:

- **Crevice corrosion** (also called embedded or concentration cell corrosion) occurs where two adjacent areas of metal differ in electric potential. It typically occurs when oxygen cannot penetrate a crevice leading to differential aeration; corrosion occurs in the area with less oxygen. The rate can be rapid especially where the substrate is particularly acidic. In ferrous fixings the process is initially manifested as either blue/black iron tannate stains or rust (Figure 5.27) Crevice corrosion requires an incubation period but once developed it proceeds at an accelerating rate. It is controlled by selecting resistant metals.

- **Galvanic** (or bimetallic) corrosion occurs where two dissimilar metals, such as aluminium and copper, are in contact with an electrolyte such as water. It is caused by the greater willingness of one metal to give up electrons relative to the other. The two metals must have an electrical connection to enable electron movement. The less easily corrodible metal forms a cathode, the other (in this case aluminium) the anode; the cathodic metal is corroded. Galvanic corrosion is prevented by several measures including: breaking the electrical contact with insulators or coatings; choosing metals that are close together on the galvanic series; or preventing water entrapment.

- **Pitting** corrosion (Figure 5.27) occurs in metals having a protective film such as a corrosion product or when a surface coating breaks down. The metal readily gives up electrons and the reaction causes tiny indentations (pits) where the local chemistry will support rapid attack. It mainly occurs wherever upward facing surfaces experience stagnant conditions. Pitting corrosion can be controlled by several measures including: selecting resistant metals, using corrosion inhibitors; or protecting the metal with a barrier or coating.

Figure 5.27 *Iron-tannate staining due to crevice corrosion of ferrous fixings*

5.7.2.1 Naturally occurring acids

Tannic acid is often assumed to be the cause of corrosion of metals by wood; this is incorrect as tannic acid can act a corrosion inhibitor [71]. The real culprit is usually acetic acid. Cellulose molecules contain mildly basic hydroxyl radicals, parts of which are combined with radicals (unpaired electrons) of acetic acid to form ester (organic salt) groupings. These can combine with water (*i.e.* they hydrolyse) to yield acetic acid and free hydroxyl radicals. This causes the moisture in wood to be constantly acidic. Acetyl radicals constitute about 1% to 6% of the weight of oven dry wood with hardwoods containing more than softwoods. The amount of acetyl radicals determines the quantity of acetic acid that can be formed. The rate of emission depends on the species; wood with a lower acetyl content can liberate acetic acid faster than another species having a higher content. The rate of acetic acid formation is affected by the temperature and moisture content of the wood, whilst the rate of emission depends on the component geometry. Kiln drying accelerates acetic acid production and, because it does not all have time to escape; the acid tends to accumulate in the wood. Kiln dried wood is therefore more immediately corrosive than air dried timber, although the effect reduces over time. Wood also contains small quantities of other acids such as formic, propionic and butyric acid, but their corrosion effects are usually minimal. Ash can contain trace amounts of sulphate and chloride radicals which can augment the corrosive action of acetic acid.

5.7.2.2 Corrosive additives

Although the natural chloride content of wood is low, it can absorb salt from spray and mist in coastal conditions and when floated as logs in seawater. Timber in roofs near the coast is particularly susceptible. Salt is also occasionally used to season timber although this does not usually occur with cladding boards.

Some flame retardants contain ammonium sulphate and other corrosive salts. These substances are also hygroscopic and thus act to increase the moisture content of the timber. Fortunately those flame retardants that are based on simple salts are not used externally due to their poor leach resistance. The flame retardants designed for external use are not corrosive.

It has long been known that copper-based wood preservatives are corrosive [72], however, the risks have tended to increase following the withdrawl of chromated copper arsenate formulations in 2006. Whilst CCA was itself relatively corrosive, many of its replacements are even more so. Some of the current ‘CCA alternatives’ include: ACQ (alkaline copper quaternary) and CA (copper azoles) and these tend to corrode steel more quickly than CCA. The rate depends upon the carrier that delivers the active chemicals. Carriers can be ammonia-based (particularly corrosive), amine-based or a hybrid [73].

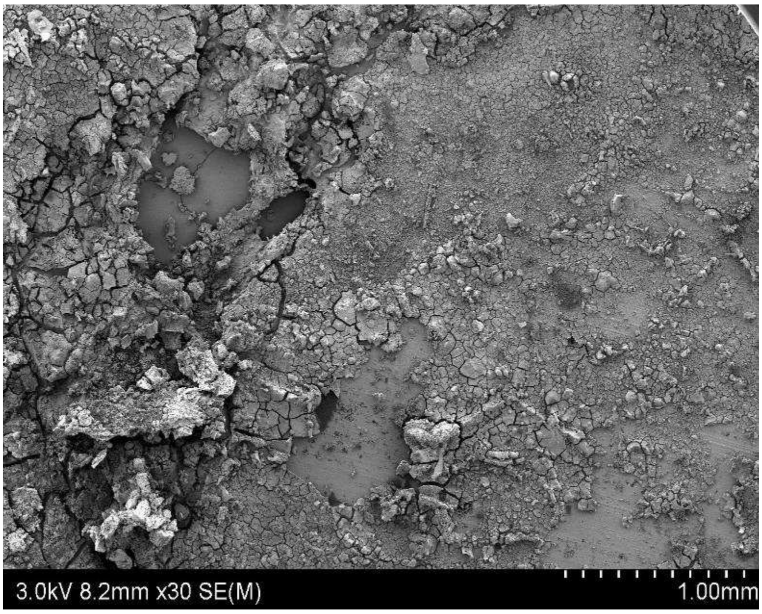


Figure 5.28 *Pitting corrosion of the aluminium foil wrapping for an intumescent cavity barrier. This occurred after two months contact with timber treated with copper based preservative.*

Copper based preservatives can leach soluble copper compounds, which are then deposited on surfaces exposed to run-off. If this occurs on iron, aluminium or zinc, a galvanic cell is formed that accelerates the corrosion of the metal substrate. The leaching is greatest from freshly treated wood, and so preserved wood should be allowed to age for at least seven days to give time for the preservative to become fixed before fasteners are inserted. Manufacturers of preservatives are addressing these issues and new, less corrosive, products are beginning to emerge although it is too early to evaluate their long-term performance [73].

5.7.2.3 Acidity of different wood species

Table 5.12 gives typical pH values for several timber species [74]. The pH of the heartwood of most timber species lies within 3.5 to 4.5. As a rough guide, timbers below pH 4 tend to be the most corrosive whilst those above pH 5 tend to be safe.

Statements about the acidity of timber are necessarily approximate: the pH varies within a wood species, within a tree (heartwood is usually more acidic than sapwood) and due to storage conditions. Timbers also vary in how easily acetyl is hydrolysed to free acetic acid. Moreover, woods with a low acetyl content (such as oak) can yield more free acid in a given time than species with a higher content; some species still emit acetic acid many years after the tree has been felled. For embedded fasteners, the rate of crevice corrosion is affected by the permeability of wood towards water, oxygen and carbon dioxide. Thus, iron embedded in impermeable woods, such as the white oak species used in barrel making, can last a considerable time even when immersed. In spite of these reservations, experience shows that some timber species are especially corrosive. These include European oak, sweet chestnut, western red cedar, Douglas fir and most eucalyptus species [70] [74].

Table 5.12 *Acidities of various external cladding timbers* [70] [74]

Common name	Botanical name	Approximate pH
Western red cedar	*Thuja plicata*	3.3
Douglas fir	*Pseudotsuga menziesii*	3.5
European oak	*Quercus* r*obur* and *Q. petraea*	4.0
Larch	*Larix* spp.	4.0
Sitka spruce	*Picea. sitchensis*	4.0
Sweet chestnut	*Castanea sativa*	4.5
European redwood	*Pinus sylvestris*	4.5
Burmese Teak	*Tectona gradis*	5.0
Iroko	*Chlorophora excelsa* and *C. regia*	5.5

Timber that has been thermally or chemically modified may be more corrosive than unmodified wood, although this varies depending upon the process involved. Mild steel and zinc coated steel are particularly vulnerable whilst stainless steel is not attacked. The effect is not fully understood but is believed to be due to residual acids formed during the treatment process. Acetylated timbers such as Accoya™ are the most corrosive although some types of thermal modification also cause problems.

5.7.2.4 Effect of moisture content

All timbers are corrosive if their moisture content is above 20% although the rate varies between species. CCA impregnated timbers are corrosive at moisture contents as low as 12% [74] and it is likely that the CCA alternatives have a similar behavior.

5.7.3 Susceptibility of different metals

The UK's National Physical Laboratory has ranked the susceptibility of different metals to attack by acetic acid vapour or direct contact with wood (Table 5.13) [70]. Although the susceptibility of zinc is as high as steel, this does not mean that zinc coated steel has no value; steel will not rust until the zinc has been corroded away, and this usually takes a long time. Although lead is frequently used as a flashing it is relatively susceptible to acetic acid corrosion and so should not be used in contact with timber.

Table 5.13 *Ranking of susceptibility of metals to attack by acetic acid in wood* [70]

Group	Metals
1. Severe attack	Cadmium Carbon steels Low alloy steels Lead and its alloys Zinc and its alloys Magnesium and its alloys
2. Moderate attack	Copper and its alloys
3. Slight attack	Aluminium and its low strength alloys Nickel
4. Insignificant attack	Austenitic stainless steels Chromium Molybdenum Silver Tin Titanium and its alloys

5.7.4 Degradation of wood by metal

Corroding steel can degrade wood due to a corrosion cell being formed where alkali is produced at the cathode and iron salts produced at the anode. Both corrosion products can attack wood, which may become sufficiently degraded for the holding power of the fixing to be lost. This is known as nail sickness. Corrosion cells in wood can be identified by their breakdown products: the dark blue iron tannate stains around ferrous metal fixings in timber are due to the interaction between iron salts and the extractives in wood. The stains are not always associated with current corrosion however as they can be caused by iron salts left over from when the timber was shaped using ferrous tools [75].

5.7.5 Corrosion testing

Although many corrosion tests have been published, none of the standardised methods are suitable for assessing the effects of wood on metal and *vice versa*. Zelinka & Rammer [76] reviewed all of the published tests in this field and concluded that electrochemical methods offer the best potential.

5.7.6 Resisting corrosion

Austenitic stainless steel fixings offer the best resistance to the corrosion effects of acetic acid or copper-based wood preservatives. Type 304 is normally adequate although the more resistant type 316 may be required near the coast.

5.8 Structural robustness

The structural performance of timber facades is often ignored. Providing the cladding is on a low-rise building and follows best practice for board profiles and fastenings then this is rarely a problem. In the UK, however, timber cladding is in a period of innovation that indicates existing guidance may be inadequate. These issues are most clearly highlighted in Scotland where structural engineers are nowadays being contracted to verify that buildings are constructed in accordance with the guidance supporting building regulations. When verifiers assess timber cladding against the guidance documents they sometimes find that it does not comply. Delays, remedial work or *in situ* testing can then ensue giving rise to two initial questions: what are the structural issues affecting timber cladding and how can these facades be constructed to ensure robustness? Both are affected by the moisture conditions of the facade.

5.8.1 Structural concerns

Non-loadbearing external cladding has been increasingly popular in the UK since the 1950s. Initially engineers were not directly involved with cladding design except insofar as it had a secondary effect on a building's structure. However, with the growing scale and complexity of this form of construction it has become common practice for structural engineers to take responsibility for cladding design or for assessing the designs of others. The first UK guidance on an engineering approach to cladding design was contained in a 1995 report [77] that considered all cladding materials including timber. A performance-based standard for cladding design has since been issued [78], although it does not address all of the performance issues relevant to a biogenic material such as timber. From an engineering viewpoint, cladding design involves the consideration of several factors including: design life, structural loads, fire performance, internal and external environments, construction tolerances and any access limitations. The design must also take account of all applicable standards, which nowadays means beginning with the relevant Eurocodes. Timber structures are designed to Eurocode 5 (EC5) [79] using the guidance in other Eurocodes as necessary. Eurocode 5 is in the course of superseding BS 5268-2 [80], although the latter norm is still in use. It should also be noted that whilst most cladding applications are bespoke designs for specific buildings, other contracts involve the use of proprietary systems developed by specialist companies. In either instance, however, wind loads are usually the main structural concern.

5.8.1.1 Wind

Although exterior cladding (of whatever material) is intended to be largely non-structural, wind can give rise to lateral loads on walls and uplift forces on roofs. The calculation of wind loads on cladding and its support assembly is based on the same criteria as the main structural design and guidance on this is given in Eurocode 1.4 [81]. The highest wind loads are experienced in coastal locations and at altitude.

For a given wind direction, the pressure will vary around and over the building and so special attention should be paid to the possibility of wind concentration at external corners, gaps between buildings and on roofs (Figure 2.2). Cladding on the leeward face of a building may experience suction forces while the windward face is simultaneously exposed to strong positive pressures. Wind suction will act to pull the cladding off its support battens and the battens off the wall; the cladding assembly has to be able to resist these actions (Figure 5.29).

Figure 5.29 *The masonry cladding on this gable near Inverness was inadequately fastened to the timber structure and so had little resistance to outward wind suction.*

It is known [82] that in coastal parts of Scotland, cladding at the outer corners of medium-rise buildings is typically exposed to peak suction loads of around -1.2 kN/m^2. Suction loads will tend to be higher on the Western Isles, Orkney, Shetland and in other very exposed locations.

A further issue may arise where a timber-framed building on a windy site is clad with timber instead of masonry. The latter type of cladding can act to stiffen a timber-framed structure against wind loads [83]. If such structures are clad with timber, however, their capacity to resist wind forces may be compromised unless the issue is addressed at the design stage. This issue mainly occurs in coastal areas, particularly northwest Scotland and the Scottish islands. All existing UK guidance on timber cladding ignores this issue.

5.8.1.2 Differential movement

Heavyweight cladding materials such as brick, stone or blockwork are constructed from the foundations and tied back to the wall structure using flexible ties that allow for differential movement between the cladding and substrate. By contrast, lightweight claddings such as timber, fibre cement boards, rendered mesh, tiles or brick slips are fixed to a support assembly that is fully supported from the wall structure [84].

Differential movement occurs wherever the cladding and wall structure move in different ways in response to moisture or temperature change. It is not normally a concern in situations where lightweight cladding is used in conjunction with a timber-framed structure [85]. However, differential vertical movement can occur at junctions between heavyweight and lightweight cladding. In the case of timber-framed and post-and-beam walls it can occur because: floor joists and other horizontal elements made of solid timber will shrink slightly as they dry out in service whereas clay brick cladding can expand. The problem also occurs where blockwork or calcium silicate bricks shrink more than the timber structure and cladding (Figure 5.30). Table 5.14 gives recommended allowances for differential movement between heavyweight cladding and timber cladding on a timber-frame. Some junctions between heavyweight and lightweight cladding will require engineering design.

5.8.1.3 Service classes

The strength and stiffness of timber are affected by changes in moisture, with dry timber having the highest strength and stiffness. As the moisture content increases, these properties steadily reduce until the FSP is reached. Above this threshold, further increases have no additional effect on timber’s mechanical properties (Figure 5.31) [86]. Engineers need to be able to take account of this variation during their designs and so EC5 gives three service classes for timber (Table 5.15) that reflect the different moisture conditions that occur in service.

It is frequently argued that the support battens behind timber cladding are sheltered from direct wetting and should therefore be assigned to service class 2, but this can be questioned. This issue is discussed in later chapters.

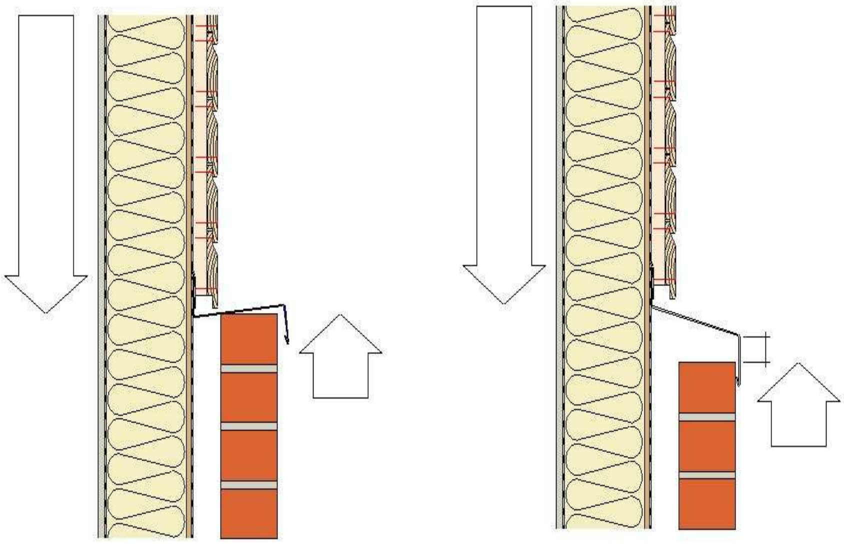


Figure 5.30 *Differential vertical movement between heavyweight and light weight cladding. Left, flashing uplift due to inadequate movement allowance. Right: uplift has been avoided using an adequate movement gap.* (After: TRADA Technology [84])

Table 5.14 *Allowances for differential vertical movement between heavyweight cladding and timber cladding on a timber-frame.* (After: TRADA Technology [84])

Location of horizontal junction between heavy and lightweight cladding	Minimum gap for differential vertical movement between heavyweight and lightweight cladding * ** *** ****
At ground floor	3 mm
At first floor	11 mm
At second floor	19 mm

Notes

* If a timber platform ground floor is used then add 8 mm to the allowances quoted

** Movement reduces if, for example, engineered wood joints or super-dried timber is used

*** Movement increases in nursing homes and other buildings where the equilibrium moisture content is particularly low. It is also high where the brickwork employed expands over time.

**** The allowances quoted are for clear gaps: they should be increased if compressible seals are installed in the gap.

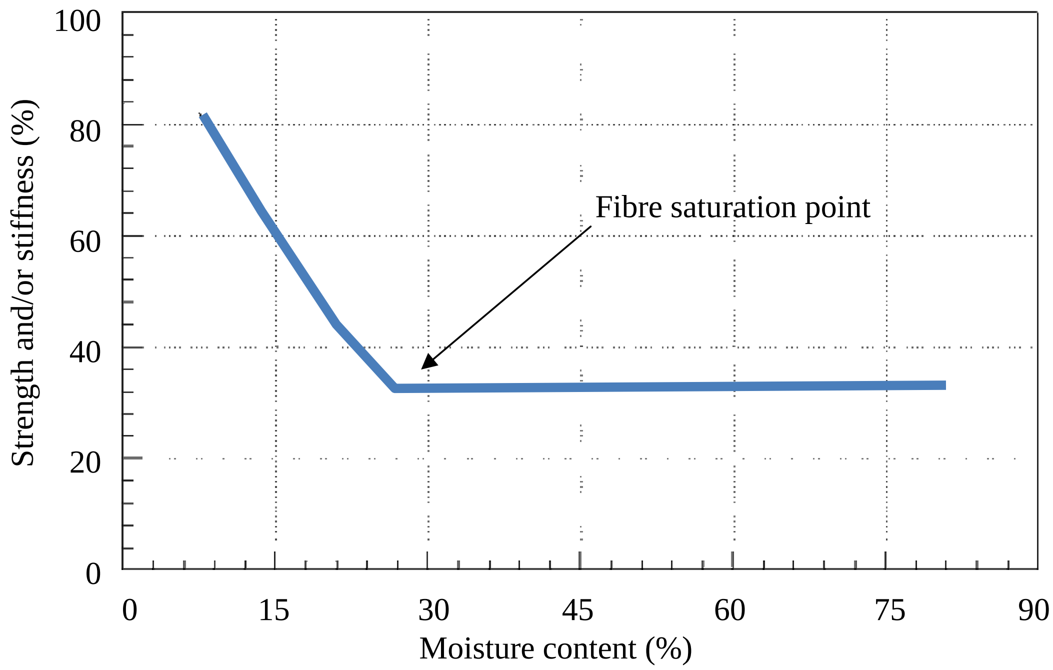


Figure 5.31 *General relationship between strength and stiffness properties and moisture content.* (After: Porteous and Kermani [86])

Table 5.15 *Services classes for timber given in Eurocode 5* [80]

Service class	Timber moisture content and associated environmental conditions
1	A moisture content of no more than 12 %: this corresponds to a temperature of 20 °C and a relative humidity below 60 % for most of the year.
2	A moisture content of no more than 20 %: this corresponds to a temperature of 20 °C and a relative humidity below 85 % for most of the year.
3	Climate conditions leading to a higher moisture content than in service class 2

5.8.2 Robustness

At its simplest, an engineering specification for cladding will prescribe [77]:

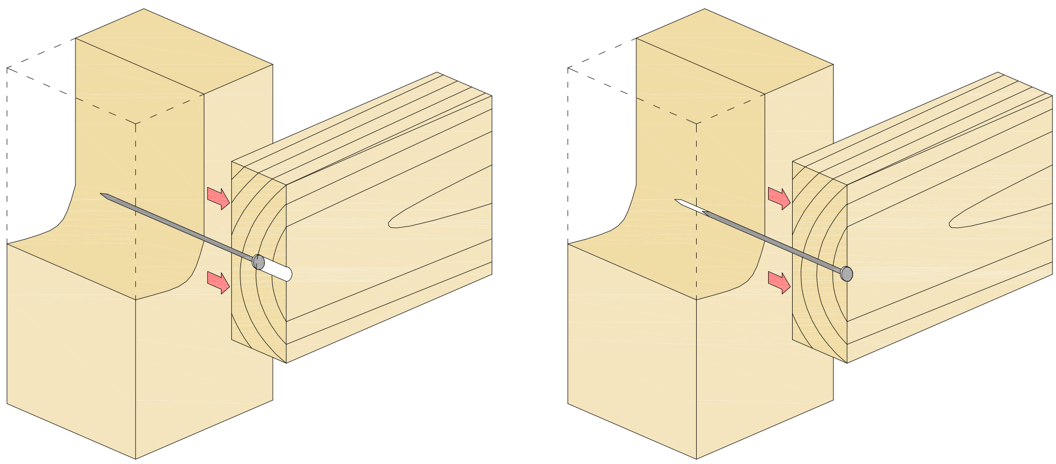
- The calculated self-weight of the cladding
- The calculated imposed loads acting from the cladding onto the wall
- The acceptable cladding attachment to the wall
- Construction movements and tolerances

Most structural questions concerning timber cladding concern attachment to the wall.

5.8.2.1 Dowel type fasteners

Most timber cladding is attached using nails or screws. In EC5 these are known as dowel type fasteners (fasteners where the load is transferred by a dowel action). Dowel fasteners can be subject to lateral loads (shear perpendicular to the line of the fastener) and axial loads (withdrawal along the line of the fastener). Dowel fasteners in timber cladding are mainly loaded axially due to wind suction. Ignoring tension failure of the dowel itself, there are two nail failure modes in axial loading (Figure 5.32) [79] [86]:

- The dowel pulls out of the timber (termed pointside withdrawal)
- The head of the dowel pulls through the timber (termed headside pull through)



Headside pull through

Pointside withdrawal

Figure 5.32 *Nail failure modes in axial loading* [79] [86]:

In the case of nails, the withdrawal capacity is taken to be the minimum of pointside withdrawal or headside pull-through. This is calculated from factors such as nail diameter, shank profile, timber thickness, nail penetration and the density of the timbers involved. In EC5 the recommended pointside penetrations of nails into the timber substrate are as follows:

Smooth nails	12*d*
Annular ring shank and other improved nails	6*d*

where *d* is the shank diameter of the fixing. If the nail head diameter is at least 2*d* it is assumed pull-through will not occur because the pull-through resistance exceeds the withdrawal resistance. Fastener lengths for timber cladding are often determined using a simple 'rule of thumb' whereby a smooth nail should be two and a half times the board thickness and an improved nail should be twice the board thickness [67] [87]. Experience suggests that this simple guidance is adequate for most low-rise buildings but, although approximately correct, it is not consistent with EC5 and so is inappropriate for taller buildings or exposed locations. In both of these locations, the cladding fasteners should be designed by a structural engineer.

Low velocity shot-fired nails are the most popular fixing method for timber cladding in the UK; this is due to their ease and speed of application. Both round and improved nails can be installed in this way. Other types of nailed fixing such as the 'T' nails used to secret-fix timber flooring should not be used with external cladding as they offer little resistance to axial withdrawal; indeed, there is no means of calculating their axial strength to meet the requirements of EC5. Lost head nails should also be avoided as they offer little resistance to pull through. Although shot fired nails are popular with contractors, their suitability for timber cladding installation can be questioned because nail guns tend to over drive the fixing and this can create water traps. In theory, this problem can be minimised by using nail guns that can be adjusted for timber density but this is not a complete solution, as many contractors will ignore this precaution and in any case timber density varies. Hammer fixed nails are, therefore, preferred wherever possible. The risk of the timber splitting should be minimised through the choice of fixing positions. These should conform to the edge and end distance requirements provided in EC5 (Figure 5.33 and Table 5.16). In addition, dense timbers (≥ 500 kgm^{-3} at a moisture content of 12%) and species prone to splitting (*e.g.* larch, Douglas fir and spruce) should be predrilled, the hole diameter being no greater than 80% of the nail diameter. Hardwood cladding timbers are normally fixed with screws as these have greater axial strength than nails. Design guidance for screw connections is given in EC5 although it does not provide minimum spacings or end distances for the board thicknesses commonly used for cladding. The maximum axial loads on the timber cladding assembly tend to occur, not in the cladding itself, but in the fixings joining horizontal support battens to the vertical counter battens (Figure 5.34). Peak suction loads can be in the order of -0.3 kN *per* fixing on many coastal sites and may be higher still in particularly exposed locations.

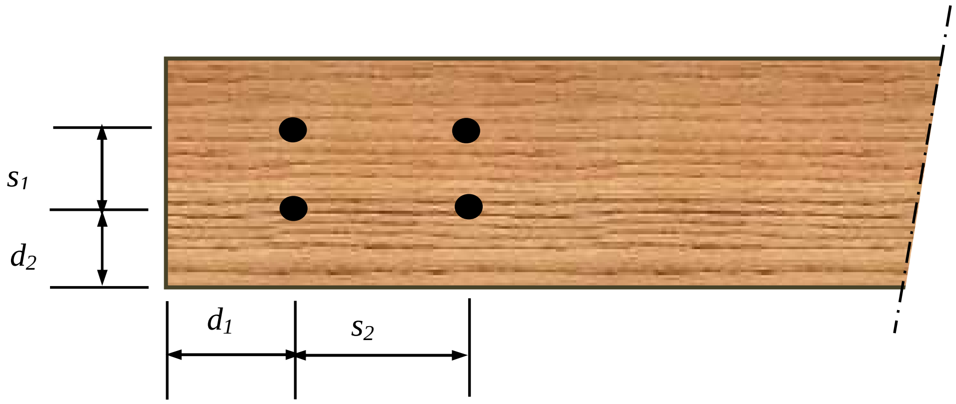


Figure 5.33 *Nail spacings and distances* (After EC5 [79]) *(see Table 5.16)*

Table 5.16 *Nail spacings and distances, d = nail diameter in mm (see Figure 5.33)* [79]

Category	No pre-drilling		Pre-drilled holes (timber density > 500 kgm^{-3} or species prone to splitting)
	Timber density ≤ 420 kgm^{-3} (at 12% moisture content)	Timber density 420 to 500 kgm^{-3} (at 12% moisture content)	
Spacing s_1 (perpendicular to the grain)	5d	5d	3d
Spacing s_2 (parallel to the grain)	d < 5 mm: 10d $d \geq$ 5 mm: 12d	15d	4d
Distance d_1 (edge with no lateral load)	5d	7d	3d
Distance d_2 (end with no lateral load)	10d	15d	7d

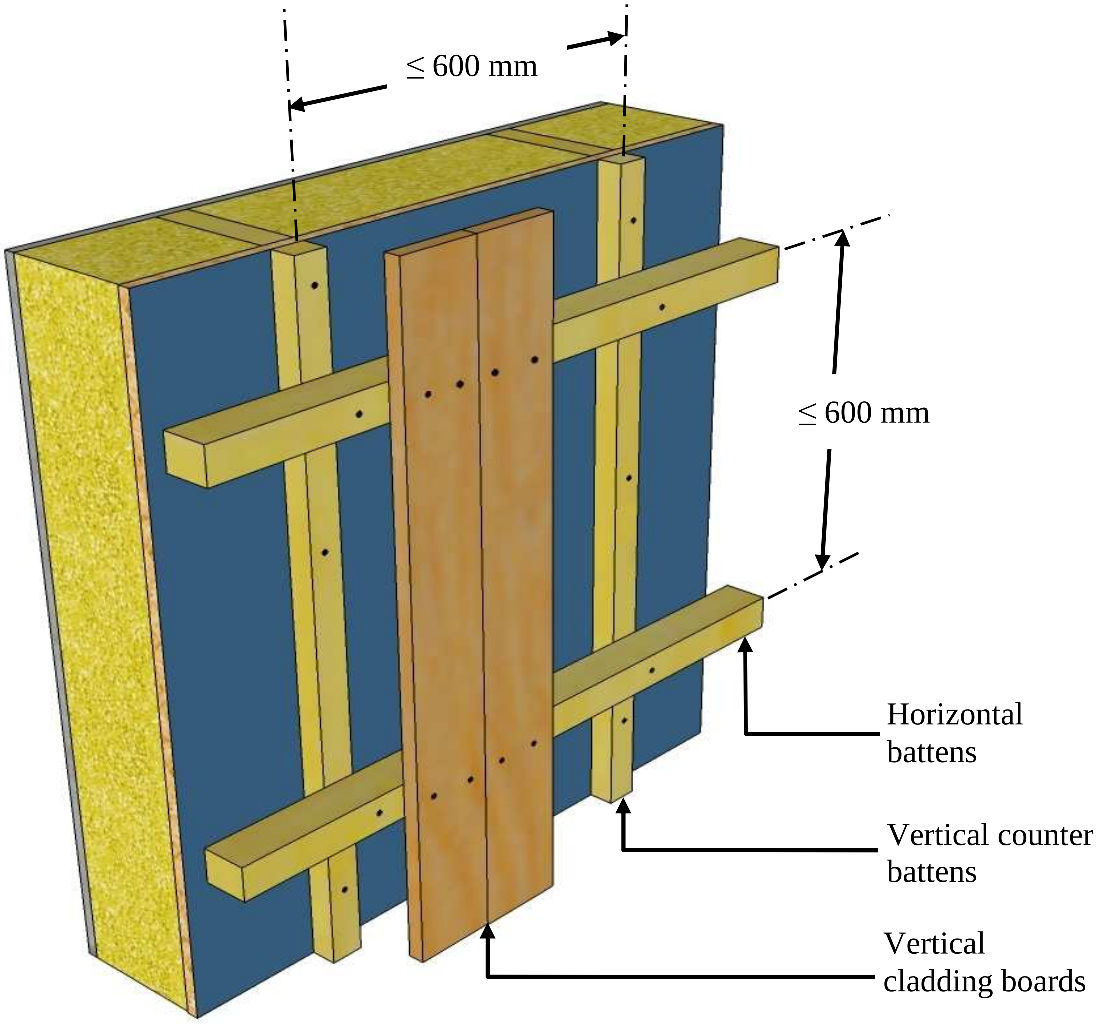


Figure 5.34 *Typical installation assembly and fixings for vertical timber cladding*

The wall studs are at a maximum spacing of 600 mm between centres. The vertical counter battens are fixed to the studs every 300 to 400 mm along their length, giving around 3 fixings per metre length or 6 *per* m^2. The horizontal battens are spaced at a maximum of 600 mm centres and are fixed where they overlap the counter battens, giving 2 fixings *per* metre length or 4 *per* m^2. The vertical boards are fixed at their overlap with a horizontal batten using 2 nails *per* overlap, giving 4 fixings *per* metre length or around 26 fixings *per* m^2 (assuming 150 mm wide boards).

Assuming a peak suction of -1.2 kNm^{-2} on the cladding, then the maximum load *per* fixing is -0.3 kN, this occurs at the 4 points where the horizontal battens are secured to the counter battens (-1.2 kN / 4). In this scenario the fixings securing the boards are only exposed to peak suction loads of -0.05 kN *per* fixing (-1.2 kN / 26).

5.8.2.2 Hidden fasteners

Hidden fixings are becoming increasingly popular with timber cladding. Most use folded or extruded metal clips to connect into a slotted joint between the boards. These clips tend to be expensive to manufacture in small volumes and so most hidden fixings tend to be components in proprietary cladding systems. These are usually derived from ceramic cladding systems and can have several advantages including appearance, ease of erection and ability to accommodate insulation within the cavity. Most systems employ a metal support assembly, such as that by James and Taylor [88], although timber-based systems are becoming available. These facades are normally supplied by specialist companies who provide the engineering calculations.

5.8.2.3 Strength grading and batten sizes

Eurocode 5 states that all timber intended for load-bearing use in buildings must be strength graded by an approved grader, either visually according to standardised rules or by an automatic grading machine. External cladding is not load-bearing and so there is no requirement for cladding boards to be strength graded. The cladding support battens do need to be graded, however, as BS 5534 [89] sets limits for their permissible characteristics and defects. Although these limits are not visual strength grades as such, they are similar to the knot criteria in the GS visual grade provided in BS 4976 [90]. This norm also specifies the timber species required for the cladding support assembly. These include UK grown larch (*Larix* spp.), Scots pine (*Pinus sylvestris*) and spruce (*Picea* spp.) plus several European and north American species. The norm also specifies that these timbers should be preservative treated for use as battens.

Minimum batten sections are determined by the need to avoid both splitting as they are fixed and the risk of deflection between supports. Vertical battens are typically at least 19 × 38 mm, whilst horizontal battens are normally at least 45 × 50 mm. Minimum batten sections may also be set at 38 mm thick due to the fire resistance requirements for cavity barriers (see below).

5.9 Combustibility

Fire – the state of combustion – takes many forms, all of which involve a fast chemical reaction that liberates heat. This reaction usually occurs between combustible gases from fuel and oxygen from the air. A flame is the visible part of a gas volume within which combustion is occurring [91].

5.9.1 The fire triangle

The mechanisms of fire ignition, growth and decay are well understood. To be sustained a fire needs three components: fuel, oxygen and heat; this is illustrated by the fire triangle (Figure 5.35). If any two of these are present, the addition of the third will trigger ignition. Similarly, a fire is extinguished when one component is removed. Once a fire has started, the heat released by combustion is usually enough to enable it to grow. A growing fire then releases more heat and so the process continues. Fire can be controlled using a range of suppression measures, most of which either remove heat (*e.g.* by spraying with water), cut off oxygen (*e.g.* with the use of foam), or both. If a fire is not suppressed it will eventually die when it runs out of fuel or oxygen [92].

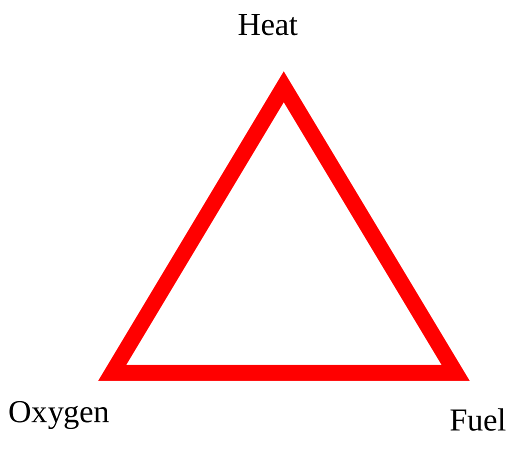


Figure 5.35 *The fire triangle*

5.9.1.1 Fuel

A fuel, in this context, is any substance that burns. The best fuels are molecules with large amounts of extractable energy held in their chemical bonds. Combustion releases this as heat (it is exothermic) due to the difference between the potential energy stored in the fuel's original molecular bonds and that stored in the bonds of the end products. By contrast, most chemical reactions consume energy (they are endothermic) because the bonds in their end products store more energy than that in the original molecules [93]. With a few exceptions such as hydrogen gas, all fuels are carbon-based. Indeed, the fossil record suggests that fire only appeared on the earth's surface after land vegetation had first evolved about 450 million years ago [94]. Fossil fuels such as coal are the remains of such vegetation. Most other fuels derive from wood or other carbon-based materials formed by organisms living today. As regards fire chemistry, the term fuel thus encompasses most substances we use in our day-to-day lives: petrol, food, fabrics, plastics, medicines, wood and paint are all carbon based. They all burn.

Although fire results from chemical reactions, the mode of burning is affected more by the physical state and spread of the fuel and its environment than by its chemistry. A log, for example, is difficult to ignite whereas kindling will readily burn if built into a suitable pile. Similarly, a layer of coal dust burns slowly but explodes if ignited as a dust cloud.

5.9.1.2 Oxygen

Although air is normally needed to support combustion, some fuels already contain oxygen, which is released as they are broken down by heat. In other cases some chemical processes can sustain combustion without oxygen. Strictly speaking the requirement is for an oxidant, which is a substance that can oxidise atoms, molecules or ions by stripping them of electrons. Carbohydrates such as timber are good electron donors, whilst oxygen is the perfect electron scavenger [95].

5.9.1.3 Heat

Heat is not an entity that can be added to something, it is instead the flow of thermal energy from a warmer to a cooler object due to temperature difference. Thermal energy is transferred in three ways. Conduction is the transfer of energy by direct molecular contact; it is mainly associated with solids. Convection is the transfer of energy between a liquid or gas and a solid; it involves the movement of the fluid. Heat radiation is the transfer of energy by the emission of electromagnetic waves; it does not require an intervening medium. These processes can be aided by mass transfer, such as the airborne movement of burning embers. The amount of energy released when a unit mass of a substance is completely burnt is termed the heat of combustion (ΔH_c), or calorific value. The gross ΔH_c of fully dry timber is around 20 kJ/g or $\cong$ 18 kJ/g at a moisture content of 12 %. For comparison, the ΔH_c of hydrogen is 122 kJ/g, methane 50 kJ/g, polystyrene 40 kJ/g, polyvinylchloride 16 kJ/g, whilst raw potatoes only yield 3 kJ/g.

The power of a fire is expressed in terms of the heat release rate (HRR), also termed the rate of heat release (RHR). This quantifies the rate at which combustion reactions convert potential chemical energy into thermal energy. The rate of fire growth (speed of HRR increase) generally begins slowly but soon accelerates. The rate depends on the size of the fire and can often be approximated using a parabolic curve known as the '*t*-squared fire' where the HRR is proportional to the square of time after ignition.

5.9.2 Burning of wood

After ignition, the burning of timber involves two main stages, decomposition and charring.

5.9.2.1 Decomposition

As wood is heated above about 100 °C, it begins to go though a process of thermal decomposition (pyrolysis) as the material state changes from solid to combustible vapour. It is the vapour that burns. The free water in wood evaporates first. As the temperature rises further, the main constituents of wood decompose into volatile gases including carbon dioxide, carbon monoxide, ethane, propane, methane and non-volatile water vapour. The decomposition temperatures are different for each of the main constituents of wood, typical values are: hemicelluloses 200 - 260 °C; cellulose 240 - 350 °C; and lignin 280 - 500 °C. Wood rapidly discolours above about 200 - 250 °C although prolonged heating at temperatures as low as 120 °C can have the same effect.

5.9.2.2 Charring

The physical structure of wood rapidly breaks down above about 300 °C. The process begins when small surface cracks form perpendicular to the grain direction. These allow volatiles to easily escape from the wood surface. At temperatures between 400 - 450 °C, about 50% of the lignin volatilises, the rest remaining as a residue of carbon, known as charcoal or char. A higher proportion of the hemicelluloses and cellulose are decomposed, although this varies depending upon the wood's composition and the temperatures involved. When wood is heated above 450 °C only 15 - 25% normally remains as char. Most char comes from the lignin. The cracks widen as the char depth increases, giving burnt wood its characteristic cubic appearance. Char looks quite similar to wood that has been colonised by brown rot fungi. This is no coincidence because, these organisms mainly degrade cellulose and hemicelluloses leaving lignin relatively unaffected.

5.9.3 Compartment Fires

Building fires usually start in a room, and then spread outwards. Spread of fire is prevented by ensuring that the walls, ceiling and floor can act as fire barriers, which sub-divide the building's interior into sections. A fire in a room is termed a 'compartment fire' and the fire barriers are 'compartmentation'. If there are sufficient fuel and ventilation available, a compartment fire typically goes through the sequence of stages shown in Figure 5.36 and Table 5.17 [96]. The key stage is known as flashover, which describes the rapid transition from a localised fire to one involving the whole compartment. Not all compartment fires follow this curve - some run out of fuel whilst others have insufficient ventilation. The fire may also be suppressed by fire fighters or sprinklers. Fully developed fires can have temperatures in the region of 800 - 1200 °C. The fire energy in a building compartment is usually expressed as the energy density *per* square metre of floor area or *per* square metre of the total surface area of a room. The latter method is normally used in Europe. Eurocode 1 [97] gives five fire load classes ranging from 250 to 2000 MJm^{-2} of floor area; a medium sized domestic room typically contains around 450 MJm^{-2}.

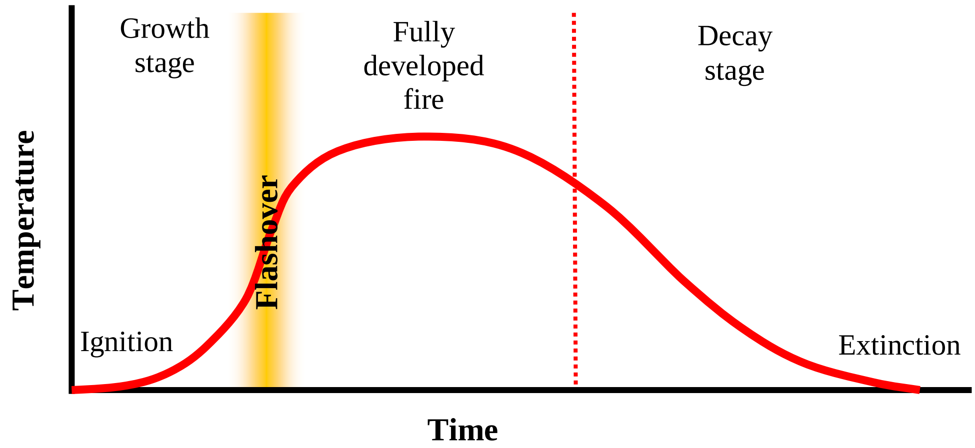


Figure 5.36 *Schematic time-temperature curve for a typical compartment fire* [96]

Table 5.17 *Stages of a typical compartment fire* [96]

Fire stage	Description
Growth stage (pre-flashover)	Once ignited, a fire either smoulders or grows depending upon fuel or oxygen availability. If the fire is fuel-controlled, combustion can continue until all available combustible materials are consumed. A fire restricted by oxygen availability (a ventilation-controlled fire) occurs where there is insufficient air to allow a large amount of fuel to be burnt. Windows and other openings may permit air to enter; in which case the burning rate is mainly set by the size of openings. Fuel controlled fires can achieve the maximum HRR for that substance and their main products are carbon dioxide and water. Ventilation-controlled fires have a lower HRR but produce large amounts of soot and toxic combustion products.[2]
Flashover	As the fire grows, hot smoke builds under the ceiling. This radiates heat and can become intense enough to ignite all combustible surfaces in the room. Termed 'flashover', this has been defined [3] as '*a rapid change from a localised fire to one involving all combustible surfaces in the compartment*'. It occurs when the buoyant smoke layer reaches approximately 550 °C.
Fully developed fire (post-flashover)	Following flashover, the fire enters its fully developed stage. At this point life becomes untenable in the compartment. The HRR increases rapidly until it is limited by the amount of oxygen that can be drawn into the compartment or when all available fuel is involved. This is the most critical stage as a post-flashover fire can cause structural damage and spread to other compartments in the building.
Decay stage	If the fire is not suppressed it will eventually burn out when it runs out of fuel. The HRR once again becomes fuel-controlled.

5.9.4 Reaction to fire and fire resistance

Because most building fires start in a room and spread outwards, fire tests of construction products typically assess what happens during the initial or later stages of a compartment fire [98]. Performance at either stage is not an intrinsic material attribute but is instead extrinsic – it is a system phenomena where the test results are affected by how a building product is assembled and installed.

- **Reaction to fire tests**: these assess relevant performance attributes up to and including flashover. This includes: ignition, flame spread, heat release rate, rate of smoke production, fire area and time to flashover. Reaction to fire is mainly expressed in terms of the performance of internal wall linings.

- **Fire resistance tests**: these assess how building components withstand the power of a fully developed fire. In these circumstances some construction elements, such as beams, need to withstand structural loads whilst others, such as cavity barriers, need only contain the fire. Performance is expressed as the time for which the element can fulfill these functions.

The relative importance of these categories varies depending upon where and how the timber component is used in a building. Although timber performs relatively badly during the initial stages of a fire it can nonetheless have a good structural performance during a fully developed fire. Accordingly timber's reaction to fire and fire resistance performance usually need separate consideration. These two categories of test do not suit all requirements. The fire conditions inside a lift shaft are poorly modelled, for example, as are the fire scenarios affecting the external face of a wall or roof. Nonetheless, the fire performance of construction materials is generally defined in terms of reaction to fire and fire resistance.

Two principal test and classification systems for fire performance are recognised in the documents supporting the various UK building regulations. National classes are given in the BS 476 series, while the European system is described in the BS EN 13501 series. The latter will, eventually, replace national fire standards such as the BS 476 series but until this happens the two systems continue to co-exist. Numerous other standards give performance criteria for specific applications: reaction to fire tests for facades, for example, are given in the BS 8414 series.

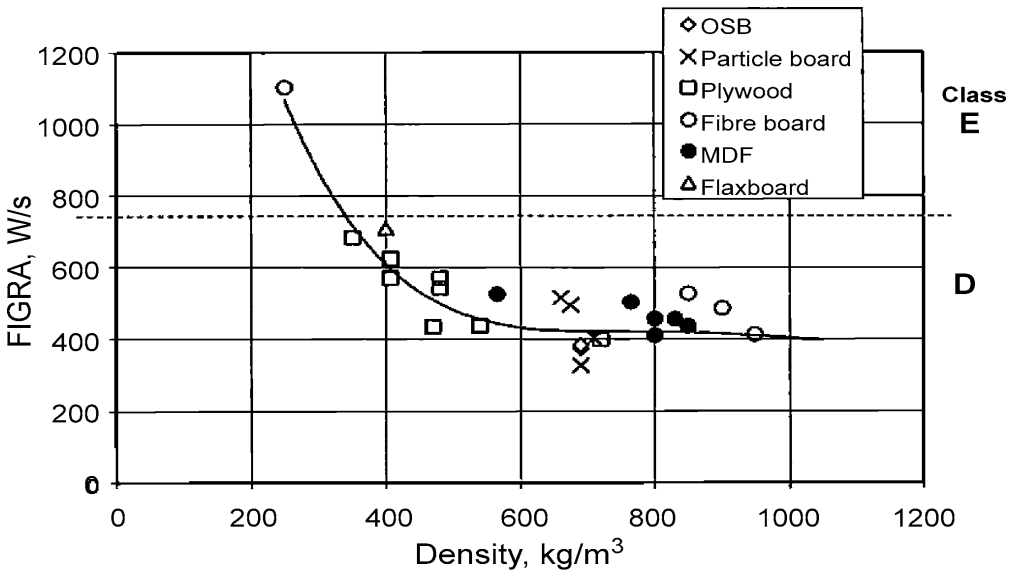
5.9.4.1 Reaction to fire performance of timber surfaces

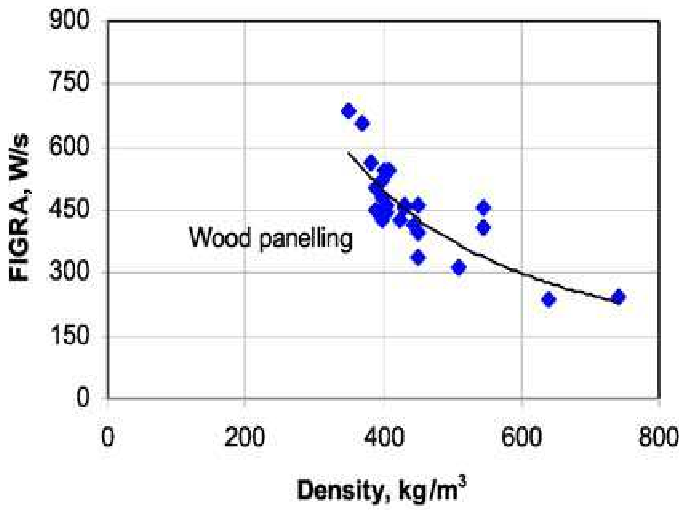
Several chemical physical and environmental factors affect flame spread over wood surfaces.

The principal chemical factors are extractives content, moisture content and flame retardants. Extractives composition varies between species with resinous softwoods being the most flammable. Moisture content is important because energy is needed to drive the water off. Flame retardants are discussed below.

Several physical factors are relevant. Low density timber is a poor conductor of heat and so the lower the density, the shorter time needed to get a surface to ignition temperature. Accordingly wood products with a density below 400 kgm^{-3} achieve a lower reaction to fire class than denser timber (Figures 5.37 and 5.38). Geometry is also significant, indeed the reaction to fire classification achieved by a product often varies considerably depending upon its orientation, section and how it is assembled. Flame spread upwards on vertical surfaces is faster than across other orientations. Small pieces of wood ignite and burn easier than large timbers, as do constructions that promote air movement. As the surface/volume ratio increases, ignition starts more easily and flames spread faster. Sharp corners and coarse surfaces enlarge this ratio and result in poor fire behaviour. Moreover, in freestanding timber elements, such as louvres or the boards in open-jointed cladding, all surfaces are exposed to flame spread; this creates a larger fire load than if the elements had closed joints (Figure 4.39) [99]. Thickness, meanwhile, affects the burn-through rate of wood: rapid burn-through of thin materials increases the area exposed to fire [100].

The main environmental factors are temperature and ventilation. Timber becomes more flammable as the temperature rises. At about 250 °C a pilot flame is needed before it will ignite, whereas ignition is spontaneous at 500 °C or more. Ventilation increases the speed of ignition and flame spread.





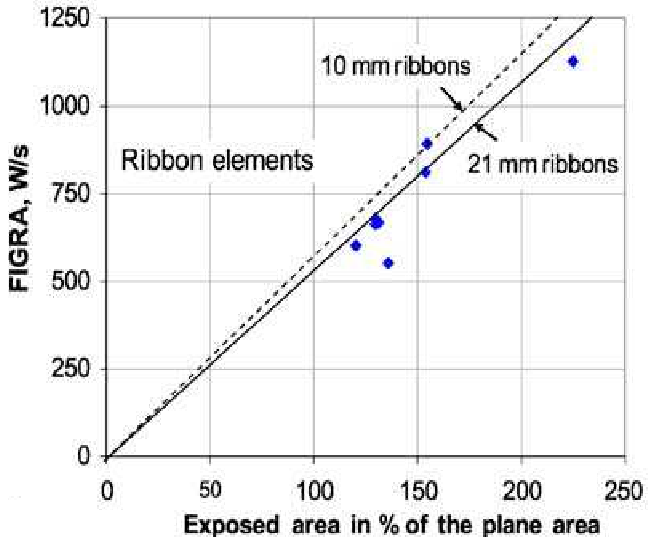


Figure 5.37 *(above) Fire growth rate (FIGRA) as a function of density for wood based panel products. The boundary between Euroclass E and D is shown as a dotted line.* (from: Östman and Mikkola [99])

Figure 5.38 *(top left) Fire growth rate as a function of density for solid wood panelling and cladding with thickness of 9-21 mm and various profiles tested with and without an air gap* (from: Östman and Mikkola [99])

Figure 5.39 *(bottom left) Fire growth rate as a function of the exposed area of free standing timber strips (ribbon elements) such as open jointed cladding or louvres.* (from: Östman and Mikkola [99])

Reaction to fire is assessed using a number of tests, each having a specific fire scenario. Typical reaction to fire classifications for wall coverings are given in Table 5.18. Most solid timber achieves Euroclass D (national class 3) but can be upgraded to Euroclass C or B using a flame retardant treatment. The only products containing wood that achieve a higher classification are those cement-bonded particleboards with a low percentage of wood fibre. A similar classification exists for roof coverings. The classifications in BS EN 15501 and BS 476 are not equivalent and so the transpositions in Table 5.18 are not exact. Some fibre cement board, for example, achieves an A2 classification under the Euroclass system but only Class 0 under the BS 476 series. Confusingly, the Building Regulations in Scotland use a different classification terminology to the rest of the UK.

Table 5.18 *Reaction to fire classes for wall linings showing the indicative transposition between BS 476, Euroclasses, and the Scottish risk categories* [99] [101] [102] [103]

Euroclass in EN 13501-1	Classification to BS 476 series	Risk categories in Scotland	Typical products (Wood-based examples shown in bold)
A1	Non combustible	Non combustible	Inorganic products such as stone, glass, concrete, ceramic and steel
A2	Limited combustibility		As above but with small amounts of organic material. Gypsum boards with thin coverings, Mineral wool. **Some cement-bonded particleboard.**
B	0	Low risk	Gypsum boards with thick coverings. Some plastic insulation. **Some flame retardant treated wood products. Some cement-bonded particleboard.**
C	1	Medium risk	**Most flame retardant treated wood products.**
	2	High risk	
D	3		Glass reinforced polyesters. **Solid wood $\geq$ 400 kgm^{-3}. Most wood-based panels.**
E	4	Very high risk	Some plastic insulation. **Solid wood < 400 kgm^{-3}.** **Low density fibreboard**.
F	Unclassified		Untested products

5.9.4.2 Fire resistance of timber

Timber can have exceptionally good structural performance in a fire. This is due to the thermal conductivity of char being around one sixth that of solid timber [104]. As the char layer develops, it acts to insulate the underlying wood from thermal degradation. The charring rate of timber follows a linear relationship with time, subject to three main variables: it decreases with increasing density or moisture content but increases with the external heat flux. Design values for the charring rates of various wood products are given in BS EN 1995-1-2 [104]; they are typically about 0.5 - 1.0 mm/min. Where the timber is not thick enough to achieve the required fire resistance; it can be protected using plasterboard or other non-combustible cladding material. If timber is protected in this way the component cannot ignite and burn until its surface temperature reaches around 400 °C.

5.9.5 Flame retardants

Timber building products can usually be used in their natural state with no requirement for flame retardant (FR) treatment. The use of flame retardants further widens their use to include situations where a relatively high reaction to fire classification is needed. Most flame retardant treatments work either by controlling ignition, reducing flame spread across a surface or lowering the rate of heat release from the material. Flame retardant treated timber may still burn, but not as quickly or at as high a temperature as untreated timber. The charring rate is not much influenced although char yield may increase. Flame retardants cannot therefore make timber non-combustible – nothing can – and so while they can improve timber's reaction to fire classification, they make no significant contribution to increasing timber's fire resistance. Many timber products suppliers make this basic error and claim that applying a flame retardant to a door will make it fire resistant.

5.9.5.1 Types of FR treatment

Flame retardants for timber can be divided into surface coatings or those that are pressure impregnated into the material.

Most flame retardant coatings are paints or varnishes that intumesce (swell on heating) thereby trapping an insulating layer of gas against the timber surface. Others release gases that interfere with the combustion reactions in the flame; these do not form a surface film or otherwise affect the timber's appearance.

Impregnation treatments are forced into the timber using a pressure vessel. As with wood preservatives, they form an 'envelope of protection' within the timber enclosing an untreated core. Timber intended for such treatment should be machined to size before being impregnated; if it is shaped afterwards the envelope will be lost. Flame retardant impregnation treatments for external use are usually organo-phosphate resins that are heat-polymerised in the timber to become water resistant.

Flame retardant coatings have a long history, with lime plaster being the earliest known example. In many ways lime is an excellent flame retardant coating, being cheap, easily applied, safe and attractive in service. It is, however, neither particularly weather resistant nor suitable in conditions where the timber is constantly changing size due to fluctuations in moisture content. Lime thus performs well as a flame retardant coating for wood in stable moisture conditions, such as down a mine, but will not give long-term protection to a timber facade unless it is regularly maintained. These issues affect every flame retardant product. All are susceptible to moisture to some extent; many require regular maintenance if used externally; and none is suitable for all applications. Accordingly it is essential that their suitability for a particular application be evidenced to the requirements of the relevant product standard. Most requirements for external timber cladding are given in EN 14915 [105] although leach resistance is not covered.

5.9.5.2 Susceptibility to weathering

Very few flame retardant treatments are leach resistant and none is totally unaffected by moisture. This is a complex subject with unresolved questions concerning the service life that can be achieved. Further research is needed this topic.

Leach resistance is evidenced by either long-term exposure trials or accelerated weathering in a laboratory. Exposure trials are more realistic but are prohibitively slow and expensive. The main accelerated weathering test for flame retardants is US Standard ASTM D 2898 [106]. A Nordic standard, NT FIRE 053 [107] has also been published, as has a draft European Standard prEN 15912 [108]. The UK Wood Protection Association (WPA) classifies the leach resistance of flame retardants [109] using a procedure similar to ASTM D 2898. Their most durable category is known as Type LR (leach resistant); only one product is given this classification at present.

