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Durability of timber members

Moisture conditions and service life assessment of bridge detailing

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Durability of timber members

Moisture conditions and service life assessment of bridge detailing

JONAS NIKLEWSKI | FACULTY OF ENGINEERING | LUND UNIVERSITY

Durability of timber members

Moisture conditions and service life assessment of bridge detailing

by Jonas Niklewski

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DOCTORAL DISSERTATION
Faculty opponent: Prof. dr. ir. Joris Van Acker

To be presented, with the permission of the Faculty of Engineering of Lund University, for public criticism in the lecture hall MA:1, Sölvegatan 20, Lund, at the Department of Building and Environmental Technology on Wednesday, the 19th of December 2018 at 09:00.

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Durability of timber members: Moisture conditions and service life assessment of bridge detailing

Abstract

The longevity of timber structures in exposed outdoor environments is often perceived to be unreliable as compared with that of concrete and steel structures. This situation is exacerbated to some extent by the fact that the European commission for standardization (CEN) currently provides no quantitative method for service life assessment of timber structures. To counteract this, the present thesis deals with methods for the quantitative service life assessment of timber in outdoor above-ground construction.

Wood moisture content and temperature, i.e. the *material climate* involved, are two fundamental indicators of decay activity of wooden members. Performance based service life assessment of wood is largely comprised of two parts: (1) establishing the relationship between the environmental conditions and the material climate, and (2) establishing the relationship between the material climate and the rate of deterioration. The former depends on factors such as weather parameters, material properties and the design of details.

Two experimental trials were conducted in order to acquire data concerning the relationship between the environmental conditions and the moisture content of the wood. The aim of the first experiment was to study typical details utilized for timber bridges with respect to their variation in moisture content. The type of detailing employed was shown to have a great effect on the moisture conditions, with the exposed contact areas and the end-grain being subject to increased levels of moisture content. The second experiment focused on the effects of long-term superficial damage on the moisture conditions of wood. It was shown that superficial damage caused by photo degradation and checking lead to increased moisture absorption and consequently to a longer duration of surface wetness.

The relationship between environmental conditions and material climate was estimated through numerical modelling, which involves the explicit modelling of moisture transport within the wooden member and the exchange of moisture at the surfaces that are exposed. The model was applied to one-dimensional transverse moisture transport as well as to multi-dimensional transport in the case of simple details, such as side-grain to side-grain contact areas. The numerical model was then coupled with decay prediction models so as to map the relative decay hazard in European climates.

Key words

wood, spruce, moisture, durability, decay, service life, detailing, model

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A doctoral thesis at a university in Sweden takes either the form of a single, cohesive research study (monograph) or a summary of research papers (compilation thesis), which the doctoral student has written alone or together with one or more author(s).

In the latter case the thesis consists of two parts. An introductory text puts the research work into context and summarizes the main points of the papers. Then, the research publications themselves are reproduced, together with a description of the individual contributions of the authors. The research papers may either have been already published or are manuscripts at various stages (in press, submitted, or in draft).

Cover illustration back: Frequency of meaningful words in the introduction chapters of the present thesis.

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List of publications

This thesis is based on the following publications, referred to by their Roman numerals:

I **Moisture content prediction of rain-exposed wood. Test and evaluation of a simple numerical model for durability applications.**
J. Niklewski, T. Isaksson, M. Fredriksson
Building and Environment, 97:126–136 (2016)

II **The effect of weathered surfaces on the moisture conditions of wood. Measurements and modelling.**
J. Niklewski, C. Brischke, E. Frühwald Hansson, L. Meyer-Veltrup
Wood Science and Technology, 52(6):1431–-1450 (2018)

III **Moisture conditions of rain-exposed glue-laminated timber members: the effect of different detailing.**
J. Niklewski, T. Isaksson, E. Frühwald Hansson, S. Thelandersson
Wood Material Science and Engineering, 13(3):129–140 (2018)