The relationship between performance in these tests and the service life achieved in the practice is poorly documented. One of the few published reports on this topic estimated that accelerated weathering tests '*seem to be equivalent to about 2 years of outdoor field exposure*' [110]. Although it may be possible to infer something about long-term performance from such a test, the risk is that manufacturers simply focus upon passing the test without considering how this relates to the real world. Thus some flame retardant products with a poor leach resistance are able to be upgraded to the top Nordic classification simply by being given a moisture-repellent surface coating; in which case their service life is dependent upon the protective coating being maintained. Even the most leach resistant flame retardant products have a limited service life in full external exposure. Unpublished test data from one manufacturer suggest [111] that the service life of their Type LR product may be 30 years. Independent data would be valuable, but to date there has been little recognition of these issues by regulatory bodies.

5.9.5.3 Effect on fungal decay

In 2006 CCA – hitherto the main exterior wood preservative – was withdrawn. Although CCA was compatible with subsequent impregnation using a Type LR flame retardant, its replacements – the so-called CCA alternatives – are not, the problem being that the copper in the replacement products becomes soluble in the alkali conditions created by flame retardant impregnation. Thus, if external timber has to be impregnated with a type LR flame retardant, it cannot presently be preservative treated. Manufacturers are addressing this issue, but in the meantime there are two main options.

It may be possible to avoid the need for a wood preservative by switching to a more decay-resistant timber. In many cases, however, this would need to be a durability class 1 or 2 species and this would preclude most UK grown timbers. Western red cedar may also prove unsuitable because it is usually preservative-treated for use on roofs in the UK.

Alternatively, it may be possible to rely on the flame retardant resin itself. It has been known for some time [112] that the pressure-impregnation of leach-resistant resins into timber can help control fungal decay. In effect, the resin is acting as a form of chemical wood modification. Unpublished test results from one manufacturer [113] suggest that a timber service life of up to 30 years can be achieved in some circumstances. Independent research on this topic is needed.

5.10 Acoustic performance

Noise is unwanted sound; and noise pollution is an increasing problem. In the UK, external noise pollution is controlled through the planning system by ensuring that buildings are separated or screened from potential noise sources such as motorways. Building regulation guidance is, therefore, only concerned with noise pollution between different parts of the same building. Acoustic performance thus becomes relevant to facades where the external envelope forms a junction with a separating wall or floor in a multi-occupancy dwelling.

5.10.1 Sound waves from other sources

When sound waves impinge on a timber surface part of their energy is reflected and the remainder enters the timber causing it to vibrate. The sound is then either intensified or absorbed. Intensification occurs when the timber acts as a resonator, such as the sound box of a violin, this is not relevant to facades. By contrast sound absorption is often an important consideration in facade design.

When sound waves enter the timber they are repeatedly refracted and reflected. This generates molecular friction that partly or completely transforms acoustic into thermal energy. The coefficient of sound absorption (*K*) is used to express the percentage of absorbed sound. Wood has a *K* value of less than 10% (*i.e*. it is a good absorber) due to its porous nature, although the coefficient is affected by several factors including density, moisture content, temperature, defects and modulus of elasticity (MOE). Timbers with a low density, low MOE, a high moisture content and at higher temperatures are the most absorbent. Wave frequency is also important and sounds with a low frequency are absorbed best.

Sound propagation in timber varies depending upon several factors including the direction (axial is faster than transverse), moisture content, MOE and species. The sound wave is damped as the vibration energy is radiated to the atmosphere or converted to heat. Defects interrupt the wave propagation, as do discontinuities in material, such as a change in density between two adjoining timbers. Sound transmission through building elements is most effectively minimised by means of mass (interposing a continuous dense material between the transmitter and receiver) or separation (providing a clear space between building elements). A complex sound path through numerous changes of material and direction can also be effective.

5.10.2 Verifying acoustic performance of buildings

It is impossible to predict accurately the acoustic performance of untested building elements. Accordingly, post-completion testing has been used for many years to ensure that new buildings meet their relevant performance requirements. This is expensive, especially if the construction fails to meet minimum standards and requires remedial work, and so Edinburgh Napier University have developed Robust Standard Details (RSD) as an alternative [114]. These are derived from tests of large numbers of completed buildings. No RSD have yet been published for timber-clad facades.

5.11 Summary

Timber has three key attributes as a facade material. It is non-uniform, moisture sensitive and combustible:

- Non-uniformity is manifested through heterogeneity and anisotropicity. It affects material selection, robustness, degradation and dimensional stability. These factors are often neglected or misunderstood by facade designers who are mostly experienced in inorganic and non-biogenic materials.

- Moisture sensitivity is manifested through biodeterioation, weathering, dimensional change, corrosion, and loss of structural robustness. Other things being equal, timber facades will first fail to meet their serviceability requirements where the local moisture content is higher than that prevailing on the wall.

- Combustibility of timber facades is mainly manifested through its reaction to fire performance. This is a system phenomenon where assembly conditions and moisture exposure are more important than chemical composition. The long-term performance of external flame retardants is poorly documented.

The control of these attributes may be constrained by the need to ensure the facade has appropriate acoustic performance.

All of timber's characteristics as a facade material are affected in one way or another by moisture. This is the key consideration that needs to be understood before timber facades can be designed for optimum performance. Moisture conditions in timber facades need to be better understood.

Further research is needed into the moisture behaviour of facade materials; leaching out of wood preservatives and flame retardants are particularly important topics.

References

1 Cotterill, R. (2008). The material world. 2nd Edition. Cambridge: Cambridge University Press.

2 Dinwoodie, J.M. (2000). Timber: its nature and behaviour. 2nd Edition. London: E & FN Spon.

3 Drysdale, D. (2000). An introduction to fire dynamics. 2nd Edition. Chichester, UK: John Wiley and Sons.

4 Eaton, R.A. and Hale, M.D.C. (1993). Wood - decay, pests and protection. London: Chapman & Hall.

5 Skaar, C. (1988). Wood-water relations. Berlin: Springer.

6 Siau, J.F. (1995). Wood: Influence of moisture on physical properties. Petersburg, USA: Virginia Polytechnic Institute and State Sniversity.

7 Tsoumis, G. (1991). Science and technology of wood: structure, properties, utilization. New York: Van Nostrand Reinhold.

8 Zabel, R.A. and Morel, J.J. (1992). Wood microbiology – decay and its prevention. San Diego, USA: Academic Press, Inc.

9 Railsbeck, B. [online] Some Fundamentals of Mineralogy and Geochemistry Dept. of Geology, University of Georgia, Athens, Georgia U.S.A <www.gly.uga.edu/railsback/FundamentalsIndex.html>

10 Kolz, J. Treichel, P. and Weaver, G. (2006) Chemistry and chemical reactivity 6th edition. London: Thomson Brooks/Cole.

11 Grime, J., Hodgson, J. and Hunt, R. (1988). Comparative Plant Ecology. London: Unwin Heyman.

12 Raynor, A.D.M. and Boddy, L. (1988). Fungal decomposition of wood; its biology and ecology. Chichester, UK: John Wiley & Sons.

13 Ridout, B. (2000). Timber decay in buildings – The conservation approach to treatment. London: E and FN Spon.

14 Davies, I., Jones, D., Sharphouse, P., Turner, P., Bush, T., Murphy, R., Ray, M., Macdonald, E., Ramsey, J., Moore, J. and Lyon, A. (in press). Grading UK-grown larch for external cladding. Forestry Commission information note. Edinburgh: Forestry Commission.

15 Fahn, A. (1962). Xylem structure and the annual rhythm of cambial activity in woody species of the east Mediterranean regions. *Intern. Ass. Wood Anatom. Bull.* 1:2-6.

16 BS EN 350-1:1994. Durability of wood and wood-based products. Natural durability of solid wood. Guide to the principles of testing and classification of natural durability of wood. London: BSI, 1994.

17 Van Acker, J., Stevens, M., Carey, J., Sierra-Alvarez, R., Militz, H., Le Bayon, I., Kleist, G. and Peek, R.D. (2003). Biological durability of wood in relation to end-use. Part 1. Towards a European Standard for laboratory testing of the biological durability of wood. *Holz als Roh- und Werkstoff.* 61(1): 35-45.

18 Rapp, A.O. and Augusta, U. (2006). Natural durability of European timbers in different use classes. Proc. 6th meeting of WG2 of COST E37, London, 17-19 September 2006.

19 BS 8417:2003. Preservation of timber. Recommendations. London: BSI, 2003.

20 BS EN 252:1989. Field test method for determining the relative protectiveness of a wood preservative in ground contact. London: BSI 1989.

21 BS EN 13183-1:2002. Moisture content of a piece of sawn timber. Determination by oven dry method. London: BSI, 2002.

22 Pratt, G.H., Maun, K.W. and Coday A.E. (1997). Timber drying manual. 3rd edn. Watford, UK: BRE Press.

23 BS EN 13183-2:2002. Moisture content of a piece of sawn timber. Estimation by electrical resistance method. London: BSI, 2002.

24 BS EN 13183-3:2002. Moisture content of a piece of sawn timber. Estimation by electrical capacitance method. London: BSI, 2002.

25 Salmén, L. (1997). The sorption behavior of wood. *Proc. Int. Conf. COST Action E8*, Mechanical performance of wood & wood products, Theme: wood-water relations. Copenhagen, Denmark: June 16-17, 1997.

26 Ahlgren, L. (1972). Fuktfixering I porösa byggnadsmaterial [Moisture fixation in porous building materials. In Norwegian] Report 36, Division of Building Technology, The Lund Institute of Technology, Sweden.

27 Rijsdijk, J.F. and Laming, P.B. (1994). Physical and related properties of 145 timbers. Dordrecht: Kluwer Academic Publishers.

28 Langmuir, I. (1916). The constitution and fundamental properties of solids and liquids. Part 1. solids. *J. Am. Chem. Soc*. 38, (11): 2221-2295.

29 Tronstad, S. (2002). Trevirke og fuktighet – fra produsent til forbruker. [Wood and moisture – from producer to consumer. In Norwegian.] Technisk småskrift 35. Oslo: Norwegian Institute of Wood Technology. Quoted in; Nore, K., (2004). Performance based design of wooden claddings – a literature review of wooden cladding design. NBI Note 61. Oslo: Norges Byggforskningsinstitutt.

30 Cartwright, K.StG. and Findlay, W.P.K. (1946). Decay of timber and its prevention. London: Stationery Office.

31 Scheffer, T.C. (1971). A climate index for estimating potential for decay in wood structures above ground. *Forest Products J.* 21(10): 25-31.

32 Schwarze, F.W.M.R., Engels, J. and Mattheck, C. (2000). Fungal strategies of wood decay in trees. Translated from German by W. Linnard. Berlin: Springer.

33 Grime, J.P. (1977). Evidence for the existence of three primary strategies in plants and its relevance to ecological and evolutionary theory. *Amer. Nat.*, 111, 1169-1194.

34 Grime, J.P. (1978). Competition and the struggle for existence. *Symp. Br. Ecol. Soc.*, 20, 123-139.

35 Grime, J.P. (1979). Plant strategies and vegetation processes. Chichester: Wiley.

36 Pugh, G.J.F. (1980). Strategies in fungal ecology, *Trans. Br. Mycol. Soc.,* 75, 1-14.

37 Cooke, R.C. and Raynor, A.D.M. (1984). Ecology of saprotrophytic fungi. London: Longman.

38 BS EN 335-1:2006. Durability of wood and wood-based products. Definitions of use classes. General. London: BSI, 2006.

39 BS EN 335-2:2006. Durability of wood and wood-based products. Definition of use classes. Application to solid wood. London: BSI, 2006.

40 BS EN 335-3:2006. Durability of wood and wood-based products. Definition of use classes. Application to wood-based sheet materials. London: BSI, 2006.

41 BS EN 460:1994. Durability of wood and wood-based products. Natural durability of solid wood. Guide to the durability requirements for wood to be used in hazard classes. British Standards Institution, 1994.

42 Soikkeli, A. (2001). Learning from the past – the durability of wooden claddings. In: Cestari, B., (Ed.). Wooden handwork/wooden carpentry: European restoration sites. *Proc*. *Culture 2000 Project*: Italian action. Paris: Elsevier SAS. 73-82.

43 BS EN 1995-1-1:2004+A1:2008. Eurocode 5. Design of timber structures. General. Common rules and rules for buildings. London: BSI, 2009.

44 Rapp, A.O. and Augusta, U., (1994). The full guideline for the ‘double layer test method’ – A field test method for determining the durability of wood in out of ground. IRG Document No IRG/WP 04-20290. Stockholm: The International Research Group on Wood Preservation.

45 Råberg, U., Edlund, M.L., Terziev, N. and Land, C.J. (2005). Testing and evaluation of natural durability of wood in above ground conditions in Europe, an overview. *J. Wood Sci.* 51(5): 429-440.

46 Van Acker, J., Stevens, M., Carey, J., Sierra-Alvarez, R., Militz, H., Le Bayon, I., Kleist, G. and Peek, R.D. (2003). Biological durability of wood in relation to end-use. Part 1. Towards a European Standard for laboratory testing of the biological durability of wood. *Holz als Roh- und Werkstoff*. 61(1): 35-45.

47 Grinda, M. and Carey, J. (2004). The COST Euro index for fungal decay - five years results. Paper prepared for COST Action E22 Final Workshop, Estoril, Portugal, 22 - 23 March 2004. [Online document] [n.l] COST Action E22. Available at: <http://www.bfafh.de/inst4/43/pdf/7euindex.pdf> [Accessed 8 July 2010.]

48 Wang, C.H., Leicester, R.H. and Nguyen, M.N. (2008). Manual No 4: Decay above ground. Victoria: Forest and Wood Products Australia.

49 Leicester, R.H. and Foliente G.C. (2000). Engineering models for timber. *Proc. 6th World Conf. on Timber Engng*. 31 July – 3 Aug. 2000. Whistler, Canada.

50 BS EN 350-2:1994. Durability of wood and wood-based products. Natural durability of solid wood. Guide to natural durability and treatability of selected

wood species of importance in Europe. London: British Standards Institution, 1994.

51 Feist, W.C. (1982).Weathering of wood in structural uses. In: Mayer, R.W. & Kellogg, R.M. (eds.) (1992). Structural use of wood in adverse environments. New York: Van Nostrand Reinhold Company. 156-178.

52 Kühne, H., Leukens, U., Sell, J. and Wälchli, O. (1970). Investigations on weathered wood surfaces. Part 1. Scanning electron-microscope observations on mold-fungi causing grey stain. *Holz als Roh- und Werkstoff*. 28(6): 223-229.

53 Schoeman, M.W. and Dickinson, D. J. (1997). Growth of Aureobasidium pullulans (de Bary) Arnaud on lignin breakdown products at weathered wood surfaces. *Mycologist*. 11(4): 168-172.

54 Williams, R. S., Knaebe, M. T. and Feist, W. C. (2001). Erosion rates of wood during natural weathering. Part II. Earlywood and latewood erosion rates. *Wood & Fiber Science*. 33(1): 43-49.

55 Edvardsen, K.I., and Torjussen, L. (1997). Håndbok 45 – TREHUS. [Handbook 45 – Wooden House. In Norwegian] Oslo: Norges Byggforskningsinstitutt.

56 Darlington, A. (1981). Ecology of Walls. London: Heinemann Educational Books.

57 Launden, J.R. (1985). Desmococcus Olivaeceus – the name of the common subaerial green algae. *Taxon*. 35(4): 671-672.

58 Blocken, B. (2004). Wind-driven rain on buildings – measurements, numerical modelling and applications. PhD Thesis, Department of Civil Engineering, Katholieke Universiteit Leuven, Belgium.

59 Canada Mortgage and Housing Corporation (1999). Wood-frame envelopes in the coastal climate of British Columbia. Vancouver: CMHC.

60 Wiseman, C. (2000). Twentieth-Century American Architecture: the buildings and their makers. New York: W.W. Norton.

61 Juniper, A. (2003). Wabi Sabi: the Japanese art of impermanence. Boston: Tuttle Publishing.

62 Meylan, B.A. (1968). Cause of high longitudinal shrinkage in wood. *For. Prod. J.* 18(4):75-78.

63 BS EN 942:2007. Timber in joinery. General requirements. London: BSI, 2007.

64 Hoffmeyer, P., (1995). Wood as a building material. In: Blass, H.J., Aune, P., Choo, B.S., Götlacher, R., Griffiths, D.R., Hilson, B.O., Racher, P. and Steck, G. (eds.) (1995). Timber engineering STEP 1. Almere, The Netherlands: Centrum Hout. A4: 1-21.

65 Brown, W. (1988). The conversion and seasoning of wood. London: Stobart & Son.

66 Building Research Establishment. (1982). The movement of timbers. Technical Note 38, 2nd Edn. London: Stationery Office.

67 Hislop, P. (2007). External timber cladding. 2nd Edn. High Wycombe, UK: TRADA Technology Ltd.

68 Nimmo, B. and Hinds, G. (2007). Beginners Guide to Corrosion. [Online guidance] Teddington, UK: National Physical Laboratory. p.1. Available at: <http://resource.npl.co.uk/docs/science_technology/materials/life_management_of_materials/publications/online_guides/pdf/beginners_guide_to_corrosion.pdf> [Accessed 30 June 2010.]

69 Illston, J. M., Dinwoodie, J. M. and Smith, A.A. (1979). Concrete, timber and metals: the nature and behaviour of structural materials. London: Chapman & Hall.

70 National Physical Laboratory. Guides to practice in corrosion control: Corrosion of metals by wood. [Online guidance] Teddington, UK: National Physical Laboratory [n.d]. Available at: <http://www.npl.co.uk/upload/pdf/corrosion_of_metals_by_wood.pdf> [Accessed on 30 June 2010.]

71 Shreir, L.L. (1976). Corrosion. Volume 2: Corrosion control. 2nd Edn. London: Newnes-Butterworths.

72 Baker, A.J. (1987). Corrosion of metals in preservative-treated wood. In: Hamel, M., ed. (1987). Wood protection techniques and the use of treated wood in construction: *Proc. Conf. Wood protection & treated wood in construction*, 28-30 October 1987, Memphis, US. Madison, Wisconsin: Forest Products Research Society. 99-101.

73 Freeman, M.H. and McIntyre, C.R. (2008). A comprehensive review of copper-based wood preservatives. *Forest Products J*. 58(11): 6-27.

74 Nguyen, M.N., Leicester, R.H., and Wang, C.H. (2008). Manual No 6: Embedded corrosion of fasteners in timber structures. Victoria: Forest and Wood Products Australia.

75 Building Research Establishment (1985), Corrosion of metals by wood. BRE Digest 301. Watford: Building Research Establishment.

76 Zelinka, S.L. and Rammer, D.R. (2005). Review of test methods used to determine the corrosion rate of metals in contact with treated wood. FPL-GTR-156. US Forest Products Laboratory general technical report. Madison, Wisconsin: US DA Forest Service.

77 Institution of Structural Engineers (1995). Aspects of Cladding. London: SETO.

78 Centre for Window and Cladding Technology (2005). Standard for systemised building envelopes. Bath, UK: University of Bath.

79 BS EN 1995-1-1:2004+A1:2008. Eurocode 5. Design of timber structures. General. Common rules and rules for buildings. London: BSI, 2009.

80 BS 5268-2:2002. Structural use of timber. Code of practice for permissible stress design, materials and workmanship. London: BSI, 2002.

81 BS EN 1991-1-4:2005. Eurocode 1. Actions on structures. General actions. Wind actions. London: BSI, 2005.

82 CP 3:1972. Code of basic data for the design of buildings. Chapter 3. Part 2. Wind Loads. London: British Standards Institution.

83 The Building (Scotland) Regulations 2004. Domestic Handbook May 2009. Section 1 – Structure. Annexes 1A – 1 F, Small Buildings Structural Guidance. Livingston, UK: Scottish Building Standards Agency.

84 TRADA Technology (2001). Timber frame construction. 3rd edition. High Wycombe, UK: TRADA Technology.

85 Grantham, R. and Engily, V. (2003). Multi-storey timber frame buildings, a design guide. BRE Report 454. London: BRE Press.

86 Porteous, A. and Kermani, A. (2007). Structural timber design to Eurocode 5. Oxford: Blackwell Science.

87 Falk, R.H and Baker, A.J., (1993). Fasteners for Exposed Wood Structures. In: *Wood Design Focus [J. Forest Products Soc.]* 14-17.

88 James and Taylor. Senses hardwood rainscreen. [Online Brochure] New Malden, Surrey, UK: James & Taylor Ltd [n.d]. Available at: <http://www.jamesandtaylor.co.uk/m12/m12_s1.htm> [Accessed 3 July2010].

89 BS 5534:2003. Code of practice for slating and tiling (including shingles). London: BSI, 2003.

90 BS 4978:2007. Visual strength grading of softwood. Specification. London: BSI, 2007.

91 Lissianski, V.V., Zamansky, V.M. and Gardiner, W.C. (2000). Combustion chemistry modelling. In: Gardiner, W.C., ed. Gas-phase combustion chemistry. New York: Springer.

92 Chitty, R. and Fraser-Mitchel, J. (2003). Fire safety engineering: a reference guide. London: BRE Press.

93 Lyons, J.W., (1985). Fire. New York: Scientific American Books Ltd.

94 Bowman, D.M.J.S., Balch, J.K., Artaxo, P., Bond, W.J., Carlson, J.M., Cockrane, M.A., D'Antonio, C.M., DeFries, R.S., Doyle, J.C., Harrison, S.P., Johnstonn, F.H., Keeley, J.E., Krawchuk, M.A., Kull, C.A., Marston, J.B., Moritz, M.A., Pretence, I.C., Roos, I.C., Scott, A.C., Swetnam, T.W., van der Werf, G.R. and Pyne, S.J. (2009). Fire in the Earth system. *Science*. 324 (5296): 481- 484.

95 Lane, N. (2002). Oxygen – The molecule that made the world. Oxford: Oxford University Press.

96 Institution of Structural Engineers, (2007). Guide to the advanced fire safety engineering of structures. London: Institution of Structural Engineers.

97 BS EN 1991-1-2:2002. Eurocode 1. Actions on structures. General actions. Actions on structures exposed to fire. London: BSI, 2002.

98 BS 476-10:2009. Fire tests on building materials and structures - Part 10: Guide to the principles, selection role and application of fire testing and their outputs. London: BSI, 2009.

99 Östman, B. and Mikkola, E. (2006) European classes for the reaction to fire performance of wood products. In: *Holz als roh- und werkstoff.* 64(4): 327 - 337.

100 Hartl, H., (1995). Behavior of timber and wood-based materials in fire. In: Blass, H.J., Aune, P., Choo, B.S., Götlacher, R., Griffiths, D.R., Hilson, B.O., Racher, P. and Steck, G, (eds.). Timber engineering STEP 1. Almere, The Netherlands: Centrum Hout.

101 Department for Communities and Local Government (2006). The Building Regulations, 2000 (as ammended). London: DCLG.

102 Scottish Building Standards Agency (2004). Building (Scotland) Regulations 2004. Livingston, UK: SBSA.

103 BS EN 13501-1:2007+A1:2009. Fire classification of construction products and building elements. Classification using test data from reaction to fire tests. London: BSI, 2009.

104 BS EN 1995-1-2:2004. Eurocode 5: Design of timber structures – Part 1-2: general rules – structural fire design. London: BSI, 2004.

105 BS EN 14915:2006. Solid wood panelling and cladding. Characteristics, evaluation of conformity and marking. London: BSI, 2006.

106 ASTM D 2898. Standard test methods for accelerated weathering of fire-retardant-treated wood for fire testing. West Conshohocken (PA), USA: ASTM International. 1999.

107 Nordtest Method NT FIRE 054. Durability of reaction to fire - Performance classes of fire-retardant treated wood-based products in interior and exterior end use applications. Oslo: Norden. 2006.

108 prEN 15912:2009:E. Durability of reaction to fire performances - Classes of fire retardant treated wood-based product in interior and exterior end use applications. Brussels: Comité Europeén de Normalisation. 2009.

109 Wood Protection Association (2006). Industrial flame retardant treatment of solid wood. Derby, UK: Wood Protection Association.

110 Östman, B., Voss, A., Hughes, P.J. and Grexa, O. (2001). Durability of fire retardant treated wood products at humid and exterior conditions – review of literature. In: *Fire and Materials*. 25(3): 95-104.

111 Arch Timber Protection. Durability of fire retardant treated wood, 42 years experience with Non-Com Exterior®. [Unpublished Internal Report, November 2009.] Castleford, UK: Arch Timber Protection. 2009.

112 Stamm, A.J. and Seborg, R.M. (1941). Resin-treated, compressed wood. *Trans. Am. Inst. Chem. Engrs.* 37: 385-397. [Quoted in] Hill, C. (2006). Wood modification. Chichester, UK: John Wiley & Sons.

113 Arch Timber Protection. Enhanced biological durability of NCX (Non-Com Exterior®) fire retardant treated timber. [Unpublished Internal Report, January 2009.] Castleford, UK: Arch Timber Protection. 2009.

114 Robust Standard Details Ltd. Website: <http://www.robustdetails.com/index.php?id=12521> [Accessed 8 November 2010] London, UK.

Chapter 6

Experimental

This experiment was designed to address the second research question posed in the introduction, namely: how wet do timber-clad facades get? It comprises an exposure trial of 16 datalogged test panels spread over two sites. The trial ran from January 2005 to December 2007.

6.1 Background

The scope and objectives of this exposure trial were constrained by its origin as one part of the larger ETC trans-national project. The trial was restricted to only one timber species, Sitka spruce (*Picea sitchenis*), and had to be carried out in the Scottish Highlands. Sitka spruce was stipulated because of its commercial importance to UK sawmills and its similarity to Norway spruce (*P. abies*) which is widely used as external cladding in Scandinavia. The Scottish Highlands were stipulated because it was the only part of Scotland covered by the EU Northern Periphery Programme when the project application was submitted in 2002.

The research tasks in the full trans-national project were divided up amongst the research contractors. BRE compared the moisture take-up and loss characteristics of Norway and Sitka spruce and graded the boards to be used in the UK. NBRI assessed cavity ventilation and the impact on moisture conditions of differences in timber growth rate, Forest Research compared wind-driven rain exposure across the NPP area. The author investigated the impact of construction detailing upon moisture conditions in the facade assembly. In principle, the outputs of each task were to be shared amongst the research providers although this was not always achieved in practice.

6.1.1 Sitka spruce

It is known that Norway spruce is the most common external cladding timber in Scandinavia, being used without preservative treatment on all but the wettest sites on the west coast of Norway and the Faroes. The timber typically achieves a service life in excess of 50 years in this application. Scandinavians argue that the timber is suitable for cladding due to its refractory nature which results in a low moisture take-up during intermittent wetting (a view reiterated in European Standard BS EN 460 [1]). Little test evidence is available to justify this assertion, however, and so it may be that other factors such as regular maintenance or a low rate of fungal decay are more important. Scandinavians take Norway spruce so much for granted as cladding that their guidance documents rarely mention other timbers and may even ignore natural durability as a relevant issue. NBRI, for example, review the performance requirements for timber facades [2] whilst hardly mentioning resistance to fungal decay.

Sitka and Norway spruce have similar timber properties (Table 6.1) which suggests that, if resistance to moisture take-up is a key factor in timber facade performance, Sitka spruce should perform well, at least on relatively dry sites. To assess this, the author's exposure trial had to be replicated across both wet and dry sites.

Sitka spruce comprises around 26% of Britain's total woodland area (692,000 ha out of 2,665,000 ha, this includes both planted forests and semi-natural woodland). The equivalent figure for Norway spruce is 3% of woodland area (79,000 ha) [3]. Small diameter logs are used to produce paper and panel products, whilst larger logs (sawlogs) are mainly converted into structural timber and fencing. Sawmills are always seeking new outlets, particularly for the outer 'falling boards' (Figure 6.1) produced as a by-product of sawlog processing and which are often difficult to sell at a profit. External cladding is seen as a potential new market opportunity for these and so the exposure trial had to focus on falling boards.

Table 6.1 *Physical properties of Sitka spruce (Picea sitchensis) and Norway spruce (P. abies) most relevant to external cladding* [4] - [6]

Physical property	Sitka spruce	Norway spruce
Mean density at w = 12%	390 kgm^{-3}	460 kgm^{-3}
Natural durability class: • fungi (4: slightly durable, 5: not durable) • common furniture beetle (SH: sapwood & heartwood are susceptible)	4 to 5 SH	4 to 5 SH
Tangential shrinkage from green to w = 12%	3%	4%
Movement class (relative humidity change from 60% to 90%)	small	medium
Treatability • heartwood (3: difficult, 4: extremely difficult) • sapwood (2: moderately easy, 3: difficult, v: variable)	3 2 to 3	3 to 4 3 v
Distinctiveness of sapwood:	generally indistinct	not distinct
Fibre saturation point (%)	$w \approx 29$	$w \approx 27$
Equilibrium moisture content • at 60% relative humidity • at 40% relative humidity	$12\% \le w \le 13\%$ $9\% \le w \le 10\%$	$12\% \le w \le 13\%$ $8\% \le w \le 9\%$
Mean acidity (pH)	4	4

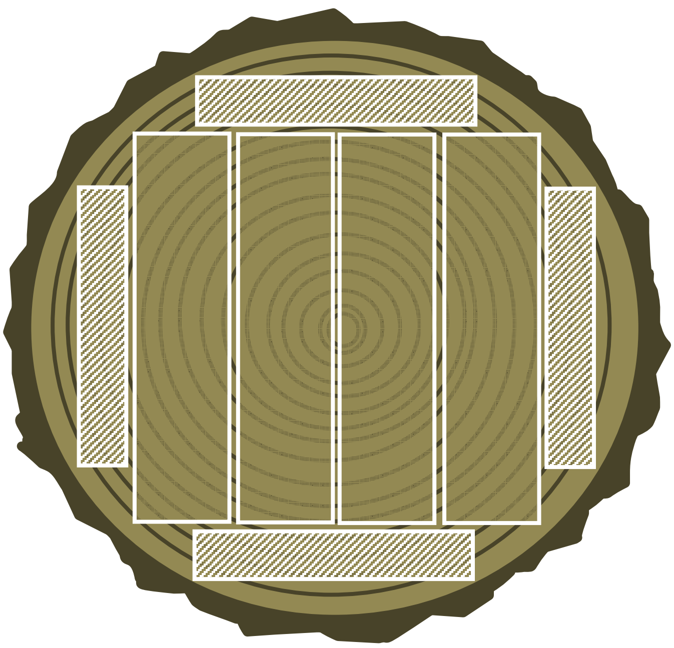


Figure 6.1 *Sawing pattern for a softwood sawlog showing the falling boards (hatched) produced when structural battens are cut from the centre of a log. Falling boards are typically around 145 mm wide and 16 - 22 mm thick. The lengths are usually 2.5 to 6 m*

6.1.2 Construction detailing and workmanship

During discussions with the ETC project steering group it was decided that this trial would focus upon establishing a base-line performance for the moisture load in normal timber cladding. The assumption being that the load would be increased by poor design and workmanship (*e.g.* the problems identified in Chapter 3) or reduced by rainwater deflection (*e.g.* wide eaves). Cavity ventilation was not assessed as this task was undertaken by NBRI and so the cavity details were those recommended across the UK and Scandinavia. The trial thus focused on three frequently occurring questions. Should the boards run horizontally or vertically? Should the joint between boards be open or closed? Should the timber be given a surface coating?

The main assessment criterion was the extent to which each variable increased or decreased the moisture load in the timber. Moisture load being defined as a duration and intensity of wetting sufficient to support fungal decay. Fungi are unable to grow effectively in wood below its fibre saturation point (FSP) [7] which varies between species, but typically 28% ≤ FSP ≤ 32%. Short duration wetting events above FSP do not pose an additional biodeterioration threat, but if the wetting lasts at least three days *per* month it can be assumed that there is a decay risk [8]. For Sitka spruce, w = 25% was chosen as the threshold. This approximated to the lowest FSP for Sitka spruce after allowing for measurement uncertainties. Fortuitously, it was also the highest moisture content that could be accurately measured using electrical resistance meters. Applying a safety margin gave a lower threshold of w = 22%.

6.1.3 Generalising the results

Although outside the scope of the ETC project, this trial was always intended to be applicable to other timber species where possible. To achieve this, the results needed to be generalised through a model allowing a timber's moisture load to be predicted from published physical properties. This was attempted using a subsidiary exposure trial. A few months into the project, the steering group introduced a requirement that all of the guidance being developed should take account of fire safety. Although too late to refocus the test programme, the author was able to take account of detailing for fire safety by participating in a parallel project led by BRE (see Chapter 7).

6.2 Methodology

The exposure trails were experimental and subsequently involved a time series numerical and statistical analysis. Aspects of the analysis were causal-comparative.

6.2.1 Time series analysis

A time series is a record of phenomena that vary irregularly with time. Time series modelling is reviewed by numerous authors [9] - 14]. There are few standard methods of time series analysis; instead the process begins with consideration of graphed data, from which the next steps and their statistical modelling are developed. Time series often exhibit periodic components linked to daily or seasonal patterns. Missing and outlying observations are also frequent occurrences and necessitate data interpolation. Time series can be classified in various ways:

- Data recorded at certain time intervals (*e.g.* hourly temperature readings) are termed discrete time series, in contrast to the continuous series recorded by an analogue device (*e.g*. a tape recorder). Discrete time series can be categorised into two types depending upon whether the recording interval is regular or irregular.

- Univariate time series consist of a single reading at each time point, whereas multivariate time series involve several simultaneous observations.

- Time series can be expressed using a stochastic model (a statistical description of a physical process whose structure involves a random mechanism). Series where the random element does not vary with time are termed stationary. Others are termed non-stationary.

- A time series with a normal distribution of the data is termed Gaussian; it is otherwise described as being non-Gaussian.

The time series in this thesis are discrete, regular, multivariate and non-stationary. Some are Gaussian whilst others are not. The frequency curves are particularly skewed.

6.2.2 Experimental design

The exposure trial had an *n*-factor experimental design whereby *n* different factors were varied so that the response to these manipulations could be measured, both singly and through their interactions. Four factors were tested, each with two levels of treatment. This may seem a small number of factors and treatments but it is important to realise that each combination of factor and treatment has to be separately tested. Every time another interaction is added the size of the experiment doubles; *n*-factor designs become unworkable if too many interactions are assessed. The experimental conditions are given in Table 6.2; although two factors are quantitative and two qualitative, all were assigned to either a high or low level for the purpose of this experiment. There were thus 16 test panels in the experiment (a 2^4 design) giving 15 degrees of freedom.

Table 6.2 *The four factors and their two levels of treatment*

Variable factor	Level	
	Low	High
Board orientation	Horizontal	Vertical
Joint ventilation (mm)	0	6
Mean coating thickness (mm)	0	0.5
Site	Exposed	Sheltered

This design can described in several ways. The factors are often labelled A, B, C and D; a plus sign is used to represent the high level of treatment and a minus for the low. This known as geometric notation as it can be visualised as two cubes. Lowercase letters, and one number, can also be used to label each treatment combination in a standardised order, namely: (1), *a*, *b*, *ab*, *c*, *ac*, *bc*, *abc* and so on. The 16 possible combinations can be presented as a design matrix (Table 6.3). Four are associated with the main effects of A, B, C and D, six with interactions AB, AC, BC etc. In Table 6.4 the high treatment levels are coloured yellow. In this trial the standard notation was altered to a four letter descriptive code to make it easier to remember. The 16 four letter panel codes are given in Table 6.3. The relationship between these code letters and the geometric representation is shown in Figure 6.2.

Table 6.3 *The four letter panel code used to describe each treatment combination.*

Panel code (red = high)	Factor				Label*
	A Orientation	B Joint	C Coating	D Site	
EHCN	Horizontal	Closed	None	Exposed	(1)
EVCN	Vertical	Closed	None	Exposed	a
EHON	Horizontal	Open	None	Exposed	b
EVON	Vertical	Open	None	Exposed	ab
EHCF	Horizontal	Closed	Front	Exposed	c
EVCF	Vertical	Closed	Front	Exposed	ac
EHOF	Horizontal	Open	Front	Exposed	bc
EVOF	Vertical	Open	Front	Exposed	abc
SHCN	Horizontal	Closed	None	Sheltered	d
SVCN	Vertical	Closed	None	Sheltered	ad
SHON	Horizontal	Open	None	Sheltered	bd
SVON	Vertical	Open	None	Sheltered	abd
SHCF	Horizontal	Closed	Front	Sheltered	cd
SVCF	Vertical	Closed	Front	Sheltered	acd
SHOF	Horizontal	Open	Front	Sheltered	bcd
SVOF	Vertical	Open	Front	Sheltered	abcd

* Label refers to the standardised labelling scheme used in most statistics textbooks when describing the treatment combinations in factorial experiments of this kind.

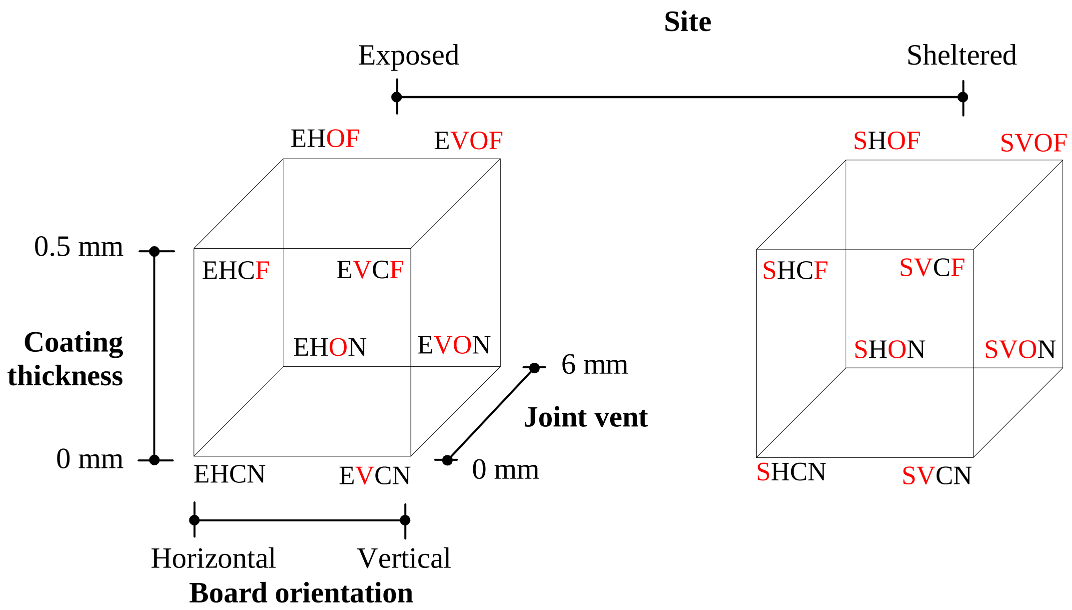


Figure 6.2 *How the panel codes, factors and treatment levels in the trial relate to the geometric view (red indicates a factor is at its high level).*

6.2.3 Sites

One of the test sites was at Leanachan, a Forest Enterprise owned forest flanking the Ben Nevis range on the west of Scotland. The nearest village is Spean Bridge, amongst the wettest inhabited locations in the UK. The other site, a forest owned by Inverness College on the east coast near Inverness, has a low rainfall. The Leanachan site was within a forest clear-fell and had no shelter from the prevailing wind, whereas the Inverness site was in a sheltered forest clearing. The location and conditions of the two sites are indicated in Table 6.4 and Figures 6.3 and 6.4.

Table 6.4 *Site locations and climate*

	Leanachan, Spean Bridge	Balloch, Inverness
Grid reference	NN 2219 7786	NH 7369 4617
Height (m) above mean sea level	190	117
Latitude	56º 51´ N	57º 48´ N
Longitude	4º 55´ W	4º 10´ W
Rainfall *per* annum (mm)	1915	636
Days at or below 0 °C *per* annum	56	33

The flora and fauna at both locations can be characterised using the biodiversity data in Humphrey *et al.* [15], which was based on the Forestry Commission’s ecological site classification zones (Table 6.5) [16]. The zones are defined from annual precipitation totals and further divided into woodland type and growth stage. The soil classification is from the Soil Survey of Scotland [17].

Table 6.5 *Typical flora and fauna at the two test sites*

	Site conditions and species counts	
	Leanachan	Balloch
Ecological site classification	Upland, Sitka spruce, pre-thicket	Foothill, Scots pine, mature forest
Soil type	Peaty podzol	Humus-iron podzol
Canopy invertebrates Coleoptera	 47	 53
Sub-canopy invertebrates • Cicadomorpha • Syrphids • Coleoptera	 33 29 52	 35 25 61
Ground invertebrates • Coleoptera (excluding carabids) • Carabids	 35 17	 30 18
Deadwood invertebrates	23	20
Fungi* Lichens Bryophytes Vascular plants Songbirds	232 46 54 40 15	210 100 31 27 17
Totals	623	627

* Wood destroying fungi are assumed to be ubiquitous

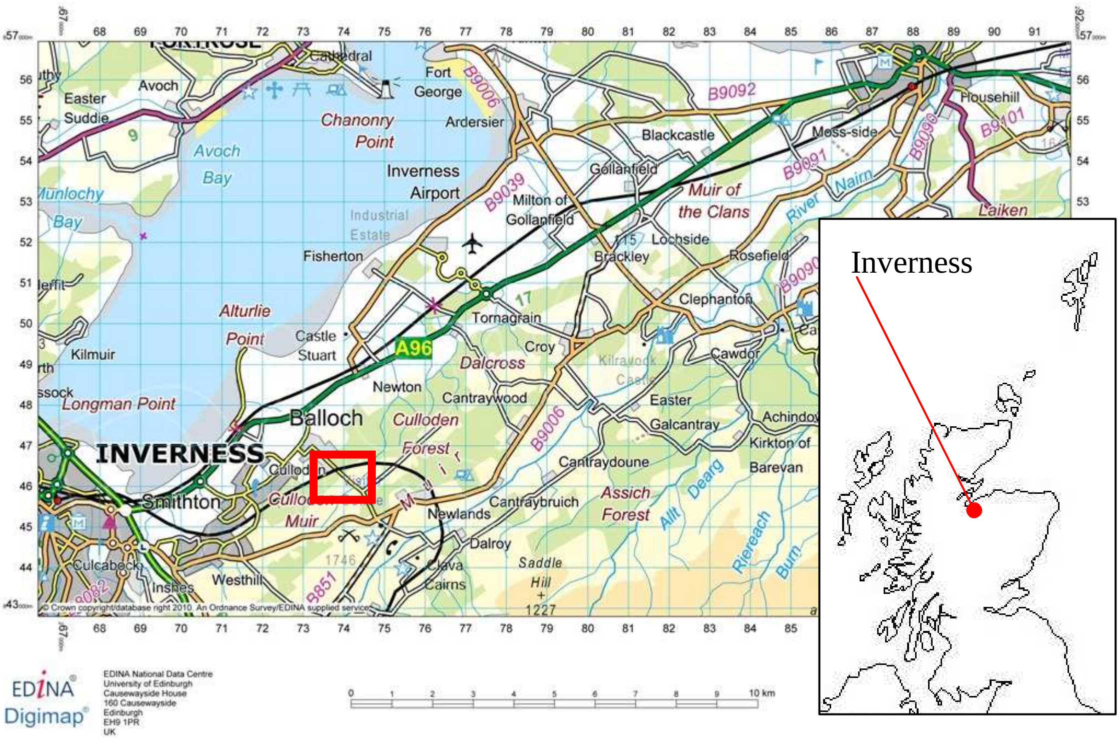


***Figure 6.3** Location of the Balloch test site near Inverness*
(Main map © Ordnance Survey)

***Figure 6.4** Arial view of the Balloch site (red line) in a forest clearing*

(Image © Google Earth)

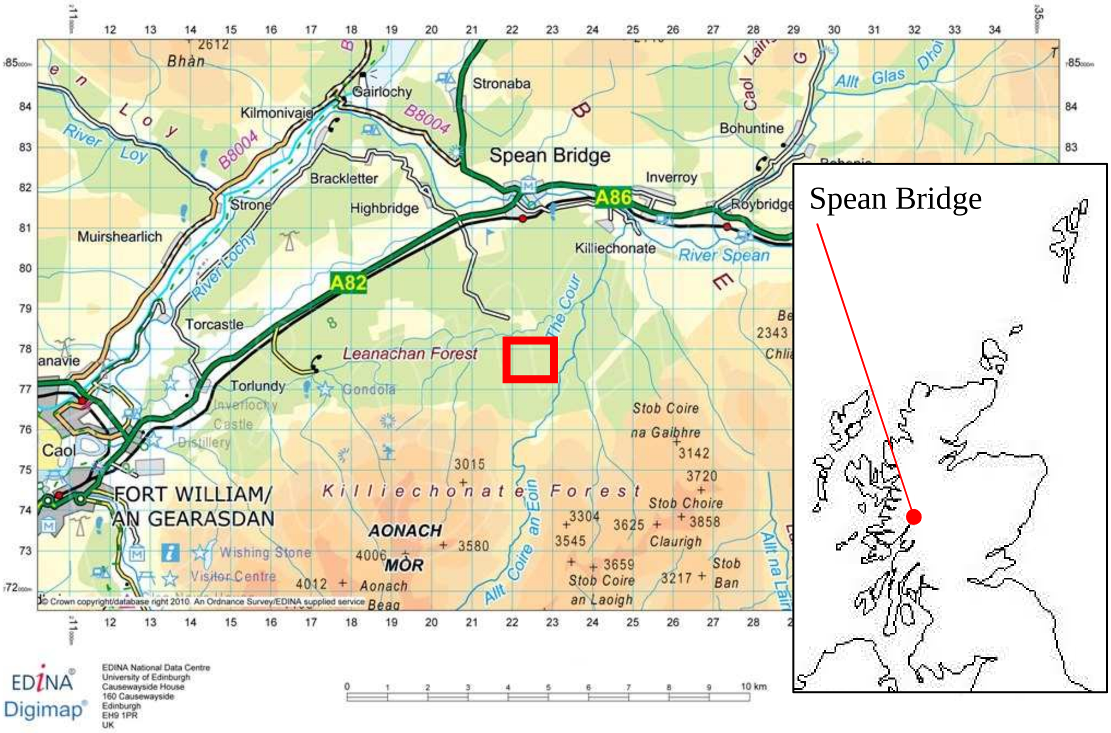


Figure 6.5 *Location of the Leanachan test site near Spean Bridge (Main map © Ordinance Survey)*

Figure 6.6 *Arial view of the Leanachan site (red line) in a forest clear-fell*

(Image © Google Earth)

6.2.4 Timber selection and processing

All timber was Scottish-grown Sitka spruce, sourced from commercial supplies of falling boards: some 2000 boards were donated by BSW Timber plc, with a similar number being given by James Jones and Sons Ltd. The board sizes were nominally 2400 x 146 x 22 mm and were obtained kiln dried to a moisture content of around 20%. Boards with mould growth were rejected by the author as this could have affected coating performance.

All boards were appearance graded to an equivalent quality to imported European whitewood (*i.e*. the timber of *Picea* spp. and *Abies* spp.). Cladding from these species is generally graded to the S/F criteria in 'The Green Book' [18] used throughout Scandinavia in preference to the relevant European Standard [19]. The S/F category combines six grades, the lowest being V and VI. UK timber distributors are familiar with selling timber graded in this way. The grading was undertaken in collaboration with BRE using both manual inspection and automatic scanning. The latter method used the Wood Eye optical scanner manufactured by Innovativ Vison [20]. The grading is discussed further in BRE Digest 500 [21]. The graded timber was delivered to Edinburgh Napier University where a final selection was made using computer generated random numbers. These boards were conditioned in a climate-controlled chamber to an EMC of 12% and then machined to profile (Figure 6.7). No measurements were made of timber density or mechanical properties.

The boards were machined on their rear face and edges to ensure a consistent thickness of 20 mm and width of 144 mm. The front was left with an off-saw finish as recommended in Scandinavia [22]. The selection of front and rear face also followed Scandinavian practice: the boards being oriented so that the side nearest the pith faced outwards on the wall [22].

Half of the boards were coated and half left uncoated. The coatings used a solvent based primer (Jotun Visor) followed by two applications of an opaque acrylic finish coat (Jotun Demidekk, white) [23]. This product was selected as it was the most popular high performance opaque timber coating in Norway. The coatings were brush applied in controlled conditions to the manufacturer's instructions. The front face, edges and ends were coated, with the rear face left without a finish.

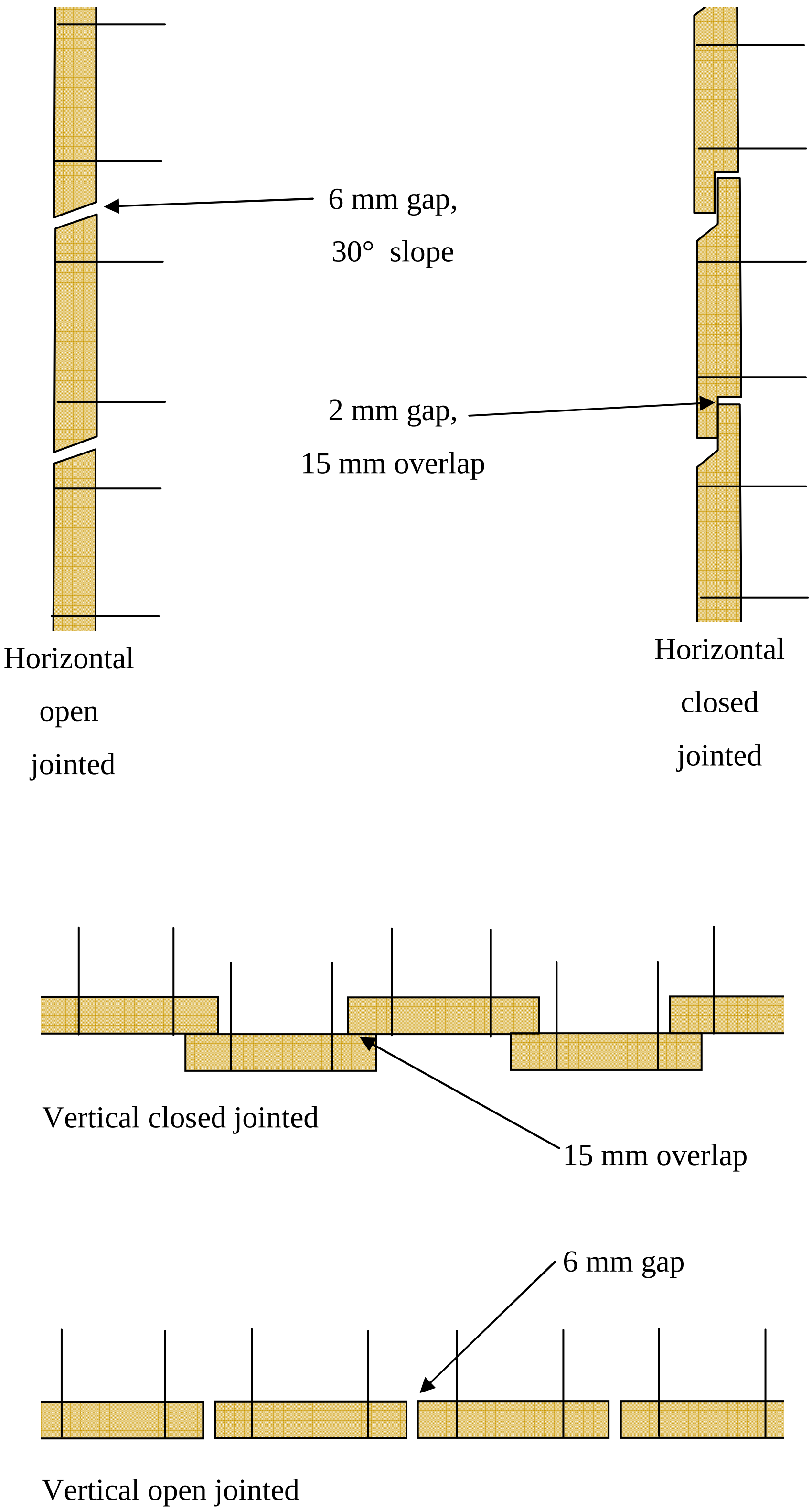


Figure 6.7 *The four board profiles used in the trial, the screws are positioned about 20 - 30 mm in from the edges of the boards*

6.2.5 Panel design

There is no published norm for exposure testing of timber cladding. Nonetheless, a number of researchers are involved in such trials and the panel design used in this experiment (Figure 6.8) was developed jointly with BRE and NBRI. Each panel consisted of a 1 m square, preservative-treated softwood frame within which were mounted the test boards. The completed panels were installed on a robust support frame oriented to the southwest so that the cladding was exposed to the prevailing wind (Figure 6.9). The panels were positioned approximately 1 m above the ground level, their order on the support frame being determined by random selection.

The boards were fixed with 45 mm long stainless steel screws onto preservative treated support battens to create a drained and ventilated cavity behind the cladding. The battens were fixed to a plywood substrate behind which was housed a waterproof (IP56) box containing a datalogger and connection node. One datalogger was used for each panel. The datalogger systems (Materialfox datalogger and Multisensor Revision 1 node) were supplied by Scanntronik Mugrauer GmbH [24]. Each datalogger accommodated 10 channels and could store 45,000 readings. The datalogger boxes were hidden behind the rear face of each panel; these were removable to allow data download to a laptop (Figure 6.10).

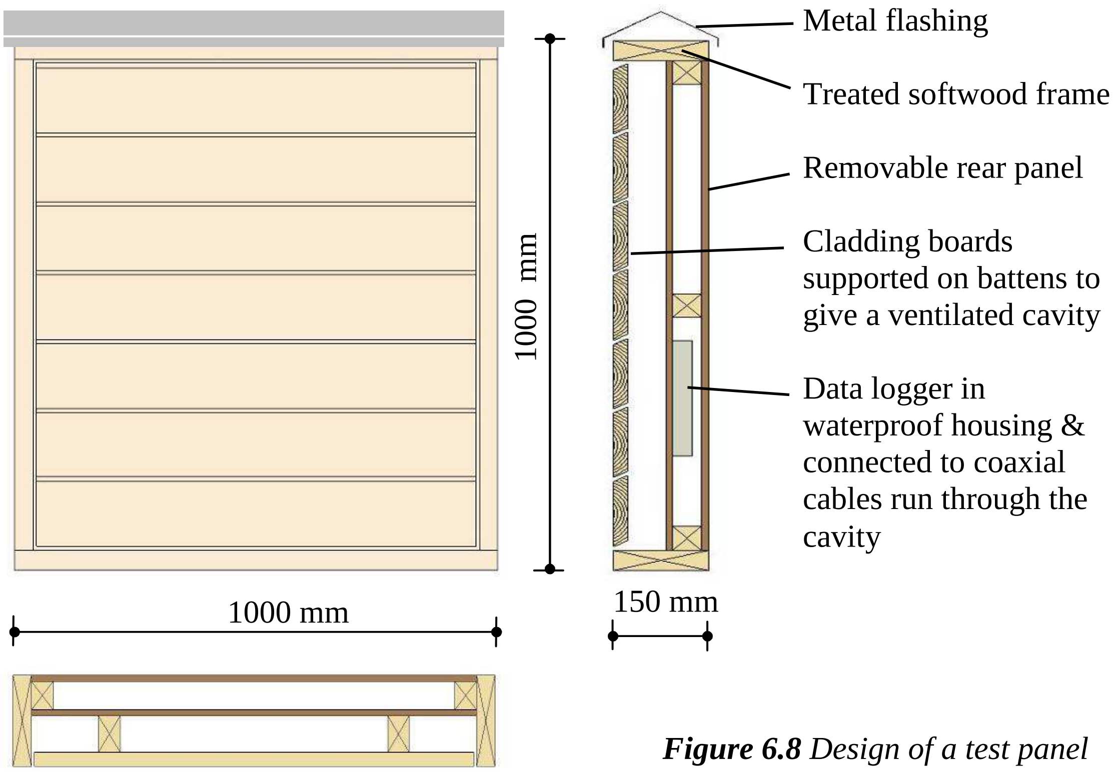


Figure 6.8 *Design of a test panel*

Figure 6.9 *The Leanachan exposure site during construction*

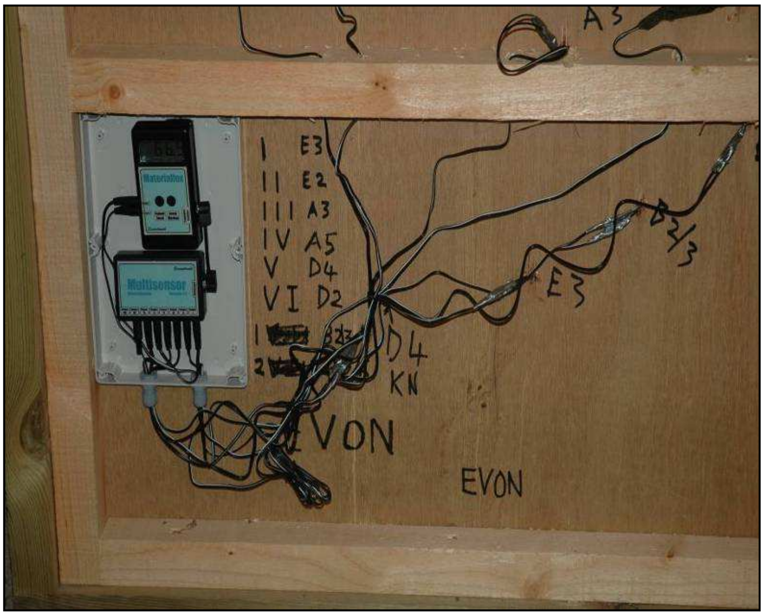


Figure 6.10 *Datalogger and node installed at the rear of a panel*

The moisture sensors were built from PVC-coated 1.5 mm diameter copper coaxial cable to a design supplied by the datalogger manufacturer. The cable end was separated in two and the plastic coating stripped back about 5 mm. The exposed ends were inserted into 6 mm diameter holes drilled from the rear face of the board. The holes were 30 mm apart and stopped 5 mm from the front face of the cladding. The cable ends were secured in the holes with electrically conductive adhesive (a mix of 50:50 by volume, graphite powder : epoxy resin, diluted with a 90 % solution of ethanol until workable) and sealed against moisture from the rear face using normal non-conductive epoxy (Figure 6.11).

The electrodes making up each sensor were positioned parallel to the grain in accordance with BS EN 13183-2 [25]. The other end of the cable was fitted with a jack plug for connection to the datalogger. To minimise signal losses due to electrical resistance, the cables were no more than 1.5 m long.

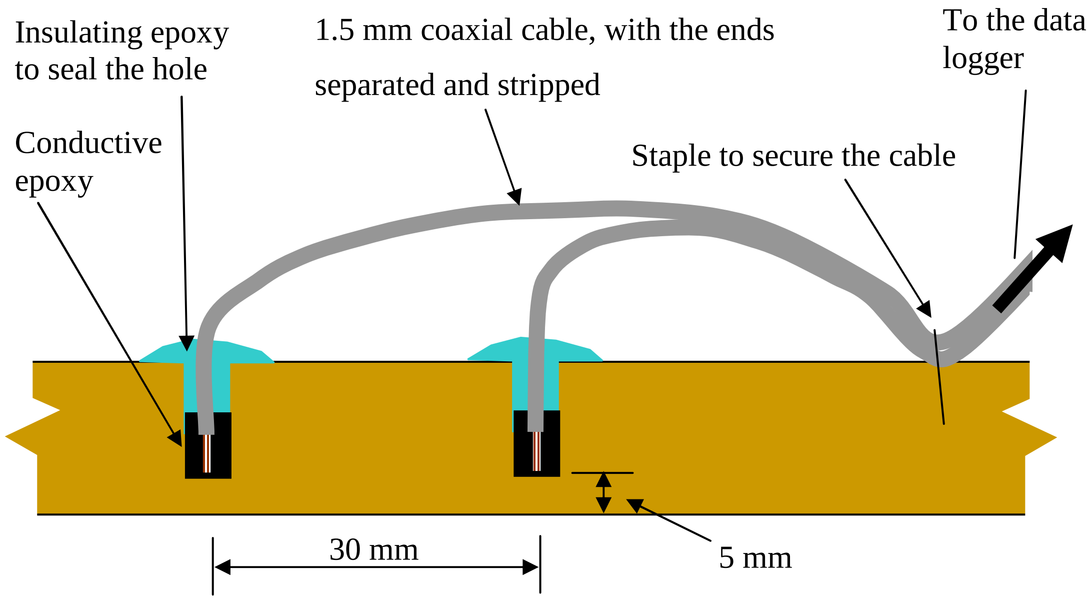


Figure 6.11 *Design of a moisture sensor*

Eight moisture sensors were installed in the rear face of the cladding boards on each panel; two in each of the following positions:

- Board centres (clear timber, away from any defects)
- Board defects (near a knot, split or area of irregular grain)
- Board edges (5 mm from the edge of a board)
- Support battens (behind the boards where two boards meet)

The position of the sensors in the board edges, board centres and cavity battens were decided by two computer generated random numbers (the first number selected the board and second the position), whilst the board defects chosen were the two worst examples on the panel (Figure 6.12). To avoid edge effects, the outer 150 mm of the panel was not sampled.

Because the support battens used in the trial were impregnated with a copper based preservative (Tanalith E) they could not be used for moisture content measurements due to their electrical conductivity being different to that of untreated timber. Accordingly, the moisture sensors for the battens were fitted into simulated battens made from short lengths of non-preservative-treated Sitka spruce installed across a junction between two boards. The ends of these simulated battens were sealed against moisture using epoxy resin.

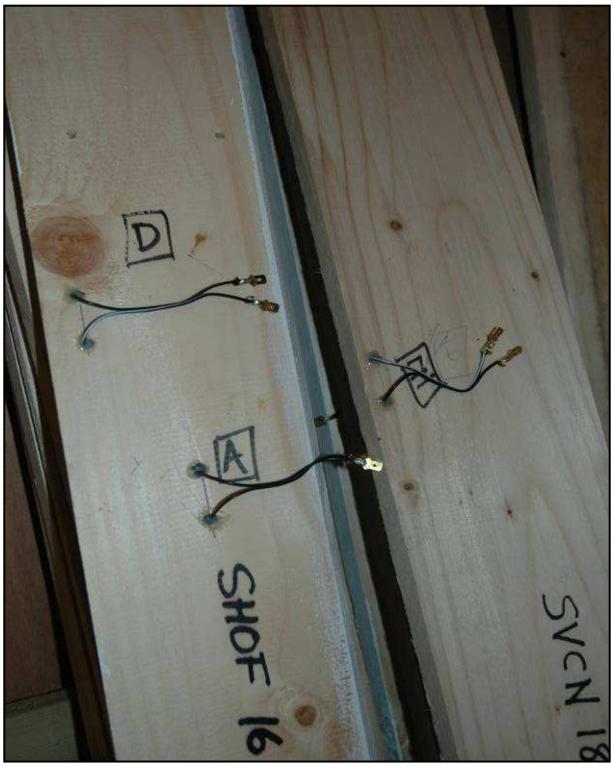


Figure 6.12 *Moisture sensors positioned near a defect, board edge and in clear timber.*

6.2.6 Data collection

At the back of each panel, two data cables were plugged into the datalogger while the other six went via a separate node. The directly connected channels were assigned to the moisture sensors in the support battens with the node taking those for the cladding.

The dataloggers were configured to record from each sensor hourly. The readings were downloaded at approximately two monthly intervals using the Softfox Version 1.2 software supplied by the datalogger manufacturer. To ensure accuracy, moisture content readings were also collected once a year using a freshly calibrated hand-held moisture meter (Protimeter Timbermaster) [26]. The data cables could be connected to the Protimeter by their jack plugs.

6.2.7 Weather data

Each site was equipped with an automatic weather station (Davis Vantage Pro2™) manufactured by Davis Instruments [27]. The stations recorded hourly readings for temperature, rainfall, relative humidity, wind speed and direction, sunshine and ultraviolet radiation. As a back-up against instrument problems, weather data for each area was obtained, under licence, from the nearest operational Met. Office site (Table 6.6.). The station nearest to the Spean Bridge site was approximately 14.5 km (9 miles) east at Tulloch Bridge. At the Inverness site, the nearest weather station from which data was available was approximately 37 km (23 miles) east at RAF Kinloss.

Table 6.6 *Location of the two Met. Office weather stations*

	Tulloch Bridge	Kinloss
Height above mean sea level (m)	237	5
Latitude	56°87´ N	57°65´ N
Longitude	04°71´ W	03°56´ W

6.2.8 Data processing

After downloading, the data were loaded into an MS Office Excel® 2003 spreadsheet for processing. The raw data (x) were converted to electrical resistance readings in megohms (MΩ) using a formula supplied by Scanntronik Mugrauer GmbH (Eq 6.1):

$$R_1 = 1\times10^{-6}\times10^{\left(x_1/10\right)} \tag{6.1}$$

The converted data (R values) were then converted to moisture content w using another formula supplied by the datalogger manufacturer (Eq 6.2):

$$w = 26.034R^{-0.164} \tag{6.2}$$

Resistance-type moisture meters can achieve an accuracy of $\pm$ 2 % at moisture contents between 6 and 25 %. Higher values are only indicative. This can be seen in Figure 6.13 which plots equation 6.2 against moisture content readings obtained whilst drying a sample of Sitka spruce that had been soaked to saturation. The readings were taken by BRE using a moisture sensor installed as above and then read (over a jack-plug connection) using a freshly calibrated Protimeter Timbermaster. The coefficient of determination r^2 was 0.9 indicating that 90 % of the data variability can be explained by the regression. The cause of the outlying data point at 375 MΩ was not investigated.

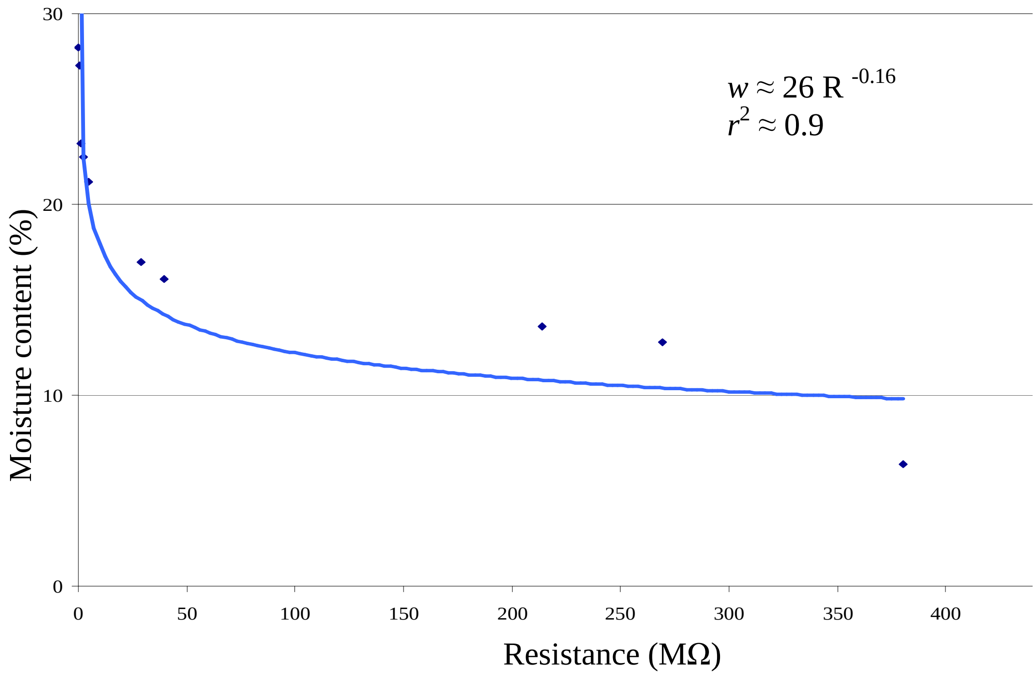


Figure 6.13 *Calibration curve used in the experiment (Data courtesy of BRE)*

6.2.9 Statistics

All data processing and analysis was done in MS-Office Excel® 2003. The statistical tools employed were:

- **Descriptive methods**: these summarise the essential characteristics of the time series using simple graphs and descriptive statistics. Most of the findings from subsequent stages of the analysis were first identified using descriptive methods. They were also useful in highlighting data gaps and other problems.

- **Time series modelling**: the selection of a model and parameter depends upon the characteristics of the time series and the objectives of the analysis. The phenomenon being measured – the duration and intensity of moisture uptake in the timber – is the realisation of one or more random variables that follow a probability distribution. Modelling therefore seeks to specify this distribution based on the data. The technique employed in this trial is a design matrix (Table 6.7), termed the Yates Algorithm [28], where every effect (main or interaction) is calculated as the mean of all results at the high level of the effect minus the mean of all results at the low level. For every effect, half the results are negative and half positive. The matrix is orthogonal and so the estimate of one effect is not affected by changes in the others. A multivariate analysis was undertaken once the effects were estimated. Each effect was squared and divided by 2^n to give the sum of squares corresponding to that effect. The result being expressed as a percent contribution.

- **Predictive methods**; these estimate the future behaviour of the time series using information extracted from the series such as correlations over time. To be a useful as a predictive tool, the correlations need to employ some readily quantifiable intrinsic or extrinsic attribute of the facade, *e.g.* a material property or assembly condition.

- **Signal extraction**: this extracts the underlying signal or other information relevant to the analysis. The signal of most interest concerns how the waveform of each time series varies on diurnal, seasonal and annual bases. This was assessed with annual radar charts and using Fourier analysis to transform data from the most uniform and most varied panel into the frequency domain.

__Table 6.7__ Design matrix used in the trial

Factors															
A	**B**	**AB**	**C**	**AC**	**BC**	**ABC**	**D**	**AD**	**BD**	**ABD**	**CD**	**ACD**	**BCD**	**ABCD**	**Scores are entered in this column**
-	-	+	-	+	+	-	-	+	+	-	+	-	-	+	
+	-	-	-	-	+	+	-	-	+	+	+	+	-	-	
-	+	-	-	+	-	+	-	+	-	+	+	-	+	-	
+	+	+	-	-	-	-	-	-	-	-	+	+	+	+	
-	-	+	+	-	-	+	-	+	+	-	-	+	+	-	
+	-	-	+	+	-	-	-	-	+	+	-	-	+	+	
-	+	-	+	-	+	-	-	+	-	+	-	+	-	+	
+	+	+	+	+	+	+	-	-	-	-	-	-	-	-	
-	-	+	-	+	+	-	+	-	-	+	-	+	+	-	
+	-	-	-	-	+	+	+	+	-	-	-	-	+	+	
-	+	-	-	+	-	+	+	-	+	-	-	+	-	+	
+	+	+	-	-	-	-	+	+	+	+	-	-	-	-	
-	-	+	+	-	-	+	+	-	-	+	+	-	-	+	
+	-	-	+	+	-	-	+	+	-	-	+	+	-	-	
-	+	-	+	-	+	-	+	-	+	-	+	-	+	-	
+	+	+	+	+	+	+	+	+	+	+	+	+	+	+	
Effect estimates are recorded in this row															

6.2.10 Subsidiary exposure trial

In addition to the main exposure trial, a small experiment was undertaken to assess the extent to which the results can be generalised to other timber specie using published physical properties. The literature [29] [30] suggested that the fibre saturation point is the most obvious physical property to use. If this is so, the maximum moisture content of any particular cladding timber will be approximately the same as its FSP, subject to a modification factor accounting for the effects of detailing and other parameters. To investigate this, a small exposure trial (Figure 6.14) was established involving samples of 12 timber species with FSP values ranging from 21% $\leq$ FSP $\leq$ 30%. and initial gravimetric moisture content w = 10%. Each sample measured 110 x 75 x 13 mm. The samples were mounted in a drained and ventilated arrangement similar to external cladding. They were attached to the support batten with one stainless steel screw The design is similar to the EVON and SVON panels in the main exposure trial.

The samples were exposed to the prevailing weather in the author's garden, 11 km (7 miles) east of Inverness (location: 57º 32´ N, 4º 00´ W, grid reference: NH 8026 5212, height above mean sea level 37 m). Using a hand held moisture meter (Protimeter Timbermaster), daily moisture content readings were taken either in the late afternoon or about three hours after rain. The trial initially ran for two months (April – May 2010). The set-up was then altered to use permanently installed moisture sensors made to the design already outlined. The other ends of the co-axial cables were fitted with jack plugs for connection to a Protimeter. This trial ran for a further two months (July – August 2010). As before the readings were taken daily, in the late afternoon or a few hours after rain.

Figure 6.14 *Front view of the subsidiary exposure trial, the overall dimensions were 1010 x 154 mm*

6.3 Results

These results cover three topics: timber, the exposure trial and the subsidiary trial.

6.3.1 Timber quality

Although the experiment did not set out to assess timber grading, the process of board selection and processing highlighted two points. Firstly, the presence of large knots and areas of cross grain meant that almost 70% of the boards could only achieve grade VI, (the lowest acceptable in the S/F category); the remainder were grade V. Non-intergrown knots were the most common reason a board was downgraded. Secondly, when the graded timber was being machined, the inner part of many intergrown knots tended to become detached. This zone typically occupied the inner four growth rings and had a diameter of about 8 mm. The detached portion of the knot usually fell out, but in some cases it only slid partway through the board creating a projecting peg that got caught in the planer or spindle moulder (Figures 6.15 and 6.16). About 15% of boards were thus affected.

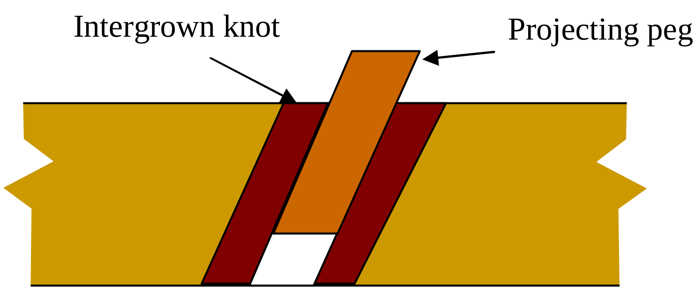


Figure 6.15 *Diagram of an intergrown knot with the central detached portion forming a peg*

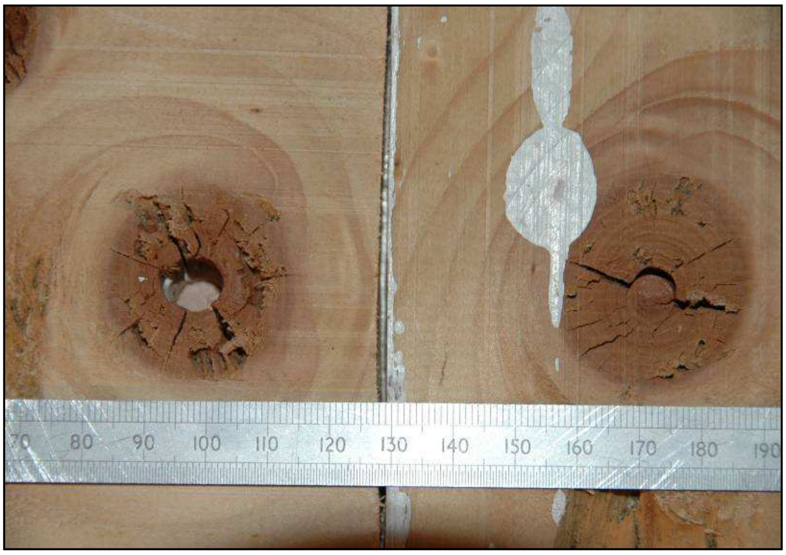


Figure 6.16 *Two intergrown knots showing how the centre breaks and can become detached.*

6.3.2 Main exposure trial

The results, in terms of moisture content *w versus* time *t,* are described according to the type of statistics used.

6.3.2.1 Descriptive statistics

In general, 10% ≤ *w* ≤ 30%, although there was considerable variation between panels. Five panels remained relatively dry (*w* ≤ 25% for at least 90% of the trial): four of these (EHOF, EVOF, SHOF and SVOF) were open-jointed with a front coating, whilst the fifth (EVCF) was on the wet site and comprised vertical closed jointed cladding with a front coating. Eleven panels were wet between November and late March. Figure 6.17 illustrates the most obvious differences between the two groups. Figures 6.18 and 6.19 show three-year moisture graphs for the 16 test panels.

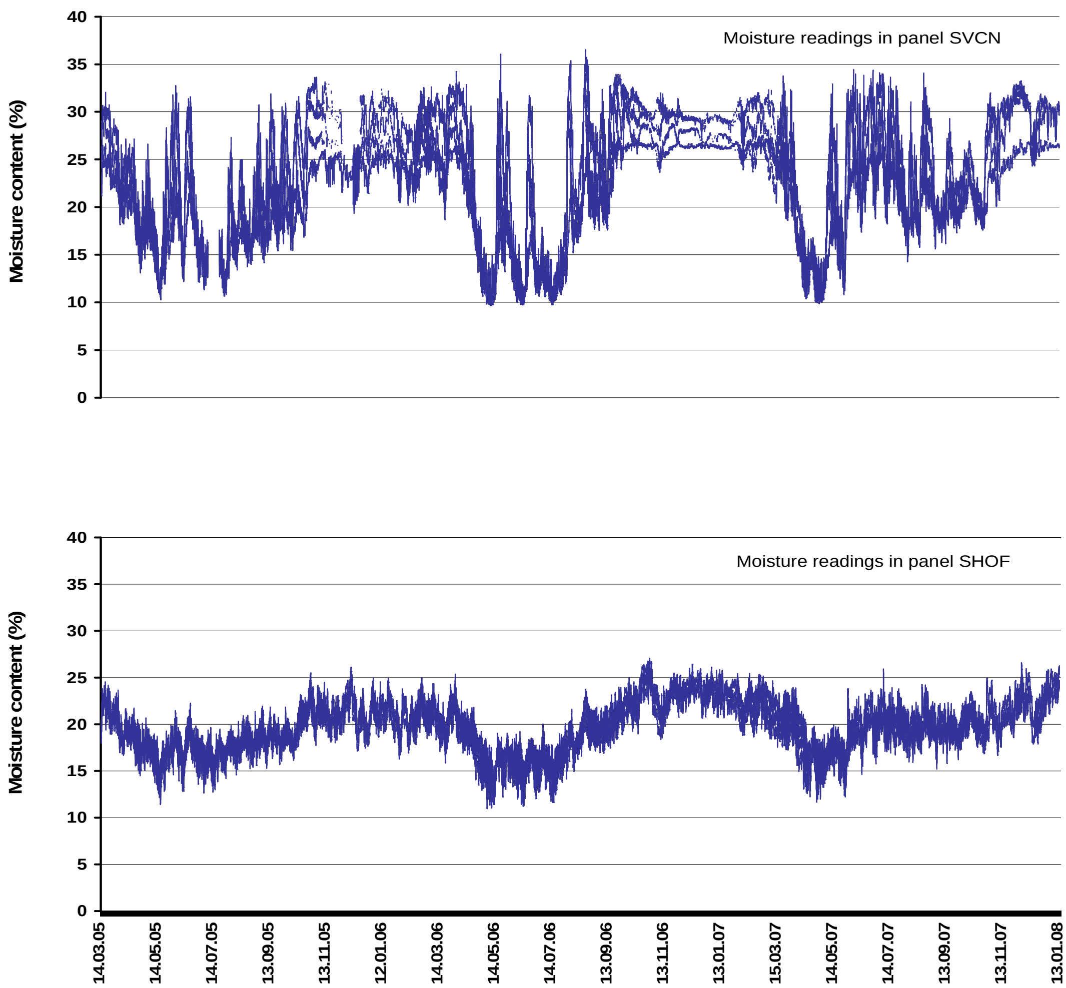


Figure 6.17 *Moisture curves for the wettest and driest panels on the Balloch site*

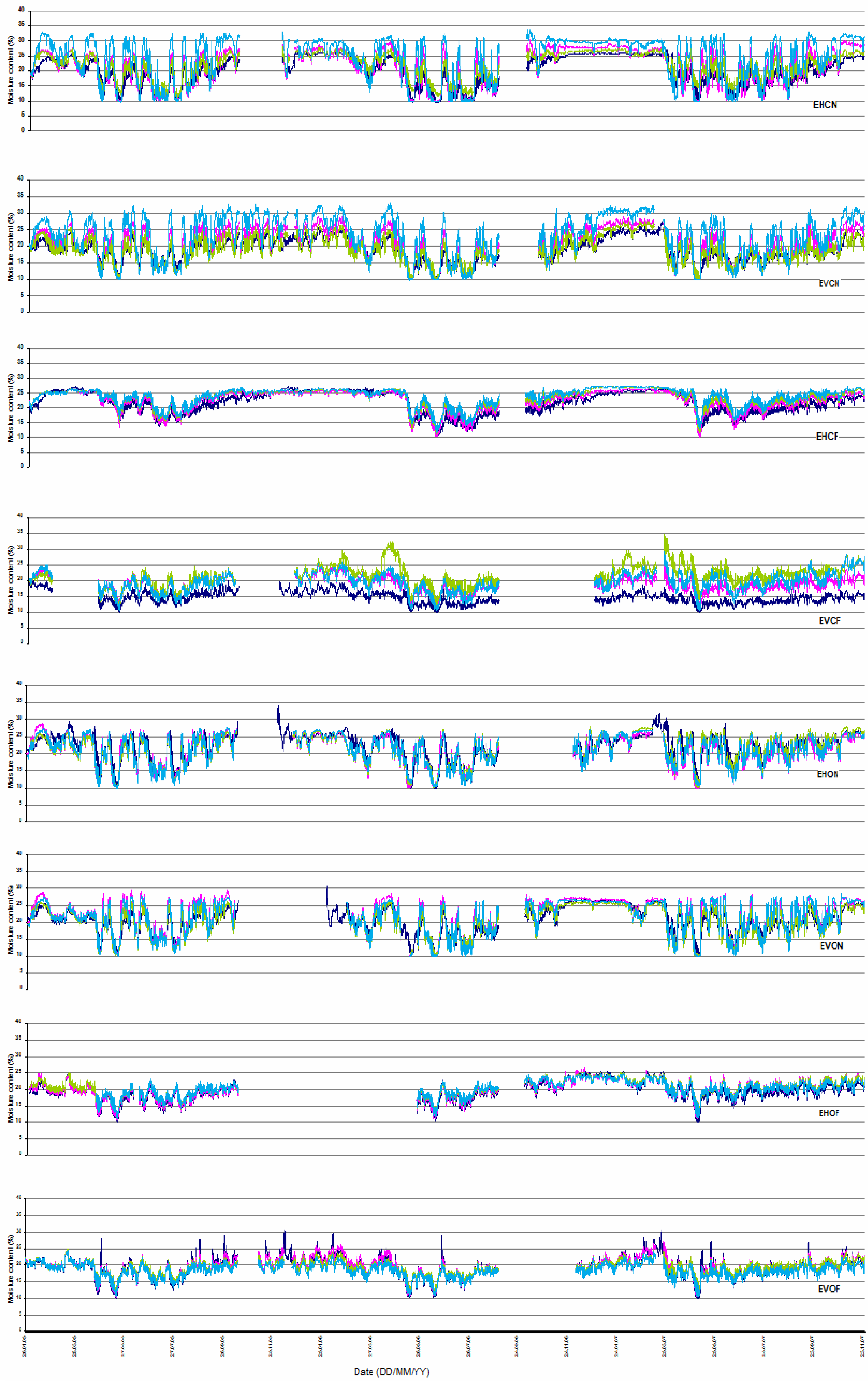


Figure 6.18 *Three-year graphs for the Spean Bridge site*

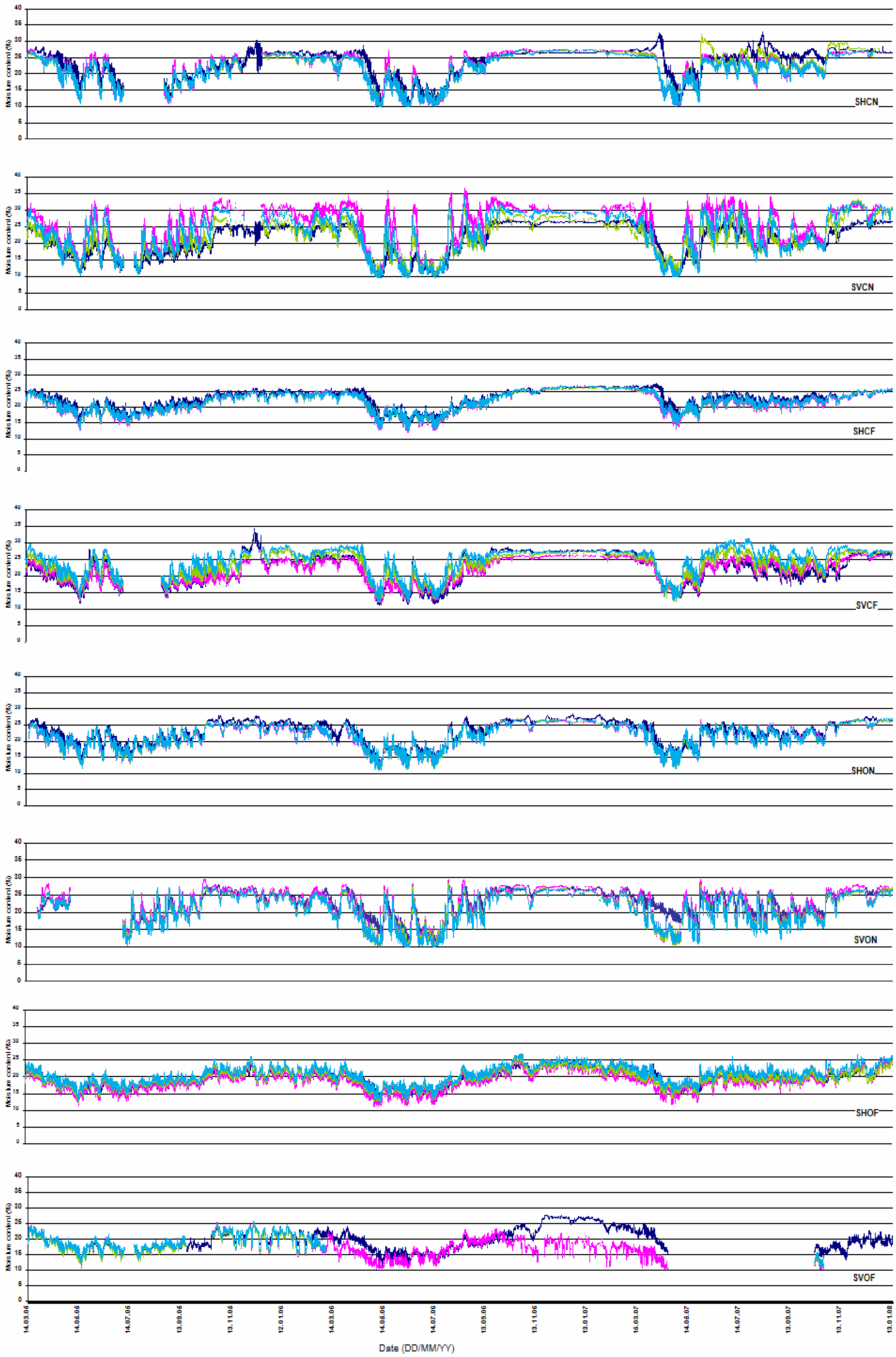


Figure 6.19 *Three-year graphs for the Inverness site*

6.3.2.2 Missing data

It is apparent from Figures 6.18 and 6.19 that there were a number of gaps in the data series. These occurred because of several factors:

- In a few cases a moisture sensor or connection failed. Most of these problems could not be resolved without dismantling the panel, which ran the risk of damaging other components. Consequently, these failures were usually not repairable.

- The two channels with direct connections to the datalogger gave few problems but those through the nodes experienced frequent signal losses. The gaps were usually less than six hours duration although they sometimes continued until the data were next downloaded.

- There were also periods when no data were recorded from a panel due to battery failures. This was most frequent on the Spean Bridge site during cold weather.

- Downloading the data often caused power surges, resulting in signal spikes.

- Most of the dataloggers experienced intermittent faults whereby the actual readings were over-written by repeat sections of existing data. This was the most serious problem as it was not spotted until all of the data had been collected and graphed. In the worst case this resulted in two months of data being lost.

A further problem occurred with the climate data. Both weather stations had gaps in their data due to battery failures. In addition, the Leanachan station experienced breakdowns due to low temperatures or snow; whilst low temperatures and blockages by leaves were problems at Balloch. The breakdowns due to temperature could only have been solved by running the stations from mains power, which, given the site locations, was impossible. Unfortunately the intact portions of the moisture content and weather station data rarely coincided. In view of this, the author tried to use the back-up climate data from the two Met. Office stations as this was almost complete. Originally it was intended to use data from a Met. Office station 2 km southwest of the Leanachan test site but this was impossible as that station also experienced frequent breakdowns. The station that was used was in a more sheltered position. The distances involved meant that the data could not reliably be temperature corrected and so this step was omitted.

Two following data interpolation methods were employed. Firstly, where only some of the channels were missing data, those remaining were used to infill the gaps. Each missing value was interpolated from the known data value for that hour, plus or minus the difference between the last known value for the missing data and the value at that same hour in the complete data series (Tables 6.8 and 6.9). Secondly, where all eight channels had missing data, gaps of up to 12 hours were infilled by linear interpolation but longer gaps were left empty. These gaps generally affected between 3% to 17% of data series for a panel. However, in one case (SVOF) around 35% of the data were missing. The implications of this data loss are considered in section 6.4.1 below.

Table 6.8 *Interpolation method where at least one channel is complete*
(Cells with complete values are shaded yellow; those with missing values are shaded green with the interpolation formulae shown).

	A	B	C	D
1				
2		= (A2 + (B1 - A1))	= (A2 + (C1 - A1))	= (A2 + (D1 - A1))
3		= (A3 + (B1 - A1))	= (A3 + (C1 - A1))	= (A3 + (D1 - A1))
4		= (A4 + (B1 - A1))	= (A4 + (C1 - A1))	= (A4 + (D1 - A1))
5				

Table 6.9 *Worked example using the formulae in Table 6.8*

	A	B	C	D
1	24.70	32.89	27.13	30.60
2	24.78	32.98	27.21	30.69
3	24.87	33.06	27.30	30.77
4	22.43	30.62	24.86	28.34
5	24.98	32.86	27.35	30.74

Table 6.9 confirms that the interpolation formula is adequate wherever the missing data series fluctuate approximately in proportion to the known data. If the series diverged (*e.g.* during a gap of a month or more) then the difference was split into two. The top half was treated as described above, with the second half being infilled backwards from the first complete value after the gap. As a final check the interpolations were plotted as a graph and were only accepted if there were no obvious discontinuities. All interpolated data points are highlighted in the accompanying CD-ROM.

6.3.2.3 Ranking using the descriptive data

To get an initial feel for the data, the gaps in each series were removed to create a continuous dataset for each panel; some of the resultant datasets spanned around 25,000 hours (almost three years), whilst the shortest was only 8,000 hours (under one year). The datasets were ranked to show the durations for which each test panel experienced $w > 22\%$ and $w > 25\%$ ($t_{w > 22\%}$ and $t_{w > 25\%}$ respectively). The actual moisture contents during these periods were expressed as averages of all positions on the boards along with the corresponding value in the support battens behind the cladding (Table 6.10 and 6.11). The means for boards and battens tended to be similar, as demonstrated by their Pearson's rank correlation coefficient r of 0.81. An r value around 0.8 indicates a positive linear dependence between the variables. Tables 6.12 and 6.13 compare the maximum duration of wetting for each sensor location (board centres, board defects, board edges and support battens). Figures 7 and 8 show the relative frequency of moisture contents averaged at each sensor location (edges, clear timber, defects and battens). Tables 6.14 to 6.16 highlight the panels with modal moisture contents below 22%, below 25% and over 25%. Several points emerge from these data:

i) Five panels remained relatively dry throughout: four (EHOF, EVOF, SHOF and SVOF) were open-jointed and coated, the fifth (EVCF) was on the exposed site and comprised vertical, closed-jointed, coated cladding. Eleven panels were wet between November and late March.

ii) Most panels experienced similar moisture conditions on both sites. The exceptions being the four with vertical closed joints: EVCF, EVCN SVCF and SVCN.

iii) Most panels had a non-Gaussian data distribution skewed towards their maximum values. The exceptions were the four panels with open joints and front coatings (EHOF, EVOF, SHOF and SVOF) and the two exposed panels with vertical closed joints (EVCF and EVCN).

iv) No sensor locations in the cladding boards were consistently wetter than the others.

v) The support battens were generally as wet as the boards although there was a lag effect in both wetting and drying cycles.

Table 6.10 *Percentage of time when moisture contents were over 22% on the exposed site (ranked by board average)*

Type of cladding			Board Average (% time)	Battens (% time)
Board orientation	Type of joint	Surface coating		
Vertical	Open	Front	14	20
Vertical	Closed	Front	35	0
Horizontal	Open	Front	41	30
Vertical	Closed	None	49	26
Vertical	Open	None	56	43
Horizontal	Open	None	58	66
Horizontal	Closed	None	62	47
Horizontal	Closed	Front	78	61
			r = 0.77	

Table 6.11 *Percentage of time when moisture contents were over 22% on the sheltered site (ranked by board average)*

Type of cladding			Board Average (% time)	Battens (% time)
Board orientation	Type of joint	Surface coating		
Vertical	Open	Front	28	34
Horizontal	Open	Front	32	33
Vertical	Open	None	59	67
Horizontal	Closed	Front	61	70
Horizontal	Open	None	61	69
Vertical	Closed	None	63	51
Horizontal	Closed	None	65	74
Vertical	Closed	Front	70	55
			r = 0.81	

Table 6.12 *Percentage of time when moisture contents were over 25% on the exposed site (ranked by board average)*

Type of cladding			Board Average (% time)	Battens (% time)
Board orientation	Type of joint	Surface coating		
Vertical	Open	Front	1	3
Horizontal	Open	Front	5	8
Vertical	Closed	Front	8	0
Vertical	Closed	None	32	7
Horizontal	Open	None	33	37
Vertical	Open	None	36	21
Horizontal	Closed	None	49	30
Horizontal	Closed	Front	55	38
			r = 0.84	

Table 6.13*Percentage of time when moisture contents were over 25% on the sheltered site (ranked by board average)*

Type of cladding			Board Average (% time)	Battens (% time)
Board orientation	Type of joint	Surface coating		
Vertical	Open	Front	2	1
Horizontal	Open	Front	5	4
Horizontal	Closed	Front	27	35
Horizontal	Open	None	35	45
Vertical	Open	None	38	45
Horizontal	Closed	None	45	62
Vertical	Closed	None	51	33
Vertical	Closed	Front	52	35
			r = 0.80	

Table 6.14 Percentage of time when moisture contents were over 22%

Type of cladding			Exposed Site				Sheltered Site			
Board orientation	Type of joint	Surface coating	Battens	Edges	Clear	Defects	Battens	Edges	Clear	Defects
Horizontal	Open	Front	30	39	43	42	33	20	30	47
		None	66	56	60	58	69	61	61	62
	Closed	Front	61	72	79	82	70	58	61	63
		None	47	58	60	69	74	66	66	64
Vertical	Open	Front	20	23	14	5	34	28	25	30
		None	43	60	50	58	67	62	57	57
	Closed	Front	0	18	56	31	55	59	71	80
		None	26	51	31	65	51	73	52	63

Table 6.15 Percentage of time when moisture contents were over 25%

Type of cladding			Exposed Site				Sheltered Site			
Board orientation	Type of joint	Surface coating	Battens	Edges	Clear	Defects	Battens	Edges	Clear	Defects
Horizontal	Open	Front	8	5	5	4	4	2	3	11
		None	37	29	34	35	45	33	35	35
	Closed	Front	38	46	56	62	35	26	27	27
		None	30	45	40	62	62	48	46	42
Vertical	Open	Front	3	2	0	0	1	3	1	3
		None	21	41	26	40	45	43	35	35
	Closed	Front	0	1	18	6	35	36	53	66
		None	7	32	12	51	33	64	37	51

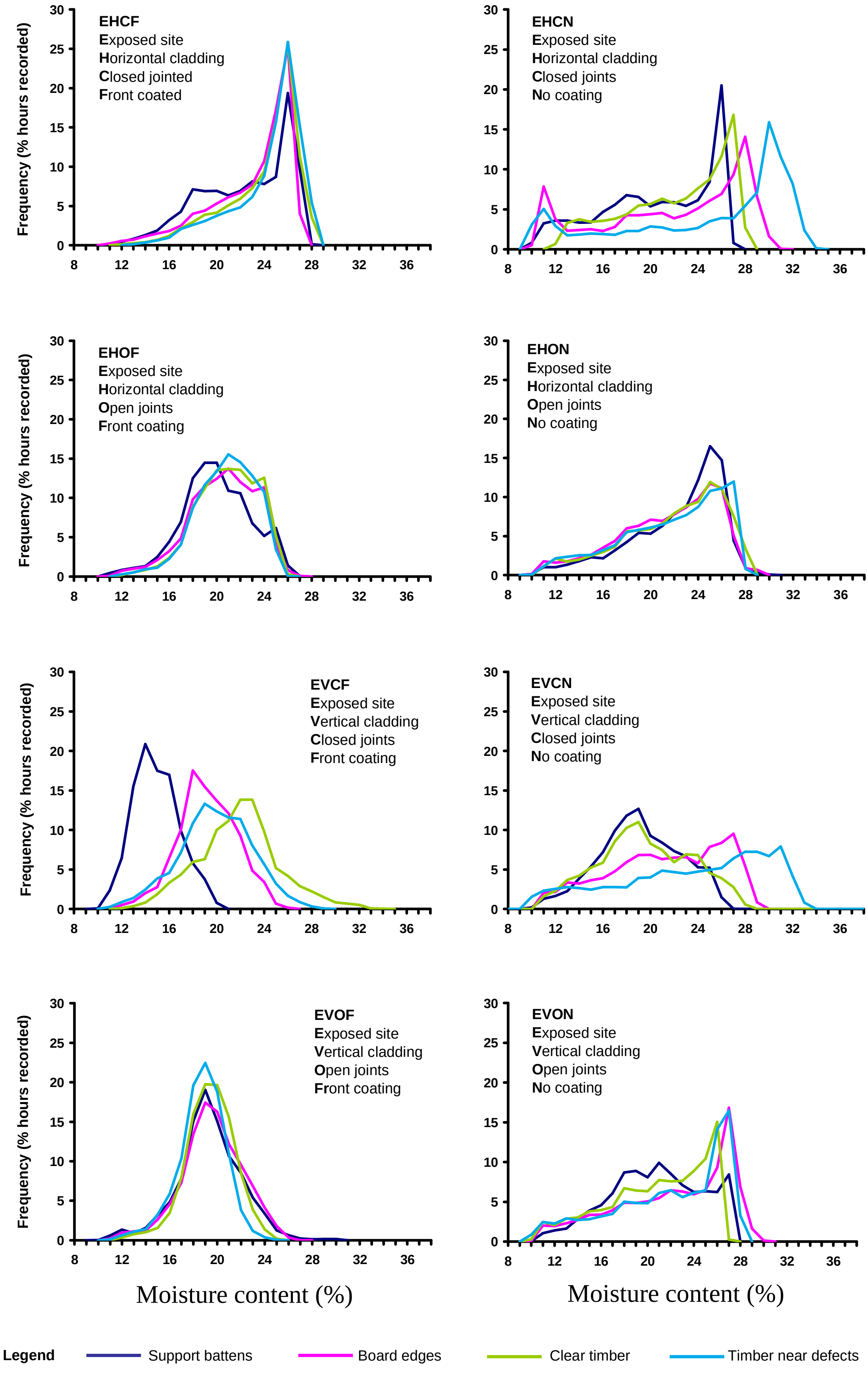


Figure 6.20 *Frequency curves showing the duration of time each panel was at a specific moisture content on the exposed site*

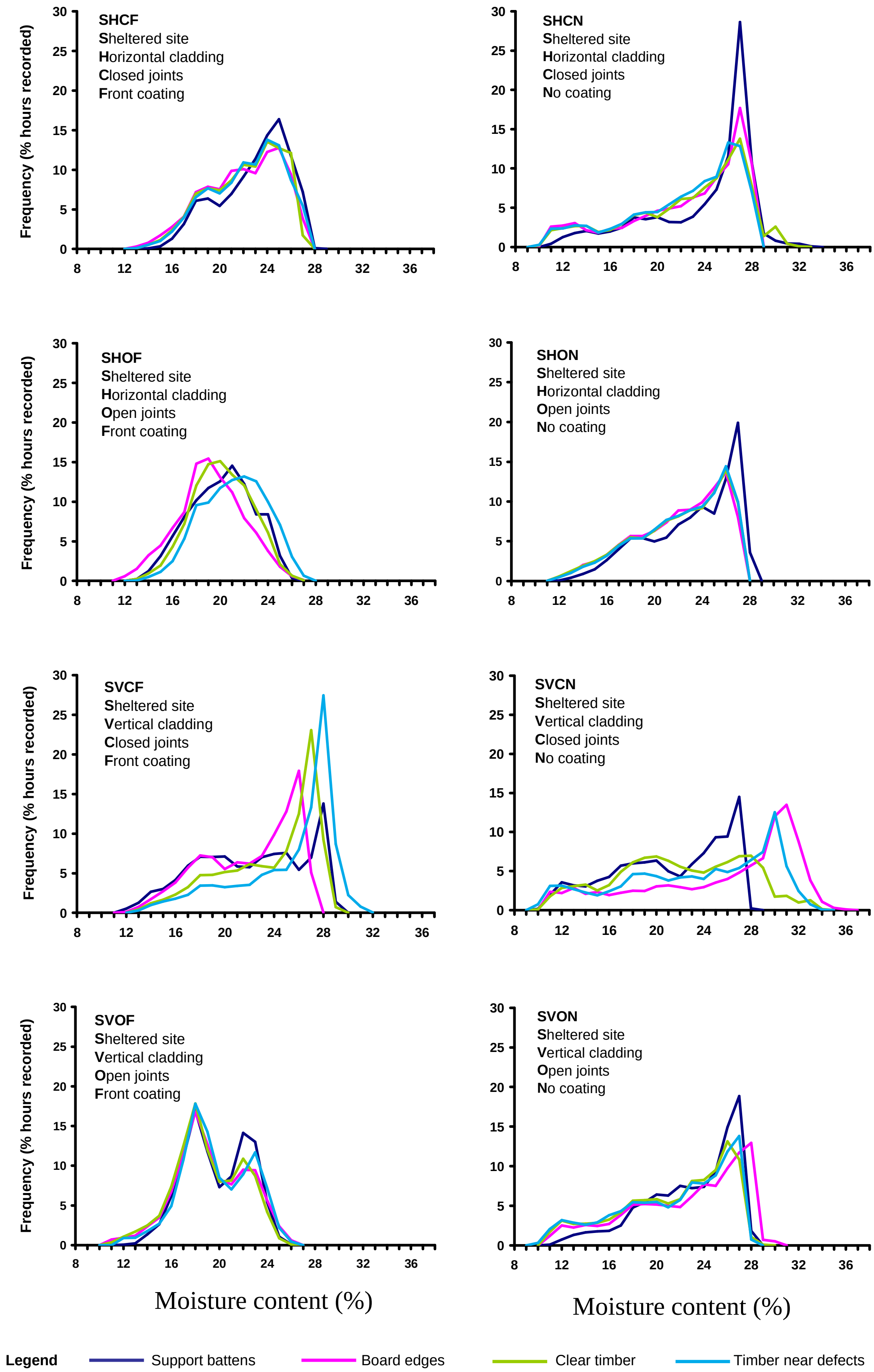


__Figure 6.21__ Frequency curves showing the duration of time each panel was at a specific moisture content on the sheltered site

Table 6.16 Moisture contents

Site	Board orientation	Type of joint	Surface coating	MEAN	MODE	MEDIAN	MAX.	MIN.	RANGE
Boards									
EXPOSED SITE	Horizontal	Open	Front	20	24	20	26	11	15
EXPOSED SITE	Horizontal	Open	None	21	26	22	28	10	18
EXPOSED SITE	Horizontal	Closed	Front	23	26	24	27	11	16
EXPOSED SITE	Horizontal	Closed	None	22	28	24	31	10	21
EXPOSED SITE	Vertical	Open	Front	19	18	19	25	10	15
EXPOSED SITE	Vertical	Open	None	21	26	22	28	10	18
EXPOSED SITE	Vertical	Closed	Front	20	19	20	30	11	19
EXPOSED SITE	Vertical	Closed	None	21	27	21	30	10	20
SHELTERED SITE	Horizontal	Open	Front	20	21	20	26	12	14
SHELTERED SITE	Horizontal	Open	None	22	26	22	27	11	16
SHELTERED SITE	Horizontal	Closed	Front	22	26	22	27	12	15
SHELTERED SITE	Horizontal	Closed	None	22	27	23	29	10	19
SHELTERED SITE	Vertical	Open	Front	19	22	18	25	11	15
SHELTERED SITE	Vertical	Open	None	21	27	22	29	10	19
SHELTERED SITE	Vertical	Closed	Front	23	27	24	29	12	17
SHELTERED SITE	Vertical	Closed	None	23	29	24	35	10	25
Battens									
EXPOSED SITE	Horizontal	Open	Front	19	19	19	26	10	16
EXPOSED SITE	Horizontal	Open	None	22	25	23	30	10	21
EXPOSED SITE	Horizontal	Closed	Front	22	25	22	27	10	17
EXPOSED SITE	Horizontal	Closed	None	20	26	21	27	9	18
EXPOSED SITE	Vertical	Open	Front	19	18	19	30	10	20
EXPOSED SITE	Vertical	Open	None	20	26	20	27	10	17
EXPOSED SITE	Vertical	Closed	Front	14	16	14	20	10	10
EXPOSED SITE	Vertical	Closed	None	19	18	18	26	10	17
SHELTERED SITE	Horizontal	Open	Front	19	18	20	26	12	14
SHELTERED SITE	Horizontal	Open	None	23	26	23	28	11	17
SHELTERED SITE	Horizontal	Closed	Front	22	26	23	27	13	14
SHELTERED SITE	Horizontal	Closed	None	23	26	25	33	10	23
SHELTERED SITE	Vertical	Open	Front	19	18	19	25	11	14
SHELTERED SITE	Vertical	Open	None	22	26	23	28	11	17
SHELTERED SITE	Vertical	Closed	Front	22	27	22	29	11	18
SHELTERED SITE	Vertical	Closed	None	21	26	21	27	10	18

Key

- Mode ≤ 22%
- Mode ≤ 25%
- Mode > 25%

6.3.2.4 Time series modelling

Due to the gaps previously outlined, it was impossible to construct complete three year time series for either site. Five periods were identified where continuous data existed for all 16 panels; two of these are analysed below. These comprise:

- Summer (22 May to 20 September 2006, see Figure 6.22)
- Winter (26 December 2006 to 20 April 2007, see Figure 6.23)

As above, the data were analysed against the minimum moisture content needed to support fungal decay *i.e.* w > 22% or w > 25%. The significance of these thresholds has been discussed in section 6.1.2.

The hourly frequency at each moisture content was determined (Tables 6.17. and 6.19) and a chi squared test undertaken (Tables 6.18 and 6.20). The null hypothesis being that each factor had no effect on moisture content. A chi squared test assumes that all values are five or higher and so to meet this requirement the frequency totals for moisture contents of 14 or fewer were added, so too the totals for 22 or more; these data are highlighted in yellow. The chi squared (χ^2) values range from 130 to 17896 with seven degrees of freedom. The two-tailed P values are less than 0.0001 which, by conventional criteria, can be considered extremely statistically significant. The null hypothesis is therefore rejected. It is also notable that the moisture content ranges in the panels with a front coating were lower than the equivalent uncoated panels. The multivariate analysis is shown in Tables 6.22 and 6.23. Tables 6.23 and 6.24 rank these results in terms of the contribution of each factor and factor combination. Those that are statistically significant (at the 95 % level) are highlighted in yellow. These two tables reinforce and quantify the effects already noted from the descriptive statistics (section 6.3.2.3). Namely:

- the combination of open joints and front coatings result in the driest conditions
- vertical, front-coated boards were dry on the exposed site but wet on the sheltered.

It is notable that 76% to 80% of the data's variance is encapsulated by the factor combinations: SV, SF, OF, SVO and F in summer, and: SVF, VF, V, O and F in winter.

Table 6.17 *Moisture content frequencies – exposed site (summer 2006)*

Moisture content (%)	Frequency (hours) at each moisture content							
	EHCF	EHCN	EHOF	EHON	EVCF	EVCN	EVOF	EVON
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	7
11	0	306	0	87	0	214	2	186
12	25	412	13	127	23	203	44	114
13	65	154	39	88	66	251	51	176
14	93	121	38	143	110	192	71	178
≤ 14	183	993	90	445	199	860	168	661
15	153	107	81	203	183	169	156	180
16	183	93	125	188	256	146	254	161
17	183	92	208	147	385	155	509	170
18	212	81	537	219	427	159	547	153
19	258	71	377	167	434	165	330	156
20	302	92	367	137	194	114	130	133
21	344	110	225	154	69	106	49	94
≥ 22	337	516	145	495	8	281	12	447
22	219	80	126	99	8	101	12	65
23	94	56	19	103	0	52	0	86
24	22	69	0	108	0	59	0	96
25	2	76	0	119	0	56	0	99
26	0	74	0	37	0	13	0	85
27	0	94	0	29	0	0	0	16
28	0	53	0	0	0	0	0	0
29	0	14	0	0	0	0	0	0
30	0	0	0	0	0	0	0	0
31	0	0	0	0	0	0	0	0
32	0	0	0	0	0	0	0	0
33	0	0	0	0	0	0	0	0
34	0	0	0	0	0	0	0	0
35	0	0	0	0	0	0	0	0

Table 6.18 *Chi squared test for each factor on the exposed site (summer 2006)*

	A	B	χ^2 $((A - B)^2)/B$
Closed or open joints	EHCN	EHON	367
	EVCN	EVON	130
	EHCF	EHOF	753
	EVCF	EVOF	141
No coating or front coating	EHCN	EHCF	4305
	EVCN	EVCF	12085
	EHON	EHOF	2950
	EVON	EVOF	17896
Horizontal or vertical boards	EHCN	EVCN	381
	EHON	EVON	154
	EHCF	EVCF	14999
	EHOF	EVOF	2861

Table 6.19 *Moisture content frequencies – sheltered site (summer 2006)*

Frequency (hours) at each moisture content

Moisture content (%)	SHCF	SHCN	SHOF	SHON	SVCF	SVCN	SVOF	SVON
9	0	0	0	0	0	0	0	0
10	0	33	0	0	0	83	0	67
11	0	264	0	0	0	331	13	364
12	0	274	0	39	0	274	171	287
13	16	263	4	88	19	244	302	249
14	82	246	42	142	102	158	307	174
≤ 14	98	1080	46	269	121	1090	793	1141
15	136	113	126	215	149	82	289	137
16	223	143	285	283	185	75	293	127
17	437	123	484	352	208	141	269	115
18	519	188	622	279	235	170	223	103
19	394	194	290	194	195	111	169	54
20	189	100	182	139	185	85	72	83
21	89	57	55	124	149	47	15	79
≥ 22	70	157	65	300	728	354	32	316
22	51	75	28	90	107	20	17	75
23	19	47	37	70	169	77	15	58
24	0	27	0	64	148	49	0	35
25	0	8	0	50	72	31	0	22
26	0	0	0	26	99	9	0	41
27	0	0	0	0	100	22	0	63
28	0	0	0	0	33	26	0	22
29	0	0	0	0	0	18	0	0
30	0	0	0	0	0	34	0	0
31	0	0	0	0	0	33	0	0
32	0	0	0	0	0	20	0	0
33	0	0	0	0	0	8	0	0
34	0	0	0	0	0	7	0	0
35	0	0	0	0	0	0	0	0

Table 6.20 *Chi squared test for each factor on the sheltered site (summer 2006)*

	A	B	χ^2 $((A - B)^2)/B$
Closed or open joints	SHCN	SHON	533
	SVCN	SVON	173
	SHCF	SHOF	154
	SVCF	SVOF	17208
No coating or front coating	SHCN	SHCF	10572
	SVCN	SVCF	8247
	SHON	SHOF	2347
	SVON	SVOF	3353
Horizontal or vertical boards	SHCN	SVCN	254
	SHON	SVON	2119
	SHCF	SVCF	1431
	SHOF	SVOF	2077

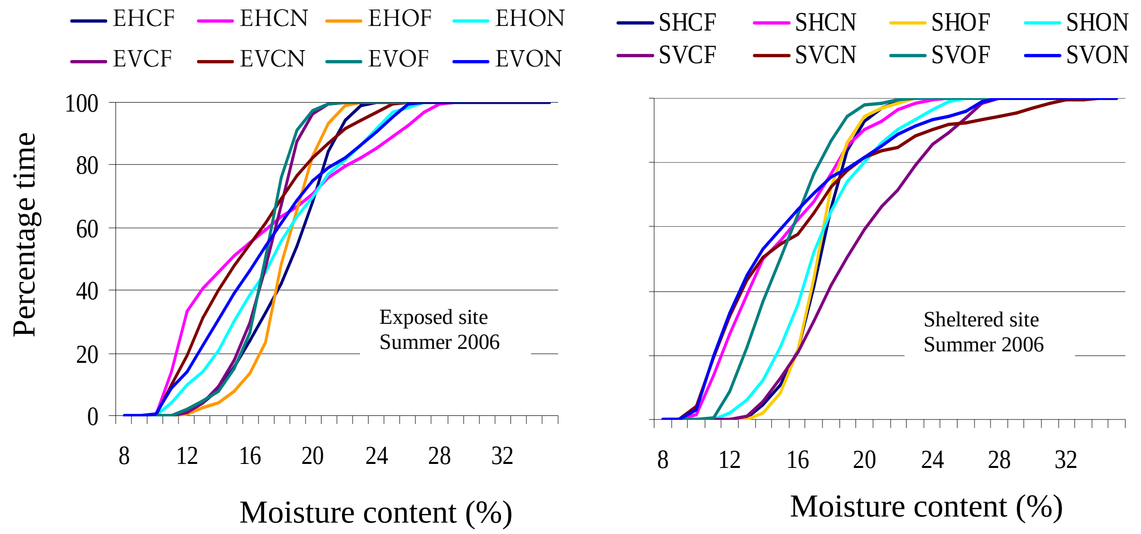


***Figure 6.22** Cumulative frequency for mean MC in boards during the summer (22 May to 20 Sept. 2006).*

***Table 6.21** Percentage time when moisture content (%) in boards ≥ 22%*

Effects and interactions in panels during the summer (22 May to 20 Sept. 2006)

Panel code	Label	% time when MC ≥ 22 %	Effect estimate	Sum of squares	Percent contribution of factor or combination
EHCN	(1)	23.94	-	-	-
EVCN	A	13.04	0.54	1.16	0.08
EHON	B	22.97	-3.71	54.95	3.81
EHCF	C	15.64	-8.52	290.42	20.16
SHCN	D	7.29	-1.27	6.45	0.45
EVON	AB	20.74	-2.84	32.18	2.23
EVCF	AC	0.37	1.35	7.31	0.51
SVCN	AD	16.43	9.18	337.25	23.41
EHOF	BC	6.73	-6.61	174.60	12.12
SHON	BD	14.66	-3.21	41.16	2.86
SHCF	CD	3.25	5.83	135.93	9.44
EVOF	ABC	0.56	-2.91	33.78	2.34
SVON	ABD	14.66	-7.28	211.97	14.71
SVCF	ACD	33.78	3.43	47.01	3.26
SHOF	BCD	3.02	-2.74	30.11	2.09
SVOF	ABCD	1.48	-3.01	36.25	2.52

Mean % time when MC ≥ 22%	12.4	Standard deviation	4.84
Degrees of freedom	15	Observations	16
Significance level (at P = 95%)	2.36	Confidence interval of effect estimate	± 5.72

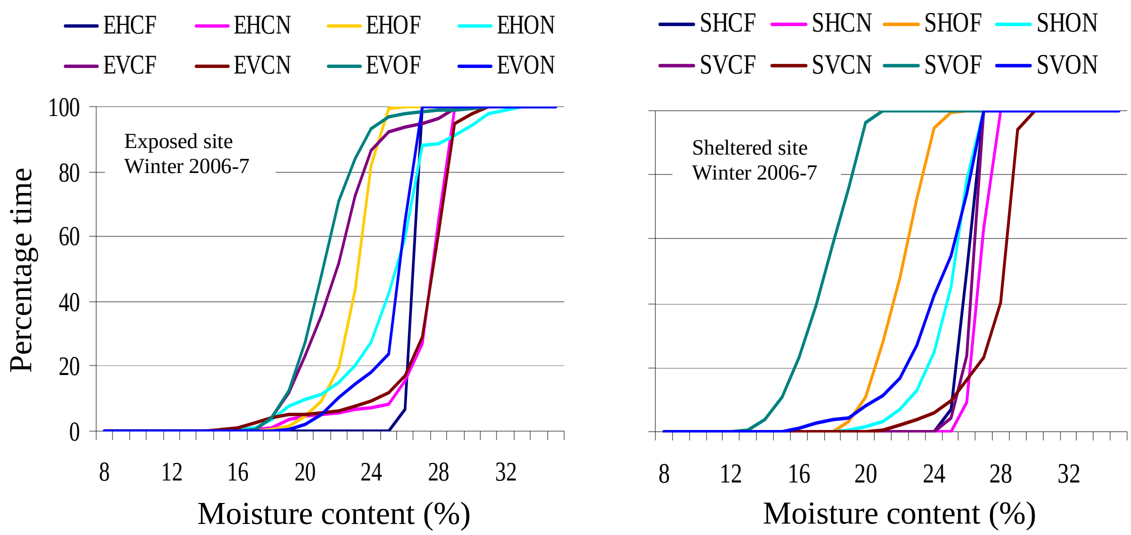


Figure 6.23 *Cumulative frequency for MC in boards during the winter (26 Dec. 06 to 20 Apr. 2007)*

Table 6.22 *Percentage time when moisture content (%) in boards ≥ 22%*

Effects and interactions in panels during the winter (26 Dec. 2006 to 20 Apr. 2007).