IV **The effects of joints on the moisture behaviour of rain exposed wood**
J. Niklewski, M. Fredriksson
Submitted to Wood Material Science and Engineering, September, 2018

V **Numerical study on the effects of macro climate and detailing on the relative decay hazard of Norway spruce**
J. Niklewski, C. Brischke, E. Frühwald Hansson, L. Meyer-Veltrup, D. Kavurmaci.
Submitted to Wood Material Science and Engineering, November 2018

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Summary in English

Wood is an extremely versatile building material with applications ranging from simple cladding and decking boards to highly engineered wood products. The material is predominantly employed for residential buildings having less than three storeys but is increasingly being utilized also for multi-storey construction. With its minimal environmental footprint, wood offers a sustainable alternative to steel and concrete for applications in the built environment.

The main issue with employing wood in exposed environments, such as the use of wood in bridge structures, is its sensitivity to water. Exposure to water leads to physical defects such as checking and warping but also to biological attack by decay fungi. In bridges, the development of decay fungi often sets a definite end to the lifetime of the structure through the material losing its structural integrity and the bridge becoming unsafe for use.

Knowledge of the quality, detailing, protection and maintenance of wood are key factors for achieving an extended lifetime for outdoor wood structures. Such knowledge tends to be highly fragmented, however, and to be largely unavailable to practitioners.

The present research aims at increasing and systematizing knowledge of the durability of wood, in particular through refining and expanding an existing framework for service life assessment. Since the moisture conditions and the service life of wood are inherently connected, a large part of the work consists of predicting how water is absorbed and distributed in wood. This includes quantitative analysis of how wood reacts to different climatic conditions, to detailing and to measures aimed at wood protection. The output of this type of analysis is then related to functions of biotic growth so as to predict the service life of the member.

The intention of this work is neither to promote nor discourage the use of wood for construction purposes, but to develop means for dealing with one of the fundamental issues related to its use. A reliable service life model gives engineers, architects and city planners a fair chance to compare the performance of concrete, steel and wood and to ultimately opt for the best choice of material for the application at hand.

1 Introduction

1.1 Background

The service life design methodology for timber products is currently far less sophisticated than that employed for concrete and steel products. In fact, neither the standards for the design of timber structures, EN 1995-1-1 (2004), nor the specific standards for timber bridges, EN 1995-2 (2004), currently provide quantitative methods for the evaluation of deteriorating mechanisms. One of the underlying problems is that the mechanisms involved are governed by a wide variety of biological processes rather than by a single chemical process and thus exhibit considerable variability. Incentives for developing quantitative models have also been lacking, since problems of durability have historically been dealt with largely through treatment by toxic preservatives, such as creosote. Creosote is still used for bridges in various countries, such as in the US and Norway. In the European Union, creosote has been banned for commercial use since 2003 and extensive restrictions has been placed on industrial use. Since legislation regarding toxic treatment is likely to become even more stringent in the future, the focus has been shifting recently towards alternative ways of ensuring the long-lasting performance of timber structures, wood protection being favoured over wood preservation (Kutnik *et al.*, 2014).

Long-lasting structures such as the Norwegian stave churches and the covered bridges in Switzerland demonstrate that untreated wood can be sustainable in outdoor environments when employed appropriately. However, knowledge of such matters as material quality, detailing, local climatic conditions and maintenance is imperative. Unfortunately, much of the knowledge of this sort is fragmented and part of local tradition and thus remains unavailable to non-wood experts. There is thus a strong need for systematic, quantitative and performance-based methods for assessment of the durability of wood. Such methods would make knowledge accessible for non-wood-experts and be useful for adapting traditional building systems to conditions produced by climate change.

The general perception of things leans currently towards the view that timber structures

are less durable than concrete or steel structures. This idea is not unfounded, since there are numerous examples of outdoor timber structures that have failed prematurely (see e.g. Pousette & Fjellström, 2016; Lorenzo *et al.*, 2018, for some examples). The difference between structures that are extremely durable and those that are subject to premature failure is clearly related to matters of exposure. Timber deteriorates only when its moisture content and temperature exceed certain thresholds. Whereas the wood temperature is governed primarily by the ambient climate, the moisture content is affected by factors such as detail design, climate, local conditions and wood species, some of which are decided upon in the design process. Minor flaws at the design stage, or in the construction process, can have major consequences for the service life of the structure.

Deterioration brought about by decay fungi is generally a concern only when the wooden elements are exposed to water. The risk of deterioration of this sort can thus largely be mitigated by providing permanent shelter. In fact, if permanent shelter is utilized for wood protection, then any additional measures are generally redundant. In Sweden, most timber road bridges with design lives of 80 years are built from untreated timber with shelter being provided by design measures. Since the performance of conventional salt-based treatments does not meet the design requirements, there are in fact few other options available. Although protection by design is a sound and feasible strategy for ensuring a long service life, several such timber bridges have reportedly failed prematurely due to deterioration brought about by decay fungi (see e.g. Pousette & Fjellström, 2016). Inspection protocols reveal that damage is often caused by errors and by flawed design solutions that allow water to circumvent protective barriers and accumulate in moisture traps, this leading ultimately to rapid deterioration, costly repairs, and possibly the need for complete replacement or structural failure.

Although fungal decay is best mitigated completely by protecting load-bearing and irreplaceable wood members from exposure to water, there is still a need for studying the process and rate of deterioration in the hypothetical scenario that the primary strategy is ineffective. A better understanding of the mechanisms involved in deterioration and better methods for evaluating them are essential for designing effective secondary strategies, such as appropriate inspection- and maintenance protocols.

1.2 About this thesis

The present thesis deals with assessment of the service life of timber in general, emphasis being placed on timber bridges. The design methodology employed builds on the premise that the durability of wood can be assessed on the basis of the physical and biological processes involved in the deterioration of wood brought on by such deteriorating agents as soft rot, white rot and brown rot fungi. Performance-based decay modelling

has progressed a great deal in recent years through research projects such as WoodExter (2007-2011), WoodBuild (2008-2013) and PerformWOOD (2012-2014). The literature offers currently several models linking moisture content and temperature to rate of decay. The thesis aims at developing this framework further. The main focus is on producing reliable input data for use in conjunction with existing decay prediction models. The process of translating known quantities, such as those concerning climate conditions and detailing, to variations in moisture is referred to as exposure modelling.

1.3 Objectives

One of the primary objectives of the present work, and of the articles that are appended, has been to develop a reliable exposure model. In so doing, the aim has been to gain a better understanding of the in-service durability of timber structures, to increase the precision and reliability of the performance-based approach employed and to extend the existing methodology for use in connection with timber bridges. Ultimately, this information is intended for use in connection with service-life planning and risk assessment in regard to both load bearing and non-load bearing structures.

1.4 Limitations

Durability of wood relates to several degrading mechanisms, including those related to decay fungi, mould, bacteria, termites and other insects. The thesis deals in this respect exclusively with fungal decay, since this is the dominant cause of problems concerning the durability of wood in Northern Europe. In addition, only timber above ground is dealt with. As such, members being in direct contact with the soil, or with fresh or salt water have been excluded. The numerical modelling of moisture transport is limited to untreated Norway spruce (*Picea abies (L.) Karst.*), although measurements in general concerning other species are included.

Since the research area spans several comprehensive fields of research, primarily those of moisture transport and decay prediction, it has been necessary to set clear boundaries with respect to the theoretical framework. Theoretical sophistication has been balanced against practicality and ease of application, while also aiming for a general level of consistency. The accuracy of each model has been secondary to the overall durability assessment. For example, large discrepancies in terms of moisture conditions at subzero temperatures have been accepted, since they have little weight in the durability assessment. As a consequence, the models employed here are not necessarily suitable for use in other applications.