Panel code	Label	% time when MC ≥ 22%	Effect estimate	Sum of squares	Percent contribution of factor or combination
EHCN	1	94.80	-	-	-
EVCN	A	94.23	-9.67	373.72	11.34
EHON	B	88.47	-12.21	596.38	18.09
EHCF	C	100.00	-13.27	704.36	21.37
SHCN	D	99.96	6.21	154.47	4.69
EVON	AB	94.89	-0.47	0.88	0.03
EVCF	AC	64.35	-8.93	319.26	9.69
SVCN	AD	99.39	7.47	223.23	6.77
EHOF	BC	90.48	-7.24	209.74	6.36
SHON	BD	88.47	-5.25	110.39	3.35
SHCF	CD	99.96	3.19	40.69	1.23
EVOF	ABC	51.73	-0.31	0.37	0.01
SVON	ABD	88.47	-1.44	8.31	0.25
SVCF	ACD	99.96	11.13	495.46	15.03
SHOF	BCD	72.13	-3.12	39.03	1.18
SVOF	ABCD	72.13	2.22	19.66	0.60

Mean % time when MC ≥ 22%	88.0	Standard deviation	7.35
Degrees of freedom	15	Observations	16
Significance level (at P = 95%)	2.36	Confidence interval of effect estimate	8.68

Table 6.23 *Ranking of factors and interactions during summer 2006*

Panel	Effect estimate	Percent contribution	Factor at high level
SVCN	9.18	23.41	Site, orientation
SHCF	5.83	9.44	Site, coating
SVCF	3.43	3.26	
EVCF	1.35	0.51	
EVCN	0.54	0.08	
EHCN	0.00	0.00	
SHCN	-1.27	0.45	
SHOF	-2.74	2.09	
EVON	-2.84	2.23	
EVOF	-2.91	2.34	
SVOF	-3.01	2.52	
SHON	-3.21	2.86	
EHON	-3.71	3.81	
EHOF	-6.61	12.12	Joint, coating
SVON	-7.28	14.71	Site, orientation, joint
EHCF	-8.52	20.16	Coating
		79.84	% of variance encapsulated (at P = 0.05)

Wetter

Statistically significant at the 95% level

Drier

Table 6.24 *Ranking of factors and interactions during winter 2006-07*

Panel	Effect estimate	Percent contribution	Factor at high level
SVCF	11.13	15.03	Site, orientation, coating
SVCN	7.47	6.77	
SHCN	6.21	4.69	
SHCF	3.19	1.23	
SVOF	2.22	0.60	
EHCN	0.00	0.00	
EVOF	-0.31	0.01	
EVON	-0.47	0.03	
SVON	-1.44	0.25	
SHOF	-3.12	1.18	
SHON	-5.25	3.35	
EHOF	-7.24	6.36	
EVCF	-8.93	9.69	Orientation, coating
EVCN	-9.67	11.34	Orientation
EHON	-12.21	18.09	Joint
EHCF	-13.27	21.37	Coating
		75.52	% of variance encapsulated (at P = 0.05)

Wetter

Statistically significant at the 95% level

Drier

6.3.2.5 Prediction of maximum moisture content

The mini-exposure trial assesses if the results of the main exposure trial can be generalised to other species. Table 6.25 gives the results of the mini-trial plotted as the average of the five maximum moisture content readings for each timber sample against the FSP for the species involved. The data are ranked by the ratio of their moisture content to fibre saturation point. Figure 6.24 gives these results as a scatter plot.

Table 6.25 *Timbers used in the mini exposure trial showing their FSP and maximum moisture content (mean of the highest five readings) ranked by their MC/FSP ratio*

	FSP (%)	MC (%)	MC/FSP
Keruing (*Dipterocarpus* spp.)	30	14	0.47
Afrormosia (*Pericopsis eleta*)	22	11	0.50
European redwood (*Pinus sylvestris*)	30	17	0.52
European oak (*Quercus petraea, Q. robur*)	30	17	0.57
Douglas fir (*Pseudotsuga menziesii*)	28	16	0.58
Iroko (*Chlorophora excelsa*)	21	12	0.59
Teak (*Tectona grandis*)	22	14	0.62
European larch (*Larix decidua*)	29	18	0.63
Greenheart (*Ocotea rodiaei*)	25	16	0.63
Western red cedar (*Thuja plicata*)	23	16	0.69
Sapele (*Entandrophragma cylindricum*)	29	20	0.70
Sitka spruce (*Picea sitchensis*)	29	21	0.71

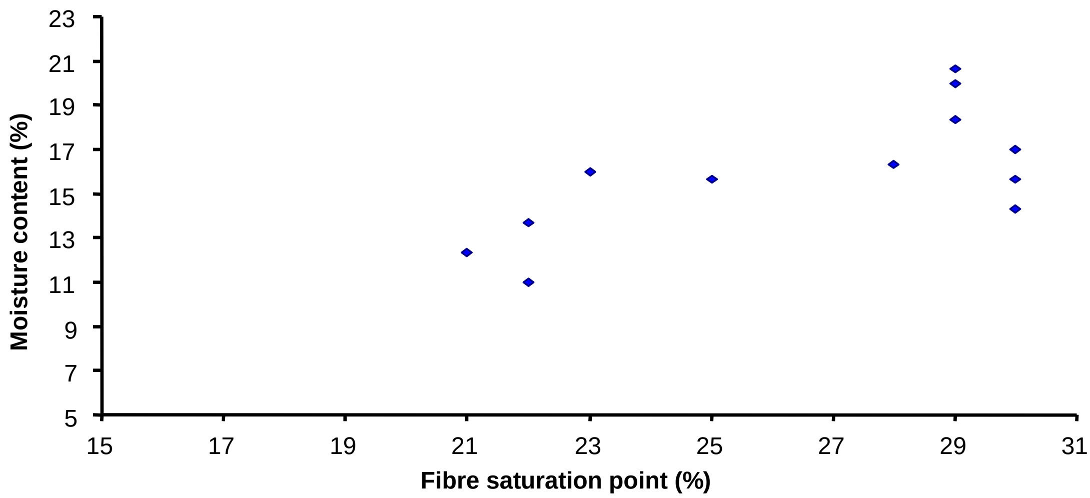


Figure 6.24 *Association of maximum moisture content and FSP.*

6.3.2.6 *Signal extraction*

Figure 6.25 illustrates the moisture content fluctuation for four test panels over a one year period on the exposed site. Three cycles can be observed:

- **Annual**; moisture contents were uniformly high between December and late April, but fluctuated widely for the other months;
- **Storm**; between late April and November moisture content fluctuations were tied to storm events. There were around 19 peaks and troughs during this period;
- **Diurnal**; the daily moisture content range was narrow during the winter but wide during the summer, moisture contents were highest at night.

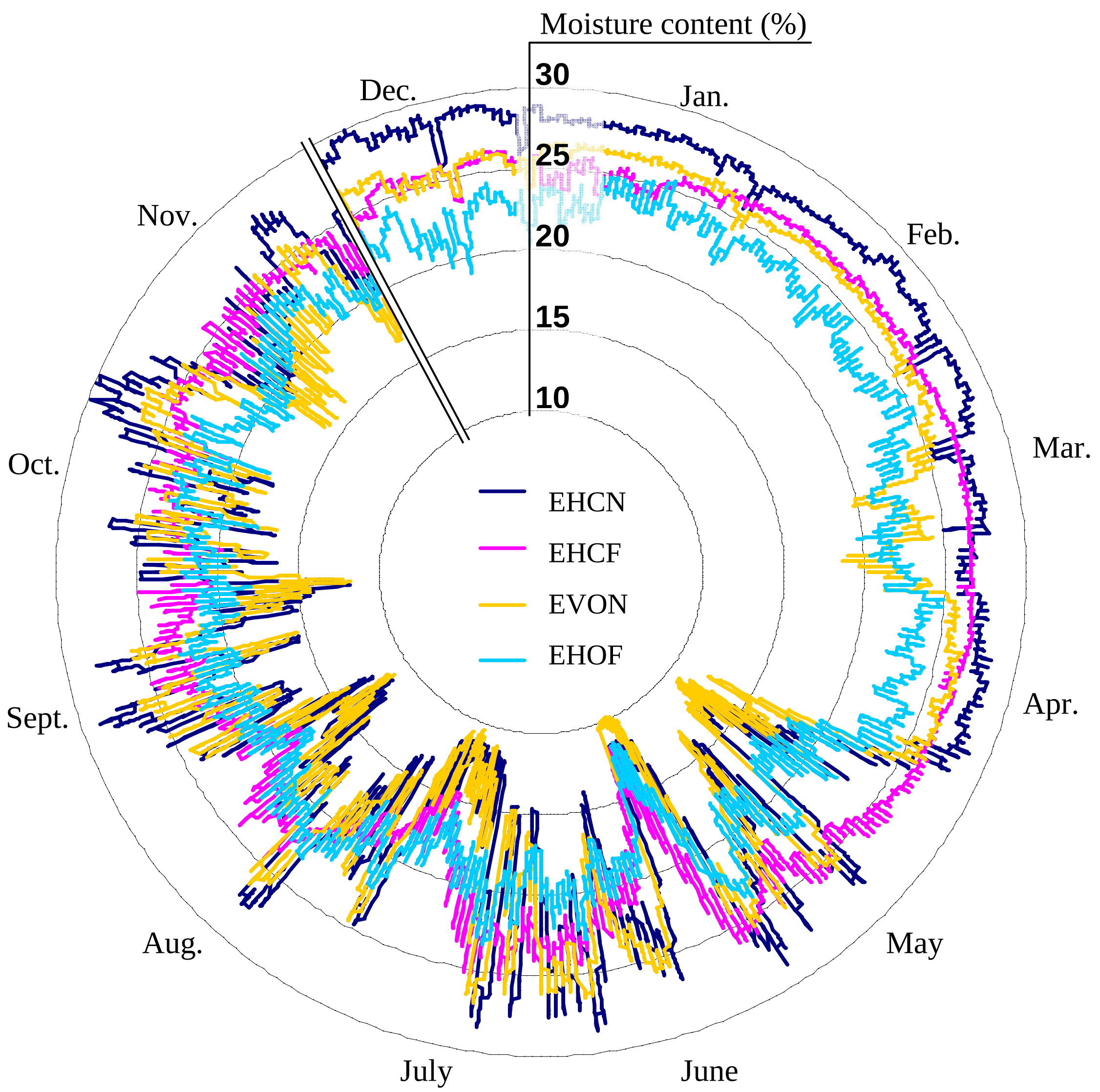


Figure 6.25 *Moisture content fluctuations in four panels on the exposed site from 25 November 2006 to 24 November 2007.*

Figure 6.26 plots the mean moisture content in one panel (EHCF) over three years. The same cycles recur although the timing varies by up to eight days. The next two figures plot how these cycles relate to the climate at the Tulloch Bridge Met. Office weather station.

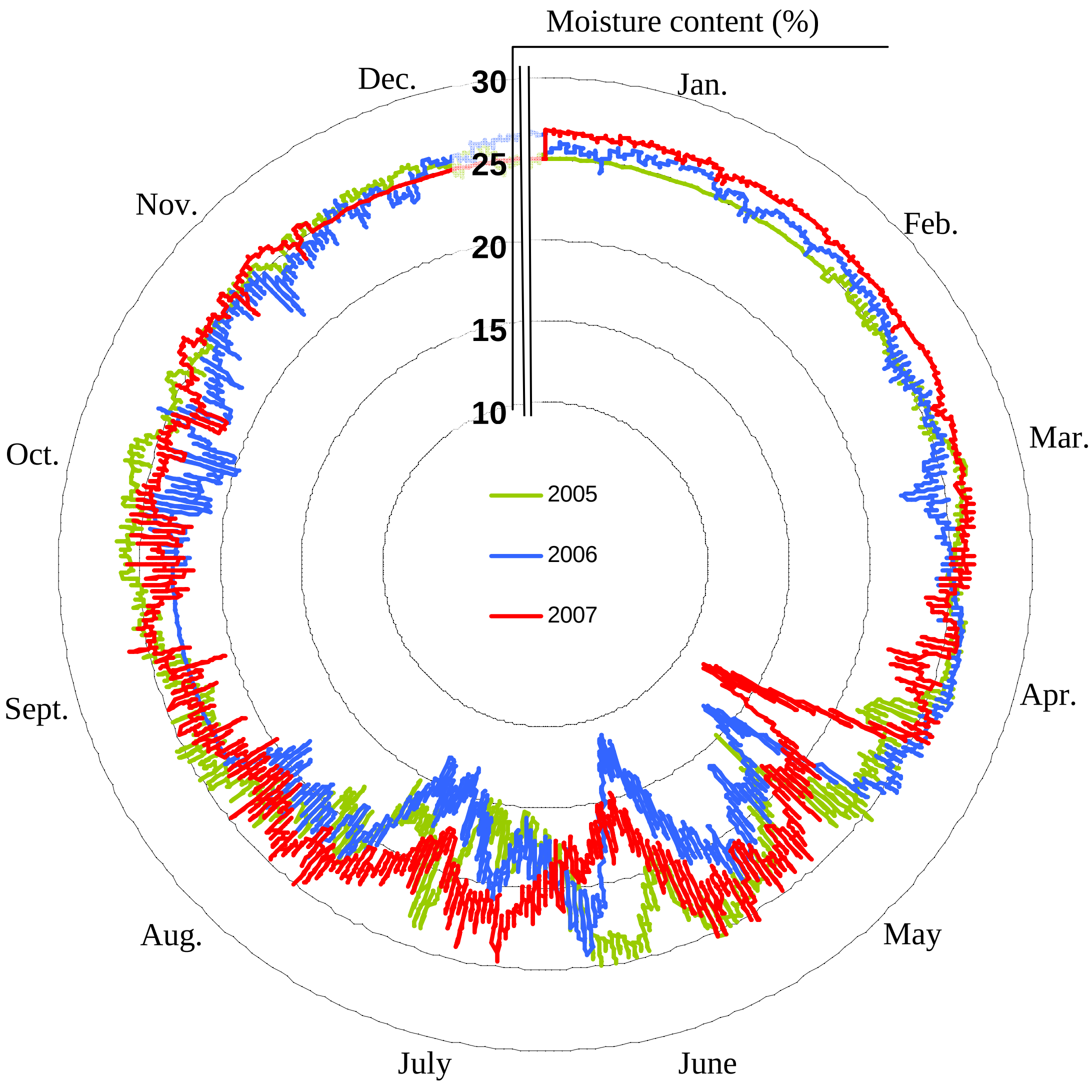


Figure 6.26 *Moisture content fluctuations in one panel (EHCF) over the three years of the trial.*

Figure 6.27 is a logarithmic plot of relative humidity against the moisture contents of four panels described in Figure 6.25. The period of lowest RH occurs in early June at the same time as the lowest moisture contents. The relative humidity drops to around 30% over several days and down to 20% on one. At these relative humilities the EMC for Sitka spruce is in the region of 6% to 8% whereas the recorded MC is 10%. Moreover, the RH curve starts to drop three days before the moisture content. It is unlikely that the time lag can fully account for the difference between the minimum moisture content and EMC; instead it appears that the increasing energy required for desorption at moisture contents below around 10% is a co-factor.

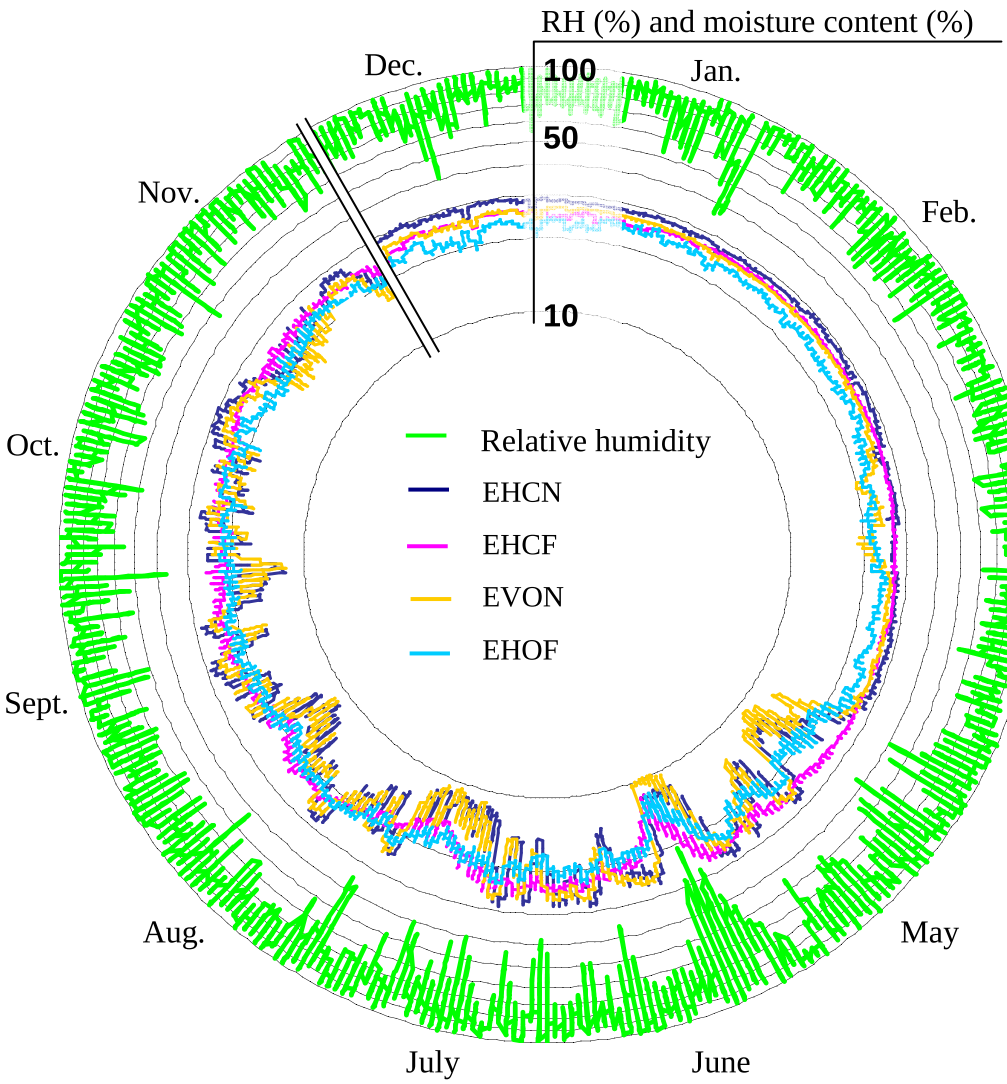


Figure 6.27 *Moisture content fluctuations in four panels on the exposed site compared to the ambient relative humidity (25 November 2006 to 24 November 2007)*

The relationships between temperature, rainfall and moisture content are less clear. It is likely that this is simply due to differences in the timing of rainfall events between the exposure site and climate station.

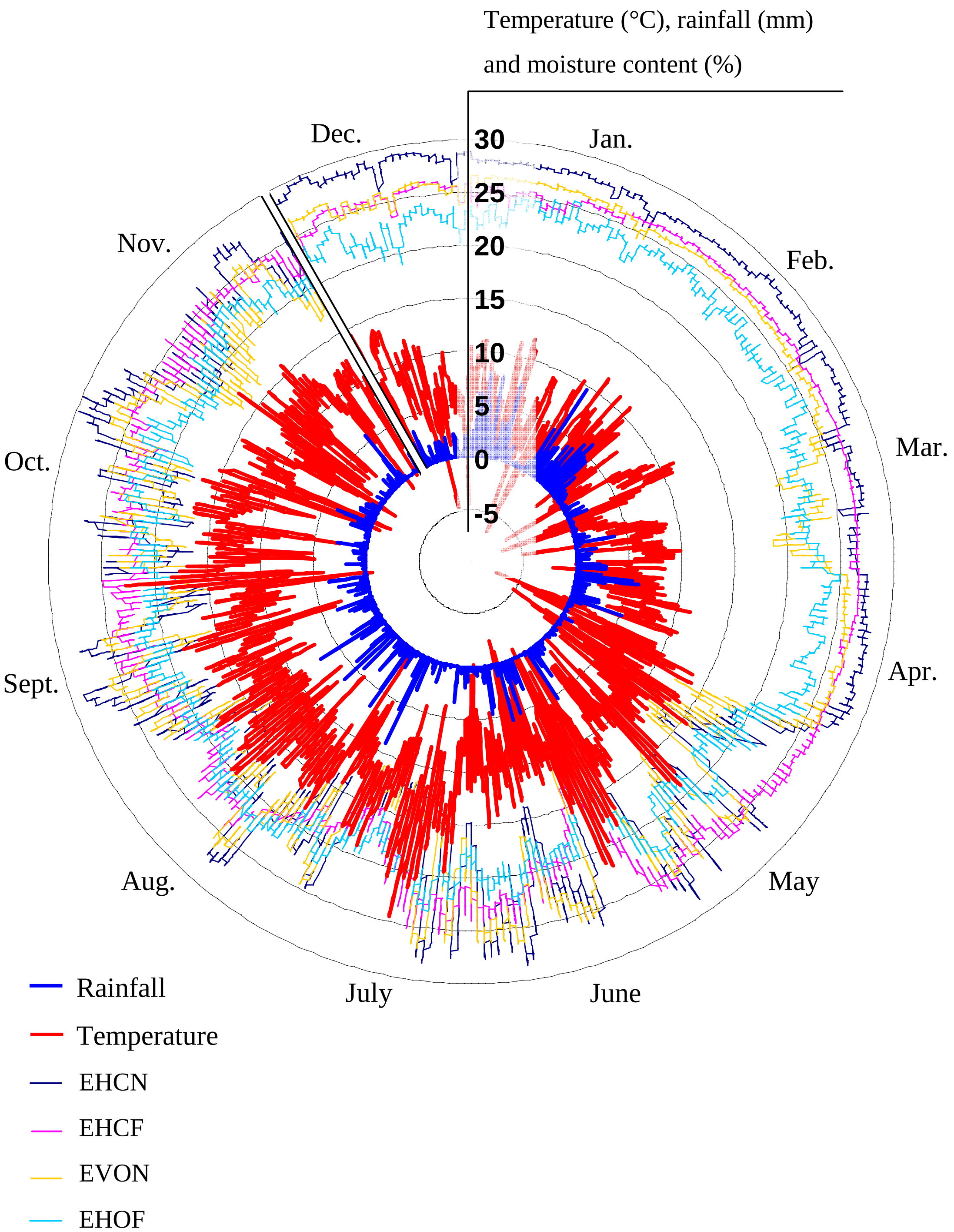


***Figure** 6.28 Moisture content fluctuations in four panels on the exposed site compared to the ambient rainfall and temperature (25 November 2006 to 24 November 2007)*

Figure 6.29 gives the moisture content on one panel during an 11 day period where the rates of moisture loss and gain were amongst the most rapid recorded in the trial. The period of desorption lasted 158 hours and involved a reduction in moisture content of 13.9%. The desorption rate over this period was 2.1% *per* day although the largest drop during a 12 hour period was 5.7%. The adsorption rate during the following 81 hours was 2.3% *per* day. During the period of drying the moisture content fluctuated over a diurnal cycle linked to RH, whereas the rate was uniform during wetting by rain.

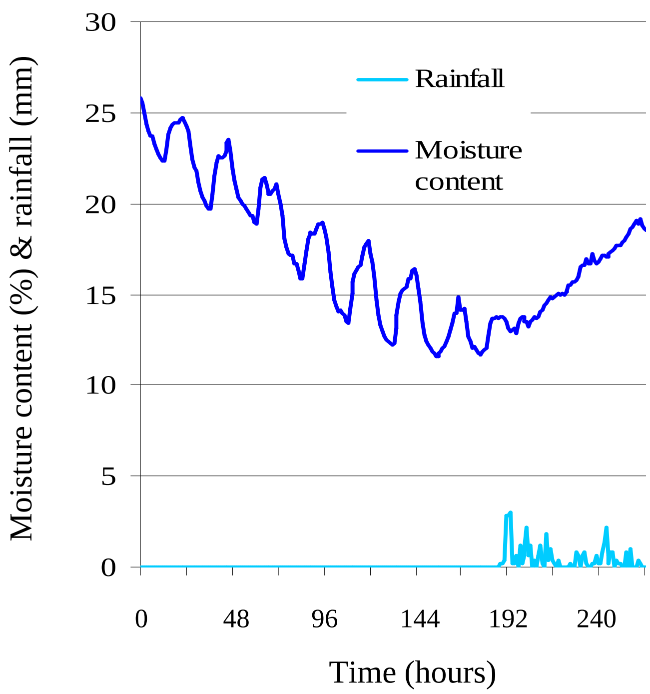


Figure 6.29 *Maximum rates of drying and wetting during the trial*

(Panel EHCF, 28 April 2007 to 9 May 2007)

The signal frequency was investigated using the Fast Fourier Transform (FFT) [31]. Mean moisture contents of two panels were sampled for periods of 4096 hours. This period was chosen because the Fourier engine in MS-Excel® 2003 requires *n* be a power of two with an upper limit of 2^{12}. The limit was, however, convenient as it covered approximately six months. This allowed the winter and summer months to be compared for the two panels (SHCN and EHCN) exhibiting the widest variation during the trial. The sampling interval was set to its maximum *i.e.* every hourly data point was used. The results are summarised in Figures 6.30 and 6.31. It appears that:

- The energy level of the signals are highest at short frequencies and over the summer
- The signal spikes at around 170 and 350 Hz may represent weather fronts.

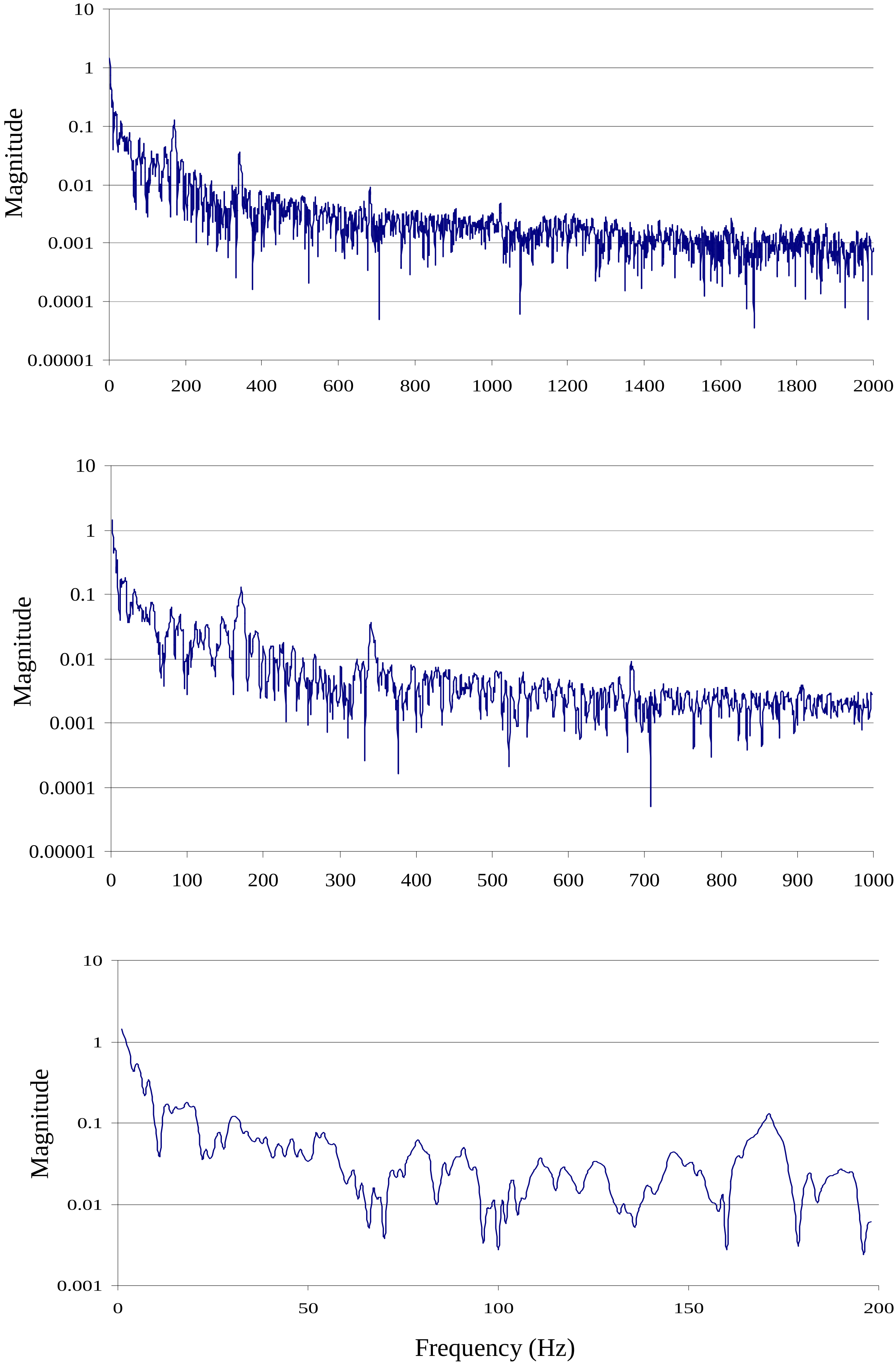


Figure 6.30 *Frequency spectrum for the SHCF panel during the winter (13 Sept. 2006 to 3 March 2007).*

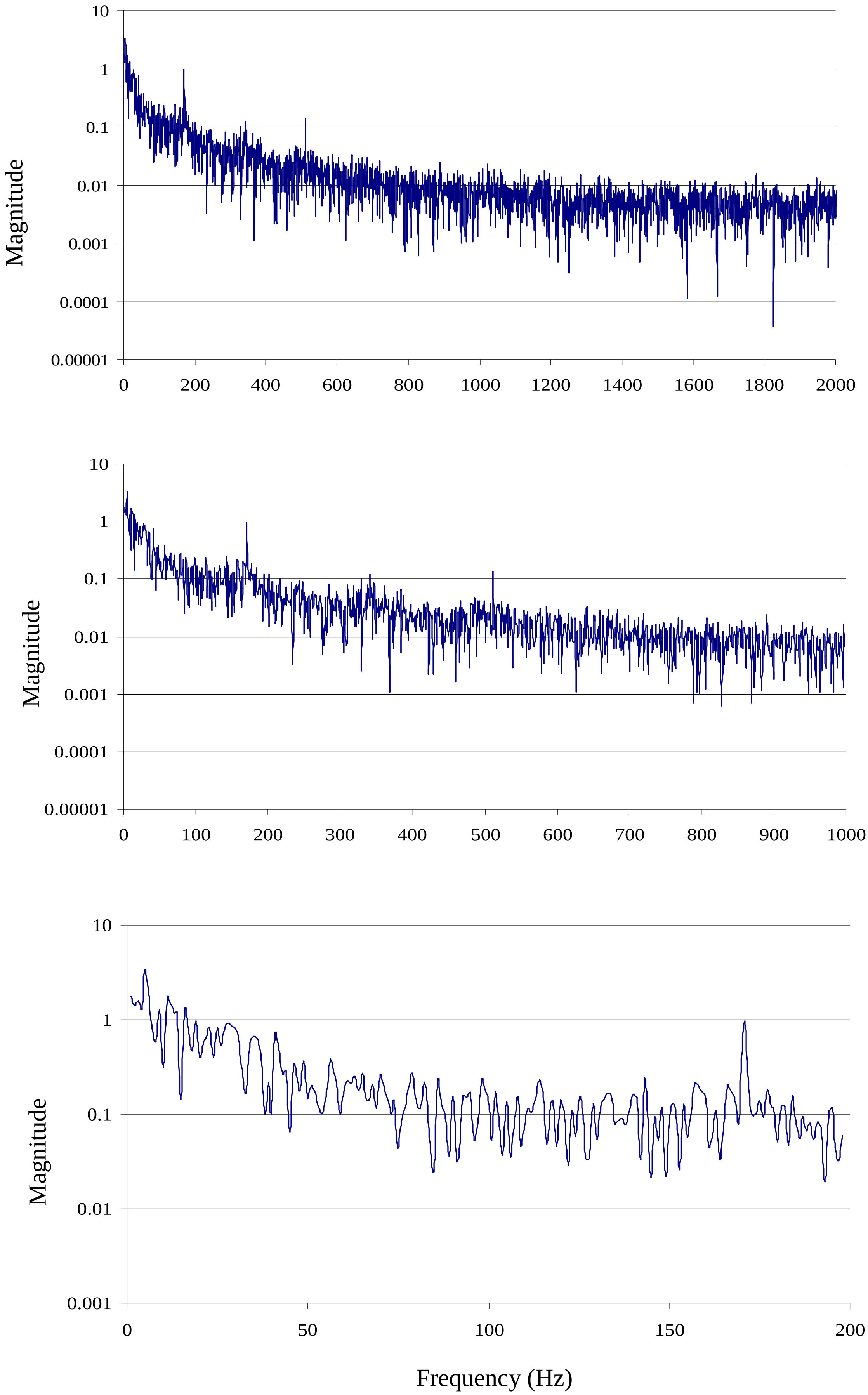


Figure 6.31 *Frequency spectrum for the EHCF panel during the summer (15 March to 1 Sept. 2007).*

6.4 Discussion

The results have clear implications for using Sitka spruce as external cladding. More generally they indicate the moisture take-up and loss that other types of timber facade will experience.

6.4.1 Uncertainties in the data

Are the results plausible? One way of answering this is to compare them with an independent data set. The most relevant [32] (p.25) is probably a survey of the moisture content in two stacks of Sitka spruce boards during one year's air drying on the west of Scotland; one stack was under a roof whilst the other was exposed to the elements (Figure 6.32). The moisture conditions in the unroofed stack are reminiscent of those observed during this exposure trial. The stack without a roof stayed wet throughout the winter, then dried during April and May at a rate of around 1% *per* day (half that recorded during this exposure trial). The moisture content fluctuated around 20% over the summer before climbing towards the FSP during October.

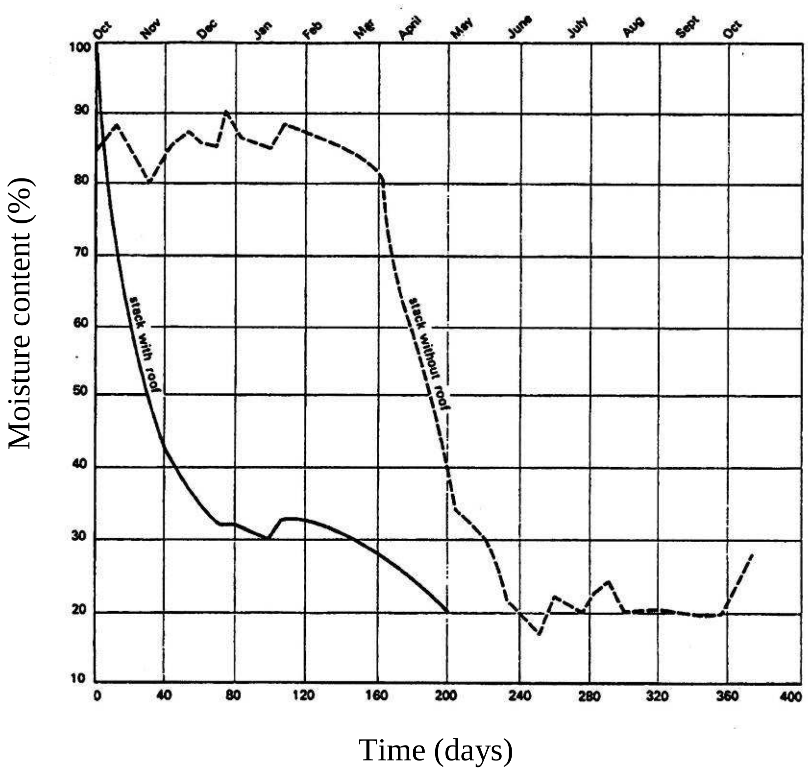


Figure 6.32 *Air drying rate of two stacks of Sitka spruce boards (100 × 50 mm section) in west Scotland. One stack was under cover and the other exposed.* (From: Pratt, *et al.* [32])

The exposure trial data have two main sources of uncertainty

- **Instrument resolution:** it is known that resistance type moisture meters can achieve an accuracy of ± 2% at $w \leq 25$ %. Higher values are only indicative.

- **Temperature:** although data from resistance type moisture meters are affected by temperature the data in this trial were not corrected: Δw was *c*. -0.1% K^{-1} below 20°C and +0.1% K^{-1} above 20°C. The moisture content may, therefore, have been overestimated by up to 2% in winter and underestimated by up to 4% in summer. The practical implications of this are minimal as moisture contents above 25% are only indicative (due to the measurement technique employed) and, as previously outlined, wetting above the FSP has no additional effect on biodeterioration.

The practical implications of this are minimal as moisture contents above 25% are only indicative (due to the measurement technique employed) and, as previously outlined, wetting above the FSP has no additional effect on biodeterioration.

In addition, all of the time series have gaps, which in the worst case (SVOF) amount to around 35% of the total length of the trial. This gap is evident in the frequency curves for SVOF given in Figure 6.21: a binomial distribution such as this is usually associated with missing data. The time series analysis has been able to work around these gaps by focusing upon the periods where data is complete for all panels. Given that the descriptive statistics, analysis, and post trial inspection (see section 6.4.4.) all point to the same conclusions, the impact of these gaps is considered to be minimal.

6.4.2 Timber

From a commercial viewpoint the timber would have been rejected as being unsuitable for most types of machining. Sitka spruce falling boards are, therefore, only suited for simple rectangular cladding profiles that do not require much profiling after the timber has been dried. Rip and pullover sawing would be possible but not thicknessing or moulding. Vertical board on board is, thus, the main cladding option.

Interestingly this profile is common on 19th century timber clad buildings in Scotland. It appears that wherever possible the boards were oriented so that sloping knots faced outwards and towards the ground. A survey in Strathspey involving the author indicated that about 80% of vertical cladding boards were oriented in this way [33]. This technique is not possible with horizontal boards as the knot whorl inevitably produces upward facing knots. Norwegian cladding practices also used this technique for timber siding although it has been discontinued now that the cladding is designed as a rainscreen [22].

Discussions with Norwegian and Swedish sawmillers indicates that Scandinavian S/F grade spruce does not contain as many large loose knots as the boards in this trial. Nor does the inner part of live knots become detached. This may be attributable to differences in timber quality although it could also be due to how the timber is processed. Much Scandinavian spruce cladding is sawn from the centre of the log. It is initially cut as a thick batten containing two boards. The batten is then kiln dried before being resawn to yield two cladding boards [34]. Scandinavians argue that this gives the most stable result. This approach is possible in Scandinavia where timber cladding is perceived as a large and valuable market, whereas in Scotland sawmillers are currently not prepared to use the middle part of the board in this way. For the moment, therefore, spruce cladding in Scotland will have to be cut from falling boards. This implies that the design options available are limited to simple board profiles as already discussed.

6.4.3 Moisture load

The most obvious conclusion from the descriptive statistics is that the four panels having open-jointed cladding with a front coating tended to stay relatively dry whereas most other combinations were wet. Two panels experienced intermediate values. It is notable that the nine relatively wet panels exhibit a skewed frequency distribution whereas the five relatively dry panels have more normally distributed curves (Figures 6.20 and 6.21). The moisture content of timber cladding is often quoted as a mean value of around 16%. This may be the case in summer on a dry site, but the frequency curves in Figures 6.20 and 6.21 suggest that such a value is misleading. The mean is only useful where the data are approximately normally distributed. If the frequency curves are skewed, then the mode is more representative of the data distribution. Four types of moisture behaviour can be identified. Figure 6.33 shows one year of moisture curves for four panels that are representative of the different types of moisture conditions recorded in the trial. A number of trends are evident:

i) All panels experienced their highest moisture contents from November to either March or April. Peak values on the wettest panels (*e.g.* EVCN) were near FSP.

ii) The closed-jointed panels (*e.g.* EHCF, EVCN) tended to experience a rapid drop in moisture content in March or April whereas open-jointed ones (*e.g.* SVON, SHOF) displayed a more gradual transition.

iii) The uncoated panels (*e.g.* EVCN, SVON) showed wide moisture content fluctuations throughout the summer.

iv) The battens behind vertical, open-jointed, uncoated panels (*e.g.* SVON) dried out more slowly than the cladding.

v) As the support battens and cladding had similar moisture contents, they both fell within structural Service Class 3, as defined by Eurocode 5 [35].

vi) The combination of open-jointed boards and front-coating (*e.g.* SHOF) stayed relatively dry.

vii) All panels experienced a similar minimum moisture content of between 10% and 11%.

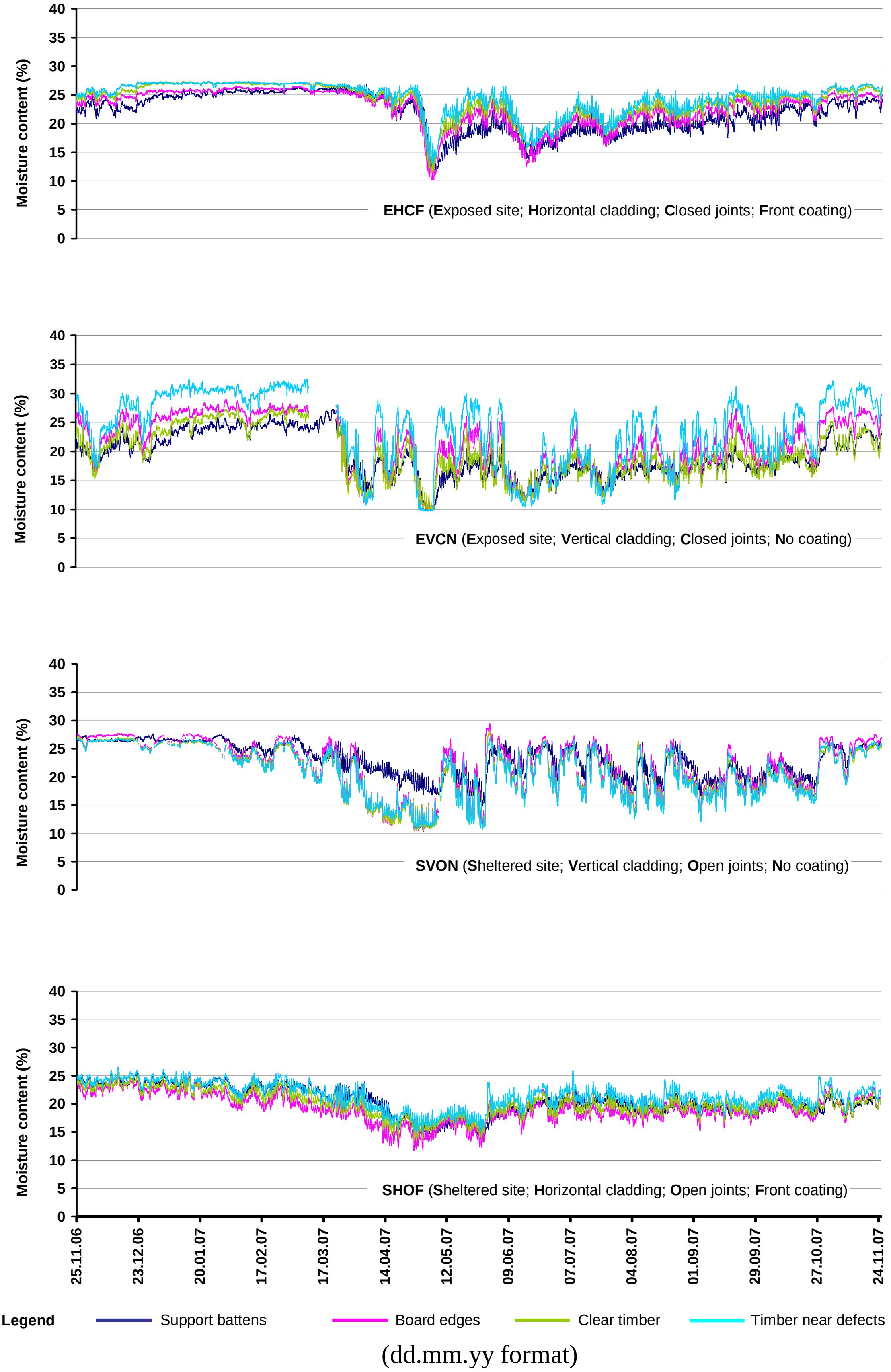


Figure 6.33 *Typical moisture profiles*

6.4.4 The inferential statistics

During the summer, a surface coating and horizontal open joint appear to be the key factor combination to maintain a low moisture load in the timber; coatings presumably act to limit water up-take whilst the open joints aid drying. Conversely, vertical boards, coatings and a sheltered site appear to result in the highest moisture loads; in this case the absence of drying by wind is probably a key factor especially where the surface coating limits evaporation. During the winter, meanwhile, a surface coating and horizontal open joint again appear to be key factors in maintaining a low moisture load although vertical boards with a coating are also important. Similarly, the factor combination that stands out as a cause of high moisture loads during the winter is vertical boards, closed joints, coatings and a sheltered site. The underlying causes are presumably similar to those during the summer. One word of caution is needed, however, as vertical open jointed boards also resulted in a high moisture load in the support battens as well as exposing them to a drying lag.

6.4.5 Follow up inspection

For operational reasons, Forest Enterprise asked that the Spean Bridge site be cleared as soon as the trial was completed. The Inverness site could however be retained, albeit with the dataloggers removed to avoid theft. The final condition of the cladding on the Spean Bridge site was:

- **Weathering;** there were no obvious differences between the panels in the weathering rate of uncoated timber. All had turned grey with the bottom 150 mm of the panel exhibiting the most pronounced staining (Figure 6.34).

- **Wasps;** uncoated boards exhibited numerous areas where weathered timber had been harvested by wasps (Figure 6.35).

- **Algal growth;** green areas were observed on the panels with a front coating, this occurred on the bottom edges of boards and at other locations where surface moisture was retained (Figure 6.36). The species was *Desmococcus olivaceus.* There was virtually no algal growth on the uncoated boards.

Figure 6.34 *Weathering of uncoated timber, the heaviest staining is near the bottom of the boards.*

Figure 6.35 *These stripes are due to wasps harvesting weathered timber.*

Figure 6.36 *Algal growth on the bottom edge of a coated board.*

The Inverness site was retained for a further three years. This allowed the condition of the panels to be inspected up to early 2010. Three findings emerged:

- **Algal growth;** the panel with horizontal open joints and a front coating (SHOF) had little algal growth whereas all the other coated panels did (Figure 6.37).

- **Staining;** all of the uncoated panels exhibited unsightly surface stains particularly when the timber was wet (Figure 6.38). The entire surface was affected and was slimy to touch.

- **Decay;** the fruiting bodies of the orange jelly mould fungus (*Dacrymyces stillatus*) could be seen on the surface of several panels. This organism is a frequent cause of fungal decay in external joinery in the UK [36] and Norway [37]. The occurrence of fruiting bodies appeared to be linked to the presence of intergrown knots which were creating localised water traps on the four uncoated panels.

These comments reinforce the findings discussed above. The EHOF and SHOF panels offered the best overall performance. All uncoated panels will experience variable staining which is most pronounced in wet weather and humid locations. The areas of decay around knots suggest that wetting from localised water traps will tend to over-ride the effect of any factor combination.

Figure 6.37 *Differences in algal growth between panels SHCF (left), SVOF (centre) and SHOF (right). The latter panel had little growth whilst the other three painted panels were colonised by Desmococcus olivaceus over most of their surfaces.*

Figure 6.38 *Widespread and unsightly surface staining along with occasional orange-red fruiting bodies (arrowed) of Dacrymyces stillatus.*

6.4.6 Scope for generalising the results

The mini-trial investigates whether these results can be generalised to other timber species using the concepts in section 6.2.10. Fibre saturation point appears to influence the relative ranking of maximum moisture content between species, even though none of the samples in the mini-trial attained moisture content values equivalent to their FSP. The moisture content result for Sitka spruce (21%) in the mini-trial is lower than the values for the SVON and EVON panels in the main trial (29% and 30% respectively). There are two obvious explanations for this discrepancy: firstly the different sampling intervals (hourly or daily) and, secondly, the differences in sample size (the short lengths of the mini-trial samples allowing drying from the ends as well as offering a smaller catchment area for WDR). In spite of this discrepancy it may be plausible to use the moisture content:FSP ratios observed in the two trials to make tentative predictions about the moisture conditions that a particular combination of timber species and detailing will experience. Two assumptions are required. Firstly, given that the mini-trial under-represented the maximum moisture content of Sitka spruce in the main trial by about 30 %, it could have had a similar influence on other samples in the mini-trial. Secondly, ghe MC:FSP ratios observed for the panel designs in the main trial (Table 6.26) would recur irrespective of the species involved. If so, then they can be applied to the species in the mini-trial although adjustment may be needed for site differences. If these assumptions are valid then the moisture conditions in any timber and detailing combination can be predicted using an expression of the form:

$$w' = \lambda_s \, \lambda_c \, w \tag{6.3}$$

where w' is the predicted moisture content, λ_s is the moisture content:FSP ratio for that species and λ_c is a ratio of moisture content:FSP ratio for the type of cladding involved (VOF, HCN *etc.*). The species parameter (λ_s) is increased by 30% to adjust for the difference between the results of the mini- and full trial. Similarly, the cladding parameter (λ_c) can be adjusted for site. Using this formula the maximum moisture content of cladding panels made from species in the mini-trial can be predicted (Table 6.27). Other moisture content predictions (*e.g.* mean or range) can be made in a similar way. A typical application of Eq. 6.3 would therefore predict 14% $\leq w' \leq$ 15% in European larch cladding under *x*VOF conditions if Sitka spruce cladding had w = 20% in similar circumstances (*i.e.* w' = 0.9 × 0.8 × 20%).

Table 6.26 *The cladding parameter for each panel type*

Orientation	Joint	Coating	Exposed site	Sheltered site	Mean of the two sites	MC:FSP ratio for each panel type λ_c
Horizontal	Open	Front	26	26	26	0.9
		None	28	27	28	0.9
	Closed	Front	27	27	27	0.9
		None	31	29	30	1.0
Vertical	Open	Front	25	25	25	0.8
		None	28	29	29	1.0
	Closed	Front	30	29	30	1.0
		None	30	35	33	1.1

Table 6.27 *Predicted maximum moisture content (%) for each species/cladding combination. Those with a potential decay risk are highlighted in red (high risk: moisture content at or above FSP) and orange (moderate risk: moisture content near FSP).*

		Cladding parameter λ_c							
Species parameter		λ_{VOF}	λ_{HOF}	λ_{HON}	λ_{HCF}	λ_{HCN}	λ_{VON}	λ_{VCF}	λ_{VCN}
Species (FSP)	λ_s	0.8	0.9	0.9	0.9	1	1	1	1.1
Keruing (30)	0.7	16	18	18	18	20	20	20	22
Afrormosia (22)	0.7	13	14	14	14	16	16	16	17
European redwood (30)	0.8	19	22	22	22	24	24	24	27
European oak (30)	0.8	19	22	22	22	24	24	24	27
Douglas fir (28)	0.8	18	21	21	21	23	23	23	25
Iroko (21)	0.8	14	15	15	15	17	17	17	19
Teak (22)	0.9	16	18	18	18	20	20	20	22
European larch (28)	0.9	21	23	23	23	26	26	26	28
Greenheart (25)	0.9	18	20	21	21	23	23	23	25
Western red cedar (23)	1.0	18	20	21	21	23	23	23	25
Sapele (29)	1.0	23	26	26	26	29	29	29	31
Sitka spruce (29)	1.0	24	27	27	27	29	29	29	32

6.5 Conclusions

Other things being equal, timber facades will first fail where the local moisture content is greater than the average across the wall. As discussed above, the key threshold being a moisture content at or above the fibre saturation point for the timber species concerned. The FSP of Sitka spruce and most other temperate species is w = 28% ≤ FSP ≤ 32%. The duration of wetting (t_w) has to be at least 10% of the exposure time. After allowance for measurement uncertainties and other factors this equates to a practical threshold of $t_{w > 22\%} \geq 10\%$.

This exposure trial has highlighted how differences in construction detailing may affect this degradation risk. The results of the main exposure trial answer two of the three research questions posed in the introduction:

- Firstly, it is clear that Sitka spruce cladding becomes relatively wet ($t_{w > 22\%} \geq 10\%$) even though it is a refractory timber species. Indeed, the moisture conditions were such that the timber is near to its fibre saturation point in many circumstances. As such it would normally need preservative treatment by impregnation before use as external cladding.

- Secondly, it appears that it may be possible to generalise the results to other species using the moisture content:FSP ratios for the timber species and cladding type involved. A formula is proposed for this purpose.

In terms of the three specific questions addressed by the exposure trial it appears that the combination of open jointed cladding with a surface coating gives the best overall performance. Knots and other water traps will, however, tend to over-ride the moisture take-up characteristics associated with any treatment combination. Consequently, all of the factor combinations tested in this trial will require preservative treatment by impregnation.

Sitka spruce falling boards are relatively knotty when appearance graded against the criteria for Scandinavian whitewood cladding. This will tend to increase water entrapment and will limit the board profiles that can be produced. The only type of external cladding that can be recommended as being suitable for Sitka spruce is therefore vertical board on board. Because the timber will be preservative treated, a surface coating is not essential although it may minimise moisture take-up as well as improving appearance. It may be possible to avoid using a biocidal primer however as the preservative impregnation can often fulfil a similar function.

The moisture contents reported in this trial are sufficient to leach out Type LR flame retardants in about 30 years although they are unlikely to have a similar effect on leach resistant wood preservatives. See Chapter 5 for more information.

Spruce cladding that has been preservative treated will not generally be compatible with flame retardant impregnation and so is unlikely to be suitable for use on public buildings. See Chapter 5 for more information.

Although the data in Table 6.27 are only speculative, equation 6.3 suggests how a predictive model could be developed. More work is, however, needed before it could be definitive. This would involve repeating some version of the exposure trial using a number of timber species.

Above all, the data quantify the moisture conditions that timber facades in the UK are likely to experience. This is the first time this has been done at this scale and complexity. The results allow the implications for moisture related degradation to be better assessed than has been possible hitherto; this is the information that facade designers are after.

References

1 BS EN 460:1994. Durability of wood and wood-based products. Natural durability of solid wood. Guide to the durability requirements for wood to be used in hazard classes. London: British Standards Institution, 1994.

2 Nore, K. (2004). Performance based design of wooden claddings – a literature review of wooden cladding design. NBI Note 61. Oslo: Norges Byggforskningsinstitutt.

3 Forestry Commission, (2003). National inventory of woodland and trees – Great Britain. Edinburgh: Forestry Commission.

4 Rijsdijk, J.F. and Laming, P.B. (1994). Physical and related properties of 145 timbers. Dordrecht: Kluwer Academic Publishers.

Moore, J. (2011). Wood properties and uses of Sitka spruce in Britain. Edinburgh: Forestry Commission.

6 Nguyen, M.N., Leicester, R.H. and Wang, C.H. (2008). Manual No 6: Embedded corrosion of fasteners in timber structures. Victoria: Forest and Wood Products Australia.

7 Zabel, R.A. and Morel, J.J. (1992). Wood microbiology – decay and its prevention. San Diego, US: Academic Press, Inc.

8 Scheffer, T.C. (1971). A climate index for estimating potential for decay in wood structures above ground. *For. Prod. J.* 21(10): 25-31.

9 Box, G.E.P and Jenkins, G.M. (1970). Time series analysis, forecasting and control. Fan Francisco: Holden-Day.

10 Jenkins, G.M. and Watts, D.G. (1968). Spectral analysis and its applications. London: Holden-Day.

11 Broomfield, P. (1976). Fourier analysis of time series: an introduction. New York: J. Wiley & Sons.

12 Chatfield, C. (1989). The analysis of time series: an introduction, 4th Ed. Boca Raton, FL: Chapman and Hall,.

13 Diggle, P.J. (1990). Time series: a biostatistical introduction. Oxford: Oxford Science Publications.

14 Kitagawa, G. (2010). Introduction to time series modelling. Boca Raton, FL: Taylor and Francis Group.

10 Humphrey, J.W., Ferris, R. and Quine, C.P. (2003). Biodiversity in planted forests. Forestry Commission, Edinburgh.

16 Pyatt, D.J. and Suáre, J.C. (1997). An ecological site classification for forestry in Great Britain, with special reference to Grampian, Scotland. Technical Paper 20. Edinburgh: Forestry Commission.

17 Macaulay Institute for Soil Research. (1981). Soil survey of Scotland, land & soil capacity for agriculture maps, coloured, scale 1:120,000. Sheets 4 & 5., Aberdeen, UK: MISR.

18 The Association of Swedish Sawmillmen (1980). Guiding principles for grading of sawn lumber (the Swedish Green Book). Stockholm: ASS.

BS EN 1611-1:2000 Sawn timber. Appearance grading of softwoods. European spruces, firs, pines, Douglas fir and larches London: BSI, 2002.

20 Innovativ Vision AB. Website: <http://www.woodeyeinc.com/en/Kontakt/index.html> [Accessed 16 July 2010.] Linköping, Sweden.

21 Jones, D. and Suttie, E. (2006). Using UK-grown Sitka spruce for external cladding. Digest 500. Watford, UK: BRE Press.

22 Edvardsen, K.I. and Torjussen, L. (1997). Håndbok 45 – TREHUS. [Handbook 45 – wooden house. In Norwegian] Oslo: Norges Byggforskningsinstitutt.

23 Jotun Paints (Europe) Ltd. Website: <http://www.jotun.com> [Accessed 16 July 2010.] London.

24 Scanntronik Mugrauer GmbH. Website: <http://www.scanntronik.de/English/index.php> [Accessed 16 July 2010.] Zorneding, Germany.

25 BS EN 13183-2:2002. Moisture content of a piece of sawn timber. Estimation by electrical resistance method. London: BSI, 2002.

26 GE Sensing, Protimeter Timbermaster website: <http://www.damp-meter-direct.co.uk/Protimeter-Timbermaster.htm> [Accessed 16 July 10.] London.

27 < http://www.davisnet.com> Hayward, CA [Accessed 6 December 2010.]

28 Yates, F. (1937). Design and analysis of factorial experiments. Tech. Comm. No. 35. London: Imperial Bureau of Soil Sciences.

29 Skaar, C. (1988). Wood-water relations. Berlin: Springer.

30 Tsoumis, G. (1991). Science and technology of wood: structure, properties, utilization. New York: Van Nostrand Reinhold.

31 Cooley, J.W. and Tukey, J.W. (1965). An algorithm for the machine calculation of complex Fourier series. *Math. Computation*, 19, 297-301, April 1965.

32 Pratt, G.H., Maun, K.W. and Coday A.E. (1997). Timber drying manual, 3rd edition. Watford, UK: BRE Bookshop.

33 Lee, U., (2002). Native timber in construction – Strathspey's unique history. In; *Scottish Woodland History Discussion Group: Notes VII*, 23-29. Stirling, UK: University of Stirling.

34 Hansson, T. (1996). Wood as a material. In: Elmia Trä 96: fair catalogue with manual about wood. Jönköping, Sweden: Elmia AB.

35 BS EN 1995-1-1:2004+A1:2008. Eurocode 5. Design of timber structures. General. Common rules and rules for buildings. London: BSI, 2009.

36 Bravery, A.F., Berry, R.W., Carey, J.K. and Cooper, D.E. (2003). Recognising wood rot and insect damage in buildings. BR 453. Watford, UK: BRE Bookshop.

37 Lamborne, R. and Strivens, T.A. (1999). Paint and surface coatings, theory and practice. 2nd edition. Abington, UK: Woodhead Publishing.

Chapter 7

Implications

Previous chapters have identified the moisture conditions and degradation mechanisms affecting timber facades in temperate coastal climates such as the UK. This chapter develops a set of performance requirements and outline specifications based on these findings. It defines the technical properties that timber facades need to both resist the moisture effects identified in previous chapters and comply with the UK's Building Regulations. The chapter ends by developing a decision sequence to guide timber facade design.

7.1 Structure

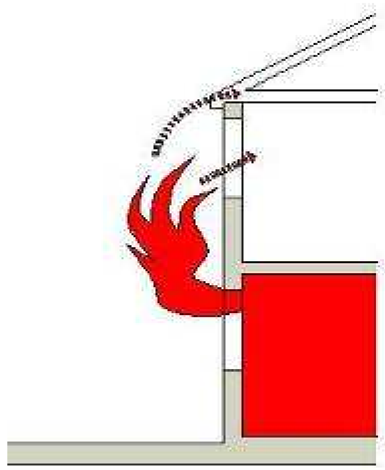
The exposure trial results suggested that all of the external timber cladding assembly, including the support battens, is in structural service class 3. This has implications for the strength and stiffness coefficients that are used in batten and fastener design. Biodeterioration resistance is also affected; as is the requirement for batten grading (Table 7.1). These findings will have little impact on low-rise timber-clad buildings away from the coast but will affect how engineers design and verify timber facades on taller buildings and those within five kilometres of the coast. Timber cladding fasteners on low-rise inland sites can continue to be sized using existing 'rules of thumb' (see Chapter 5) but formal calculation to Eurocode 5 [1] will be required in more demanding locations, this could be assisted by developing tabulated guidance for fastener design. Batten grading is discussed in the book arising from this thesis [2].

Table 7.1 *Main options for ensuring robustness*

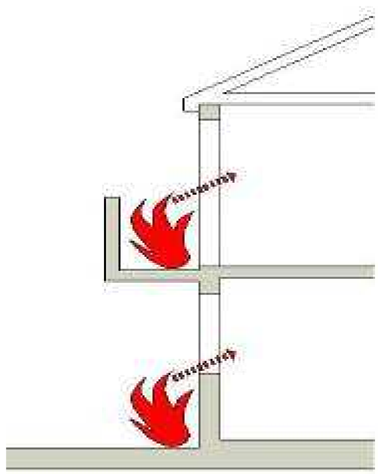
Specification option	Benefits	Problems	Solution
Fastener sizing using 'rules of thumb'	Simple and adequate for low-rise inland sites	Not consistent with EC5	Only use on low-rise buildings away from the coast
Fastener sizing by calculation to EC5 may be needed for low-rise buildings and certainly will be for medium-rise and above	Robust	It may be unclear if a particular cladding job needs formal engineering design	Get advice from a structural engineer where there is any doubt
Accommodate differential movement	Essential where heavy and lightweight cladding are in contact	None	Ensure differential movement is addressed at the design stage and that contractors understand what is needed
Grading battens to BS 5534 [3]	Grading helps ensure robustness and is simple to carry out	The contractor needs to be able to grade to BS 5534	Ensure specific joiners are familiar with batten grading

7.2 Fire safety

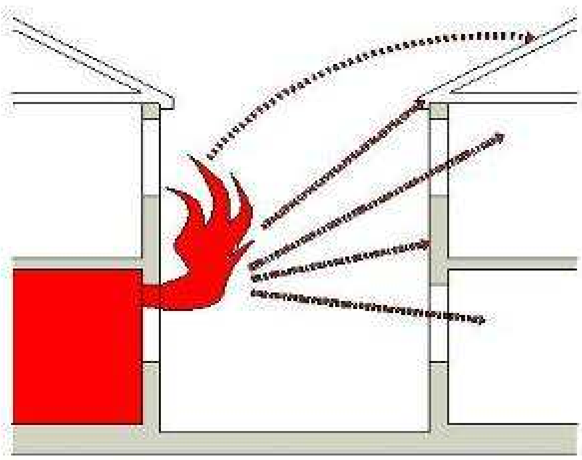
Fire can start on or spread onto the external envelope of a residential or public building through any of three main fire scenarios (Figure 7.1) [4] - [6]. Scenario 1 is usually the most problematic. Industrial building envelopes are exposed to additional risks which are outwith the scope of this chapter.



Scenario 1: Compartment fire



Scenario 2: Small fire near the facade



Scenario 3: Fire in an adjacent but non-adjoining building

Figure 7.1 *The main fire scenarios affecting the external envelopes of residential and public buildings* [4] - [6]

External fire spread can be limited in several ways [4] - [6]:

1. Compartmentation (*e.g.* using plasterboard room linings);
2. Preventing external flame plumes (*e.g.* using internal sprinklers);
3. Controlling fire spread from fires in neighbouring buildings or similar sources (*e.g.* separating buildings with clear space or non-combustible materials);
4. Limiting flame spread in cavities (*e.g.* using cavity barriers);
5. Reducing the reaction to fire class of the building envelope assembly (*e.g.* using flame retardants);
6. Deflecting external flaming (*e.g.* using projecting baffles);
7. Protecting openings (*e.g.* using fire resistant glazing or window sprinklers).

Most of these techniques are well established although their implementation may vary between countries. Those most relevant to the UK are as follows:

7.2.1 Techniques for limiting fire spread

Compartmentation: because most building fires start internally, fire codes make provision for compartmentation to limit fire spread and structural damage. The requirements at separating walls will affect the design and position of cavity barriers on the facade as well as the design and combustibility of roof coverings. Confusingly, the fire resistance of cavity barriers is only defined in terms of heat insulation against a fire emerging from an opening and, although a performance criterion is given, there is no standardised test available. This creates much confusion as building control officers sometimes impose their own arbitrary criteria, whilst cavity barrier manufacturers are able to make all sorts of unverifiable performance claims. A standard test is needed.

Preventing external flame plumes: if automatic sprinklers are installed, compartment fires should not develop to flashover; in which case flaming from a window will be prevented, or have a relatively low HRR. The remaining risks are then due to fire spread from a large fire nearby, or a fire being ignited near the facade. Regulators have resisted the introduction of sprinklers for residential use in the UK but this is starting to change. If internal sprinklers are adopted the design of timber facades will be simplified.

Fire spread from a large adjacent fire: the risks of fire spread from a large fire in a neighbouring but non-adjoining building are determined by the extent to which the facade and roof are exposed to heat radiation and flying embers. In the UK, the main risk to the facade is assumed to be heat radiation, whilst the roof is also vulnerable to embers. The minimum allowable boundary distance between facades is calculated assuming an incident heat flux threshold of 12.6 kWm^{-2}; the minimum needed for ignition of wood in the presence of a pilot light. Wherever the radiant heat flux on the receiving surface will exceed its heat flux threshold, buildings will have to be positioned further apart or the affected facade must achieve a low reaction to fire classification [7]. The requirements vary between fire codes: the Scottish codes require that a non-combustible material be used near boundaries (driven largely by the high incidence of arson in Glasgow) whilst the rest of the UK accepts a Euroclass B classification or equivalent. Non-combustibility precludes timber, but Euroclass B will allow flame retardant treated timber to be used.

Fire spread in cavities: none of the provisions outlined above is designed to limit flame spread across a facade where buildings are in direct contact with each other (*e.g.* a terrace). This is because heat radiation across the junction between them is minimal; thermal transmission due to conduction and convection within the cavity is the main concern and this is controlled using cavity barriers. Accordingly, cladding at separating wall junctions does not need a low reaction to fire classification unless, as described in the previous section, it is also close to, and facing, a boundary. This is a frequent source of confusion amongst both designers and building control officers. There are several types of cavity barrier. The most common is a continuous band of non-combustible material such as mineral wool installed so that it fully blocks the cavity at all times. The second type is an intumescent strip that permits the through-flow of air in normal use but expands when heated to close the gap. Both need to have a defined period of fire resistance, although some other materials (*e.g.* timber battens at least 38 mm thick) may be accepted on low- and medium-rise buildings. Detailing cavity barriers within masonry cavity walls is usually straightforward, but it has become apparent that these techniques are not always suitable for use with timber cavity walls. This is due to three conflicting design criteria:

1. Timber cladding needs to function as a rainscreen with a drained and ventilated cavity between the cladding and wall structure;

2. The cavity has to incorporate horizontal and vertical barriers to block ventilation during a fire;

3. The cladding assembly has to limit flanking sound transmission across the separating walls and floors of multi-occupancy dwellings.

The first criterion seeks to ensure free air movement to promote evaporative drying whilst the second stops ventilation to limit flame spread. The third criterion compounds these difficulties by limiting those elements, such as timber battens, that span across separating wall junctions. Many cavity barriers used with timber cladding do not fulfil all three criteria. Most problems arise with horizontal barriers; vertical barriers are more straightforward as they do not require through ventilation. The sound transmission criteria mainly apply to vertical junctions; these are discussed below in the section on acoustics. A further issue can arise where the fire penetrates the timber cladding on each side of the cavity barrier even though the barrier itself maintains its integrity. This issue is most acute with open-jointed cladding, although simple overlapping joints are also vulnerable. Force-fitted joints such as tongue and groove offer the best protection [8] although even they are likely to burn through in less than 30 minutes.

As a result of these issues vertical cavity barriers can generally be mode of softwood timber at least 38 mm thick whilst horizontal barriers need to be intumescent strips. The minimum thickness requirement for timber cavity barriers is of uncertain origin but appears to be an attempt to prescribe sufficient fire resistance to the batten. Combustible cavity barriers such as timber battens are generally prohibited at heights above 18 m. The intumescent strip barriers are of recent origin. They are tested for fire resistance to BS 476-20 [9] and BS 476-22 [10] but do not block low temperature smoke. This can be a problem as some building control officers insist on horizontal cavity barriers being able to act as smoke barriers even though there is no performance level set for this in building regulations. Nor indeed is there a published test standard.

Flame retardants; many building codes require FR treatment where timber is used to clad the facades and roofs of tall buildings and near boundaries. As already highlighted, even the most leach-resistant flame retardants will have a maximum 30 year service life in exterior exposure, although there is currently no recognition of this issue in building codes. If this changes, timber cladding will probably be restricted to a maximum height of 18 m and excluded on public buildings and near property boundaries.

Facade geometry; there is growing interest (particularly in Germany, Switzerland and Finland) in using construction detailing to reduce flame spread on timber cladding. The most common approach involves using horizontal projections to deflect flames away from the wall. To be fully effective the deflector needs to project by 1 m and extend to 1.2 m on each side of the opening [11]. This is usually impractical and so narrower deflectors are used (Figure 7.2). These have little effect on a flame plume from a fully developed fire but can slow the spread of small fires providing they are used in combination with other measures such as a non-combustible rear face to the cavity [8]. The author has observed designers mistakenly employing these deflectors in the UK without realising that they do not work in isolation, some construction guidance [12] also makes this error (Figure 7.3).

Figure 7.2 *Horizontal flame deflectors used to slow external flame spread on a timber-clad block of flats in Porvoo, Finland.*

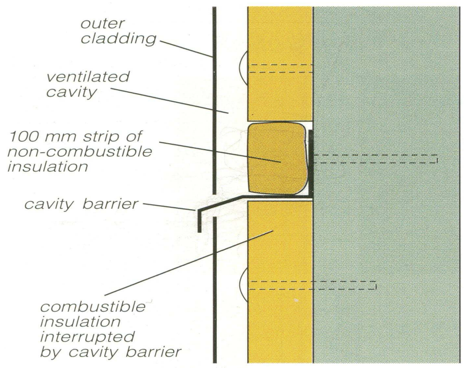


Figure 7.3 *Cavity barrier guidance in BRE Digest 262* [12]. *Details such as this enable cavity ventilation but cannot stop upward fire spread as there is nothing to prevent fire bypassing the barrier.*

Glazing; windows are generally the part of the facade most vulnerable to external fire. If a flame plume spreads out of an opening onto a facade, windows in the storey above can fail allowing the fire entry into that compartment. The window frame is also important, plastic frames tending to fail before the glass does: the glass in timber framed windows lasts longer, but not as long as those made from aluminium. Several measures are available to help prevent windows failing, with fire-resistant glazing being the most common. UK regulators resist this approach as test procedures are not yet standardised.

Fire safety engineering; whilst many of the foregoing provisions are relatively straightforward, some facades and roofs require alternative solutions involving a fire safety engineering approach. This has been defined [13] as the *'… application of scientific and engineering principles to the protection of people, property and the environment from fire'*. This approach may be the only practical way to achieve fire safety in large, complex or historic buildings. The solutions include a combination of measures such as automatic fire detection, fire suppression, ventilation systems and passive fire protection. An extensive programme of tests has recently been completed in Germany and Switzerland with the result that the fire safety of medium-rise timber facades is now fully documented. However, the results cannot readily be transferred to low-rise buildings in the UK as the costs are prohibitive and due to the lack of rapid (< 15 minute) fire brigade arrival times in rural areas. There are also questions over some of the details would perform in the UK's wet and windy climate.

7.2.2 Fire testing in the UK

In view of the confusion and complexity affecting the fire performance of timber facades in the UK, the author participated in a full-scale *ad hoc* fire test of separating wall and floor junctions (Figures 7.4 to 7.8). The design of the timber frame junctions and cavity barriers was based on the details being developed for this thesis. With minor adjustments the method appeared to provide a template for future standardised testing of cavity barrier performance behind timber cladding. It has confirmed that only a full-scale, semi-natural test is capable of modelling the fire conditions on a timber facade. The smaller scale tests currently being employed are meaningless as they do not model three-dimensional fire behaviour, such as burn through of the cladding on each side of the cavity barrier. Although it was an ad hoc test, and so cannot be definitive, the results suggested that the cavity barrier details will be able to meet the performance criteria in current building regulations. However, further testing is required to confirm this. The test is described in a BRE report [14].

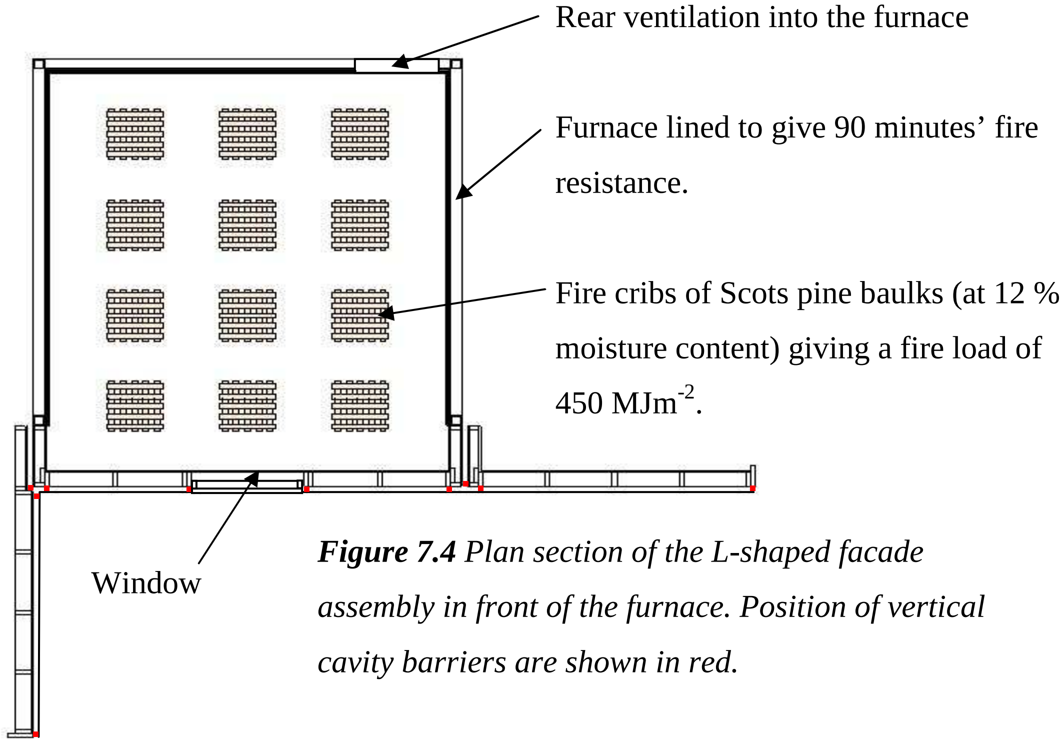


Figure 7.4 *Plan section of the L-shaped facade assembly in front of the furnace. Position of vertical cavity barriers are shown in red.*

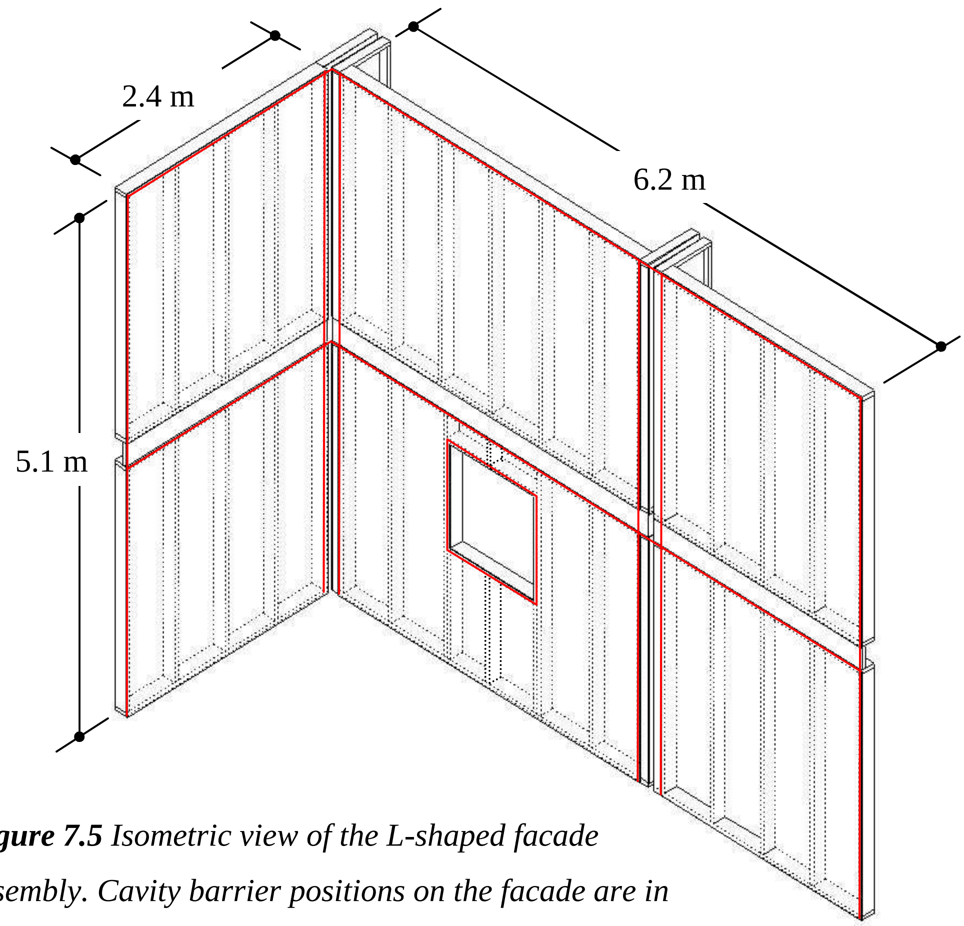


Figure 7.5 *Isometric view of the L-shaped facade assembly. Cavity barrier positions on the facade are in red. Vertical barriers on the facade are 38 mm thick timber battens whilst the horizontal barriers are intumescent strips. The two vertical mineral wool barriers between the separating walls are not shown.*

Figure 7.6 *View of the facade just after flashover. The paint above the window has burnt off and the window frame is alight.*

Figure 7.7 *View of the facade 53 minutes into the test. The cladding has burnt through above the window and on each side of the horizontal cavity barrier at first floor level. The cavity linings are alight at ground level.*

Figure 7.8 *View of the facade after the fire was extinguished. Although the fire had spread the full height of the facade it had not spread laterally beyond the vertical cavity barriers (dashed lines).*

7.3 Acoustics

Noise pollution is a growing problem between attached dwellings (*e.g.* flats) and so the UK's building regulations are setting ever more demanding acoustic requirements for these buildings. Criteria are given for minimising airborne sound transmission through walls and floors (*e.g.* from people talking) and impact sound transmission through floors (*e.g.* footsteps). A wall between attached dwellings is termed a separating wall whilst the floor between flats is termed a separating floor. Sound can be transmitted directly through separating walls and floors or across the junction between them and an exterior wall, in which case it is known as flanking sound (Figure 7.9) [15] [16].

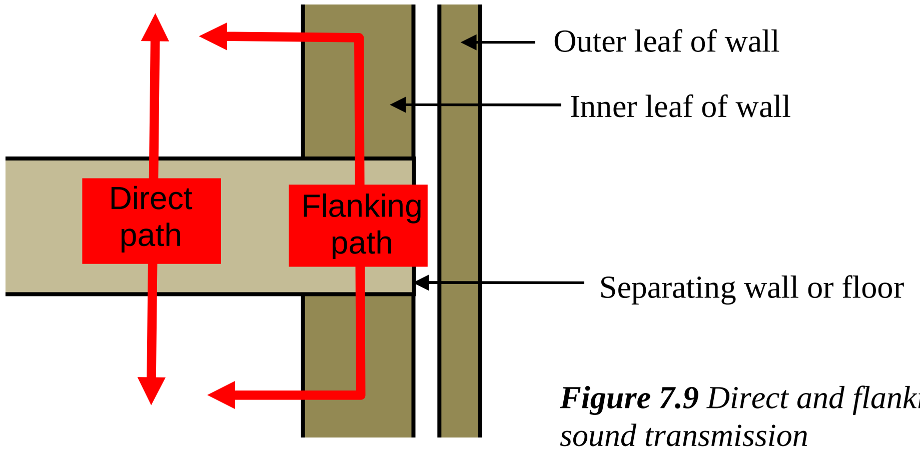


Figure 7.9 *Direct and flanking sound transmission*

The continuous vertical structure of the external wall provides a ready sound path. Consequently, flanking sound transmission between floors has to be minimised by providing layers of acoustic damping to isolate the floor and ceiling from the external wall. Separating wall junctions are simpler to detail as a clear space can be maintained between the two dwellings. The implications for timber cladding are that it can span across separating floors with no need for acoustic separation but flanking sound paths across separating wall junctions require three separate cavity barriers (two behind the cladding on each side of the junction and a third within the junction itself).

The existing guidance typically uses cavity stops made of mineral wool or a similar material separated from the masonry cladding using an impermeable membrane. This detail is unsuited for use with timber cladding due to risk of water entrapment – and thus fungal decay – between the cladding and cavity stop. To avoid this risk, the vertical cavity stops need to be constructed using two timber battens with a third barrier, of mineral wool or a similar material, located in the gap between the separating walls.

7.4 Durability and workmanship

Degradation is controlled using a range of measures encompassed by the term ‘design for durability’. The options vary depending upon the cladding design, materials and service conditions. Selection used to be a relatively straightforward choice between a small number of prescriptive approaches but this is no longer the case as much of the relevant guidance is becoming performance-based. This move has coincided with a growing concern to avoid the negative environmental impacts associated with some traditional approaches and this has stimulated the development of new wood protection processes. The net result is that designers of timber facades now have an unprecedented range of options available to them and, although this freedom is to be welcomed, it does put considerable onus on designers to ensure that the approach they select will deliver the performance they – and their clients – expect. The technical priorities most relevant to timber facade designers are often summarised [17] as the 4Ds:

1. **Deflection:** rainwater needs to be deflected away from the facade using eaves and flashings;
2. **Drainage:** rainwater that enters the facade assembly should be able to drain through unrestricted openings at the base of every cavity; horizontal surfaces should be sloped wherever possible;
3. **Drying:** cavities should have openings at the top to promote moisture evaporation;
4. **Durability:** the materials should be resistant to all the degradation effects that may occur due to moisture.

These are a useful first approximation although it is worth adding a fifth D to the list:

5. **Destruction:** the life safety costs and other consequences of component failure should be taken into account as these may limit the actual options available [18].

The first three points concern the design and construction of a rainscreen whilst the final two are about material selection.

7.4.1 Fungal decay and insect attack

The exposure trial results suggested that – with the possible exception of open jointed, coated designs – timber cladding is at risk of decay on any site exposed to regular wetting or limited drying. This includes most of the western half of Britain (see Figure 2.6) plus any sites where the mean annual relative humidity is above 90% (this mainly includes sites near open water or sheltered by woodland). The main material-based options for controlling wood destroying organisms are listed in Table 7.2 but it must be stressed that minimising moisture uptake should always the first line of defence.

Table 7.2 *Main options for controlling wood destroying organisms*

Type of timber specified	Benefits	Problems	Solution
Low durability	Avoids biocides, enables readily available and low cost local timber to be used.	Regular maintenance essential, impossible to guarantee, needs a surface coating.	Only suitable for low-rise buildings.
Naturally durable heartwood	Can reduce maintenance, durability class can be selected according to service life, complexity *etc*.	Some unpredictability remains, grading essential, can be prohibitively expensive.	Only use if the client is prepared for some unpredictability. Mill must be prepared to grade out sapwood
Wood modified	As naturally durable but with increased predictability, guarantees are possible, good substrate for coatings.	Local sourcing currently limited in the UK. Brittle.	Specified as being equivalent to naturally durable heartwood.
Preservative treated	Minimal maintenance, predictable.	Appearance not to everyone's taste, contains biocides, incompatible with flame retardants.	May be the only option where a guaranteed long-term performance is needed.

Several recent publications give general technical principles for designing a timber rainscreen to minimise moisture up-take and promote drying. [12] [19] - [21]. These can be summarised as follows:

Eaves and flashings: if most rainwater is diverted before it can wet the wall then the need for other wood protection measures is reduced. Where large eaves are not appropriate – perhaps because of the desire to avoid differential weathering problems – it is still important to protect the wall head using a flashing. The endgrain of vertical boards should always be protected. Flashings should project by at least 50 mm.

Splashzone: a common problem occurs where timber cladding is brought too close to the ground or another horizontal surface. The resultant splashing causes rapid localised weathering and can lead to fungal decay. A minimum vertical gap of 150 mm is recommended although 200 - 250 mm will give better protection. In most cases the splashzone will be formed of rendered masonry although metal sheeting is also used.

Cavity drainage and ventilation: a 10 mm gap is recommended at the base of the cavity to allow rainwater to escape whilst also ensuring that ends of boards do not form water traps. cavities always need to be ventilated (open at the top and bottom to allow through flow of air). The gap at the cavity head need only be 6 mm wide and should always be protected from rainwater. Open joints between boards and surface coatings can also help to keep the timber dry. The depth of cavity required is often overstated. Providing that there is a 4 mm deep continuous air gap, the effect of additional depth is minimal. That said, the cavity normally has to be deeper than this to ensure that the support battens are robust and to avoid the cavity becoming blocked over time. Horizontal battens or cavity barriers should not obstruct the free movement of air in normal circumstances. Cavity barriers must fully bridge the cavity during fire and this usually requires that horizontal cavity barriers be intumescent. A vermin mesh is needed at openings near the ground.

Breather membranes: the rear face of the cavity functions not only as an air seal, it provides a second line of defence against rainwater penetration and must allow water vapour diffusing from inside the building to escape. A high performance breather membrane is normally used to fulfil these functions although other options (*e.g.* latex impregnated fibre-board) are possible.

Openings: in Scotland, window and door openings in masonry walls were traditionally protected using what was called a check reveal. In this detail the joinery was set back from the face of the wall and the junction covered with render. A similar detail is beneficial with timber cladding and is included in most Scandinavian recommendations [21] (Figures 7.10 and 7.11). This would need modification before use in the UK due to differences in fire regulations.

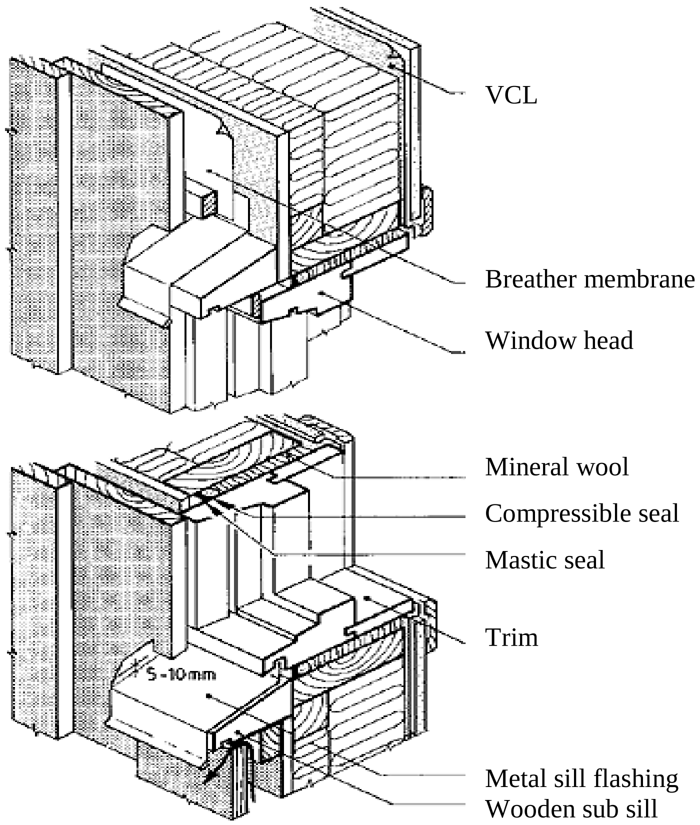


Figure 7.10 *Recommended window detail for southern and central Norway.*

(NBRI, with permission)

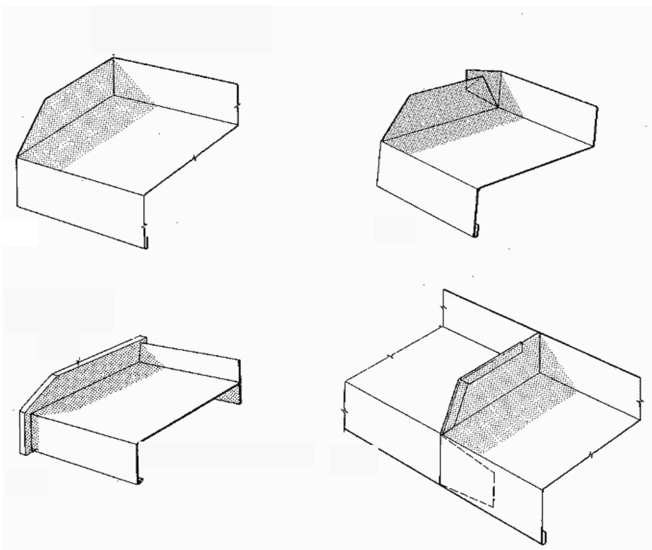


Figure 7.11 *Recommended flashing details for window sills in Norway*

(NBRI, with permission)

7.4.2 Weathering

It is impossible to make any specific statements about how a building will weather unless one has information on the local climate and how this is modified by the shape of the building and those around it. This is rarely available. Even with such information there would still be considerable uncertainly as no reliable weathering model has yet been developed. Coatings give a uniform appearance but cannot be guaranteed to protect the timber from moisture gain and its effects. Leaching out of flame retardants can be a problem if the facade has to have a service life of over 25 years. The main options are given in Table 7.3 below.

Table 7.3 *Main options for controlling weathering*

Type of timber specified	Benefits	Problems	Solution
Uncoated, naturally durable or wood modified	Can minimise maintenance.	Unpredictable.	Only use if the client is prepared for unpredictability.
Surface coated	Gives uniform predictable appearance.	Requires regular maintenance, the most durable products contain a biocide.	Opaque with a fungicidal primer gives the best performance, factory coated, wood modified substrate preferred. Preservative treated timber may avoid the need for a fungicidal primer.
Uncoated, preservative treated	Minimal maintenance, predictable.	Appearance not to everyone’s taste, contains biocides, incompatible with flame retardants.	May be the only option where a guaranteed long-term performance is needed.

In addition, if the facade combines requirements for a low reaction to fire classification (*e.g*. Euroclass A1 to C) with a 50 year service life then timber cannot be used due to the incompatibility of type LR flame retardants and the current generation of CCA alternative wood preservatives.

7.4.3 Dimensional Change

Designers often try to accommodate movement with a 2 mm gap between boards. While better than nothing this can lead to problems where the expansion is greater than 2 mm or the gap is closed during installation. If either of these occurs the result can be catastrophic (see Figure 7.12). It is therefore prudent to estimate the movement that will occur and essential to ensure the specified gap is provided on site (Table 7.4). On simple cladding jobs the three movement classes (see Chapter 5) allow designers to select the appropriate timber. Those with a medium or low class suit most applications though a small movement timber should be selected for tongued and grooved profiles, boards over 150 mm wide or any design where size change is difficult to accommodate. Large movement species can also be used providing the detailing can accommodate the size changes that will occur. Where there is any doubt, however, movement should be calculated using any Equation 5.14 or 5.15.

Table 7.4 *Main options for estimating dimensional change in cladding*

Specification option	Benefits	Problems	Solution
2 mm gap	Maximum simplicity.	Often inadequate.	Only use within limitations.
Using the movement classes	Reasonable simplicity.	Not particularly accurate.	Adequate for small or simple jobs.
Calculation using published formulae	A relatively straightforward calculation.	Some designers and contractors may be resistant to algebra.	Use a specialist if in doubt.

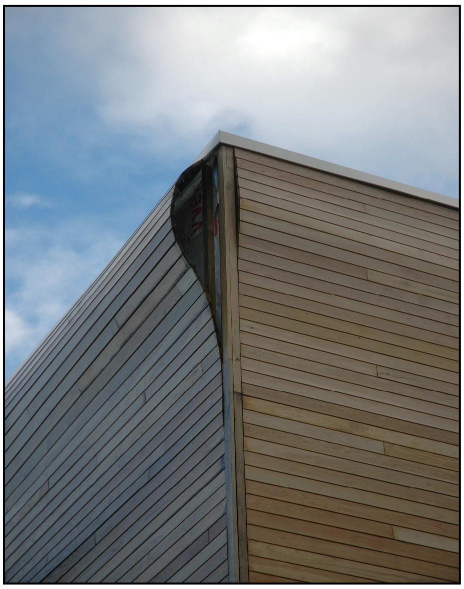


Figure 7.12
Cladding failure due to American white oak timber being installed too dry (moisture content around 8 - 10%) and with no expansion gaps. Unsuitable fixings were also a factor.

7.4.4 Corrosion

Although corrosion is well understood it can be difficult to predict in some cases such as where new wood preservatives are used. In general the best advice is to ensure that cladding fixings are made from austenitic stainless steel. Flashings can be in several materials although lead in contact with damp timber should be avoided as it can be corroded by acetic acid. The main options are given in Table 7.5.

Table 7.5 *Main options for controlling corrosion*

Specification option	Benefits	Problems	Solution
Galvanised steel	Cost effective, widely available, particularly suitable for flashings.	Can be chipped, not fully resistant to acetic acid.	Only use fixings on simple facades with surface coatings.
304 grade austenitic stainless steel	Resistant to virtually all corrosion mechanisms affecting wood.	Cost, availability.	The best solution in most cases.
316 grade austenitic stainless steel	Resistant to marine exposure.	Cost, availability.	Only required within 2 km of coast.
Brass and other copper alloys	Malleable, attractive.	Not fully resistant to acetic acid, fixings have limited availability, cost.	Sometimes used with western red cedar.
Aluminium	Useful for flashings and protecting intumescent cavity barriers	Bimetallic corrosion if in contact with copper.	Must be separated from copper (including timber treated with copper based wood preservatives).
Coatings and other barriers	Cost-effective,	Susceptible to damage.	Mainly useful for separating aluminium from copper based preservatives.

7.5 Decision sequence

Cladding designers need simple guidance that takes them through the sequence of decisions that allow timber facades to be designed for durability, whilst ensuring that fire safety and acoustic performance are also addressed. There are presently two main options. Firstly, BS EN 335-2 [22] gives a decision sequence for selecting natural durability or wood preservation but it is mainly targeted at the wood protection industry and is all but unusable by facade designers because it is too detailed on treatment processes whilst ignoring other design criteria (*e.g.* compatibility with flame retardants). Secondly, the WPA has issued generic specifications for most generic product types, including timber cladding [23]. These are simple to use but they omit several options and are now out of date. Although the WPA is in the process of updating this it is unlikely that they will address the range of issues of concern to facade designers. Accordingly Figure 7.13 provides a decision sequence to guide design and material selection. It is based on BS EN 335-2 but has been updated and modified to make it usable by facade designers. Each box or diamond in Figure 7.12 corresponds to a heading below. In working through this decision sequence, designers are in effect moving through the 5Ds from the bottom up, beginning with a consideration of life safety.

7.5.1 Preliminary facade design

This initial stage uses the performance concepts already outlined in this chapter to define the functional demand for the design and to sketch out preliminary solutions.

7.5.2 Define the performance requirements and use class

Once the performance concept for the facade is understood, the cost of component failure or replacement needs to be considered; this varies with the type of component and affects the choice of wood protection measure. The performance requirements of timber components in the UK are discussed in BS 8417 [18], which recommends different natural durability or preservative treatment specifications based on the life safety and economic considerations anticipated during the service life of the component. These are shown in Table 7.6. The standard assigns timber components to one of four service factors depending upon their ease of replacement and cost of failure.

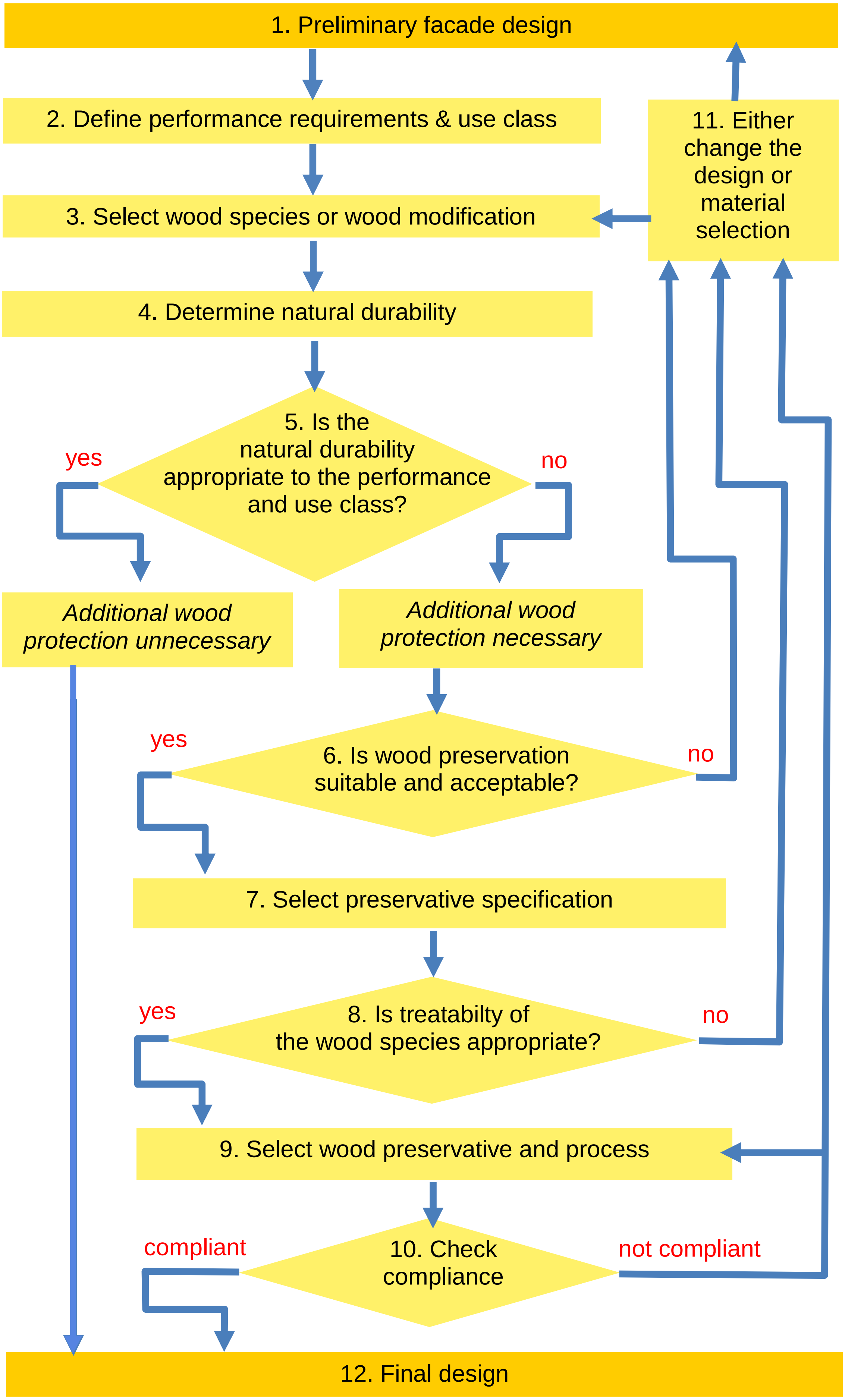


Figure 7.13 *Decision sequence to aid selection of design for durability options*

Table 7.6 *Timber selection for service life performance* (after BS 8417 [18])

Safety and economic considerations	Need for high level of resistance to wood destroying organisms	Service factor
Negligible	Unnecessary	A
Where remedial action or replacement is simple	Optional	B
Where remedial action or replacement is difficult or expensive	Desirable	C
Where structural collapse would be a serious danger to persons or property	Essential	D

BS 8417 assigns external cladding to service factor C, meaning that remedial action or replacement is difficult or expensive. This is certainly the case for most buildings but low-rise domestic buildings may be relatively simple to maintain. Whilst it is normally desirable that timber facades have a high level of resistance to biodegradation, this may be optional on small buildings, or where components are straightforward to replace should the need arise [24]. It can be argued that service factor B may be more appropriate in such cases.

As previously discussed, European standards employ the term 'use class' to describe the microclimate conditions and associated biodegradation risk that characterise particular groups of timber components. Use classes are defined in BS EN 335-1 [25], and their application to solid timber is given in BS EN 335-2 [22] (see Chapter 5.). Each class requires a different combination of wood protection measures. External cladding comes under use class 3. The use class system applies throughout Europe and necessarily involves a degree of approximation. For example, the system is mainly determined by the moisture load in the timber and does not take account of temperature. The risks of fungal decay and insect attack are affected by temperature and so there will be regional differences in the biological agents that occur or the extent to which they cause damage. Some countries describe the effect of these factors in national standards.

The use class system was revised in 2006. Before this revision, the classes were termed 'hazard classes' but this was seen as being too alarmist. The older term is still found in some standards. The revision also introduced sub-classes in use classes 3, 4 and 5 to reflect variations in microclimate conditions or the occurrence of particular biological agents. The practical application of these sub-classes is not yet clear, however, with some people arguing that the presence of a surface coating on external timber is sufficient to change the sub-class from 3.1 to 3.2. Others point to the likelihood that coatings will not be maintained as evidence that class 3.1 should only applied in conditions where the wall is well protected by physical features such as wide eaves. The exposure site data in Chapter 6 suggest that the second, more conservative, approach is the most accurate.

Once the use class has been determined, the biodegradation organisms that are locally important in each microclimate need to be assessed. Several standards and other documents give guidance on wood protection selection according to the biological agents locally present in each use class [18] [26] - [28]. In use class 3 conditions in the UK the main risk is decay fungi; wood boring beetles are only a minor problem and termites are not present.

7.5.3 Select the wood species or wood modification product

The physical properties of most wood species of commercial importance in Europe are defined in BS EN 350-2 [29]. Several properties usually need to be considered and those usually most important for external cladding [30] - [32] are given in Table 7.7. If, for example, the cladding boards are tongued and grooved they generally cannot accommodate dimensional change of more than 2 mm and so a low movement species is required and this will tend to drive the species selection.

Table 7.7 includes examples of wood modified products. For the purposes of this decision sequence, they can be considered as being equivalent to a wood species. Wood modification is a rapidly-evolving field and several new products are likely to become available in the next few years. Modified timber does, however, tend to be more expensive than preservative-treated wood and the type of biodegradation resistance these products offer is usually more specific than the wide-ranging protection offered by traditional biocides.

Table 7.7 *Selecting a natural durability or wood protection approach*

Species or trade name Plus origin where relevant	Average density (kg m^{-3})	Natural durability class	Movement class	Treatability class	
				Sapwood	Heartwood
Accoya™	475	1	Small	Not applicable	
Thermowood D™	420	2	Small		
Robinia (*Robinia psudoacacia*)	740	1 - 2	Medium	Generally not relevant	
Sweet chestnut (*Castanea sativa*)	590	2	Small		
European oak (*Quercus robur* and *Q. petraea*)	710	2	Medium		
Imported western red cedar (Thuga plicata)	370	2	Small		
American white oak (*Quercus* spp.	750	2	Medium		
Imported Douglas fir (*Pseudotsuga menziesii)*	530	3	Small	3	3 - 4
Siberian larch (*Larix sibirica*)	610	3	Small	?	?
UK western red cedar (*T. plicata*)	370	3	Small	3	3 - 4
UK grown larch (*Larix* spp.)	540	3 - 4	Small	2	4
European redwood / Scots pine (*Pinus sylvestris*)	520	3 - 4	Medium	1	3 - 4
UK Douglas fir (*P. menziesii*)	510	3 - 4	Small	2-3	4
Norway spruce (Picea *abies*)	460	4 - 5	Small	3	3 - 4
Sitka spruce (*P. sitchensis*)	390	4 - 5	Small	2-3	4

(green)	**Wood modification used instead of wood preservation** Wood modified timbers are used in a similar way to naturally durable timbers of the same durability class. They should not normally be used for structural applications.
(orange)	**Wood preservatives usually unnecessary** The heartwood is usually suitable for use as external cladding without preservative treatment (western red cedar shingles need to be preservative treated).
(light green)	**Wood preservatives optional or desirable** Timbers with a mean natural durability class of 3 can be used as external cladding without preservative treatment. This is appropriate on many low- or medium-rise buildings but should be avoided where the cost of failure is high. Preservative treatment is needed in such cases.
(blue)	**Wood preservatives desirable except on low rise buildings** Timber with a variable natural durability class may be appropriate on low-rise buildings but should be avoided if the cost of failure is high. Preservative treatment is needed in such cases.
(purple)	**Wood preservatives normally essential** Low durability timbers or those with a wide sapwood zone (*e.g.* Scots pine) should normally be preservative treated before use as external cladding. It may be possible to avoid this on some low-rise buildings if the cladding is easy to maintain.

7.5.4 Determine the natural durability

European Standard BS EN 350-2 [29] gives natural durability classifications for most timber species that were of commercial importance in Europe during the 1990s (see Table 7.7). If a species is not listed in the standard, test data should be obtained from a reputable independent source. The use of tropical hardwoods are discussed in Davies and Wood [2]. Wood modification is not currently covered by BS EN 350-2; the supplier should be able to provide durability data from a reputable and independent source if required. Specification for the durability of modified wood products should be expressed using the same classification as unmodified timbers.

7.5.5 Is the natural durability adequate?

European Standard BS EN 460 [26] gives guidance on the level of natural durability or preservative treatment needed for resistance against fungal decay (Table 7.8). This covers the whole of Europe and so is necessarily quite general. Country-specific information is published in national standards such as BS 8417 [18] (see Table 7.9). If the natural durability of the selected species is sufficient, then additional wood protection is unnecessary and the designer can finalise the design using the principles in Section 6.4.1. Many of the relevant construction details are given in Chapter 8. If, however, the natural durability of the timber in question is deemed unsuitable then additional wood protection will be required.

7.5.6 Is wood preservation suitable and acceptable?

Where wood protection is deemed necessary, the designer has to decide which options are suitable for the particular facade. Preservative treatment requires pressure impregnation with a leach-resistant biocide. Brush or dip applications of preservative are relatively ineffective as well as posing a health and safety risk. Problems can, however, occur where the timber also needs to be impregnated with a flame retardant, in which case it may not be compatible with wood preservative impregnation. This can be a particular challenge with shingles and shakes as these are generally preservative treated for use in UK conditions. Some people may also want to avoid wood preservatives due to concerns over their safety or eco-toxicity. In cases where wood preservation is not suitable designers may need to change the facade design or the timber species they propose to use.

Table 7.8 *BS EN 460 Natural durability or preservative treatment needed for resistance against fungal decay* [26]

Durability class / **Use class**	**1** Very durable	**2** Durable	**3** Moderately durable	**4** Slightly durable	**5** Not durable
1. Above ground, covered, dry.					
2. Above ground, covered, risk of wetting.					
3. Above ground, not covered, periods of wetting.					
4. In ground or fresh water.					
5. In sea water.					

Key

	In these conditions natural durability is always sufficient and there is no requirement for preservative treatment
	Natural durability is normally sufficient in these conditions but for certain uses where condensation is likely preservative treatment is advised
	Natural durability may be sufficient in these conditions, but, depending upon the wood species and end use, preservative treatment may be needed
	Preservative treatment is normally advised in these conditions but natural durability may be sufficient in some cases
	Preservative treatment is always necessary in these conditions

Table 7.9 *BS 8417 Service life of timber in different use classes in the UK* [18]

Component	Use class	Service factor	Durability class where heartwood can be used without treatment		
			Desired service life (years)		
			15	30	60
Internal joinery	1	A	5	5	5
Roof timbers dry	1	B	5	5	5
Roof timbers dry (*Hylotrupes* area)	1	D	3b	3b	3b
Roof timbers risk of wetting	2	C	4	3	2
External walls, ground floor joints	2	B/C/D	4	3	2
External joinery	3	C	4	3	2
Fence rails, garden decking	3	B/C/D	4	3	2
Sole plates below the DPC	4	D	2c	1	1d
Fence posts	4	B/C/D	2c	1	1d
Poles	4	D	2c	1	1d
Sleepers	4	D	2c	1	1d
Timber in fresh water	4	D	2	1	1
Cooling tower packing, fresh water	4	D	2	1	-
Timber in salt water	5	D	1e	- f	- f
Cooling tower packing, salt water	5	D	1	-	-

a) Natural durability classes from BS EN 350-2.

b) Any hardwood can be used. House longhorn beetle (*Hylotrupes bajulus*) can attack heartwood of some low durability softwood species wherever the species is locally present.

c) Some durability class 3 timbers can achieve 15 years service life.

d) Some durability class 1 timbers can achieve 60 years service life.

e) Preferred species are listed in the standard

f) Most durability class 1 species will not give more than 15 years service though a few can give longer service if large sections are used.

Table 7.8 is oversimplified whilst Table 7.9 has a number of gaps. Moreover, these tables are inconsistent. Consequently these two tables have been redrawn as Table 7.10 to make them more compatible. The new table contains a number of suppositions including the service life of cladding made from durability class 4 or 5 timber.

Table 7.10 *Natural durability or preservative treatment requirements for timber components* (after BS EN 460 [26] and BS 8417 [18])

Use condition and natural durability class / Component	Use class	Service factor	Durability class (BS EN 350-2)				
			1	2	3	4	5
Internal joinery and structural timber	1	A					
Roof timbers dry	1	B					
Roof timbers dry (*Hylotrupes* area)	1	D					
Roof timbers with a risk of wetting	2	C					*1*
Structural timber in external walls & ground floors	2	B/C/D					*1*
External joinery *e.g.* cladding & windows	3	C					*1*
Fence rails, decking, hand rails	3	B/C/D					*1*
Structural parts of timber bridges	3	D	*1*	*1*	*1*	*1*	*1*
Fence posts	4	B/C/D					
Sole plates below the DPC	4	D					
Transmission poles, sleepers	4	D					
Timber in fresh water	4	D					
Cooling tower packing in fresh water	4	D					
Timbers in salt water	5	D					
Cooling tower packing in salt water	5	D					

Key

	Service life of at least 60 years without preservative treatment unless water traps.	The service life varies but is often greater than these minimum estimates which represent 'worst case' conditions. Where, however, a *guaranteed* service life greater than the estimates is required, there is no alternative but to use preservatives or some types of wood modification.
	Service life of at least 30 years without preservative treatment unless water traps.	
	Service life of at least 15 years without preservative treatment unless water traps.	
	Service life usually less than 15 years unless regular maintenance is employed.	
	Preservative treatment normally recommended. Depending upon the species, and exposure conditions, natural durability may give at least a 15 year service life.	
	Preservative treatment recommended.	

Notes: (*1*) Not shown in BS 8417 but included here for clarity

7.5.7 Select preservative specification

Wood preservative specification is described in BS 8417 [18], BS EN 351-1 [25] and BS EN 599-1 [33]. In principle, the specification is written in terms of the results of the preservative treatment process: the required penetration of the biocide into the wood has to be stated along with its concentration in a defined zone. The goal being to achieve a sufficient loading of preservative to guarantee a service life of either: 15, 30 or 60 years. These documents are complex and so the WPA has issued generic specifications for many product types [23]. Cladding is covered by WPA commodity specification C6.