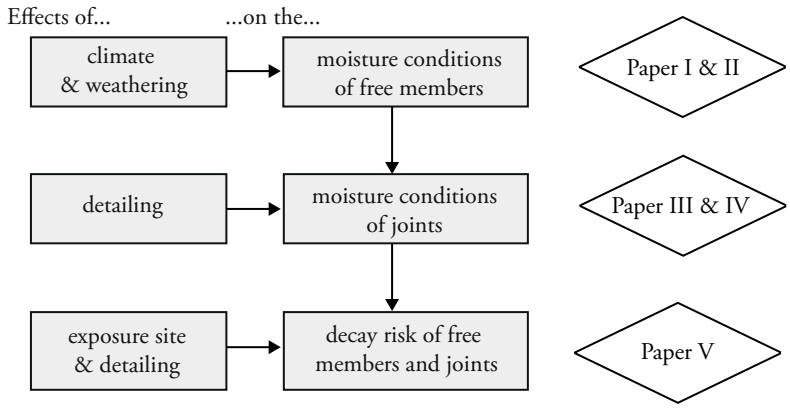


Figure 1.1: Topics and structure of the appended papers.

1.5 Research questions

The objective here is to develop a general exposure model for timber, one that can be broken down into a number of explicit research questions, including the following:

- How do climate parameters such as precipitation, relative humidity and temperature relate to variations in wood moisture?
- How can the effects of detailing on the moisture variation of wood best be described?
- Can models be extrapolated over long periods of time or are there any significant long-term effects involved?
- How does the relative risk of decay vary across different European climates, and how can this effect best be included in a factorized design framework?

These research topics are briefly summarized in Figure 1.1.

1.6 Progress and new findings

- A newly developed model describing the effects of exposure (precipitation, relative humidity and temperature) and detailing (i.e. contact areas) on the wood moisture content was integrated with an existing decay prediction model so as to estimate the service life of weather-exposed wood in above-ground applications. The model has been used to calculate the following:
  - the spatial distribution of the risk of decay in the wooden members.

  - the geographical distribution of the relative and the absolute risk of decay in the European region.

- Data on the moisture conditions in bridge details was collected for almost two years in a comprehensive outdoor experiment. An empirical model for evaluating the moisture performance of structural details exposed to different climates was developed on the basis of the same data.
- A colorimetric method for evaluating the surface conditions of rain-exposed wood was developed. This method can be used to detect the presence of water on the surface of the wood and in cavities that are visible.
- The effects of ageing and of weathering on the moisture conditions of rain-exposed wood were examined experimentally. The photodegradation of the wood surfaces and of cracks were found to have significant effects on the moisture conditions present during cyclic wetting, in particular in terms of the cumulative duration of the surface wetting.
- For purposes of knowledge-transfer and of practical applicability, the findings obtained in the thesis have been integrated into performance based design guidelines for bridges provided by Pousette *et al.* (2017).

1.7 Outline of the thesis

The thesis is divided into six chapters. Chapter two provides a brief overview of the problems of interest and describes the performance-based design framework. Chapters three and four describe the methods of durability modelling and the basic theory of moisture transport in wood, respectively. The fifth chapter describes the means of data acquisition involved, the focus being primarily on resistance-type moisture sensors. Finally, chapter six describes the various data sets that were employed in the thesis, special focus being placed on the new measurements that were carried out. Text-boxes have been placed throughout chapters two to five in order to highlight how the content relates to the papers that are appended.