7.5.8 Is the treatability adequate?

Wood species vary in their permeability to preservative impregnation; this is known as treatability. The treatability of most commercial timbers is given in BS EN 350-2 [29] (see Table 7.7.) If the treatability of the timber species in question is adequate then the preservative can be selected. If not, then another species should be chosen.

7.5.9 Select wood preservative

The WPA manual [23] gives guidance on selecting the most appropriate preservative treatment products and process. The UK list of approved pesticides is regularly updated, however, and current information is available from the Health and Safety Executive website [34] [35].

7.5.10 Is it compliant?

The preservative supplier must be able to demonstrate compliance with relevant standards. Facade designers cannot be expected to be able to assess this themselves and so adherence to the relevant WPA specification [23] is essential. If compliance is achieved then designers can proceed with their design; if not then a different preservative or process may be needed or the facade design or timber selection could be changed.

7.5.11 If all else fails start again

It may be necessary to go through this decision sequence a number of times before an appropriate solution emerges. This may involve adjusting the facade design to improve moisture performance, allow component replacement or use a more degradation-resistant timber. Whatever option is chosen the designer must ensure that the measures employed give sufficient degradation resistance in the anticipated service conditions.

7.5.12 Final design

Once the design for durability approach is fully worked out, the construction details and specifications in Chapter 7 can be used to help ensure that the facade complies with the other performance requirements in the applicable building regulations. Detailing can begin. This is discussed in the next chapter.

7.6 Summary

This Chapter has provided outline specifications and a decision sequence for the design of low- and medium-rise timber facades in the UK. Key points from this chapter are:

- There is a conflict in UK Building Regulations between fire safety, design for durability and acoustic insulation. This can be resolved using a combination of measures including intumescent cavity barriers.

- The fire safety of timber facades needs further work: a test standard is required for cavity barriers and for full-scale facade tests. The *ad hoc* test outlined in this chapter provides a template for such research.

- An improved decision sequence for timber cladding design is provided. This is targeted at the needs of facade designers whilst ensuring compliance with regulatory requirements for wood protection.

References

1 BS EN 1995-1-1:2004+A1:2008. Eurocode 5. Design of timber structures. General. Common rules and rules for buildings. London: BSI, 2009.

2 Davies, I. and Wood, J. (2010). External timber cladding: design, installation and performance. Edinburgh: arcamedia.

3 BS 5534:2003. Code of practice for slating and tiling (including shingles). London: BSI, 2003.

4 BS 476-10:2009. Fire tests on building materials and structures - Part 10: Guide to the principles, selection role and application of fire testing and their outputs. London: BSI, 2009.

5 Colwell, S. and Martin, B. (2003). Fire performance of external thermal insulation for walls of multi-storey buildings, BRE Report 135. Watford, UK: BRE Press.

6 Yung, D. and Oleszkiewicz, I. (1988). Fire Spread via Exterior Walls of Buildings. Proceedings of 4th Conference on Building Science and Technology, 18-19 February 1988, Toronto, Ontario. Ontario: National Building Envelope Council.

7 Read, R. E. H. (1991). External fire spread: building separation and boundary distances. BRE Report 187. Watford, UK: Building Research Establishment.

8 Bart B., Kotthoff, I. and Weiderkehr, R. (2009). Aussenwände – Konstruktion und Bekleidungen. [External construction – cladding. In German] Zurich: Lignum – Dokumentation Brandschutz.

9 BS 476-20:1987. Fire tests on building materials and structures. Method for determination of the fire resistance of elements of construction (general principles). London: British Standards Institution, 1987

10 BS 476-22:1987. Fire tests on building materials and structures. Methods for determination of the fire resistance of non-loadbearing elements of construction. London: British Standards Institution, 1987.

11 Harmathy, T.Z. (1974). Flame deflectors. Ottawa: National Research Council of Canada.

12 Stirling,C. (2002). Thermal insulation: avoiding risks. BRE Report 262. Watford, UK: BRE Press.

13 BS 7974:2000. Application of fire safety engineering principles to the design of buildings - Code of practice. London: BSI, 2000. p4.

14 Lennon, T. (2008). The fire performance of timber facades. Test report 243-505. [Unpublished report to the Forestry Commission]. Watford, UK: BRE Global.

15 TRADA Technology (2000). Acoustic performance of party floors and walls in timber framed buildings. Report 1/2000. High Wycombe, UK: TRADA Technology Ltd .

16 Smith, S., Wood, J.B. and Mackenzie, R. (2006). Housing and sound insulation – improving existing attached dwellings and designing for conversions. Edinburgh: arcamedia.

17 Canada Mortgage and Housing Corporation, (1999). Wood-frame envelopes in the coastal climate of British Columbia. Vancouver: CMHC.

18 BS 8417:2003. Preservation of timber. Recommendations. London: BSI, 2003.

19 Hislop, P. (2007). External timber cladding. 2nd edn. High Wycombe, UK: TRADA Technology Ltd.

20 Davies, I., Walker, B. and Pendlebury, J. (2002). Timber cladding in Scotland. Edinburgh: ARCA Publications.

21 Edvardsen, K.I., and Torjussen, L. (1997). Håndbok 45 – TREHUS. [Handbook 45 – wooden house. In Norwegian] Oslo: Norges Byggforskningsinstitutt.

22 BS EN 335-2:2006. Durability of wood and wood-based products. Definition of use classes. Application to solid wood. London: BSI, 2006.

23 Wood Protection Association (2007). WPA Manual: industrial wood preservation specification and practice 2007. [Compact Disc] Castleford (West Yorkshire), UK: WPA.

24 The Building (Scotland) Regulations 2004. Domestic Handbook May 2009. Section 0.8.2. Scottish Building Standards. Livingston, UK. 2009.

25 BS EN 335-1:2006. Durability of wood and wood-based products. Part 1. Definitions of use classes. General. London: BSI, 2006.

26 BS EN 460:1994. Durability of wood and wood-based products. Natural durability of solid wood. Guide to the durability requirements for wood to be used in hazard classes. London: British Standards Institution, 1994.

28 Bravery, A.F. (2003). European standards for wood preservatives and treated wood. Information Paper 1/03. Watford, UK: BRE Press.

29 BS EN 350-2:1994. Durability of wood and wood-based products. Natural durability of solid wood. Guide to natural durability and treatability of selected wood species of importance in Europe. London: British Standards Institution, 1994.

30 Rijsdijk, J.F. and Laming, P.B. (1994). Physical and related properties of 145 timbers. Dordrecht, The Netherlands: Kluwer Academic Publishers.

31 Farmer, R.H., Maun, K.W. and Coday, A.E. (2000). Handbook of hardwoods with 1997 supplement. Watford, UK: BRE Press.

32 Building Research Establishment (1977). A handbook of softwoods. 2nd edition. London: Stationery Office.

33 BS EN 599-1:2009. Durability of wood and wood-based products. Efficacy of preventive wood preservatives as determined by biological tests. Specification according to use class. London: BSI, 2009.

34 Health and Safety Executive. Non-agricultural pesticides approved under: The Control of Pesticides Regulations 1986 (as amended). Available from: <http://www.hse.gov.uk/biocides/copr/approved.htm> [Accessed 10 July 2010.]

35 Health and Safety Executive - Chemicals Regulation Directorate. Website: <http://www.pesticides.gov.uk/> York, UK: HSE. [Accessed 10 July 2010.]

Chapter 8

Detailing

This chapter develops construction details for timber cladding on low- and medium-rise buildings in the UK. They have been developed in response to the findings of previous chapters. In particular:

- The detailing and workmanship survey in Chapter 3 suggests that many challenges presented by timber facades occur at junctions such as above access ramps, around windows or where different cladding materials meet. Defects at these junctions can create water traps (leading to degradation) and compromise fire safety.

- The exposure trial results presented in Chapter 5 employed a moisture index (expressed as the percentage of time when the moisture content of the cladding is over 22% or 25%) to evaluate the degradation risks in 16 test panels clad with Sitka spruce. Only the combination of open jointed cladding with a surface coating achieved a low moisture index score on both test sites (*i.e.* the degradation risk was low). The moisture content range in the other panels was higher, in many cases fluctuating between 10% up to near the FSP. A supplementary test suggested that a similar pattern of moisture behaviour may occur in other timber species.

- The technical information on timber facades available in standards and building regulation guidance is often incomplete, inconsistent and inaccurate. Small wonder then that designers and contractors make frequent detailing and workmanship errors.

8.1 Scope

The details provided here are designed for use with low-rise residential buildings although many are also suitable, or can be adapted, for taller facades or non-domestic applications. Each detail is designed to be compliant with the performance criteria given in the guidance documents supporting the UK's building regulations as at February 2011. Although the energy performance standards in these details will be superseded in due course, their fire safety, durability and acoustic principles continue to be relevant.

Construction detailing in the UK is in flux as governments and regional assemblies seek to improve the energy performance and sustainability of buildings. Although some design codes or accredited construction details are available [1] - [3], there is little consensus on how these improvements are to be achieved and, as a consequence, designers and builders are responding with a range of technical solutions. In view of this, most of the details in this chapter use a standard timber-framed structure, as this is currently the commonest substrate for timber cladding in the UK. Other wall build-ups, such as a 'reverse wall' can be developed using the principles illustrated in these drawings. Similarly, a zone for services can be created under the plasterboard, or additional insulation installed on the inner, or outer face, of the structural frame. Other wall substrates such as masonry can also be used. Figures 8.1 to 8.4 give examples.

Although open jointed and coated cladding performed best in the exposure trial, no construction details are given below provided for this type of facade. This is because open jointed cladding is incompatible with the criteria for cavity barriers in the current guidance to the UK's building regulations. The issue is that, even if the cavity is blocked with a cavity barrier, there is little to prevent fire bypassing the barrier through the open joints. This does not mean open-jointed cladding is unsuitable for use in the UK, but rather that it has to be used in combination with internal room sprinklers to fully comply with UK fire regulations. If sprinklers are available then both open and closed jointed cladding can be detailed in the same way. Diagonal cladding is also omitted. This is because it is detailed in a similar way to vertical cladding; the boards are normally fixed to horizontal battens on counter battens. Diagonal battens can also be used, but they do not remove the need for counter battens.

8.2 Objective

The objective of the details included here is to provide a ready means of reconciling the sometimes-conflicting performance requirements for:

1. The prevention of rain penetration;
2. The restriction of unseen spread of flame through cavities;
3. The limiting of flanking sound transmission across party wall and floor junctions.

Other performance requirements, such as airtightness, have not been addressed to the same extent as they are already covered by recent industry guidance *e.g.* the Association for Environment Conscious Building's CarbonLite programme [4], which gives construction details based on the German PassivHaus [5] (Passive House) approach.

8.3 Construction details

Three types of facade junction are illustrated: horizontal, vertical and miscellaneous (Figure 8.5). There are nine groups of drawings as listed in Table 8.1.

It is rare that a new construction detail is entirely without influences or precedent. So how original are the details given below? They certainly build upon and refine cladding details published by NBRI [6] and TRADA Technology [7] [8]. But they also go beyond these sources in several ways. Most importantly:

- They integrate timber cladding design with design of the underlying wall junction, this had not been attempted in the UK;
- They apply acoustic separation techniques [9] to timber cladding for the first time;
- They resolve, for the first time, the building regulation conflict between durability, fire safety and acoustics;
- They provide different cavity barrier detailing depending upon if the rear face of the cladding is smooth or uneven.

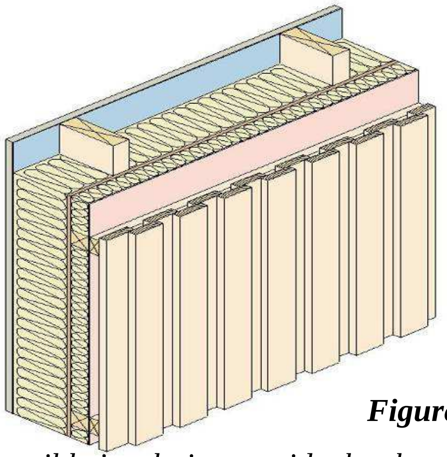


Figure 8.1
Compressible insulation outside the sheathing

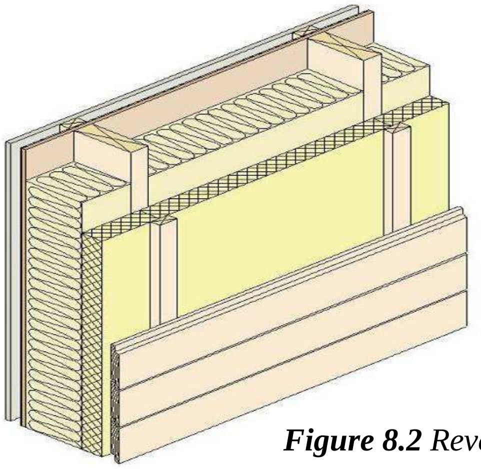


Figure 8.2 *Reverse wall with rigid insulation behind the cavity*

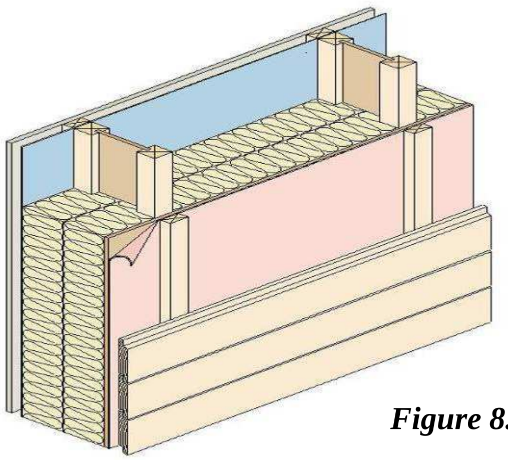


Figure 8.3
Wall frame made from I joists

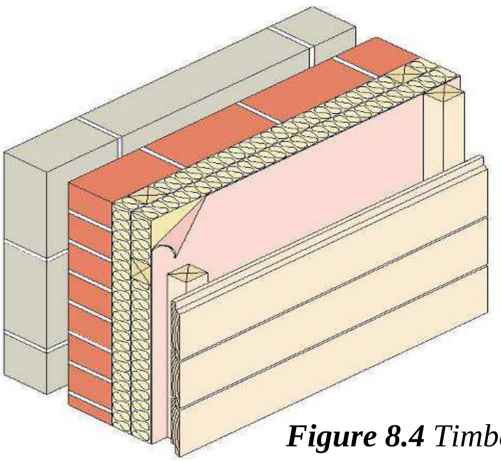


Figure 8.4 *Timber -clad external insulation on a masonry wall*

In Figure 8.1 the sheathing is lined externally with compressible insulation supported on 50 mm square battens. These also carry the cladding support battens; no vertical counter-battens are used. This detail is adequate for a dry site but requires counter-battens to allow additional ventilation in wet locations.

Figure 8.2 shows reverse wall construction where the sheathing is positioned on the inner face of the timber frame. The outer face of the frame is lined with rigid insulation. The cladding battens are fixed through this to the vertical studs. A breather membrane may not be needed if the insulation is moisture resistant (*e.g.* latex impregnated fibre board).

In Figure 8.3 the cladding battens are fixed to I joists used to create a deep wall section with minimal thermal bridging. The Larsen truss uses a similar, but non-proprietary arrangement, where studs are built of vertical battens with plywood gussets.

In Figure 8.4 the thermal performance of a masonry wall has been upgraded using compressible external insulation protected by a timber rainscreen. This approach is valuable on exposed sites or where it is uneconomical to refurbish the masonry to make it weather proof.

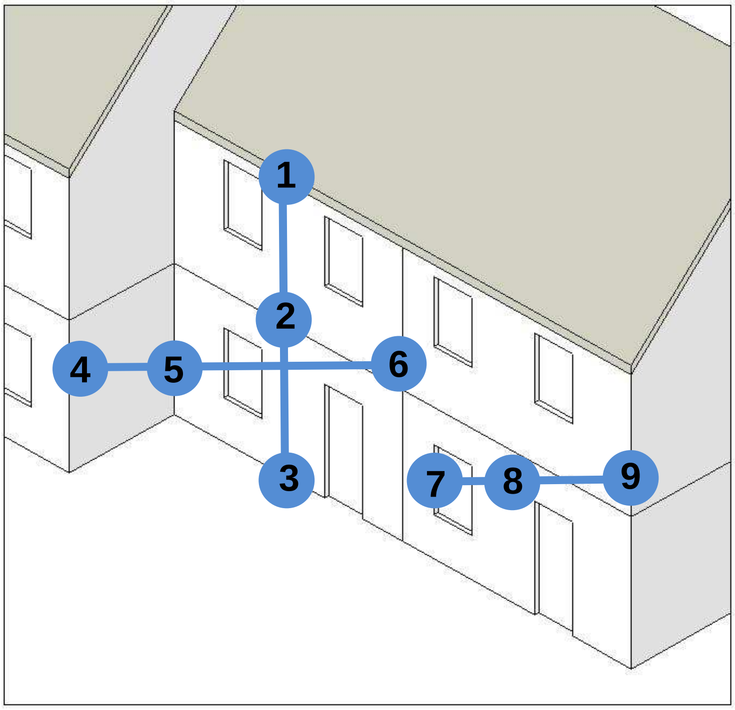


Figure 8.5 *The nine groups of construction details*

Table 8.1 *Descriptions of the nine groups of construction details*

Type of junction	Description of group
Horizontal	1) Eaves and parapets
	2) Floors (separating or intermediate)
	3) Ground level, flat roofs or other near horizontal surfaces
Vertical	4) External corner
	5) Internal corner (intermediate or separating)
	6) In-line junctions (intermediate or separating)
Miscellaneous	7) Windows and doors
	8) Junctions between cladding boards
	9) Junctions with other cladding materials

Group 1. Eaves and parapets

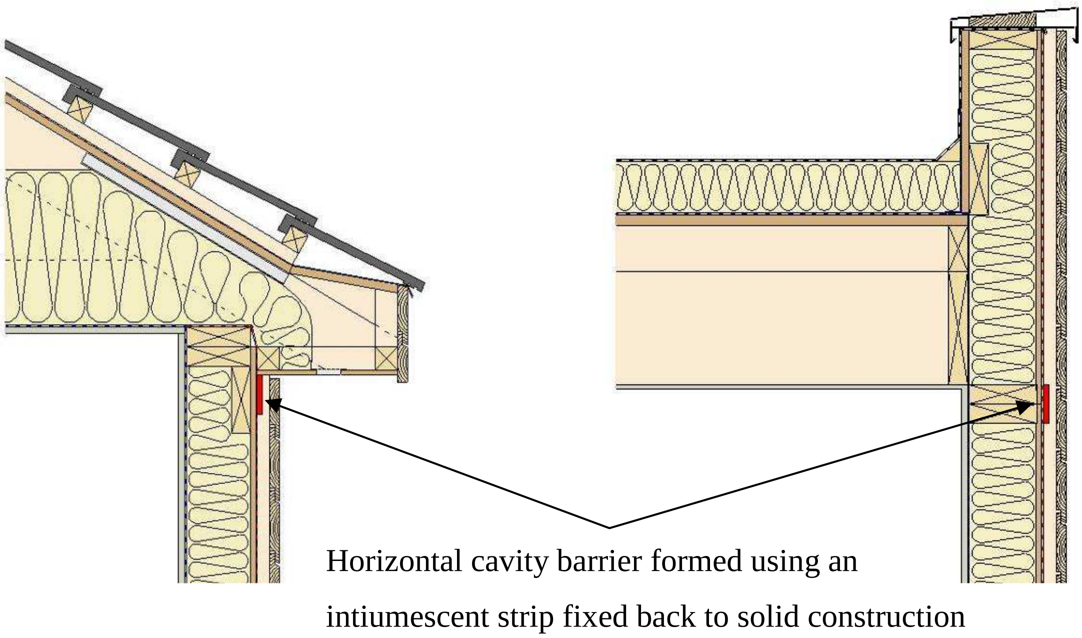


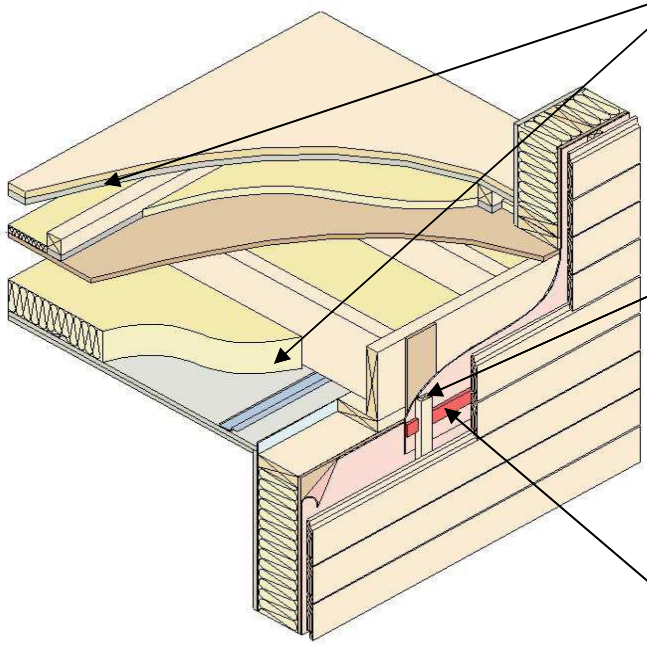
Figure 8.6 *Junction with normal to deep eaves*

Figure 8.7 *Junction with a parapet*

Normal or deep eaves (Figure 8.6) shelter the top of the wall, although to protect the full height they would need to extend by a quarter of the height of the facade, a solution that is usually impractical. If the cladding is left uncoated, deep eaves can lead to uneven weathering of the wall below. If this is a concern the eaves depth can be reduced, although this will tend to increase the moisture load on the facade. Alternatively the cladding can be carried above roof height as a parapet (Figure 8.7). This has the benefit of minimising the risk of an external fire (such as arson) spreading to the roof. The detail does, however, tend to increase wind-driven rain concentration at the top of the facade.

The wall cavity is normally ventilated (*i.e.* open at both base and top to allow through ventilation) and so a 6 mm gap should be provided at the top of cavity. The top opening should have an intumescent cavity barrier to prevent fire spread; these are shown in red. The intumescent barrier should be fixed back to solid timber (*e.g.* a stud or dwang) in accordance with manufacturer's instructions. These figures show horizontal cladding. Vertical cladding has similar junction details at the eaves although the cavity depth will be greater.

Group 2. Separating or intermediate floor



Acoustic battens, quilts and other products are used to minimise flanking sound transmission between floors.

Vertical timber battens span across the floor junction. If the vertical batten is also a cavity barrier, it may need rear packing (*e.g.* with OSB) to ensure the cavity is closed.

Horizontal cavity barrier formed using an intumescent strip.

Figure 8.8 *Junction with a separating floor*

Note: thermal insulation between joist ends near the ring beam has been omitted for clarity.

Figure 8.8 illustrates how the cladding support assembly (in this case vertical timber battens) and a horizontal cavity barrier at a separating floor can be provided whilst minimising flanking sound transmission through the external wall and maintaining through-ventilation of the cavity.

For structural reasons, there is no alternative but to have direct physical contact between the load-bearing elements in the wall; vertical flanking sound transmission can, therefore, only be controlled by isolating the floor and ceiling using acoustic battens, quilts or similar products. Vertical cladding battens are thus able to span across the separating floor without unduly compromising the flanking sound performance of the junction. If a vertical timber batten also has to function as a cavity barrier, it may need to be packed out at the floor junction to ensure that the cavity is fully closed; the batten itself should be at least 38 mm thick. Where a horizontal cavity barrier is required, an intumescent strip can be used. Intermediate floor junctions are much simpler to detail as there are fewer flanking sound issues.

Group 3. Ground level or abutments with roofs and decks

The base of the cladding is normally kept at least 200 mm above ground level (or other horizontal surface) in order to avoid splashing onto the wall.

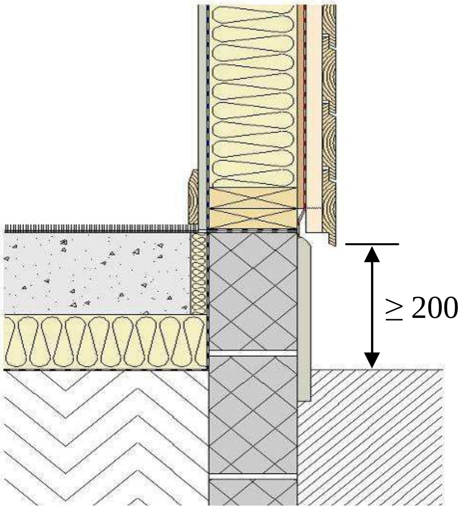


Figure 8.9 Normal ground level junction

If a 200 mm gap cannot be provided the splash risk can be avoided using a gutter and grille against the wall.

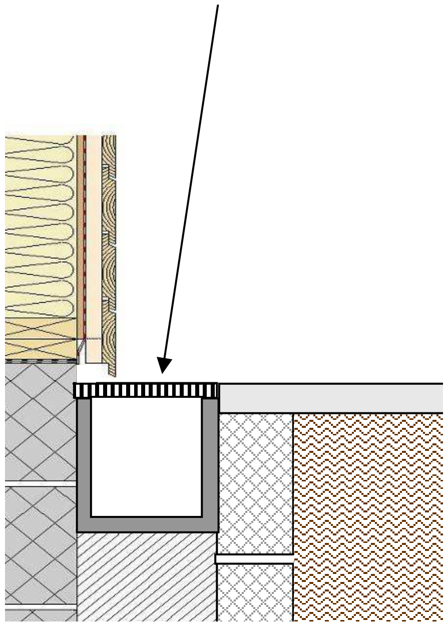


Figure 8.10 Junction without splashzone

Where timber cladding is brought near to a horizontal surface such as the ground or a roof abutment there is a risk of localised wetting of the facade due to splashing. This can cause uneven weathering or even fungal decay. The height of the splash zone is up to 200 mm. The cladding needs to be kept above this zone and so a separation of at least 200 mm is needed (Figure 8.9). If this is not possible, then the horizontal surface needs to be covered with free draining and uneven materials (*e.g.* gravel) or be provided with a gutter (Figure 8.10). If the gutter is at ground level or alongside decking it will need covering with a grille conforming to the A15 or B 125 load classes in BS EN 1433 [10]. In addition, the grille elements must be as narrow as possible to minimise splashing; this will generally require vertical strips formed of galvanised steel or plastic. Cavity barriers are not required at ground level but may be necessary in other locations, *e.g.* where a balcony abuts the facade. If vermin enter the cavity, they can damage the breather membrane and also gain access into the building. A metal vermin mesh is thus needed at all openings into the cavity near the base of the facade. The maximum mesh size is 4 mm.

Group 4. External corners

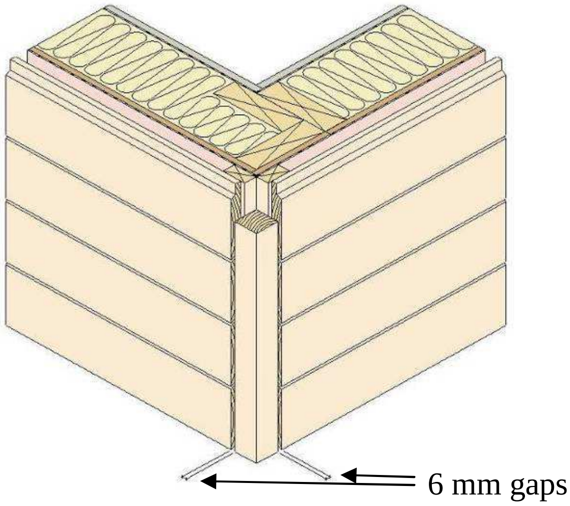


Figure 8.11 *External corner with horizontal boards*

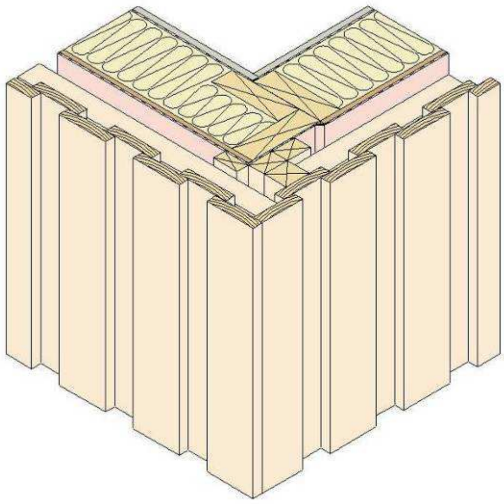


Figure 8.12*. External corner with vertical boards*

There are numerous ways of detailing external corners. Figures 8.11 and 8.12 show two examples. The following points should always be addressed: Vertical cavity barriers are needed at all external corners. They have a duel function of limiting fire spread and preventing horizontal air movement within the cavity. Vertical cavity barriers are formed from softwood battens at least 38 mm thick. Cavity barriers must fully close the cavity. This is straightforward where the rear face of the cladding is flat (Figure 8.11) but is more complex where the rear face is uneven. In some cases the cavity barrier batten will need to be continued through to the face of the cladding with the ends of the cladding boards butted tightly against it (Figure 8.18, for example). The cladding boards may need to be predrilled to comply with the edge and end distances for fixings, alternatively the batten width or position could be changed.

Wherever horizontal boards meet another surface near an external corner a 6 mm gap should be provided to enable the endgrain to dry quickly after rain (Figure 8.11).

Group 5. Internal corners

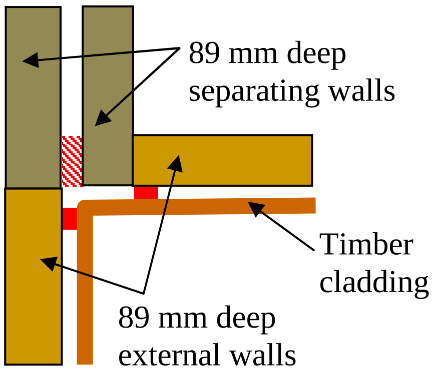


Figure 8.13 *Plan view of a staggered wall with all frames the same depth*

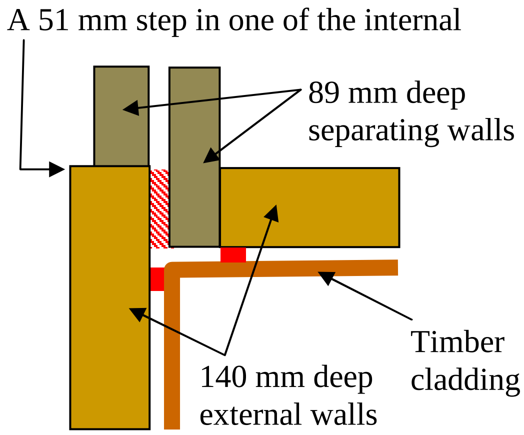


Figure 8.14 *Plan view of staggered wall with a stepped internal wall due to the separating and external walls being different depths*

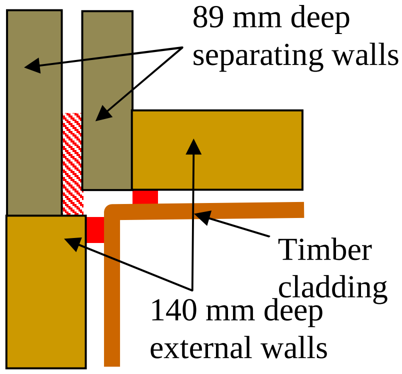


Figure 8.15 *Plan view of a staggered wall avoiding the stepped internal wall*

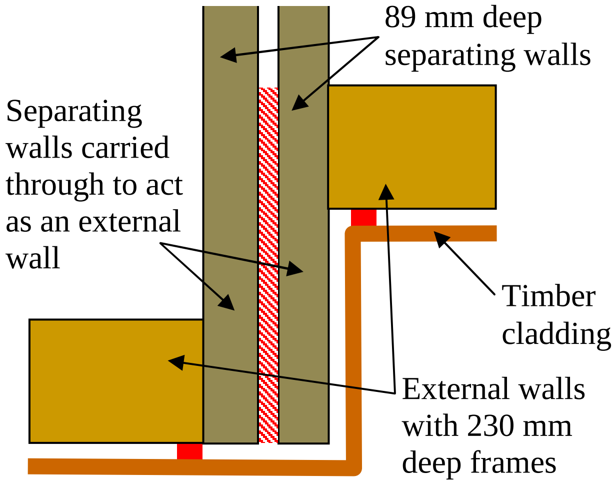
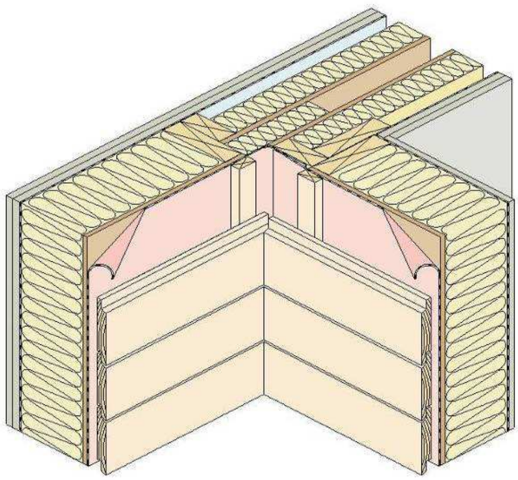


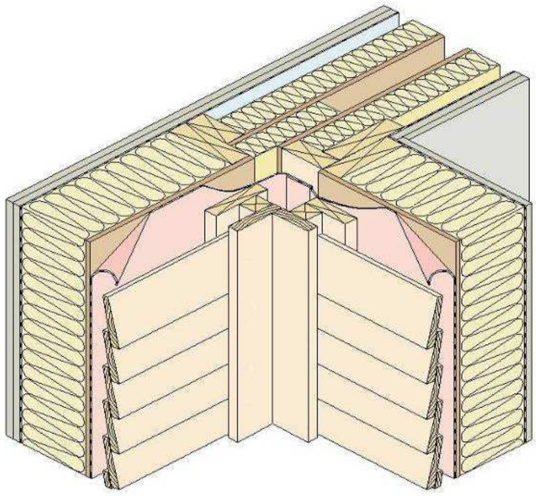
Figure 8.16 *Plan view of the kind of staggered wall arrangement that becomes feasible as wall thicknesses increase further*

Acoustic batt cavity barrier

Timber cavity barrier

Internal corners often involve a separating wall junction (*i.e.* a staggered wall). Most UK staggered wall details for timber frame employ a 89 mm deep frame. This is simple to detail since both the external and separating walls are the same thickness (Figure 8.13). But where the external wall becomes 140 mm thick, difficulties arise at internal corners because the separating wall frames usually stay at 89 mm thereby creating a step in one of the internal walls (Figure 8.14). To solve this, a new staggered wall detail was developed for this thesis to ensure fire and acoustic separation whilst avoiding the need for a stepped internal wall (Figure 8.15). The next page gives examples of how the detail works in practice. This is only an interim solution as it is likely to be superseded by existing Scandinavian details (Figure 8.16) as UK thermal efficacy requirements further increase.





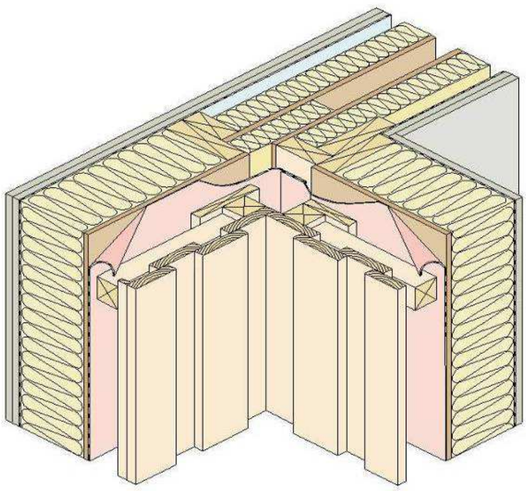


Figure 8.17 *(top left) Horizontal cladding with a flat rear face*

Figure 8.18 *(top right) Horizontal cladding with an uneven rear face*

Figure 8.19 *(left) Vertical cladding with an uneven rear face*

Three separate vertical cavity barriers are needed at this junction.

The two timber barriers should block the cavity irrespective of the type of cladding profile. This requires different construction details depending upon whether the rear face of the cladding is flat (*e.g.* tongued and grooved boards) or irregular (*e.g.* board on board). The barriers are positioned so that they do not come into direct contact with each other since that could increase flanking sound transmission.

The compressible barrier also needs to fully block the cavity. The key consideration is that the sheet material lining the separating wall junction (*e.g*. OSB) must not continue across the vertical gap separating the frames.

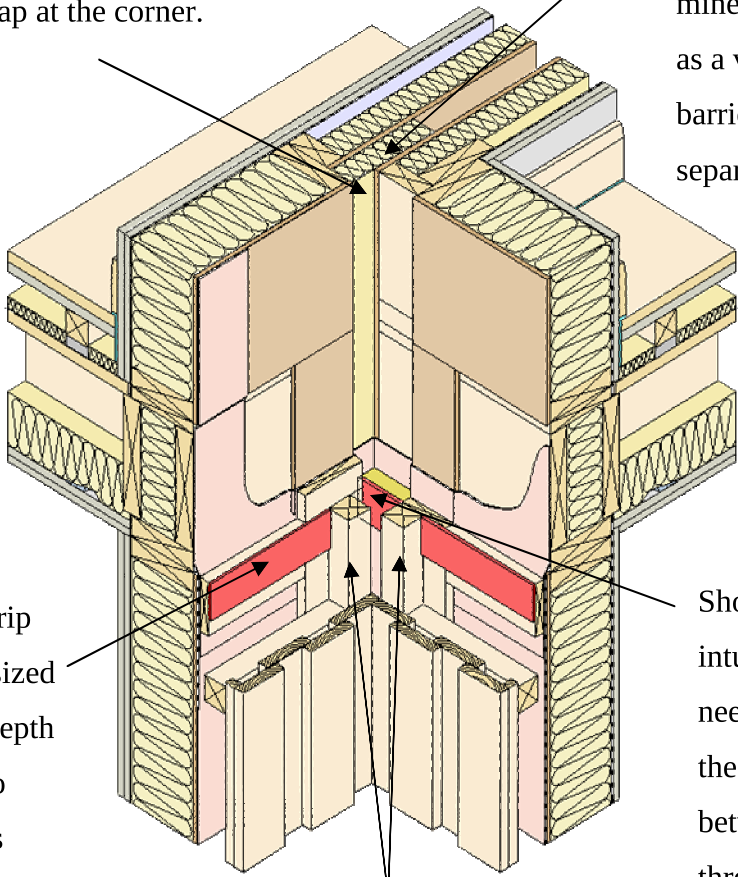
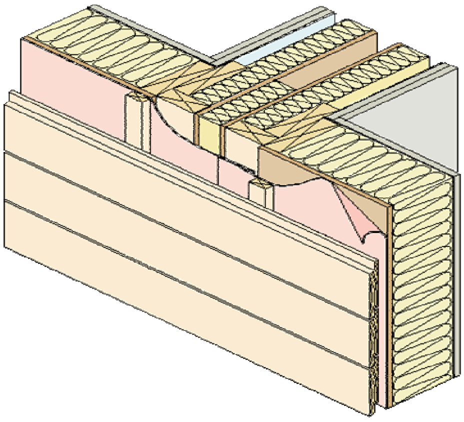
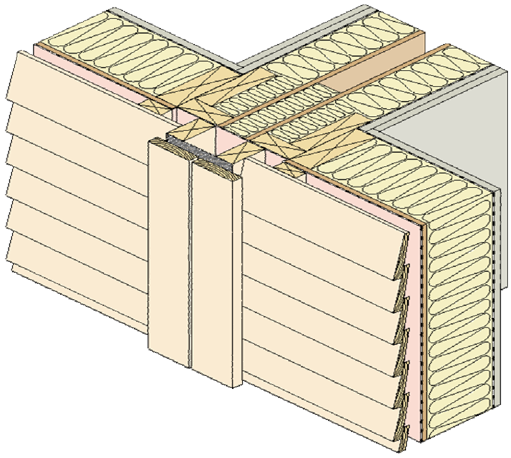


Figure 8.20 *Junction between a staggered wall and separating floor*

This is generally the most complex junction to detail and construct. All of the principles in Groups 2 and 5 apply. In addition, a short intumescent strip is needed to close off the void between the three vertical cavity barriers.

Group 6. In-line junction





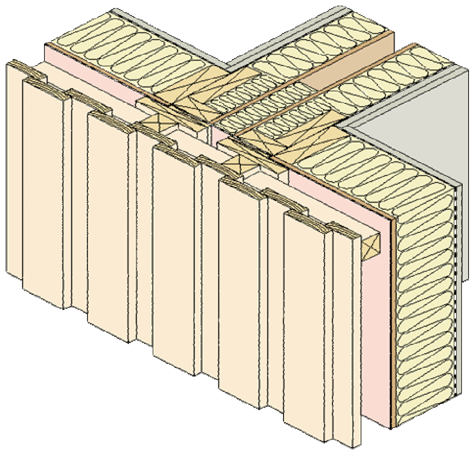


Figure 8.21 *(top left) In-line junction with horizontal boards having a flat rear face.*

Figure 8.22 *(top right) In-line junction with horizontal shiplap cladding. The boards are butted against the timber cavity barriers.*

Figure 8.23 *(left)In-line junction finished with a vertical board on board cladding.*

Detailing these junctions can cause confusion because the fire regulations are often interpreted incorrectly to mean that the cladding needs to be non-combustible for 1 m on each side of the separating wall. In reality, the 1 m rule only applies where two buildings face each other across their mutual boundary. The rule is designed to limit fire spread by heat radiation between adjacent but non-adjoining buildings. This mechanism of fire spread does not occur where the buildings are attached and in the same plane (*e.g.* a terrace). As with staggered wall junctions, there are two vertical timber cavity barriers behind the cladding, with a third in mineral wool between the separating walls. The design of the timber cavity barriers varies according to the cladding profile and direction.

Group 7. Windows and doors

Although windows are often tested for weather tightness and other requirements, this only demonstrates the performance of the window itself. The joint between the window and wall is equally important and needs to be both weather tight and fire resistant. In terms of weather tightness, window installations tend to be a weak link in the facade. This is usually because rainscreen principles have not been followed. Wherever possible there should be discrete rain and wind-proofing layers separated by a drained and ventilated cavity. Most weather tightness problems occur at the junction between the base of the window and the wall: a properly designed and installed flashing is therefore essential at this point (Figure 8.24). Planted wooden sill extensions give poor performance. The window should be installed so that the upper edge of the flashing is flush with, or slightly outside, the wall's air seal layer [6].

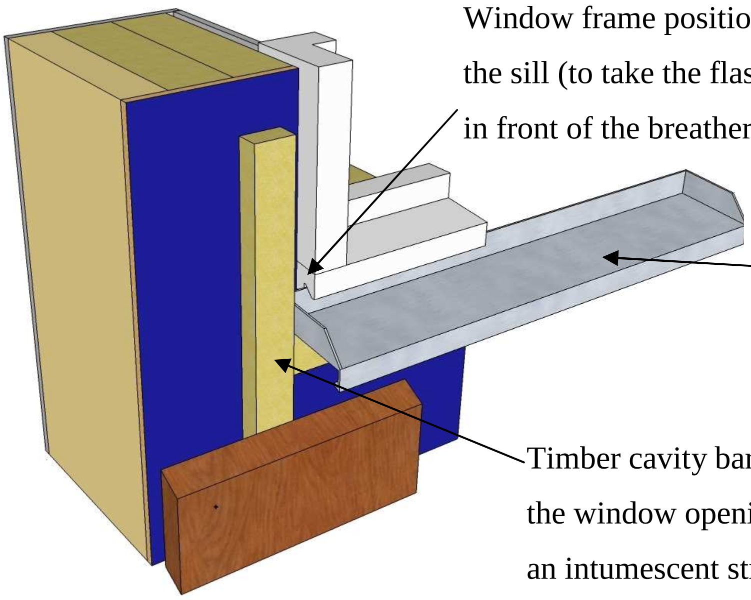


Figure 8.24 *Sill detail showing metal sub-sill flashing*

To achieve fire resistance, window openings in timber-clad walls have to be have cavity barriers at the head, jambs and sill. Those on the jambs and sill are normally formed from a timber batten at least 38 mm thick, whilst the barrier at the head is an intumescent strip. Because there is no ventilation gap under the sill, the cladding support battens beneath the window should allow ventilation to each side. The window details below are unquestionably compromises since they prioritise compliance with fire safety requirements at the expense of drainage and ventilation. If this is a concern, the timber cavity barrier at the jambs could be replaced with intumescent strips although this would incur additional cost.

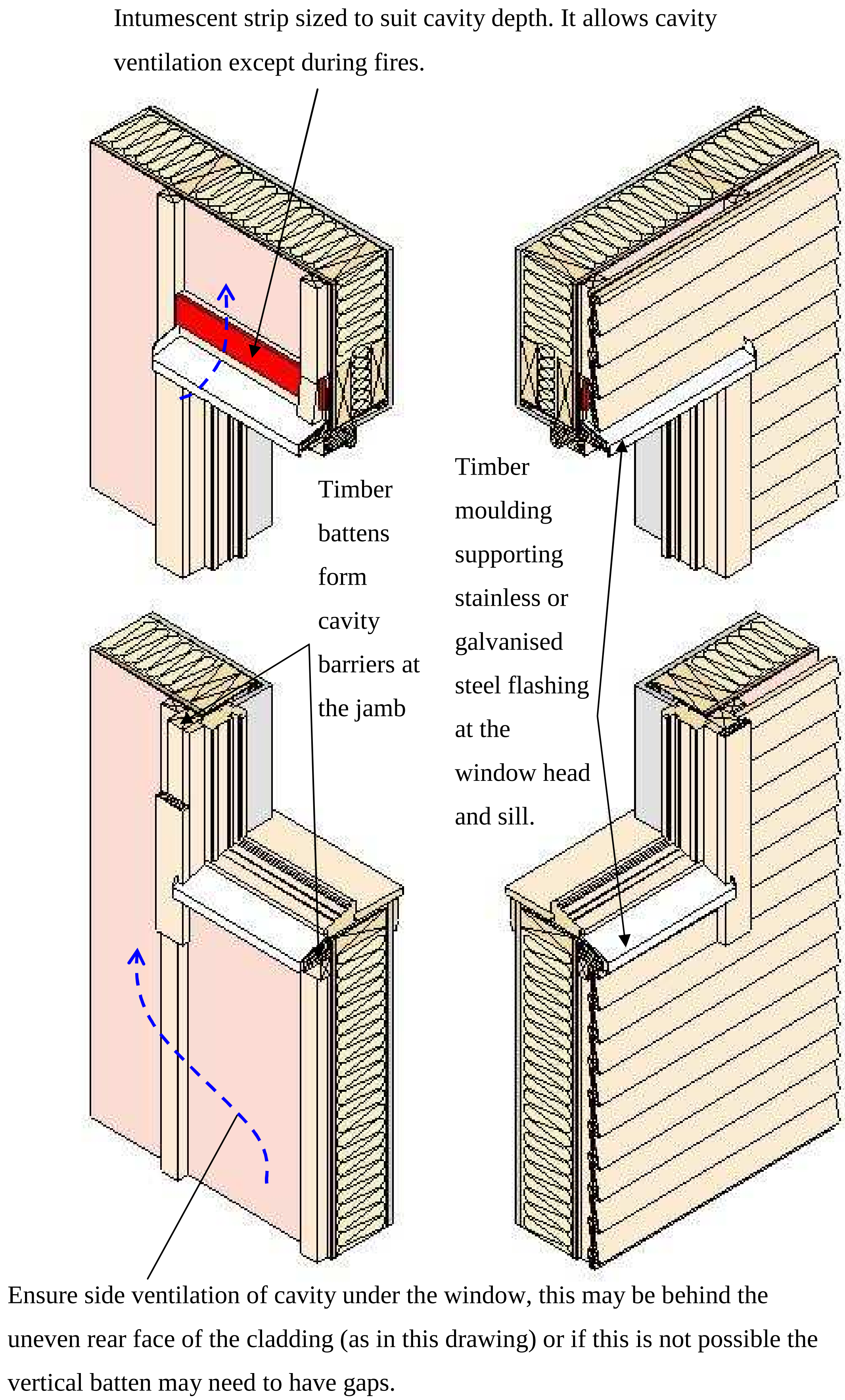


Figure 8.25 *Horizontal cladding at window showing the support assembly and final appearance*

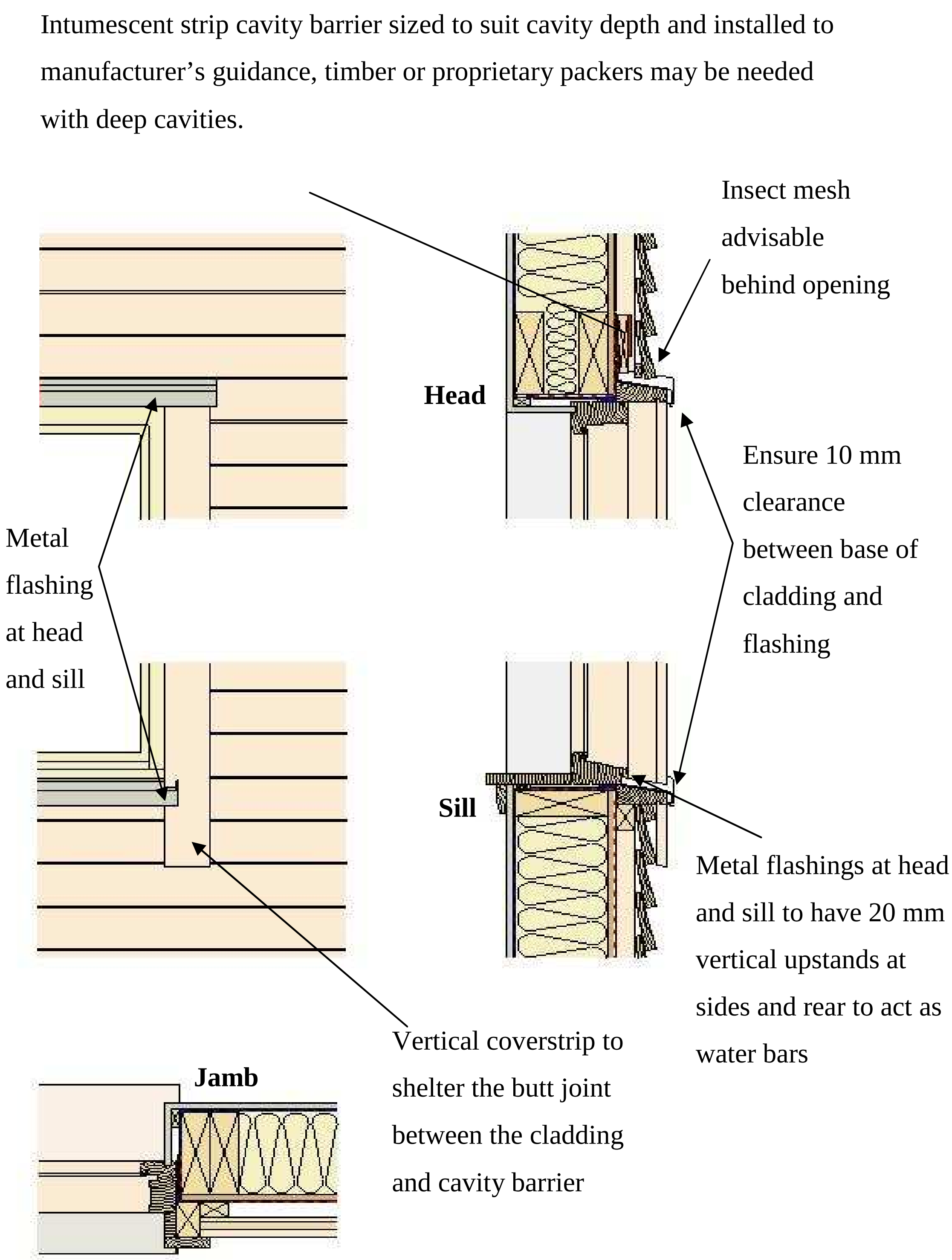


Figure 8.26 *Elevation and section of horizontal cladding at a window*

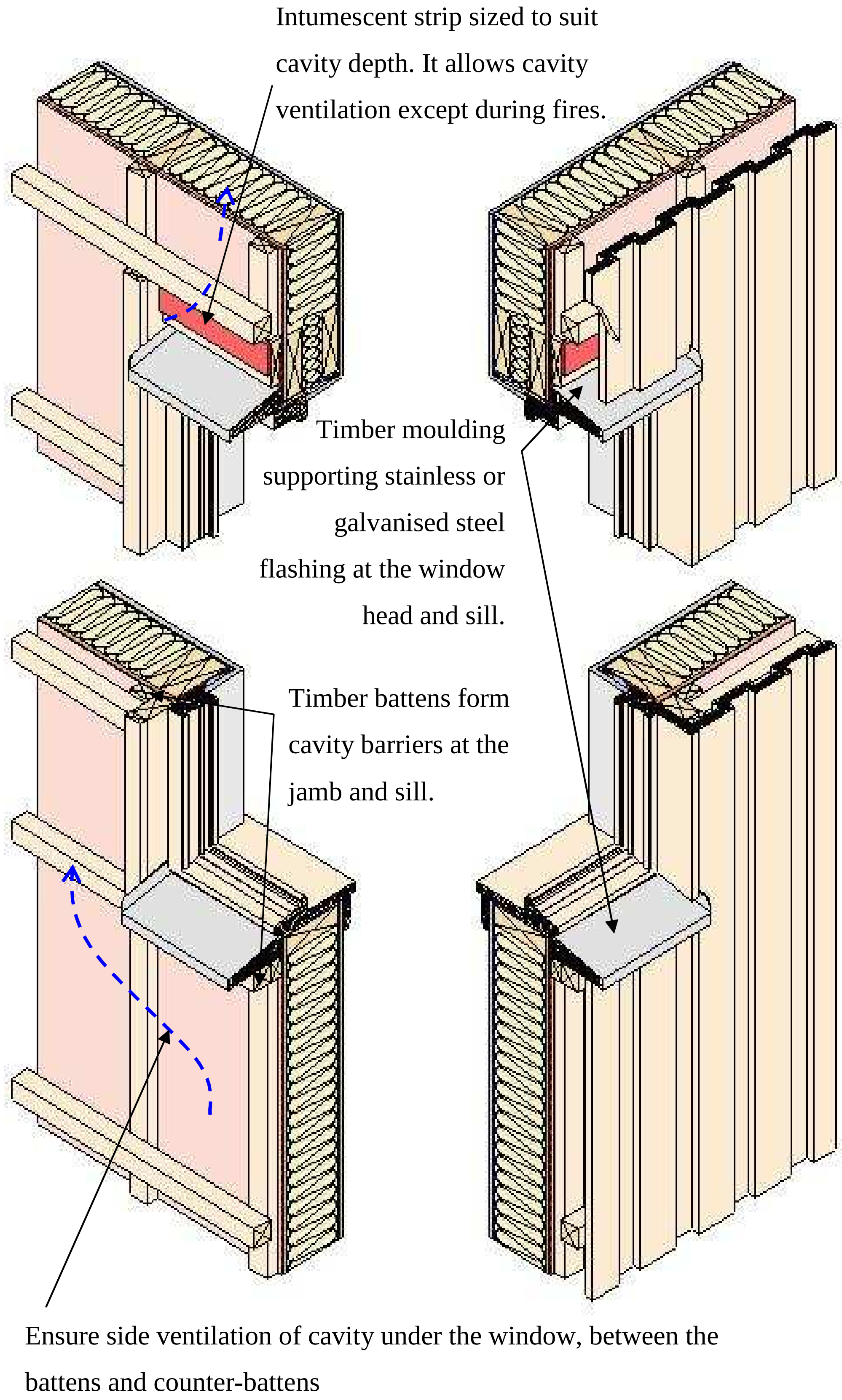


Figure 8.27 *Vertical cladding at a window showing the cladding support assembly*

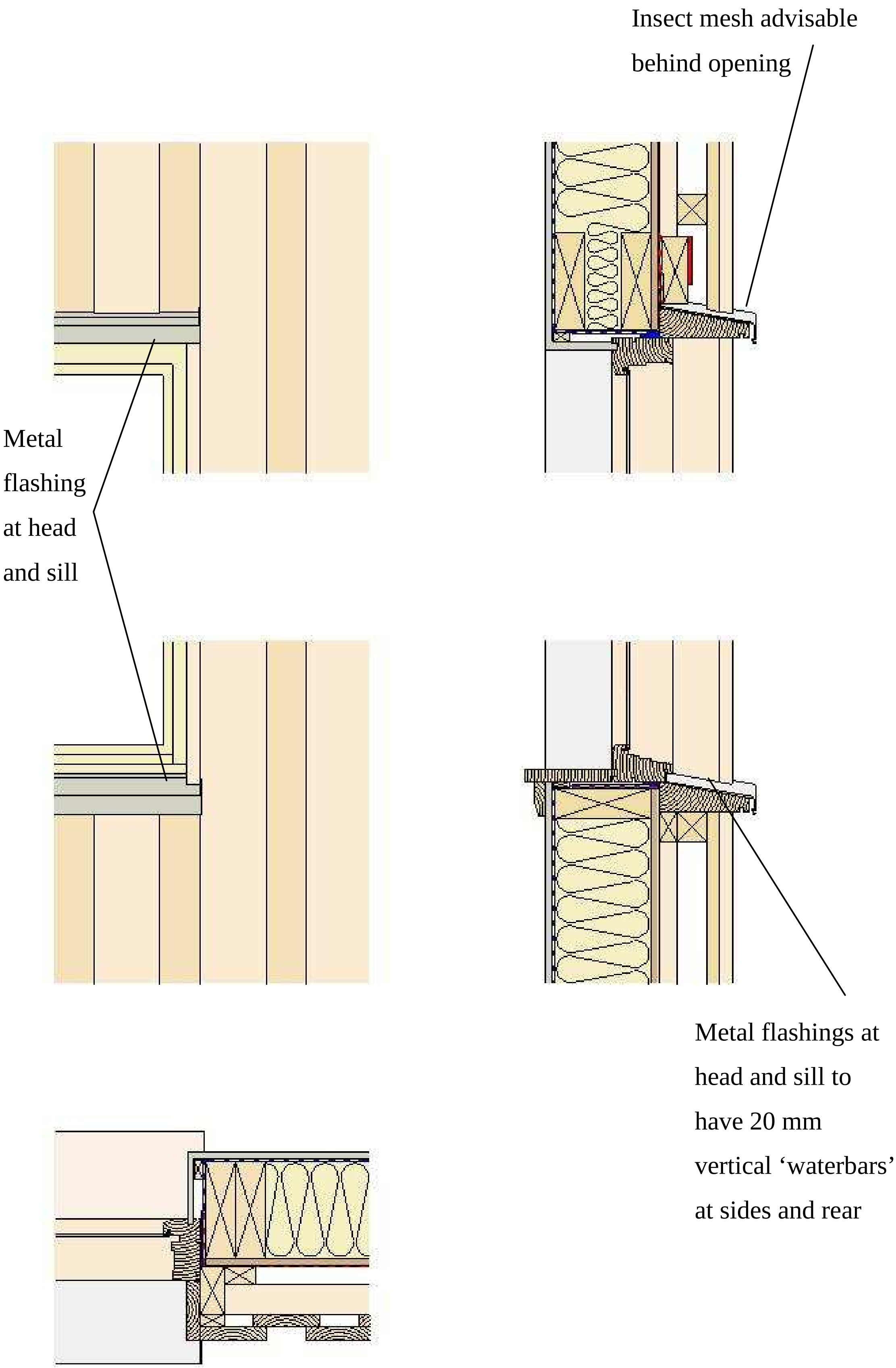
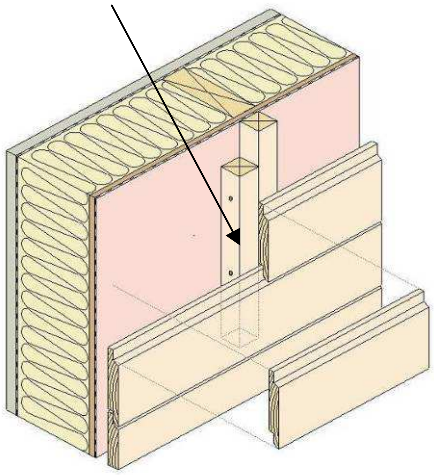


Figure 8.28 *Elevation and section of vertical cladding at a window*

Group 8. Junctions between boards



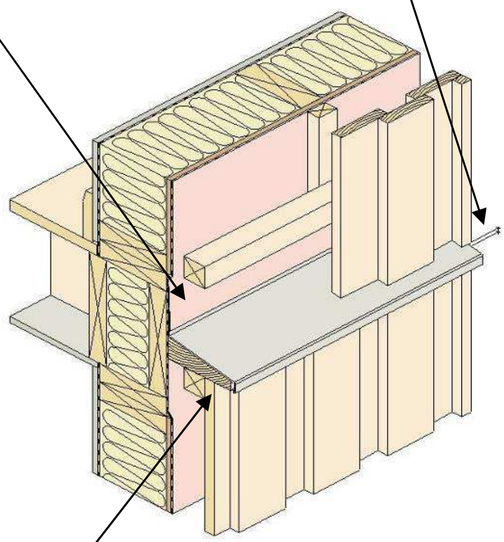
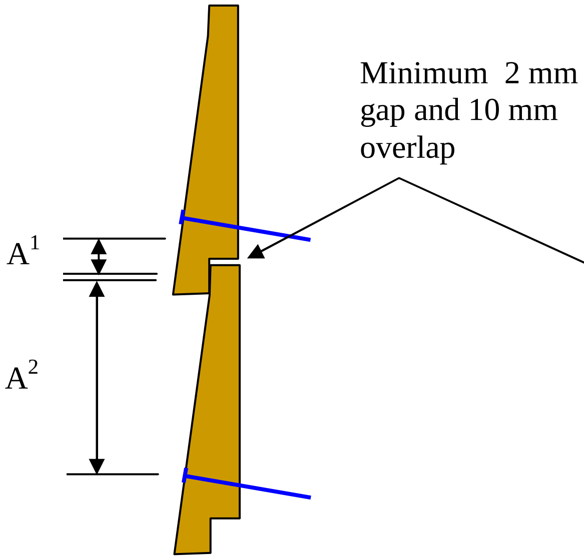


Figure 8.29 *End junction between horizontal boards*

Figure 8.30 *End junction between vertical boards at an intermediate floor*

Junctions between boards generally involve either staggering the joints or aligning them all. With slight adjustments these options can be used with both horizontal and vertical boards. To allow for fixing, the length of boards should coincide with the batten positions. To comply with the end and edge distance requirements in Eurocode 5, staggered joints usually require an additional short batten to be fixed alongside the main batten to accommodate fixings for the second board (Figure 8.29). If vertical boards are joined in this way, their ends should be sloped outwards to allow the endgrain to drain. It is usually more convenient to stop vertical boards at storey height where the line of the facade can be interrupted by a horizontal metal flashing sloped to the exterior (Figure 8.30). The cavity above and below the flashing will need to be protected by intumescent strips if the floor junction is a separating floor.



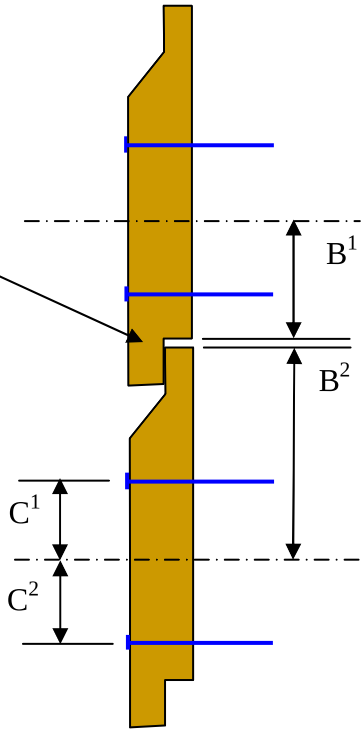


Figure 8.31 *(above) Detailing board installation to accommodate movement with single fixings*

Figure 8.32 *(right) Detailing board installation to accommodate movement with double fixings*

In most cases the combination of a 2 mm gap and 10 mm overlap is sufficient to accommodate movement between boards. Where there is any doubt, however, the movements involved in a specific timber species, moisture content and board width combination are determined from Equations 5.14 and 5.15 and the details adjusted accordingly. Different issues apply depending on whether the boards are fixed once or twice across their width. Single fixings minimise the risk of boards splitting but do not give sufficient support for wide boards. With **single fixings** (Figure 8.31), the board movement takes place either side of the fixing and can be accommodated at the junction between boards as the sum of the movements occurring at $A^1 + A^2$. The fixing is positioned near to the joint but taking account of the minimum edge and end distances in Table 5.31. With **double fixings** (Figure 8.32) the movement takes place each side of the centre line of the fixings as the sum of movements occurring at $B^1 + B^1$. The minimum gap between boards should make allowance for this. Change at the fixings is determined as the sum of movements occurring at $C^1 + C^2$. Fixings are located at the quarter points of the front face of the board. To minimise the risk of boards splitting as they dry the fixings may need to be installed in predrilled, slightly oversized, holes; this is mainly a concern with dense timbers, boards over 150 mm wide, or species known for large movement. Typical board profiles for closed jointed cladding are given in Figures 8.33 and 8.34.

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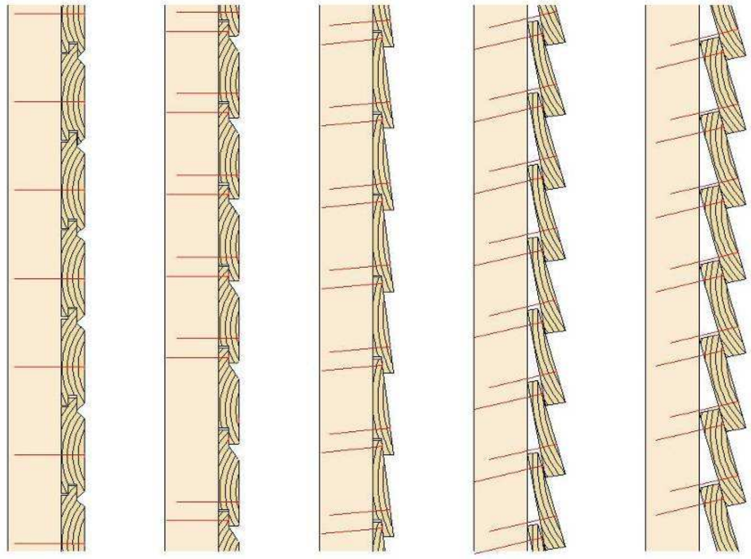


Figure 8.33 *Typical profiles and fixings for horizontal closed jointed cladding*

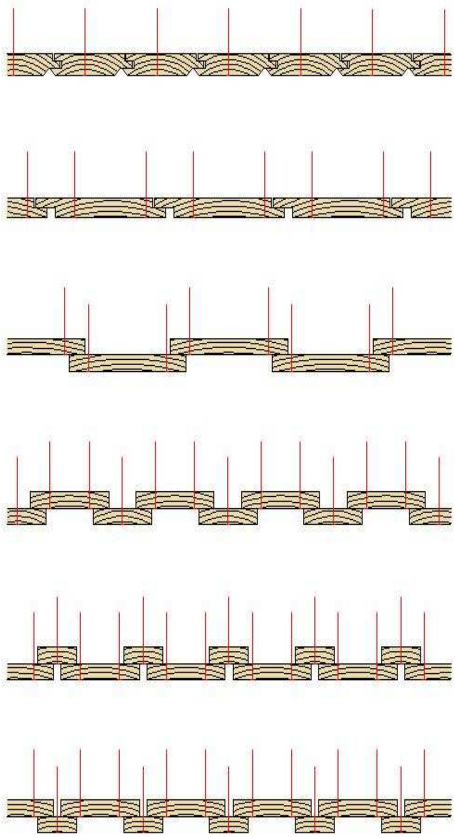
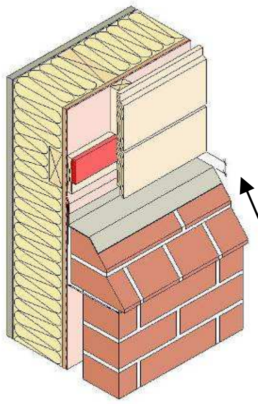
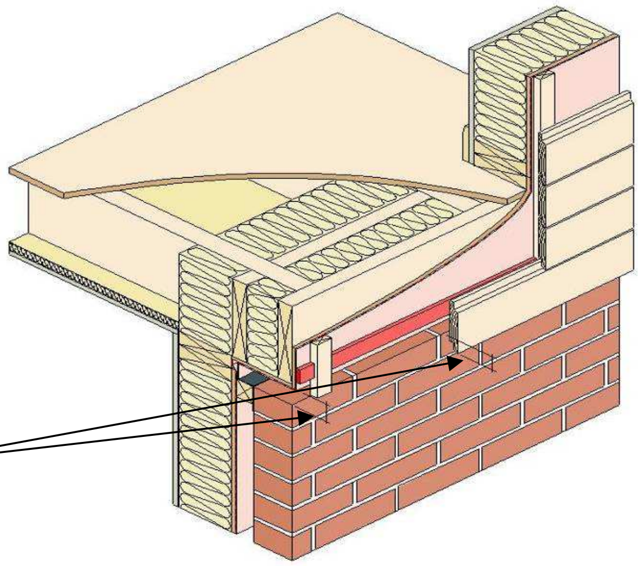


Figure 8.34 *Typical profiles and fixings for vertical closed jointed cladding*

To minimise the risk of splitting, boards should be installed so that the side nearest the pith faces outwards on the wall. Tongued and grooved boards should have a maximum width of 125 mm with small movement class timber; less if a medium movement class species is used. Tongue length should be at least 9 mm. Avoid secret fixing near the tongue as this tends to split the boards and may force them together thereby closing up expansion gaps. Shiplap joints should typically have a 15 mm joint overlap. If the profile is tapered the minimum thickness should be 9 mm (to comply with guidance supporting the fire regulations in England and Wales). Board-on-board/batten type joints should typically have a 20 mm overlap. Fixings should be sized and positioned in accordance with the guidance in Chapter 5.

Group 9. Junctions between heavy and lightweight cladding





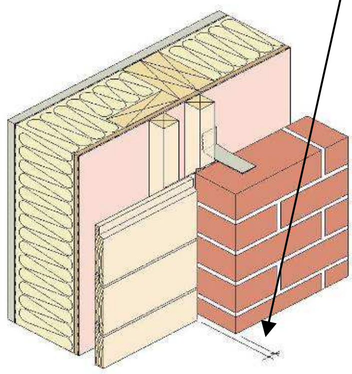


Figure 8.35 *(top left) Horizontal flashed junction between timber and brick cladding*

Figure 8.36 *(top right) Intermediate floor junction where the upper wall panel has been cantilevered to allow the timber cladding to oversail the brickwork.*

Figure 8.37 *(left) Typical vertical junction between lightweight and heavyweight cladding.*

Any lightweight cladding, such as timber, that butts onto or overhangs heavyweight cladding needs to allow for differential movement. The cavity behind heavyweight cladding is normally vented whilst the cavity behind timber cladding is ventilated. A vented cavity needs to be closed at the top using a cavity barrier, in this case a timber batten at least 38 mm deep. Horizontal cavity barriers in ventilated cavities are formed by an intumescent strip. Vertical cavity barriers can be formed from timber battens at least 38 mm thick. Horizontal junctions are of two types: either the lightweight cladding is flashed out to the heavyweight cladding (Figure 8.37) or the upper wall panel is cantilevered to allow the lightweight cladding to be in the same plane as the wall below (Figure 8.36). In both cases the gap between the two types of cladding needs to be sized according to the predicted movement of the heavyweight cladding. The cantilevered floor in Figure 8.36 must be designed by a structural engineer. Vertical junctions (Figure 8.35) are generally easier to build. The main issue being that the battens behind vertical lightweight cladding may need to be thicker than normal to bring the cavity either side of the junction to the same depth.

8.4 Summary

This chapter has developed construction details for timber cladding on low- and medium-rise buildings in the UK. Each detail is designed to be compliant with the performance criteria given in the guidance documents supporting the UK's building regulations as at February 2011. No details are provided for open-jointed cladding because these types of facades are incompatible with the criteria for cavity barriers in the current guidance to the UK's building regulations.

The objective of the details included here is to provide a ready means of reconciling the sometimes-conflicting performance requirements for: prevention of rain penetration, restriction of unseen spread of flame through cavities and limiting flanking sound transmission across party wall and floor junctions. Three types of facade junction were illustrated: horizontal, vertical and miscellaneous.

References

1 Scottish Building Standards Agency (2007). Accreditated Construction Details (Scotland) (For the limitation of thermal bridging and air leakage in low and medium rise domestic type). Edinburgh: SBSA.

2 Department for Communities and Local Government (2007). Accreditated Construction Details. 1st Edition, 2007. Weatherby, UK.

3 Department for Communities and Local Government (2010). Code for sustainable homes, Technical guide. London: Communities and Local Government Publication.

4 Association for Environment Conscious Building (2007). CarbonLite Programme. [Online] Available from: <http://www.carbonlite.org.uk/carbonlite/> [Accessed 16 July 2010].

5 BRE. PassivHausUK website : <http://www.passivhaus.org.uk/> [Accessed 16 July 1210].

6 Edvardsen, K.I., and Torjussen, L., (1997). Håndbok 45 – TREHUS. [Handbook 45 – Wooden House. In Norwegian] Oslo: Norges Byggforskningsinstitutt.

7 Hislop, P. (2007). External timber cladding. 2nd Edition. High Wycombe, UK: TRADA Technology.

8 TRADA Technology (2001). Timber frame construction. 3rd edn. High Wycombe, UK: TRADA Technology.

9 Robust Standard Details. Website: <http://www.robustdetails.com/index.php?id=12521> [Accessed 8 November 2010] London, UK.

10 BS EN 1433:2002. Drainage channels for vehicular and pedestrian areas. Classification, design and testing requirements, marking and evaluation of conformity. London: BSI 2003.

Chapter 9

Conclusions

This thesis has attempted to go beyond the simple and oft repeated statements about how timber facades work, and consider instead what is really going on and how this can better inform design decision making. In doing so it has challenged some of the prevailing assumptions about moisture, its effects, and how they are best controlled. It has also reviewed how moisture issues affect, and are affected by, the need to ensure that fire safety and acoustics are fully addressed.

9.1 Key findings

The key findings are:

1. There is more – much more – timber cladding being used in the UK than is commonly acknowledged.

2. Timber cladding offers a unique combination of performance benefits. These are relevant to cladding on both a timber structural frame (*e.g*. timber frame) and to massive walls (*e.g.* masonry or log construction).

3. Timber is an organic and biogenic material. It, therefore, has three key characteristics as a facade material: it isnon-uniform, combustible and has an

intimate relationship with moisture. The performance-based design of timber facades is largely about the management of these characteristics.

4. Although performance-based design aims to be solution independent, the designer's background always conditions its application. Some designers are only familiar with the performance issues relevant to inorganic and non-biogenic materials such as steel or masonry. They may therefore miss, or misunderstand, issues that only occur with organic-biogenic materials. Accordingly the discipline of facade engineering will need to encompass a wider range of performance issues if it is to design successfully with timber.

5. Conventional timber cladding design also has its gaps. Much existing guidance stresses, quite correctly, the importance of resistance to fungal decay but gives less attention to other degradation mechanisms, particularly movement and weathering.

6. Similarly, structural robustness receives insufficient attention. Although timber facades generally have enough strength and stiffness to withstand the wind loads to which they are exposed, this is not always the case. The guidance on this topic is limited.

7. The exposure trial has developed a robust test panel design that is suitable for testing virtually all types of timber cladding. The associated analysis method readily estimates the moisture load effects of each factor and their interactions.

8. The trial measured the moisture take-up and loss characteristics of UK grown Sitka spruce and the extent to which the Scandinavian practice of using such timber without preservative treatment was transferable to the UK. It found that the moisture conditions were such that preservative treatment was essential.

9. The trial also found that the knot characteristics of Sitka spruce falling boards are only suitable for cladding profiles that require minimal machining (*e.g.* vertical board on board or horizontal shiplap).

10. UK grown Sitka spruce is, therefore, only able to supply large volumes of external timber cladding providing the customer is prepared to accept preservative treatment and a limited choice of cladding profiles.

11. It appears from the small supplementary exposure trial that it may be possible generalise the results to other timber species. If so the moisture content range experienced by most types of timber cladding is wider than often stated. It appears that the minimum moisture content of timber cladding is around 10% irrespective of the species involved. The maximum is more variable but in some cases tends to fluctuate around the fibre saturation point of the species concerned. Cladding with water traps will experience still higher maximum values.

12. A preliminary model is proposed for predicting the moisture conditions in timber facades.

13. Cladding support battens also tend to be relatively wet. This places them in structural service class 3, which means that they are wetter – and therefore weaker – than is often assumed.

14. The only timber cladding that appears to stay relatively dry in most site conditions is open jointed boards used in combination with a surface coating. Vertical closed jointed cladding also appears to have a relatively low moisture content on exposed sites. Surface coatings do not appear sufficient, by themselves, to ensure a low moisture content in the timber substrate, nor does uncoated open jointed cladding.

15. These two board profiles – open joints and simple overlapping joints – are also significant for another reason, as they tend to have the worst performance in a fire. This is no surprise given that a high level of ventilation is a requirement for both rapid drying and rapid flame spread.

16. The state-of-the-art review highlighted that the service life of even the most leach resistant flame retardants is unlikely to match that of the timber cladding. In extreme cases it is even possible to pass the relevant weathering test for flame retardants while offering only about four years’ maintenance free performance in the real world. This problem is concealed by flame retardant manufacturers – so much so

that neither cladding suppliers nor building regulators were aware of it. All current UK publications on timber cladding miss this problem as do the Building Regulations. As this changes, it is likely that timber cladding will be prohibited on public buildings, near boundaries and those parts of a facade over 18 m high.

17. The guidance documents supporting the UK's building regulations contain a conflict between three performance requirements affecting cavity barriers behind timber cladding. The barriers need to be ventilated to promote evaporative drying yet they also need to block off air movement during a fire, and minimise the degree to which they span across separating wall junctions. These issues can be reconciled using careful detailing, possibly involving intumescent cavity barriers but no suitable construction details were available. Those that exist either ignore the conflict or propose solutions derived from masonry cladding that create water traps when used with timber.

18. There is no standard fire test for cavity barriers. This leads to confusion and allows cavity barrier manufacturers to make unverifiable claims. Accordingly, the author participated in the development of a full-scale *ad hoc* test for cavity barriers behind timber cladding. For financial reasons only one test was carried out. Although not definitive the test results indicate that the cavity barrier details developed for this thesis are likely to meet UK regulatory criteria.

19. Chapter 7 outlines all of the performance criteria and specifications that apply to timber facades in the UK and gives an improved decision sequence to guide timber cladding design.

20. Probably the most significant output of this thesis is the suite of construction details for timber-clad facades, based on a combination of new experimental data and a fresh appraisal and synthesis of existing information. Although their performance cannot currently be verified, these details illustrate – for the first time – how the various requirements affecting timber facades could be reconciled so as to fulfil all relevant performance criteria in the UK.

9.2 Recommendations for future work

Several topics merit further investigation:

1. The most immediate gap is a UK code of practice for timber cladding. This thesis provides most of the research needed to draft such a document.

2. Although the moisture load in Sitka spruce cladding has been quantified, more work is needed before such data can be used to estimate service life. The moisture load concept (*i.e*. the duration and intensity of wetting) appears to offer a means to do this providing the assessment is carried out for a decade or so and is combined with temperature and other meteorological data.

3. The exposure trial needs to be repeated with other timber species to assess the extent to which the FSP-based model for moisture content estimation can be generalised. This requires a multi-site test involving timber species with a range of fibre saturation points.

4. The long-term appearance of uncoated timber cladding remains unpredictable. A weathering model is therefore desirable although the likelihood of it succeeding is probably quite slim.

5. Further guidance is needed on the structural robustness of timber cladding. The results should be presented in tabular form linked to a wind map, thereby allowing fastener length to be readily estimated, at least for low- and medium-rise buildings.

6. The *ad hoc* fire test for cavity barriers needs to be standardised and repeated by other laboratories. Until this occurs, the fire performance of the type of timber facades being designed in the UK will remain unquantifiable.

7. Independent test data are needed on the service life of flame retardants. Building regulators need to consider their implications for the fire safety of timber facades that will have a long (*i.e*. 50 year) service life, or which are over 18 m high.

8. Independent tests are needed of the effectiveness of impregnation with Type LR flame retardants as a form of wood modification against fungal decay.

9. Many more construction details are needed. Further feedback is also required on those already produced. Much more training needs to be delivered on the detailing and installation of timber facades.

A number of construction details could not be included in this thesis because the supporting evidence was not available, nor can some of the results yet be considered definitive. This is an inevitable limitation of an evidence-based approach. As Wittgenstein wrote, in the last line of the *Tractatus* [1]: *Whereof one cannot speak, thereof one must be silent.*

References

1 Wittgenstein, L. Logisch-Philosophische Abhandlung (Tractatus Logico-Philosophicus), [online], Wilhelm Ostwald (ed.), Annalen der Naturphilosophie, 14 (1921) C. K. Ogden (London: Kegan Paul, 1922), prepared with assistance from G. E. Moore, F. P. Ramsey & Wittgenstein, L. Routledge & Kegan Paul, parallel edition including the German text on the facing page to the English text. <http://people.umass.edu/phil335-klement-2/tlp/tlp.pdf> [Accessed 10 July 2010].

Appendix 1

Publications

The following conference proceedings and book were derived from this thesis. A set of these papers is bound in this appendix; the book is reduced to thumbnail format. Full permission from the relevant publisher or copyright holder has been obtained.

1. Davies, I., Stupart, A. and Choo, B.S. (2004). Timber cladding on the coastal fringe of North-west Europe. In: *Proc. 8th World Conf. on Timber Engng*, Lahti, Finland. 14 – 17 June 2004.

2. Davies, I. (2008). Evidence-based design of timber facades. In: *Proc. 10th World Conf. on Timber Engng*, Miyazaki, Japan. 2 – 5 June 2008.

3. Davies, I. and Wood, J. (2010). Exterior timber cladding: design, installation and performance. Edinburgh: arcamedia, ISBN 978-1-904320-04-3.

Two journal papers have been submitted. They are not included in this appendix as they are currently under review.

Davies, I., Fairfield, C., Stupart, A. and Wilson, P. Moisture conditions in timber cladding: field trial data. (Under review by *Proc. ICE, Construction Materials*).

Davies, I., Fairfield, C., Stupart, A. and Wood, J. External timber cladding: design and performance. (Under review by *The Structural Engineer*).

1. **Davies, I., Stupart, A. and Choo, B.S. (2004). Timber cladding on the coastal fringe of North-west Europe. In: *Proc. 8th World Conf. on Timber Engng*, Lahti, Finland. 14 – 17 June 2004.**

Timber Cladding on the Coastal Fringe of North-west Europe

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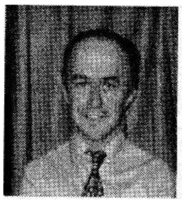

With a background in forest products technology Ivor has worked as a researcher and research manager on a range of timber technology projects in the UK and Scandinavia. In 2002 he was lead author of *Timber Cladding in Scotland.*

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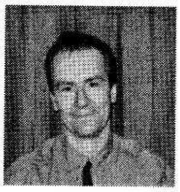

Alastair recently joined CTE from the Building Research Establishment where his principal involvement was assessing the durability of construction materials .In particular, water/UV resistance of coatings and the comparison of laboratory and natural weathering trials.

Abstract

This paper describes the interim results of a trans-national project investigating the design and durability of external timber cladding on the exposed coastal fringe of north-west Europe. A decision support tool is given, which is based on a model of the interaction of factors that affect the service life of timber cladding in temperate areas subject to wind-driven rain.

Keywords: timber durability, hazard class 3, external timber cladding, wind-driven rain.

1. Introduction

In early 2003 a trans-national project, *External Timber Cladding in Maritime Conditions*, was launched to develop best practice in the design and construction of timber cladding in Scotland, western Norway, the Faroes, and Iceland. This area is characterised by moderate temperatures for the latitude, and frequent wind-driven rain (driving rain). There is a marked difference between this coastal climate and inland areas of Scandinavia and Europe, but the area appears broadly similar to other temperate maritime climates such as coastal British Columbia. The project is addressing two issues. Firstly, local differences in fungal decay risk may affect the transferability of timber cladding technologies between countries. This is significant because Norwegian cladding practices, (particularly the use of untreated spruce) appear to have potential in other coastal areas of north-west Europe but this has not been tested. Secondly, despite extensive technical guidance being published in Norway [1] and Canada [2] there is a need for further information on standard detailing of timber cladding for exposed coastal conditions.

2. State-of-the-art

2.1 Factors influencing the durability of timber cladding

In temperate regions fungal decay is usually the most important factor limiting the service life of external timber. The occurrence and rate of decay is controlled by the microclimate, the characteristics of the timber, and the decay organisms involved [3].

2.1.1 Microclimate

European Standard EN 335-1 groups the end-uses of timber into five 'hazard classes' according to the decay risk they are exposed to [4]. Cladding is in class 3 where components are out of ground contact but otherwise exposed to intermittent wetting. Here fungal attack can occur, particularly where the timber is unable to dry out properly. Service life in these conditions will vary as a result of local variations in exposure to sun, wind and rain. Performance also varies according to the vulnerability to surface wetting, for example vertical surfaces with limited wetting and rapid dryin tend to perform better than upward facing rebates that act as a water trap. In temperate coastal area wind-driven rain is generally the most important wetting mechanism, moisture transfer from the building interior is of less concern in these conditions [2]. While rain penetration risk has been use to define limits for types of masonry walls [5] this approach has not been fully applied to timber. I any case the data on wind-driven rain is incomplete - good data exists for parts of the project area [6] but there is no region wide information.

2.1.2 Timber characteristics

Natural durability and preservative treatment are the most well known material factors limiting decay though other factors are also important. In western Norway both the heartwood and sapwoo of Norway spruce are used successfully for external cladding, yet, despite the low durability class of the timber, it is seldom preservative treated. It is believed this is possible because the low rate o moisture flow in spruce limits moisture take-up. This has not been fully investigated [7].

2.1.3 Fungal decay

Scheffer (1971) proposed an index for fungal decay risks in out of ground contact conditions for tl USA [8]. He concluded that temperature and rainfall were the two climatic factors that determine decay risk in such conditions. For temperature he assumed a linear relationship with decay rate above a minimum temperature of 2^0C. For rainfall the number of days with precipitation above 0.25mm was chosen as the critical value. Rainfall of less than three days per month was discounte Sheffer expressed this index through the following equation:

$$\frac{\sum_{Jan}^{Dec}[(T-2)(D-3)]}{16.7}$$

where T is the mean monthly temperature in ^{0}C, and D is the mean number of days per month witl 0.25mm or more of precipitation. The divisor is arbitrary and is chosen to give a rating of betweer zero and 100 for most of the USA. The Scheffer Index is in the process of being adapted for European conditions through an EU COST Concerted Action.

2.2 Durability specification

European Standard EN 460 describes several approaches to timber durability specification in hazard class 3. There is a general acceptance that very durable and durable timbers can be used without preservative treatment while moderately durable timbers normally have sufficient durability but preservative treatment is needed for some uses. Where slightly durable or not durable species are used, there is, however, less consensus and the Standard notes that such timber may, or may not, need preservative treatment depending upon the wood species, its permeability, and the end-use [9]. In the context of timber cladding, Davies et al [7] argue that EN 460 should be interpreted to mean that, where low durability timbers are used, either wood preservation is needed or moisture take-up has to be minimised through a combination of detailing-for-durability and moisture repellent coatings. The use of an impermeable timber such as spruce may further limit moisture take up.

2.3 Test procedures for timber cladding

Wood scientists use a combination of field exposure trials and laboratory tests to assess fungal decay risk in particular environments. Exposure trials are slower but more reliable. To date, exposure trials in timber have mostly focused on assessing the decay risks in ground contact conditions or, where out of ground performance is considered, the tests have been on window joinery. These tests are, however, only as useful as the criteria on which they were based. There is no test that covers all conditions and all are only an indication of relative durability based on performance in a specific set of environmental conditions. There are no normative tests for assessing the durability or rain penetration resistance of external timber cladding.

2.4 Range of design approaches

Designers of timber cladding use a number of detailing practices and this can lead to confusion and problems when practices from one area are transferred uncritically into a different climate zone [2].

- **Unventilated cladding** - In most parts of the world external cladding is fixed directly to the underlying structural frame without any intervening cavity. This is a satisfactory arrangement in most climate conditions but can cause problems in areas subject to wind-driven rain.
- **Ventilated cladding** - In areas subject to driving rain the techniques of detailing-for-durability become particularly important and Norwegian and Canadian researchers have pioneered the use of a drained and ventilated cavity behind the timber cladding in exposed conditions. This approach is also used in the UK and, to a varying extent, in other similar climates.
- **Pressure equalised cladding** - Differences between external air pressure and pressure behind the cladding can lead to rainwater being forced into the cavity. It is frequently argued that these differences should be equalised through the use of sheltered openings in the cavity combined with cavity compartmentalisation. Much so-called pressure equalised cladding is, however, not based on adequate research. Moreover, Straube (2001) questions the value of this technique in cases where the cladding material itself is porous. He also argues that, due to the effects of short duration gusts, moderation of pressure differences are only possible when cavity compartments are less than $1m^2$ [10]. Consequently this approach may not be relevant to timber cladding.

3. Surveys

The project is undertaking surveys of timber clad buildings. The aim being to gather data on how different material and detailing combinations have performed under a range of environmental conditions and maintenance practices. The Norwegian surveys are focused in the 19^{th} century fishing village of Sør-Gjæslingan located on an island north-west of Namsos. The Norwegian cultural heritage department has been working in the village since 1978 and has gathered information on paint and wood quality and the different maintenance practices. The project is extending this and evaluating how different maintenance procedures affect service life. Similarly the Scottish surveys have assessed how the performance of 19th century timber cladding can be related to timber quality, detailing-for-durability, maintenance, and exposure to driving rain. The survey work in Norway and Scotland will be extended to include a comparison of 20th century social housing in both countries. This gives an opportunity to study how performance of the buildings has been affected by differences in climate and maintenance.

4. Technical research

The project partnership is undertaking a range of technical work including:

- Application of the Scheffer Climate Index to the north-west coastal fringe of Europe.
- Production of a driving rain map covering the project area.
- Assessing how the interaction of material and detailing variables influence the moisture conditions in cladding.
- Assessing the suitability of Scottish grown spruce for use as external cladding.

5. Interim results

5.1 Surveys

Seven buildings have been surveyed in Scotland including, in one case, a detailed examination of historical records. A similar amount of work has been done in Norway. The main points identified to date include:

- A wide variation in the service life of cladding linked the microclimate and the timber species.
- The worst performance identified so far concerns untreated Scots pine cladding in Scotland, which has failed in less than 20 years due primarily to poor detailing practices.
- In contrast, Scots pine cladding on a 170 year old cottage in Scotland is performing well with only isolated timber decay due to recent poor maintenance. In this case the cottage has adequate detailing-for-durability and the historical records indicate that:
    - the timber used was plantation grown in Scotland;
    - although the cladding timber is a mixture of heartwood and sapwood it was not preservative treated; it was however painted immediately after being built.

5.2 Exposure trials

Interim results show that:

- The moisture contents in the test panels range from 12% to over 30% depending upon both detailing and driving rain conditions.
- The speed of moisture content fluctuation is rapid with poorly drained and ventilated components experiencing the fastest wetting and slowest drying.

5.3 Model

The survey information and experimental data are being used to develop a decision support tool based on the interaction of factors that affect the performance of timber cladding on the north-western coastal fringe of Europe. The tool will enable designers to select cladding options suitable for the technical limitations of their site and the anticipated construction and maintenance standards. Some site conditions are constants while others are variable. This gives opportunities to explore available options and, if none are suitable, to adjust the site variables to enable other designs to be used. For example, designers could choose to use a more durable timber or increase the size of the eaves overhang. The model is being tested and standard details prepared.

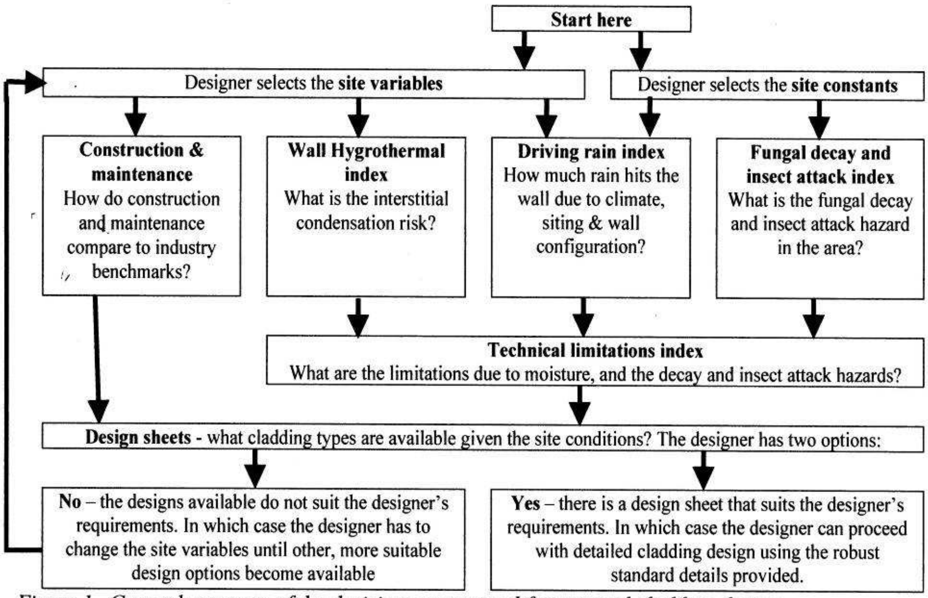

Figure 1. General structure of the decision support tool for external cladding design

6. Discussion

Current design guidance for external timber cladding in Europe tends to be prescriptive as opposed to performance based. This study suggests that a limit state approach may be suitable for timber cladding design. This means that design requirements could be linked to performance states beyond which the cladding no longer satisfies specified criteria. The potential performance limits are:

- The **ultimate limit states** include component failure due to decay, and water penetration into the structure of the building.
- The **servicability limit states** include moisture conditions conducive to decay, corrosion of fixings, unsightly growth of mould and sapstain.

The parameters identified in the model are stochastic variables, that is, they cannot be predicted with certainty but can be described probabilistically. The research is producing distribution functions for these, and it is anticipated that this numerical approach can be used, to some extent, to provide probability based design guidance for timber cladding in different conditions.

7. Conclusions

A trans-national project investigating the durability of external timber cladding on the north-west coastal fringe of Europe is underway. From the state-of-the-art review, surveys, and initial exposure trials the following points can be drawn:

- The service life of external timber cladding can vary by a factor of 10 depending upon a number of material, moisture exposure, construction, and maintenance parameters.
- Improved test procedures are needed for external timber cladding that take account of the range of parameters affecting service life.
- A preliminary model of the interaction of parameters affecting the service life of timber cladding has been developed.
- The model is being refined as a decision support tool to assist timber cladding design.
- The model appears to be feasible but needs further refinement using a limit state approach.

Acknowledgements

The project is being funded by the EU Northern Periphery INTERREG 111 Programme and a number of national co-funders. The project is managed by the Highland Council Planning and Development Service. Other project participants, particularly BRE and the Norwegian Building Research Institute, have contributed to the scientific research upon which this paper is based. Historical research in Scotland is by Claudia Bölling and the Royal Commission for Ancient and Historic Monuments in Scotland. Norwegian historical research is by Nord Trøndelag County.

References

[1] Byggforsk, *Byggforsk kunnskapssystemer ver 1.0,* Oslo, 1998.

[2] Canada Mortgage and Housing Association, *Wood-frame Envelopes in the Coastal Climate of British Columbia*, Vancouver, 1999.

[3] Raynor A. D. M. and Boddy L., *Fungal Decomposition of Wood: Its Biology and Ecology*. John Wiley & Sons, Chichester, 1988.

[4] EN 335-1: 1992. *Hazard classes of wood and wood based products against biological attack. Classification of hazard classes.*

[5] Building Research Establishment, *Thermal insulation: avoiding risks*, Watford, 1994.

[6] BS 1804: 1992, *Code of Practice for assessing exposure of walls to wind driven rain.*

[7] Davies I, Walker B, and Pendlebury J., *Timber Cladding in Scotland.* ARCA Publications, Edinburgh. 2002.

[8] Scheffer T. S., A Climate Index for Estimating Potential for Decay in Wood Structures Above Ground. In: *Forest Prod. J.* 21 (10), p25-31, 1971.

[9] EN 460: 1994. *Durability of wood based products. Natural durability of solid wood. Guide to the durability requirements for wood to be used in hazard classes.*

[10] Straube J., Pressure Moderation and Rain Penetration Control, in: *Pressure Equalised Rainscreens.* Proceedings of a conference held on Nov 21 2001, Ontario Building Envelope Council.

2. **Davies, I. (2008). Evidence-based design of timber facades. In: *Proc. 10th World Conf. on Timber Engng*, Miyazaki, Japan. 2 – 5 June 2008**.

Evidence-Based Design of Timber Façades

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Summary

This paper reports on the Scottish part of a three year trans-national project to assess the performance of timber façades in temperate maritime conditions. The experimental programme comprised an exposure trial and fire testing. This work is informing the development of a book and website giving evidence-based construction details for timber façades.

1. Introduction

Timber is an established cladding material on low-rise housing in North America and Scandinavia and is becoming popular in some other countries, including the UK. Moreover, timber is nowadays being used to clad medium-rise buildings and for non-domestic applications. These developments are driven by architectural fashion and a growing awareness of the performance advantages of timber compared to other façade materials.

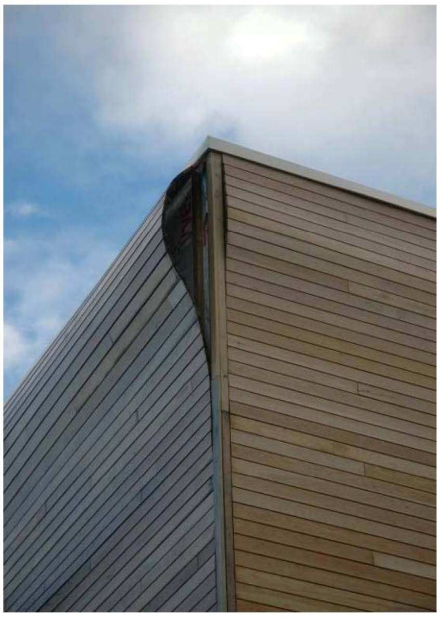

Fig 1. Failure of timber cladding due to inadequate movement provision

Timber cladding is used in many ways, indeed this design freedom is one of its main attractions. These façades can, however, pose a number of technical challenges including: durability, dimensional change, weathering, corrosion, and – most controversially – fire safety. The issues are being manifested through enquiries to technology organisations, concerns expressed by regulators, and as poor design or site practice which, in turn, results in building component failures (*Fig 1*).

These issues have created a need for new guidance on the performance requirements for timber façades and how they can be delivered through evidence-based design. This paper reports on the final stages of research by the Centre for Timber Engineering (CTE) to develop this information. The work was undertaken as part of a larger project spanning Scotland, Norway, the Faroes, and Iceland.

2. Methods

Following a state-of-the-art review, the project tested the moisture conditions and fire performance of timber façades and, based on this, is developing a suite of evidence-based construction details. The experimental work was supported by surveys of existing buildings and investigations into façade failures. The resultant information will be published as a book and on the web [1].

All of the cladding tested was designed as a rainscreen - it incorporated a drained and ventilated cavity between the cladding and the wall substrate. The experimental work drew upon the interim findings of other research undertaken as part of the trans-national project - most importantly an exposure trial by the Norwegian Building Research Institute which examined the impact of different levels of cavity ventilation.

2.1. Exposure trial

An exposure trial (*Fig 2*) was set up in Scotland to investigate the interaction of factors affecting the moisture content of timber façades. Although some effects were already understood, others were not. The trial investigated four factors where the effects were particularly difficult to quantify. These are listed in *Table 1*. A key objective was to assess the extent to which moisture control measures (such as large eaves, avoidance of water traps, water repellent surface coatings etc.) were, *by themselves,* sufficient to ensure an adequate service life for external timber cladding in different exposure conditions.

Fig 2. Part of the exposure trial during construction

Eight test panels were replicated at 2 sites. The first, near Fort William, was one of the wettest places in the UK, while the other, near Inverness, was in a woodland clearing with low rainfall but high relative humidity. Each panel was exposed to the prevailing weather and data-logged to record hourly measurements of moisture content at 8 points in each panel. The timber used was UK grown Sitka spruce. Ambient climate was recorded using an automatic weather station. The trial ran for 3 years.

Table 1. Factors tested in the exposure trial

Factor	Levels
Rainfall exposure	exposed or sheltered
Joint type	open or closed
Surface condition	coated or uncoated
Board orientation	horizontal or vertical

2.2. Fire tests

In parallel with this project, BRE were contracted to assess the fire performance of timber clad façades on a two storey timber framed terrace with an internal corner. The procedure was adapted from BR136 [2] and BS 8414-2 [3]. The general test arrangement is given in *Fig 3*.

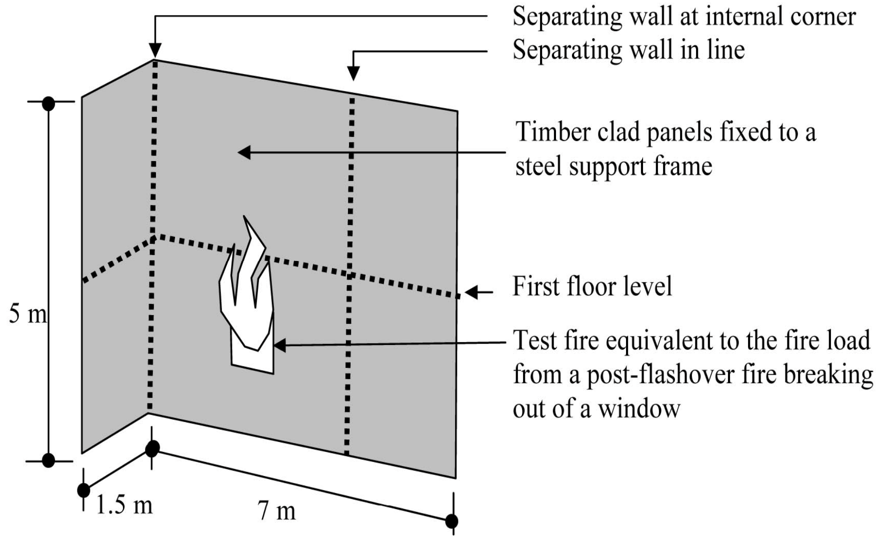

Fig 3. The reaction to fire test showing locations of junctions and test fires

The fire test gave CTE the opportunity to develop timber cladding details and measure their fire performance at key junctions. Cavity barriers were designed to meet three sets of performance criteria:

- **Durability** – to enable a timber façade to achieve a satisfactorily service life, barriers have to allow unrestricted vertical airflow in the cavity except during fires and avoid water entrapment
- **Acoustics** – new separating walls and floors in Scotland need an acoustic insulation of ≥53 dB, similar limits apply in other parts of the UK
- **Fire** – horizontal cavity barriers have to achieve 30 minutes fire resistance and vertical barriers require 60 minutes

To date, building regulations in the UK do not generally require that internal sprinklers are installed. Consequently, there are few mechanisms for preventing post flashover fires from spreading onto the façade. Because of this, the fire tests and resultant construction detailing in this project are limited to low-rise buildings without compartment floors.

The test simulated the effect of a post-flashover fire spreading onto the façade from a room within a building. Because it was already known that this flame plume would quickly spread up the façade, the main objective was to measure lateral fire spread across the vertical fire compartmentation.

3. Results

The range of variation in moisture content in the exposure trial is illustrated in *Fig 4* and *Fig 5* which show data for the driest and wettest panel over a 15 month period. The time series have been smoothed using a moving average.

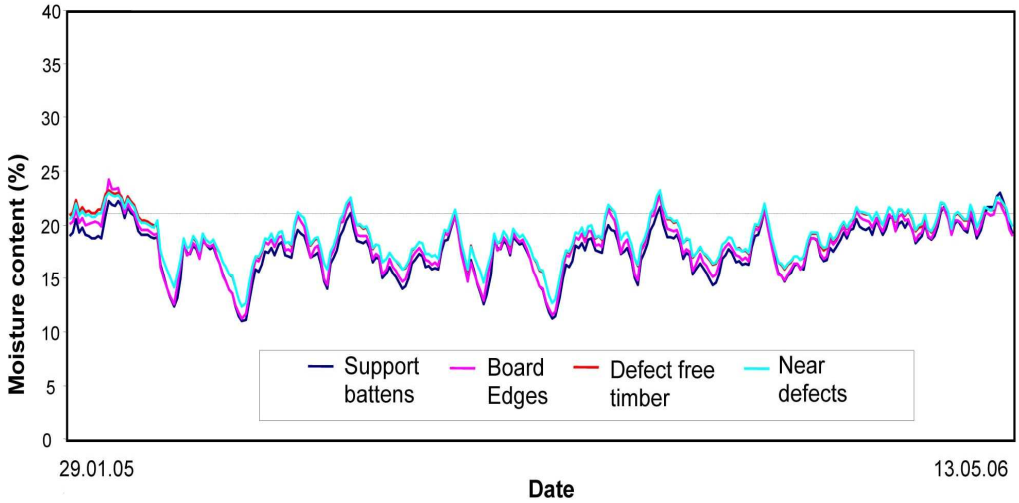

Fig 4. Driest test panel: (exposed site, horizontal boards, open jointed, surface coated)

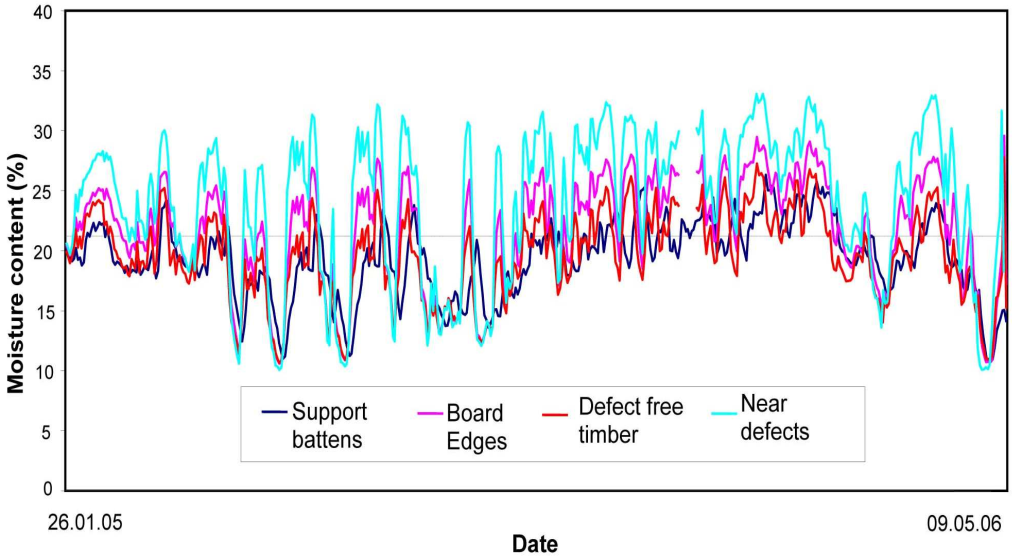

Fig 5. Wettest test panel: (exposed site, vertical boards, closed jointed, uncoated)

At the time of writing the results of the fire test were still being analysed.

4. Discussion

The exposure trial results indicate that timber cladding can experience a wider range of moisture contents than is often quoted in the literature. European Standard EN 942 [4], for example, quotes a moisture content range of 12 to 19%, whereas the values recorded during this trial range from 10% up to above the fibre saturation point. Similarly the average values recorded in the trial are 17 to 22% whereas the published values are around 16%. This suggests that, in coastal conditions such as north and west Scotland, the risk of moisture effects such as fungal decay and dimensional change occurring in timber façades are higher than is recognised in the literature.

The risk of fungal decay can be evaluated by assessing the moisture conditions in each panel against published thresholds for fungal activity. *Fig 5* shows the panels ranked against both the duration and the intensity of wetting. The minimum decay threshold is taken to be a moisture content of 22% for at least 10% of the time, and the requirement for optimum growth is taken to be a moisture content over 30% [5] [6] [7]. Whilst necessarily approximate, these thresholds allow the performance of each panel to be ranked against the risk of fungal decay.

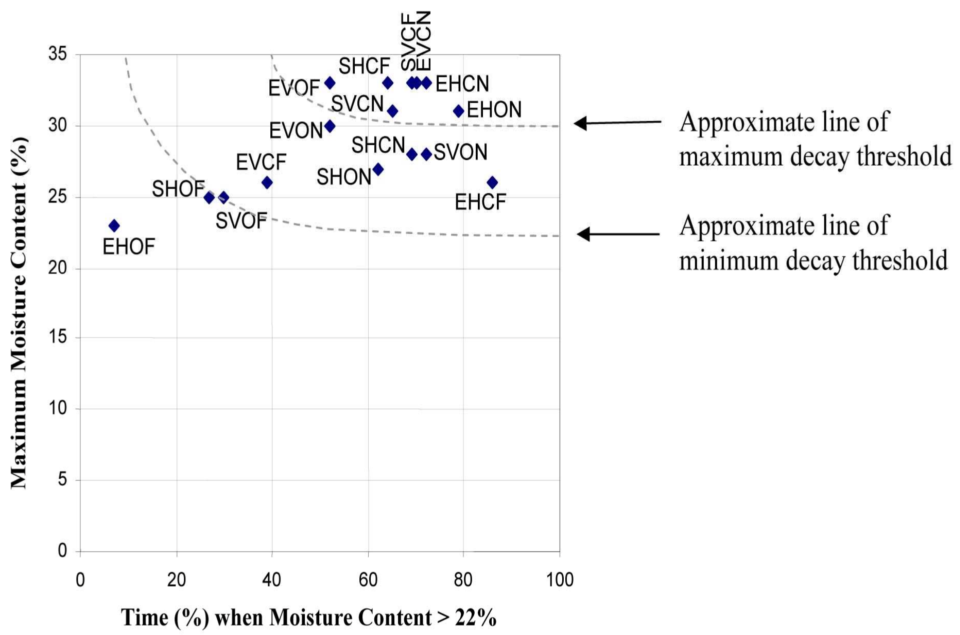

Fig 6. Duration and intensity of wetting in each of the test panels

In *Fig 6* the panels with a combination of open jointed timber cladding and a surface coating (EHOF, SHOF, SVOF) have experienced a lower moisture load than other experimental treatments. All the other panels on the sheltered site experienced high moisture loads during the winter months and wide moisture fluctuations during the rest of the year. On the exposed site the four panels without a surface coating performed particularly badly. In several panels the support battens experienced moisture loads as high, or higher, than the cladding itself. These findings suggest that in temperate coastal conditions such as Scotland, moisture management techniques do not, by themselves, generally provide sufficient protection against wood destroying organisms. Thus, whilst European redwood and whitewood can be used externally without wood preservation or modification in parts of Europe [8], this approach cannot be expected to provide an assured service life in the UK. This statement should be balanced by the survey results, however.

The surveys recorded timber cladding with a service life ranging from 17 years to over 170 years even though, in both cases, the timber used was not durable, nor was it preservative treated (*Fig 7*). The long service life appears to be due to the combination of a dry sheltered site and regular maintenance. The implication of this is that in temperate coastal conditions, the service life of timber façades can vary by a factor of 10 due to microclimate and maintenance. Consequently, where a *guaranteed* service life is required for timber cladding there is probably little option but to use the minimum published values for externally exposed timber of a particular durability class [9]. It should, however, be recognised that these estimates assume poor design, construction and maintenance. Good practice can extend the service life of timber cladding far beyond the minimum. This variation has implications for the service life prediction such as the procedures being developed under ISO 15686-2 [10].

Fig 7. Most of this cottage was built in 1834 and has survived remarkably well even though the timber used was not durable, nor preservative treated. Other timber cladding in the area has failed in as little as 17 years.

Two main issues remain unresolved: Firstly, while the Norwegian test results indicate that a ventilated cavity is beneficial in reducing the moisture load in timber cladding on exposed sites, it was not possible to predict cavity performance in all conditions. Nor was it possible to directly measure airflow within the cavity. Secondly, fire-safe detailing for timber cladding with open joints was not resolved. It is virtually impossible to fit functional cavity barriers in the cavities behind open jointed cladding and so, although this cladding type performed well in the exposure trial, it cannot at present be recommended for use where fire safety is a concern. Similarly, it was not possible within the scope of this project to develop or test any fire-safe timber cladding details for buildings higher than two storeys or with horizontal fire compartments.

Conclusions

An exposure trial and fire test have been completed on external timber cladding in Scotland. This work is informing the development of evidence-based construction details which will be published shortly. Key outputs of the research include:

- Information on the interaction of factors influencing moisture conditions in external façades
- New fire-safe construction details for timber façades on low-rise buildings
- A guide to timber façade design and construction in temperate maritime conditions

Acknowledgements

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References

[1] Davies I., (In preparation) *Designing the Timber Façade.* To be published by: arcamedia, Edinburgh. ISBN 978-1-904320-04-3

[2] Colwell S. and Martin B., 2003. *Fire performance of external thermal insulation for walls of multi-storey buildings*, BR135 2nd Edn. BRE Bookshop, London.

[3] BS 8414-2:2005. *Fire performance of external cladding systems – Part 2: Test method for non-loadbearing external cladding systems fixed to and supported by a structural steel frame*. BSI, London.

[4] EN 942:1996. *Timber in joinery – General classification of timber quality*. BSI, London.

[5] Zabel R. and Morrell J., 1992. *Wood Microbiology – Decay and its Prevention.* Academic Press, London.

[6] Viitanen H. and Ritchkoff A., 1991. *Brown rot decay in wooden constructions. Effect of temperature, humidity and moisture.* Swedish Univ. of Agri. Sc., Dept, of For. Sc. Report No.222.