2 Framework

2.1 Durability of timber bridges

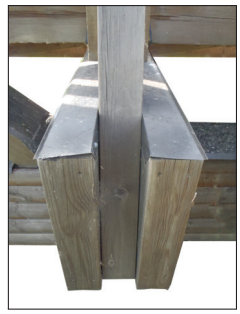
A large part of the work that was carried out in connection with the thesis falls within the scope of the European project Durable Timber Bridges (*DuraTB*) with one of the key deliverables being a service life model for timber bridges. Several previous projects, such as WoodExter (2007-2011), WoodBuild (2008-2013) and PerformWOOD (2012-2014), have focused on service life assessment of non-structural wood. In general, the material used in wooden bridges is not very different from that involved in other types of wooden assemblies, such as cladding and decking. Bridge structures, however, involve larger members and different types of details. In addition, the level of safety and the service life requirements are more stringent. Finally, and perhaps most important, the consequences in the event of premature failure are more serious.

In Sweden, the preferred strategy for achieving durable road bridges has been to cover all permanent members as a means of mitigating any exposure to rain or to splash. National requirements are described in TRVK Bro (2011), where a minimum service life of 80 years is prescribed to members being protected by a closed deck, a roof structure or by covering of individual members. In general, sheltered members do not decay and any additional measures such as chemical treatment can thus be regarded as redundant. As a result, untreated spruce is frequently employed as the preferred building material. Since their members require structural protection, the selection of feasible bridge superstructures is limited. Generally, bridge types involving less detailing and fewer exposed members are favourable. Most Swedish timber road bridges that have been built in the last decade consist of short-span continuous stress-laminated timber decks made of untreated glulam beams (Crocetti, 2014).

For pedestrian bridges, the required service life is shorter than for road bridges. A minimum service life of 40 years can be achieved by chemical treatment and covering of sensitive areas such as detailing and horizontal surfaces (TRVK Bro, 2011). In practice,

(a)

(b)



(c)

Figure 2.1: A truss bridge (a) with partial sheltering of the load-bearing members and details (b-c).

a combination of treated pine and protection by design is commonly used. Since the requirements placed on structural protection are less demanding, many types of load-bearing systems are available, such as truss- and cable-stayed bridges.

Figure 2.1 shows a typical truss-type pedestrian bridge. In this case, sufficient durability has been attained through use of treated pine, together with cladding and metal sheeting being placed on the exposed side and the top surfaces, respectively, of the main beams. In addition, detailing has been designed to lead water away from contact faces.

Despite the stringent requirements, there are quite a number of cases where bridge members have decayed prematurely. Fully exposed preservative-treated bridge members are to some extent more predictable in their performance than sheltered untreated members in the sense that the former are designed for severe exposure and the minimum service life is governed by the performance of the treatment used. Although damage due to excessive exposure in combination with poorly performing treatment may occur, the members involved are less sensitive to design errors. Sheltered members rely on the performance of the design details, and are thus sensitive to design errors. In fact, issues involved in the use of sheltered bridges are often related to matters of water bypassing the shelter,

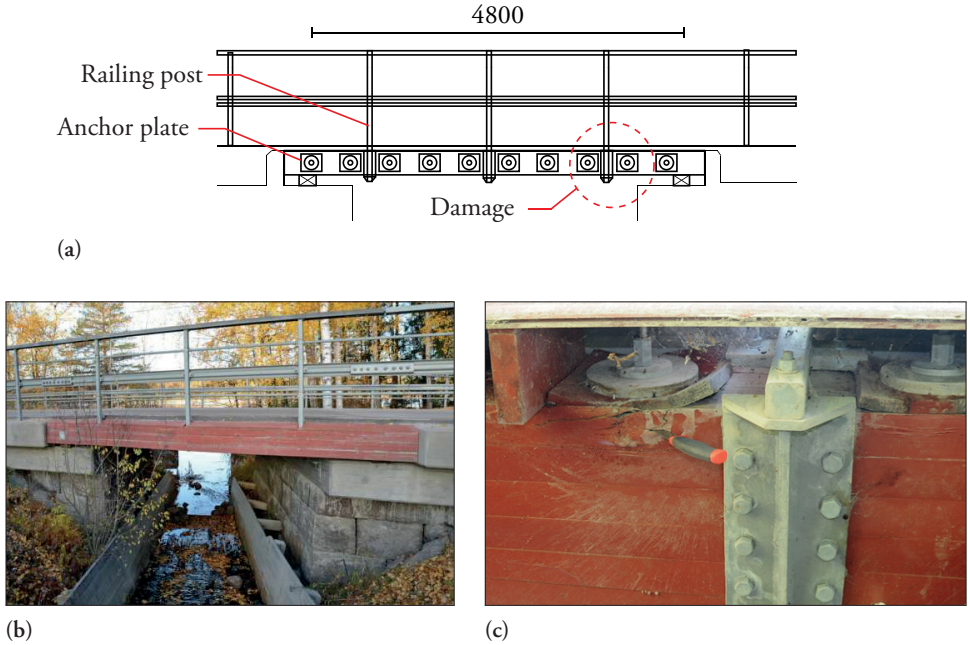


Figure 2.2: Damaged cross-laminated timber bridge. Photograph courtesy of A. Pousette & P.A. Fjellström.

since a functional protective design can be difficult to achieve, even in the case of bridges of less complex types.

Figure 2.2 shows a typical continuous cross-laminated timber deck, reproduced from a report by Pousette & Fjellström (2016). The metal sheeting along the sides of the bridge is intended to lead water away from the deck. In addition, the sides of the bridge have been designed with wooden cladding so as to shelter the sides of the deck from wind-driven rain. The issue with this bridge, which ultimately led to premature failure, is that the railing piles penetrate the metal sheeting and connect directly to the sides of the timber deck, thus allowing water to run alongside the piles and reach the sensitive area between the anchor plates and the deck. In this case, water accumulation caused severe decay after the bridge had been about 7 years in service.

There are numerous examples of sheltered bridges in which the actual exposure of members has exceeded the intended exposure level, due to leakage resulting from design error or construction error or from damage to, or insufficient maintenance of, the sheltering system. A flowchart showing some possible outcomes in the event of a leak is shown in Figure 2.3. The cost of intervention is relatively low if the problem is revealed and is resolved before significant decay has taken place. Continuous monitoring can be used for increasing the probability of early detection of issues related to water, and several sys-

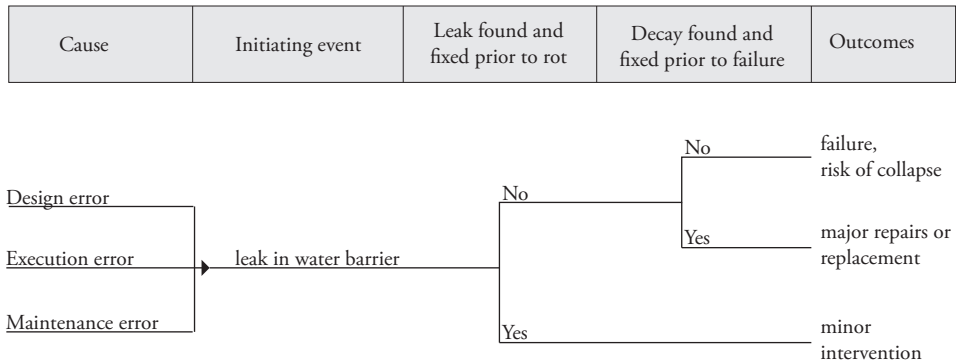


Figure 2.3: Flow chart showing the possible outcomes resulting from a leak in the water barrier.

tems for continuous monitoring have already been installed on timber bridges and other structures (see e.g. Franke *et al.*, 2013; Pousette *et al.*, 2014; Dietsch *et al.*, 2015; Björngrim *et al.*, 2016, 2017; Li *et al.*, 2018). Relying solely on sensors for detecting leakage is problematic, however, since the extent of leaks and the sensor coverage are generally quite limited. In the event that the leak goes undetected until the structural integrity of the member is affected, costly repairs or replacement can be required. The risks related to leakage should thus be considered in the design, and regular inspection should be carried out to guarantee that decay does not progress to a point at which the structure becomes unsafe. Regular inspection is generally performed at regular intervals (every 6th year in Sweden), independent of the type of bridge involved.