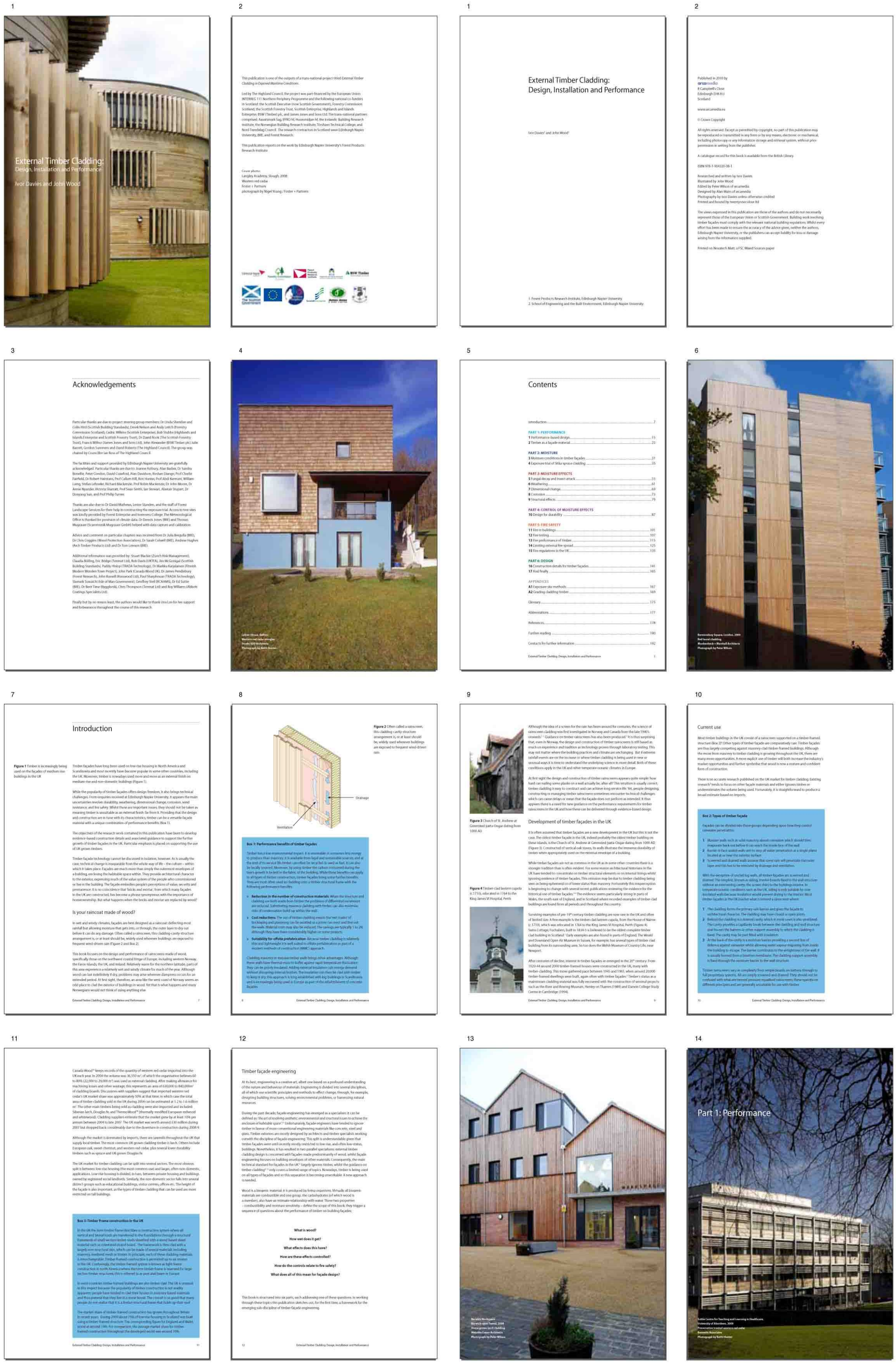
[7] Viitanen H., Modelling the Time Factor in the Development of Brown Rot Decay in Pine and Spruce Sapwood – The Effect of Critical Humidity and Temperature Conditions. *Holzforchung* **51** 2, 1997, pp 99-107. Berlin.

[8] EN 460 1994. *Durability of wood and wood based products – Natural durability of solid wood – Durability classes and hazard classes.* BSI, London.

[9] BS 8417:2003. *Preservation of Timber – Recommendations*. BSI, London.

[10] ISO 16686-2: 2001. *Building and construction assets – Service Life Planning: Part 2: Service Life Prediction Procedures.* The International Organisation for Standardisation, Geneva.

3. **Davies, I. and Wood, J. (2010). Exterior timber cladding: design, installation and performance. Edinburgh: arcamedia, ISBN 978-1-904320-04-3.**



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Performance-based design

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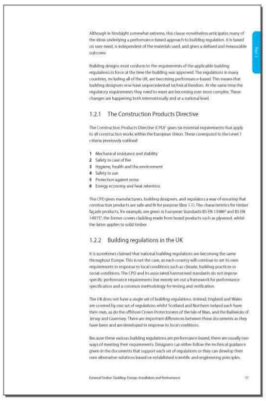

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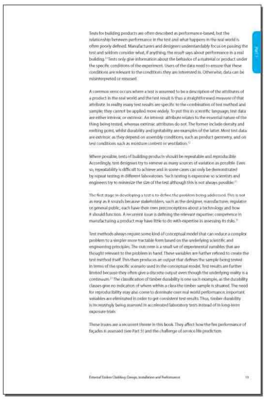

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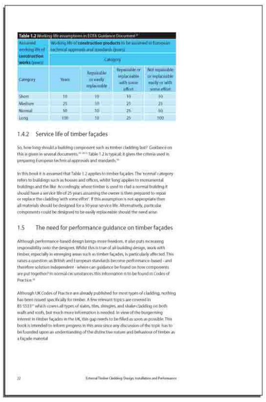

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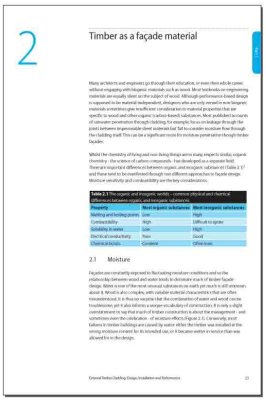

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Timber as a façade material

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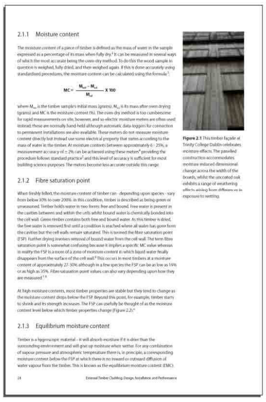

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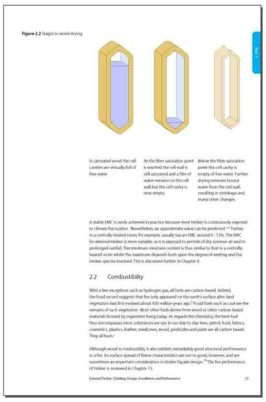

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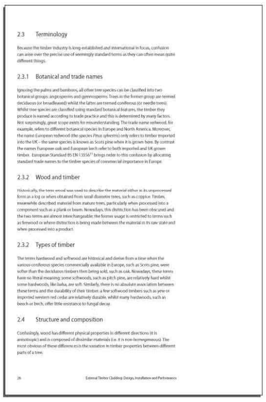

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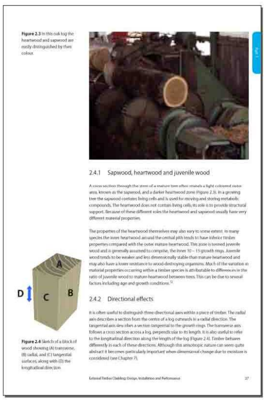

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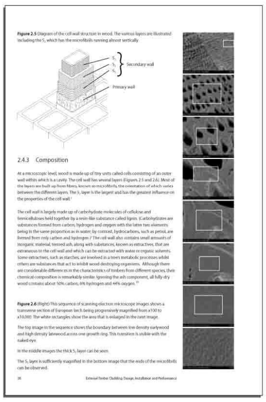

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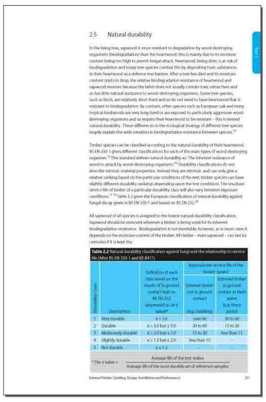

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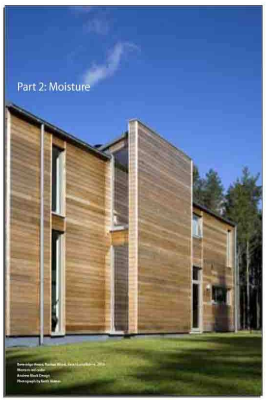

Part 2: Moisture

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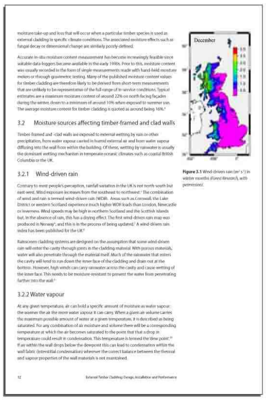

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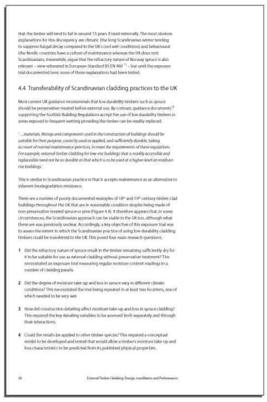

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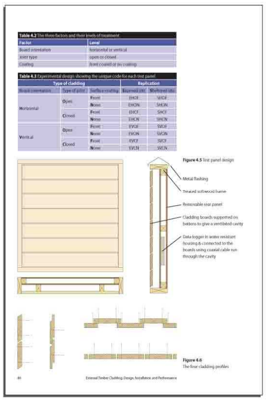

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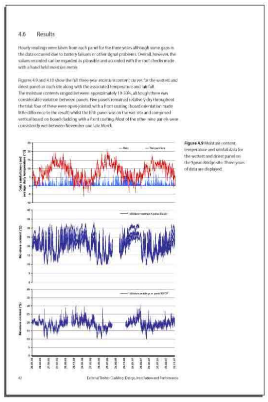

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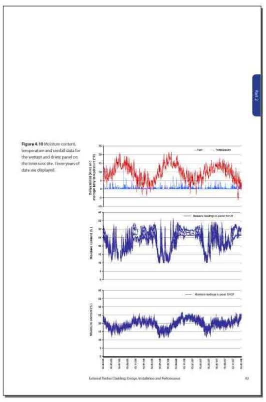

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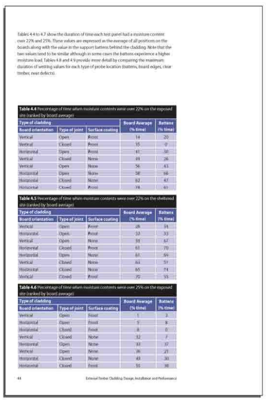

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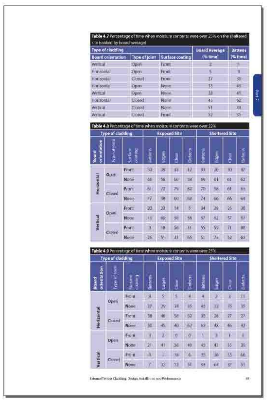

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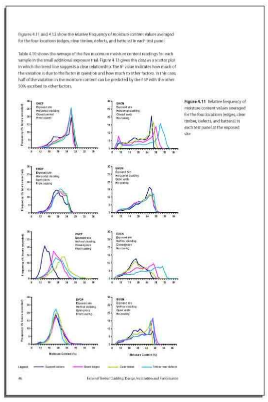

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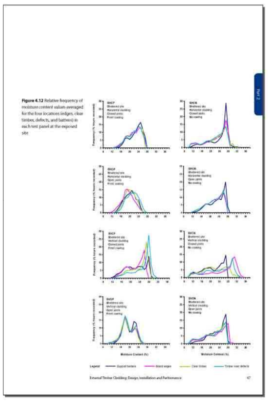

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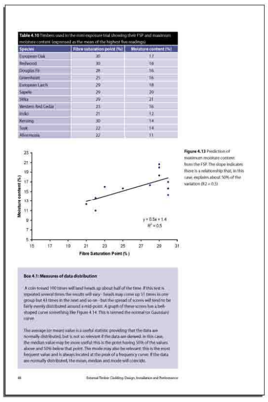

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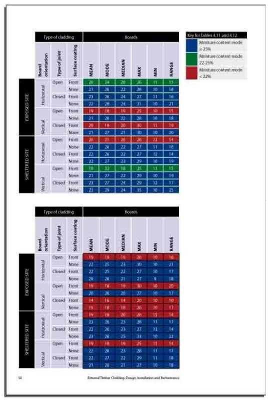

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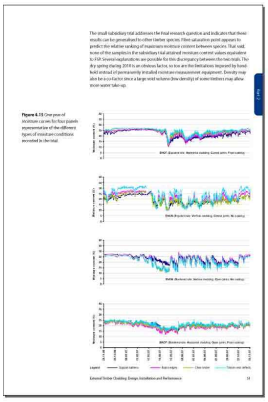

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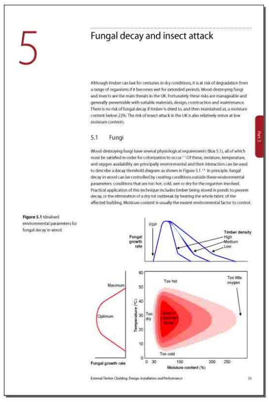

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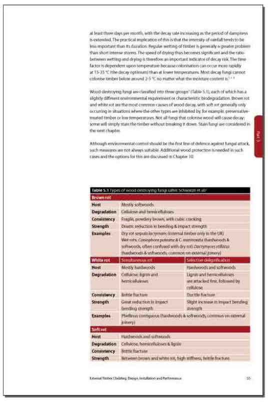

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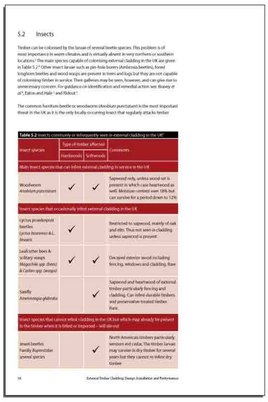

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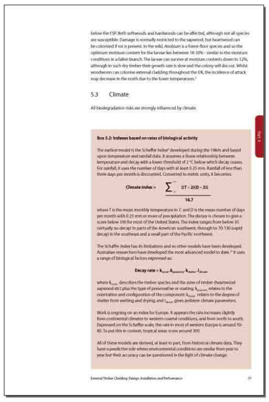

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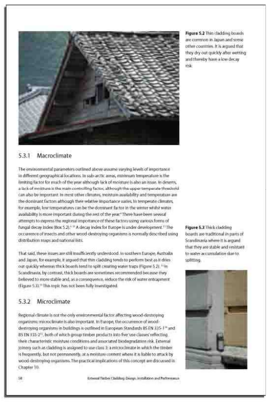

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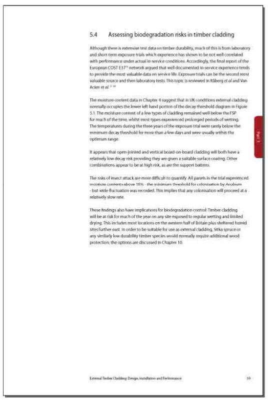

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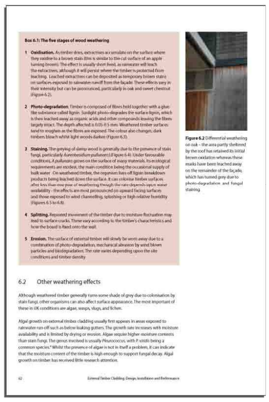

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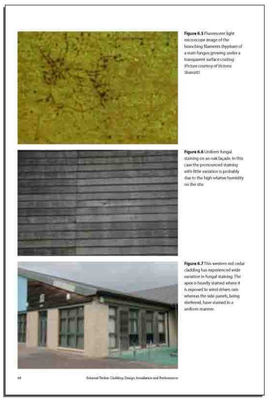

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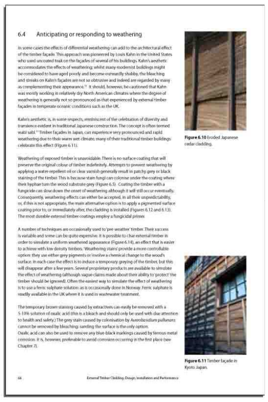

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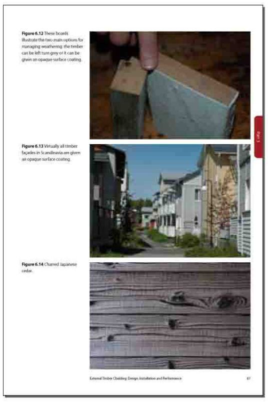

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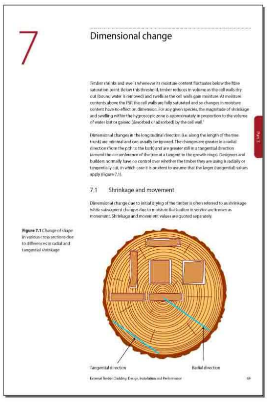

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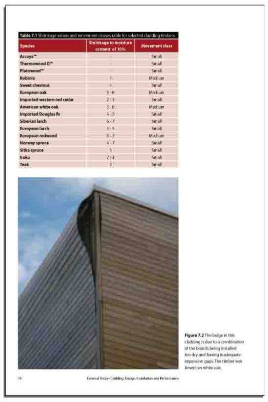

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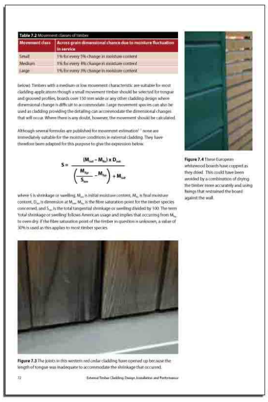

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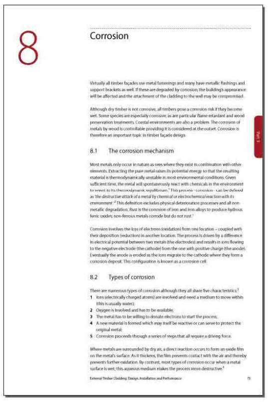

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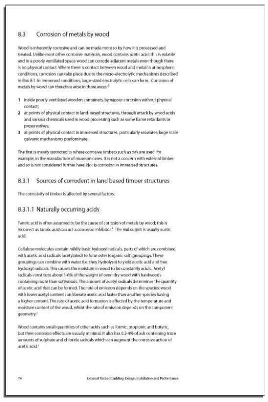

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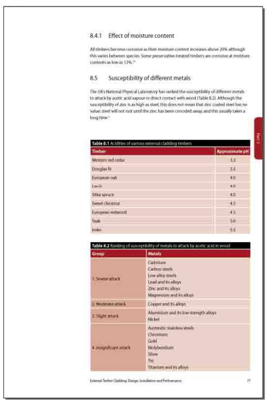

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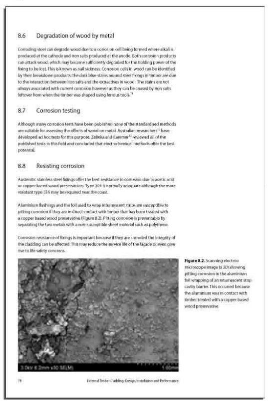

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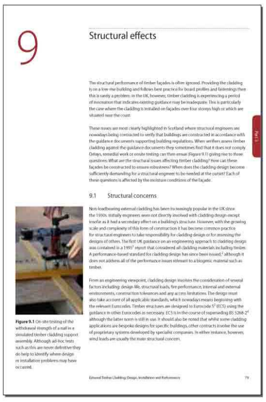
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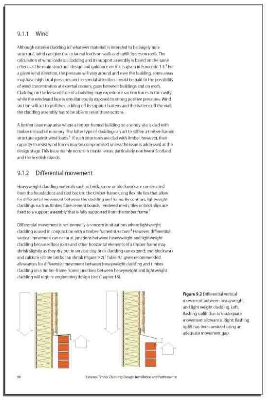

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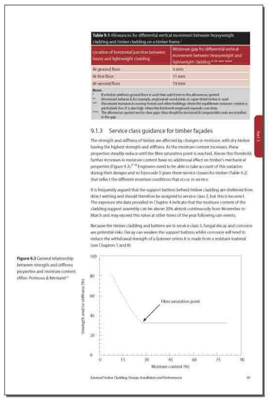

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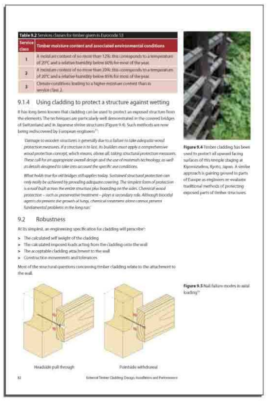

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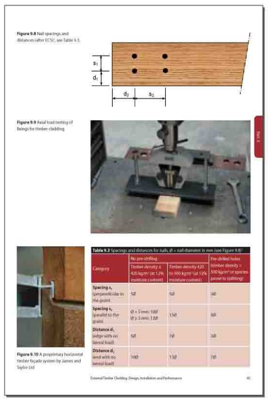

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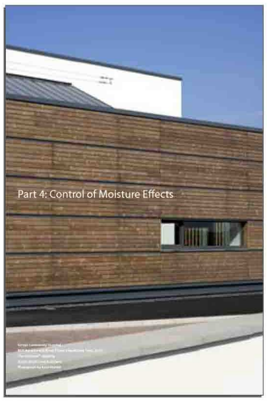
Part 4: Control of Moisture Effects

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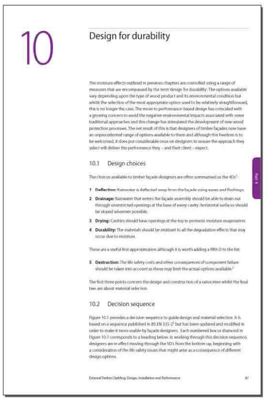
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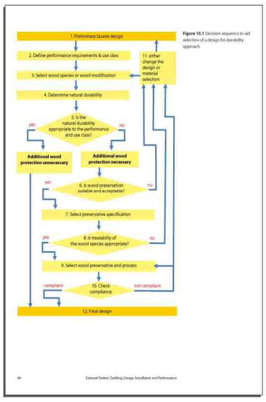

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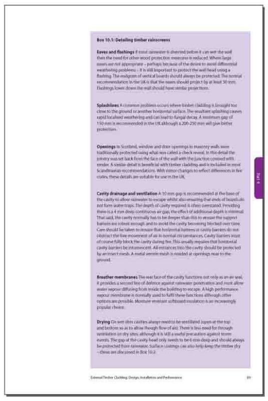

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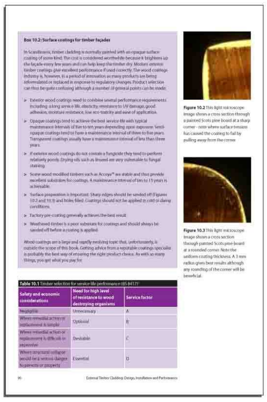

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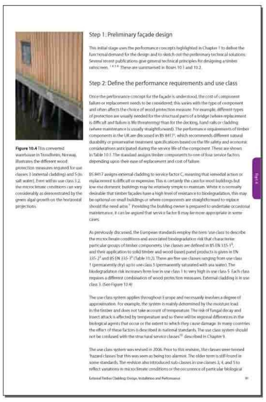

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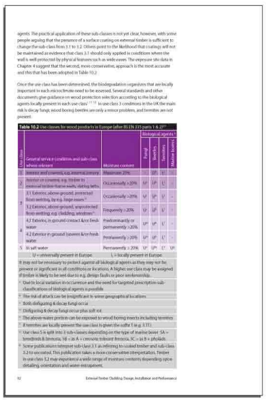

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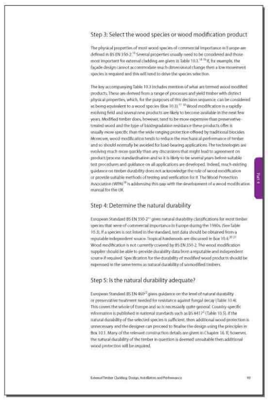

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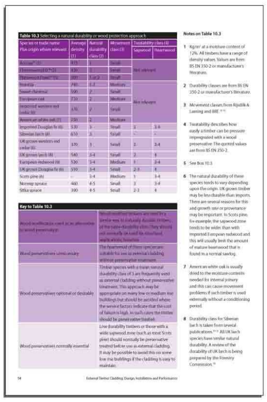

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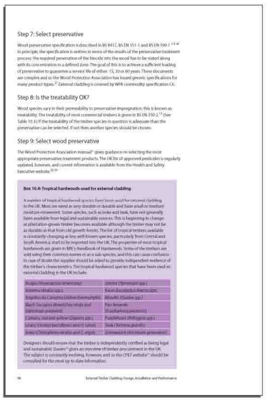

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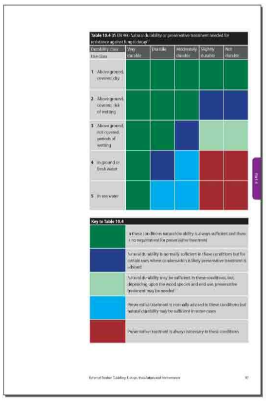

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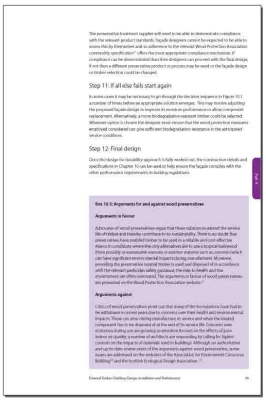

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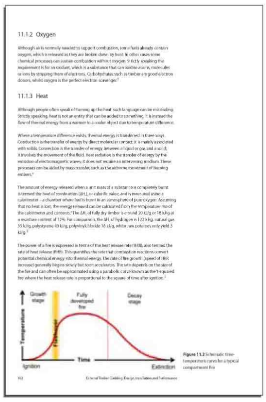

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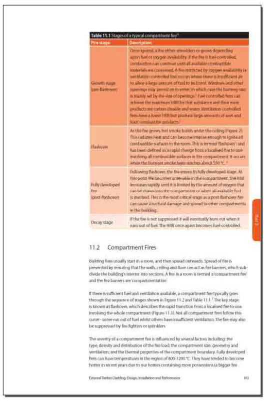

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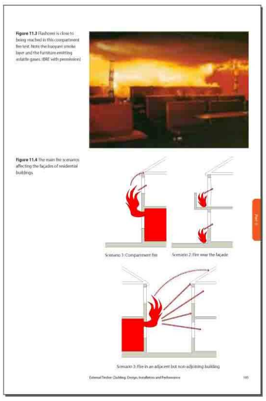

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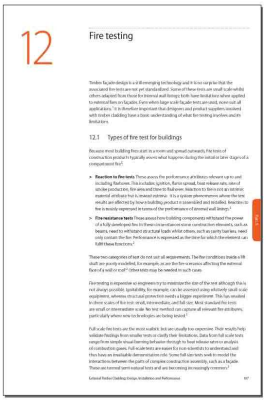

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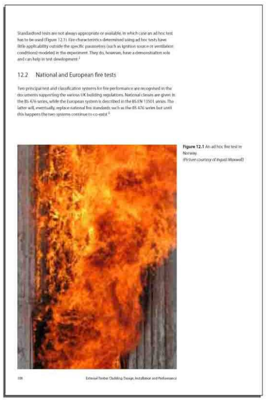

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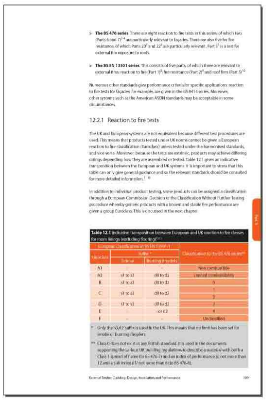

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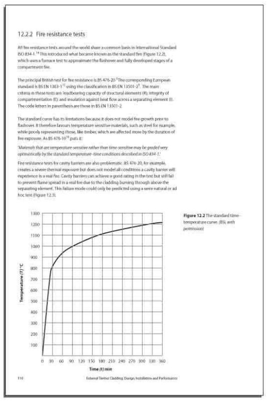

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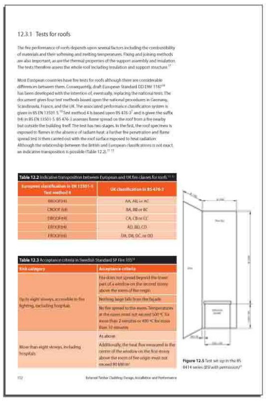

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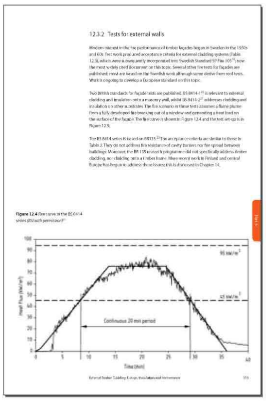

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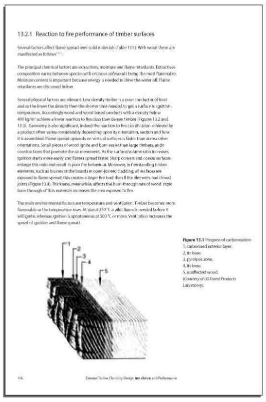

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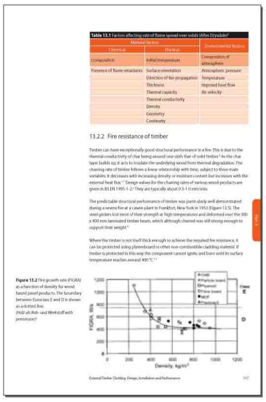

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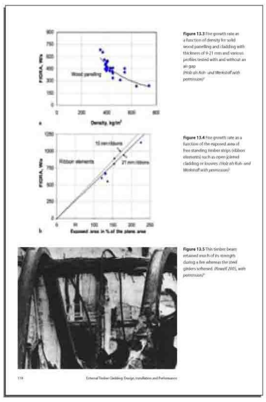

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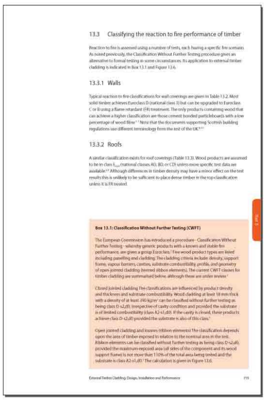

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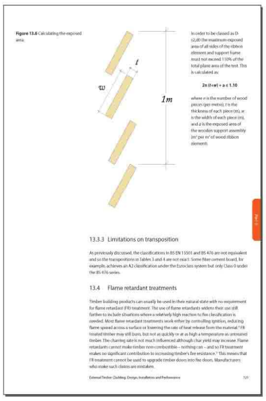

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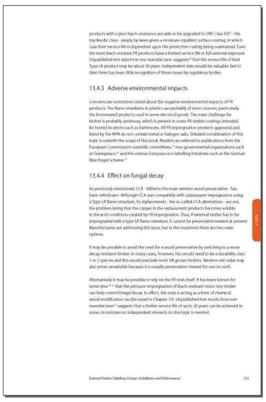

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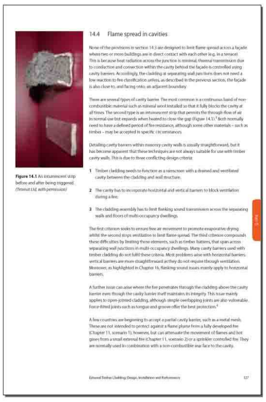

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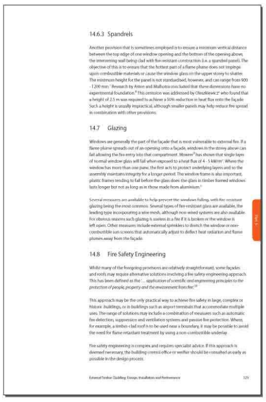

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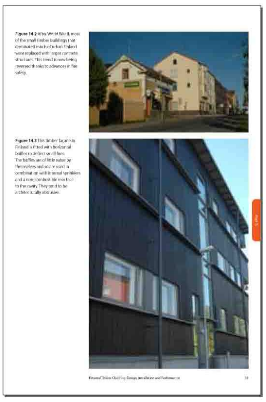

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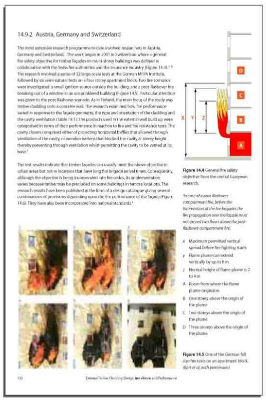

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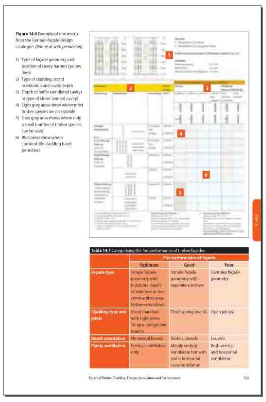

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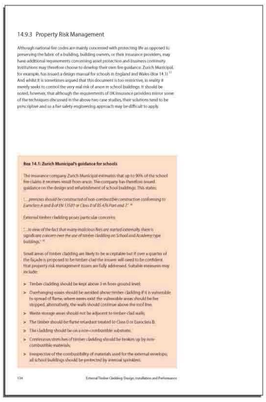

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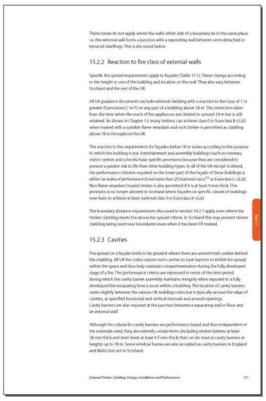

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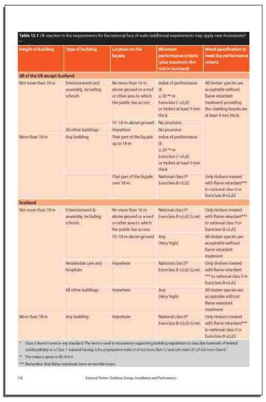

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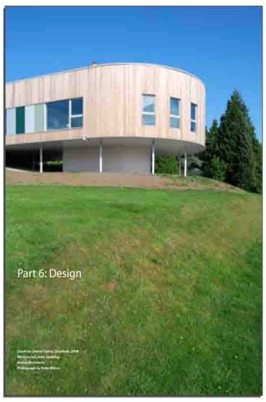

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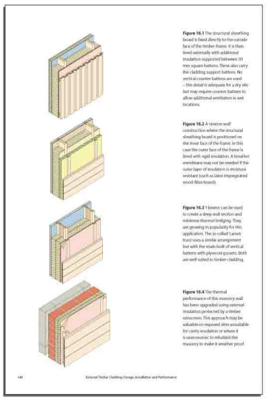

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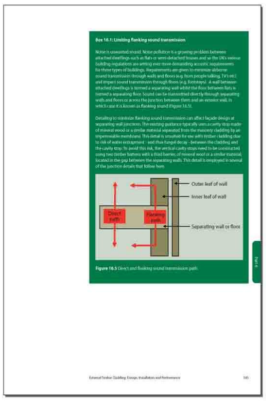

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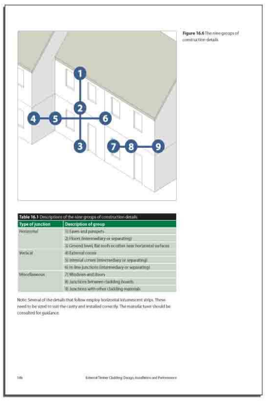

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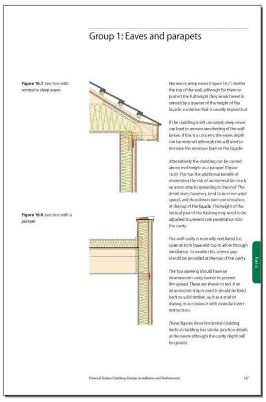
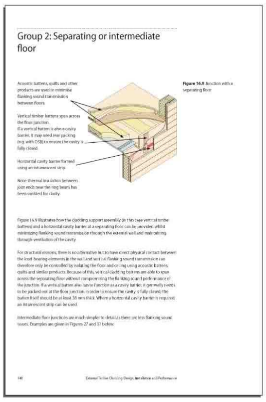


Group 1: Eaves and parapets

148



Group 2: Separating or intermediate floor

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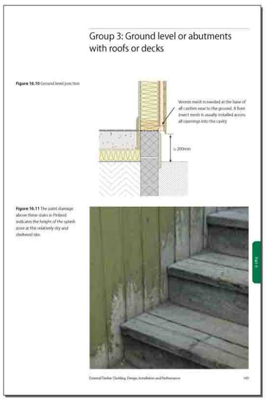

Group 3: Ground level or abutments with roofs or decks

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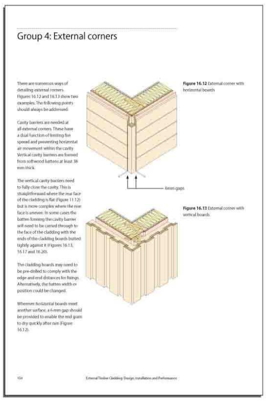

Group 4: External corners

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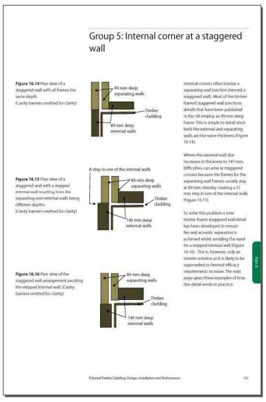

Group 5: Internal corner at a staggered wall

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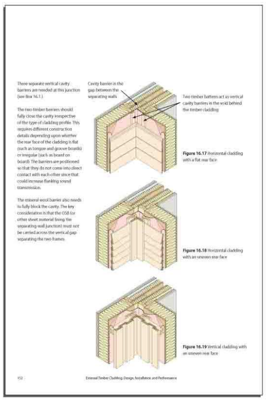

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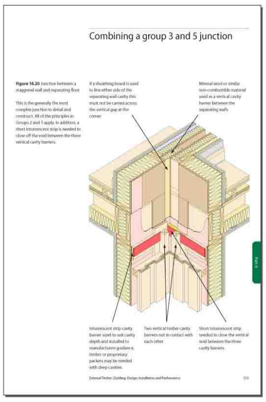

Combining a group 3 and 5 junction

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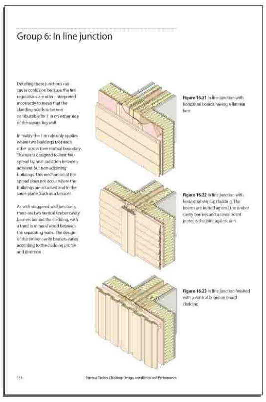

Group 6: In line junction

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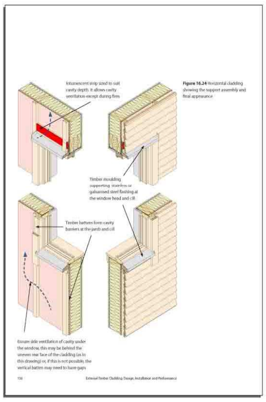
Group 7: Windows and doors

156



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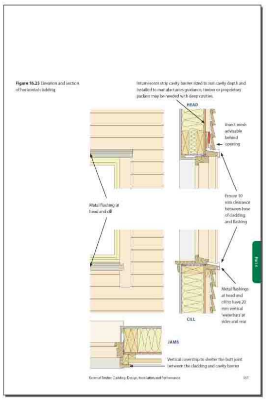

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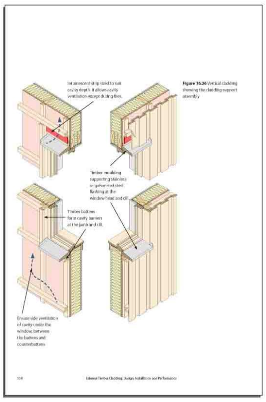

159

160

Group 8: Junctions between boards

161

162

163

Group 9: Junctions between heavy and lightweight cladding

164

165

17 And finally…

166

167

Appendix 1

Exposure site methods

168

169

Appendix 2

Grading cladding timber

170

171

172

173

174

175

Glossary

176

177

Abbreviations

178

References

179

180

181

182

183

184

185

186

187

188

189

190

Further reading

191

Fire

Bart B., Kotthoff, I. & Weiderkehr, R. Aussenwände – Konstruktion und Bekleidungen. [External construction – cladding.] Zurich: Lignum – Dokumentation Brandschutz, 2009.

Chitty, R. & Fraser-Mitchel, J. Fire Safety Engineering: A Reference Guide. London: BREPress, 2003.

Drysdale D. An Introduction to Fire Dynamics. Chichester, UK: John Wiley & Sons, 2000.

Wood Protection Association. Industrial Flame Retardant Treatment of Solid Wood. Derby, UK: Wood Protection Association, 2006.

Timber procurement

Davies, I. Sustainable Construction Timber – Sourcing and specifying local timber. Edinburgh: arcamedia, 2009.

British and European standards

BS 1186-3:1990 Timber for and workmanship in joinery. Part 3. Specification for wood trim and its fixing. London: British Standards Institute, 1990.

BS 5534:2002+A1:2010 Code of practice for slating and tiling (including shingles). London: BSI, 2010.

BS 8417: 2003 Preservation of timber. Recommendations. London: BSI, 2003.

BS EN 14915:2006 Solid wood panelling and cladding. Characteristics, evaluation of conformity and marking. London: BSI, 2006.

BS EN 1995-1-1:2004+A1:2008 Eurocode 5. Design of timber structures. General. Common rules and rules for buildings. London: BSI, 2009.

BS EN 335-1:2006 Durability of wood and wood-based products. Definitions of use classes. General. London: BSI, 2006.

BS EN 350-2:1994 Durability of wood and wood-based products. Natural durability of solid wood. Guide to natural durability and treatability of selected wood species of importance in Europe. British Standards Institution, 1994.

BS EN 460:1994 Durability of wood and wood-based products. Natural durability of solid wood. Guide to the durability requirements for wood to be used in hazard classes. London: British Standards Institution, 1994.

BS EN 599-1:2009 Durability of wood and wood-based products. Efficacy of preventive wood preservatives as determined by biological tests. Specification according to use class. London: BSI, 2010.

192

Contacts for further information

Research, consultancy and testing

BRE	www.bre.co.uk
Centre for Window and Cladding Technology	www.cwct.co.uk
Institute for Forest Products Research	www.napier.ac.uk/randkt/forestproductsresearch
TRADA Technology Ltd	www.trada.co.uk

Timber

Association of Scottish Hardwood Sawmillers (ASHS)	www.ashs.co.uk
Forestry Commission	www.forestry.gov.uk
Timber Decking and Cladding Association	www.tda.org.uk
Timber Trade Federation	www.ttf.co.uk
UKFPA	www.ukfpa.co.uk
Wood Knowledge Wales	www.woodknowledgewales.co.uk

Timber certification and procurement

Central Point for Expertise on Timber	www.cpet.org.uk

Wood Preservation and modification

Wood Protection Association	www.wood-protection.org

Sustainable construction

Association for Environment Conscious Building	www.aecb.net
BRE	www.bre.co.uk
Scottish Ecological Design Association	www.seda.uk.net

Building regulations

England & Wales	www.communities.gov.uk/planningandbuilding/buildingregulations
Northern Ireland	www.buildingcontrol-ni.com
Scotland	http://scotland.gov.uk/Topics/Built-Environment/Building/Building-standards
Guernsey	www.gov.gg/ccm/navigation/environment/planning/building-control
Isle of Man	www.gov.im/dlge/planning/build/welcome
Jersey	www.gov.je

194

No longer an unusual feature on buildings in the UK, the design, installation and performance of external timber cladding on new construction nevertheless continue to generate detailed questions from architects, specifiers and contractors. In response, Edinburgh Napier University's Forest Products Research Institute, an acknowledged central point of expertise in this field, has produced *External Timber Cladding: Design Installation and Performance*. The result of extensive research, testing and detail development, this new publication provides the user for the first time with evidence-based information on how to respond to the contradictory demands of moisture control and fire, the two biggest issues affecting the use of timber on building facades. Divided into six clearly distinguishable sections, the book offers easily referenced guidance to current legislation, detail drawings and answer to the majority of questions surrounding a subject that is technically more complex than it might at first seem.

A wood scientist and technologist, **Ivor Davies** is a Research Fellow within Edinburgh Napier University's Forest Products Research Institute where he has led or participated in a number of trans-national and national timber research projects. As an internationally recognised expert on external timber cladding, he is regularly called upon to provide consultancy advice and expert witness services. Ivor Davies' previous publications include: *Timber Cladding in Scotland* (with Bruce Walker and James Pendlebury); *Making the Grade* (with Guy Watt) and *Sustainable Construction Timber*.

A Reader in Architectural Technology and CAD at Edinburgh Napier University's School of Engineering and the Built Environment, **John Wood** is Head of Product Innovation and Continuing Professional Development within the University's Institute of Sustainable Construction. Along with Professor Sean Smith and Richard Mackenzie, John Wood co-authored *Housing and Sound Insulation: Improving Existing Attached Dwellings and Designing for Conversions* and was also part of the team that developed the *Robust Standard Details* for sound and for which the Queen's Anniversary Prize was awarded to Edinburgh Napier University in 2010.

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Appendix 2

Defects

This appendix is a catalogue of cladding defects. It illustrates the problems that typically occur and highlights the associated risks.

Figure A.2.1 *Poor window installation. The lack of space below the boards ends will trap water, as will the mastic sealant. There is no water bar at the end of the metal sub-sill flashing.*

Figure A.2.2 *Poor window installation. The sub-sill is wooden with end joints that will trap water. Also note the use of lost head nails, these have little resistance to axial loads.*

Figure A.2.3 *Poor window installation. The flashing has been sealed with mastic thereby preventing cavity drainage and ventilation. There is no water bar at the end of the flashing. The space under the flashing will allow insects into the cavity.*

Figure A.2.4 *These butt-jointed boards will create a water trap. Also note the use of lost head nails, these have little resistance to axial loads.*

Figure A.2.5 *These shot fired nails have been overdriven thereby creating water traps and splits.*

Figure A.2.6 *This duct cover is only suitable for use with masonry cladding. It has created a water trap when used with timber.*

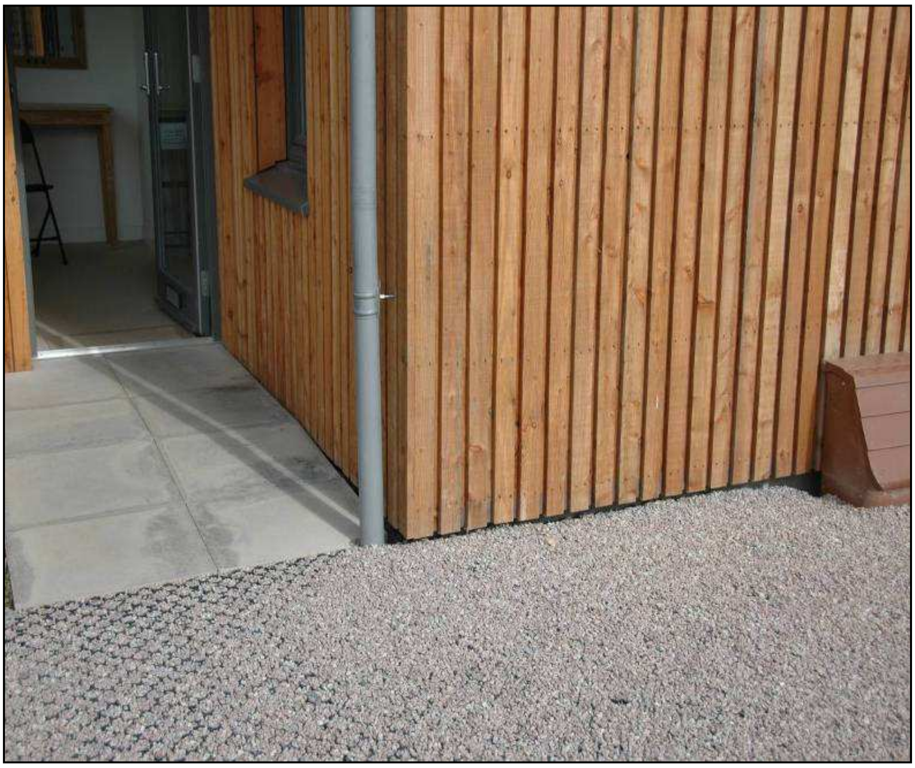

Figure A.2.7 *This access ramp to a door will cause a splashzone, as will the ground level being too close to the cladding, and the plastic meter box.*

Figure A.2.8 *These boards have been nail gunned together, thereby creating a risk of splitting the boards by preventing them from moving. Also note poor insect mesh installation and the over-driven nails.*

Figure A.2.9 *No eaves ventilation.*

Figure A.2.10 *Decking has been carried up to the wall, thereby creating a splashzone on the cladding (cladding timber unknown)*

Figure A.2.11 *These circular plastic vents are above and below a horizontal cavity barrier at a separating floor. This vent is designed for vented cavities and is inadequate for those that are ventilated. Also note water traps around the duct covers and flashing.*

Figure A.2.12 *A plastic DPC has been positioned between the cladding and vertical cavity barrier. Although essential with masonry cladding this detail is a potential water trap if used behind timber. Timber: preservative treated western red cedar.*

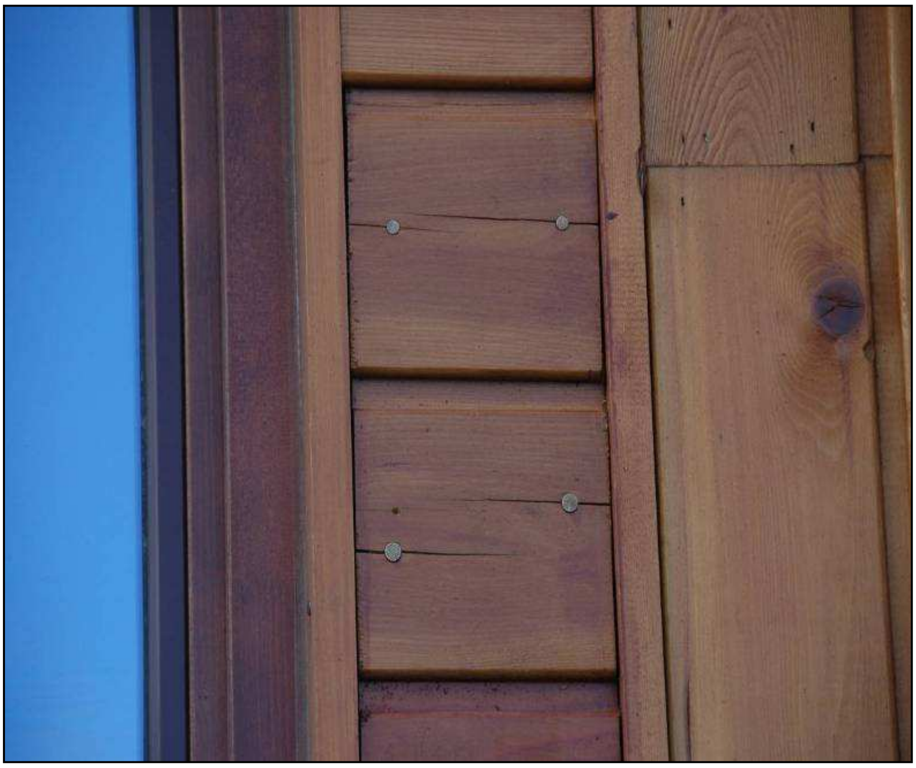

Figure A.2.13 *Unsuitable fixings – the short boards should have been predrilled, while the vertical board has been fixed with flooring sprigs that offer little withdrawal resistance. Also note the numerous butt joints that will trap water.*

Figure A.2.14 *The light coloured areas are sapwood, this should have been graded out. Also note the use of lost head nails.*

Figure A.2.15 *These boards have been butted against a flashing thereby creating a water-trap as well as blocking off cavity ventilation.*

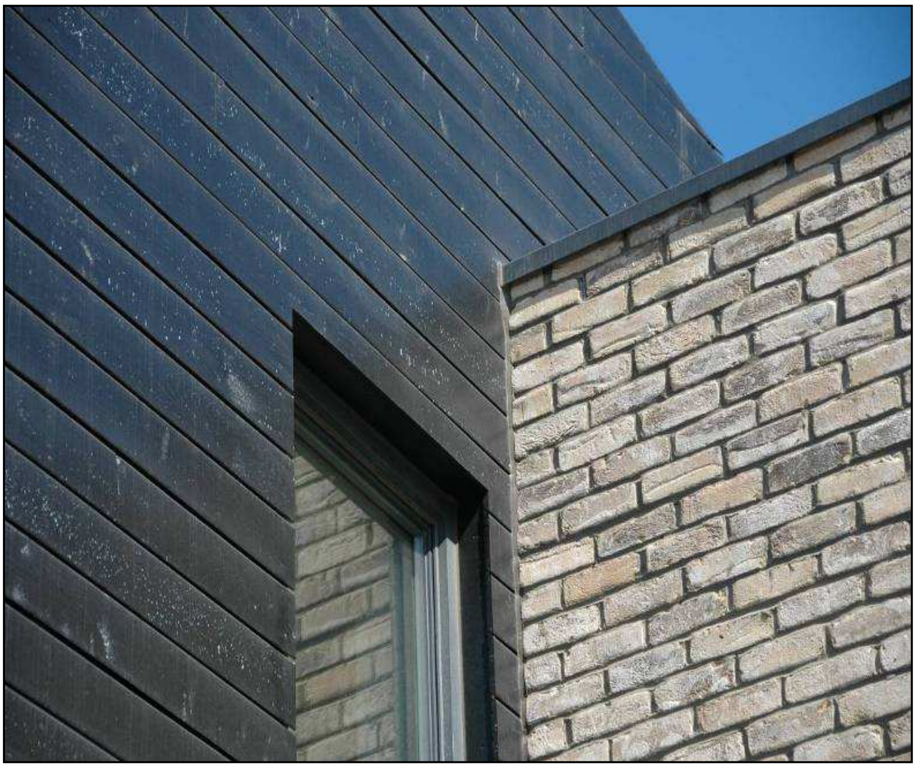

Figure A.2.16 *This junction between heavyweight and lightweight cladding does not make adequate provision for differential movement. Also the use of mastic at the board ends will trap water.*

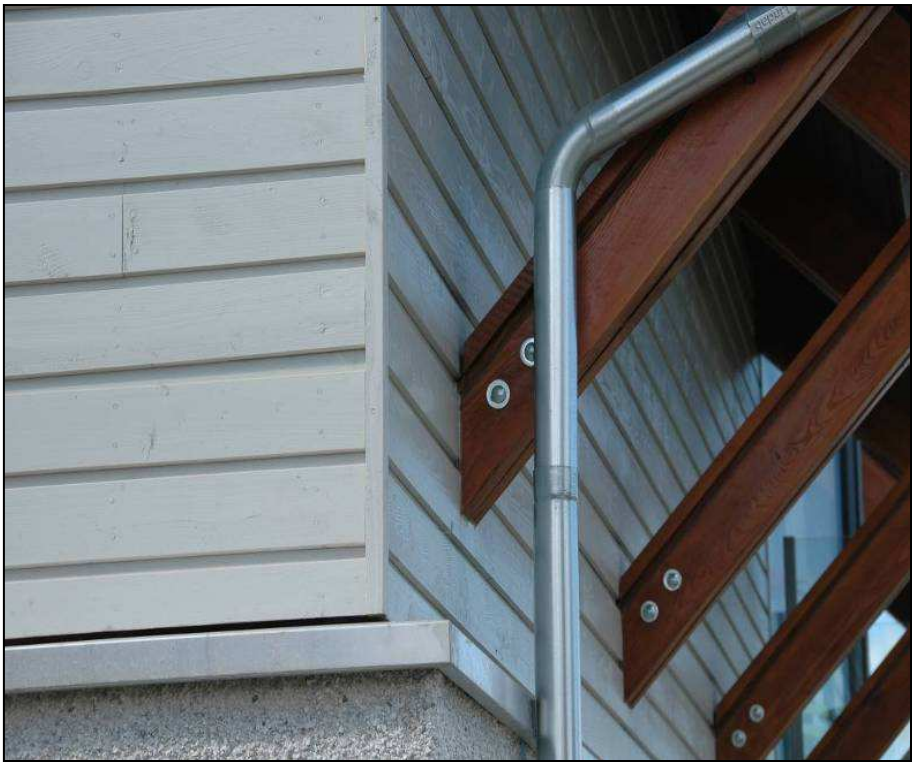

Figure A.2.17 These exposed structural timbers are butted against the cladding with a risk of water entrapment. Also the structural timber is local Douglas fir which offers little resistance against fungal decay.

Figure A.2.18 This pattern has been routed into the timber using a simple rectangular cutter profile. Every routed line has horizontal edges that will trap water.

Appendix 3

Data

The enclosed CD-ROM contains three folders; their contents are as follows:

Exposure site data: has two folders each with eight files giving data and calibrations:

Inverness	**Spean Bridge**
SHCF	EHCF
SHCN	EHCN
SHOF	EHOF
SHON	EHON
SVCF	EVCF
SVCN	EVCN
SVOF	EVOF
SVON	EVON

Weather: has two files giving the weather data from the nearest Met. Office sites

Analysis: has three files. Two have the calibrated data with gaps in-filled wherever possible using data interpolation. The third is the analysis with seven worksheets containing:

Full data	All data after calibration and interpolation
Summer 06 (Yates)	Analysis of sample data using the Yates algorithm
Winter 06-07(Yates)	Analysis of sample data using the Yates algorithm
FFT winter 06-07	Fast Fourier Transform of sample data
FFT summer 07	Fast Fourier Transform of sample data
Chi sq	Chi squared test on the descriptive statistics
Prediction	Combined results of the main and mini exposure trial