2.2 Eurocode approach

The following sections deal with the current durability design methods given by Eurocode 1995-1-1 (EN 1995-1-1, 2004) and describes how the principles involved differ from the performance-based approach proposed in the present thesis. Challenges and problems related to the different methods are discussed.

The design principles for achieving durability, as detailed in the EN 1990 (2002) reads as follows:

"The structure shall be designed such that deterioration over its design working life does not impair the performance of the structure below that intended, having due regard to its environment and the anticipated level of maintenance"

If the performance of the material is expressed as a function of the material resistance, R,

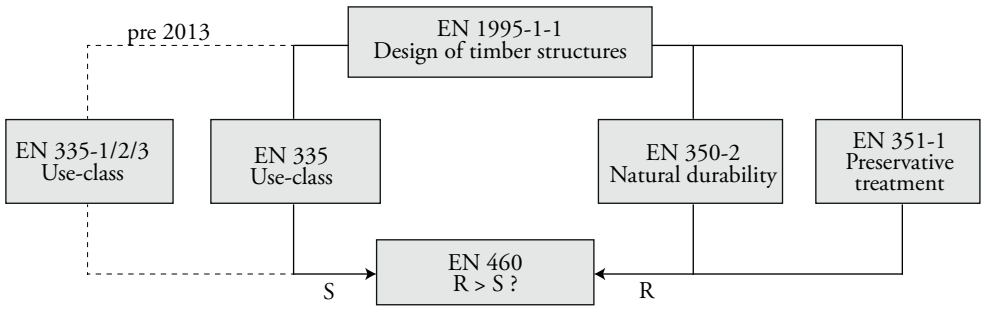


Figure 2.4: Design guidelines involved in durability design, according to EN 1990 (2002). Note that the EN335-1/2/3 standards have been replaced by EN 335 (2013).

and environmental exposure, S, then the performance requirements can be considered satisfactory when the design resistance exceeds the design exposure, i.e. when $R_d > S_d$, implying that the design service life exceeds the target service life. No quantitative methodology for describing the resistance or the exposure is provided by the Eurocode, however. The standard detailing the design of timber structures, EN 1995-1-1 (2004), refers to a number of documents, including EN 335 (2013), EN 350-2 (1994) and EN 460 (1994).

Figure 2.4 shows the European standards involved in durability design of timber. EN 460 (1994) recommends the use of either preservative treatment or a minimum natural durability for a given use-class (UC). Use-classes are defined by the expected environmental exposure of the wooden component, with respect to moisture. For definitions of the use-classes involved, EN 1995-1-1 (2004) refers to EN 335 (2013). In 2013, EN 335 (2013) replaced three separate standards: EN 335-1 (2006), EN 335-2 (2006) and EN 335-3 (1995). Use-classes were, prior to this change, defined quantitatively on the basis of the expected moisture content, whereas the current standard defines use-classes qualitatively in terms of the expected frequency of wetting and the potential for re-drying. Five different use-classes, including indoors (UC 1), sheltered (UC 2), above-ground (UC 3), in-ground (UC 4) and submerged (UC 5), are defined. The third use-class is commonly subdivided into UC 3.1 and UC 3.2, depending upon the potential for re-drying involved.

The durability of untreated and of preservative-treated wood is defined by EN 350-2 (1994) and EN 351-1 (2007), respectively. The natural durability of untreated wood is characterized by its durability class, which is determined experimentally in accordance with the procedure described in EN 252 (2014). The durability classes range from 1 to 5, a lower value being indicative of better performance.

In the standards, the use-class and the durability class are dealt with independently. Dealing with the exposure and resistance separately tends to introduce uncertainties and other issues, as discussed in the sections that follows.

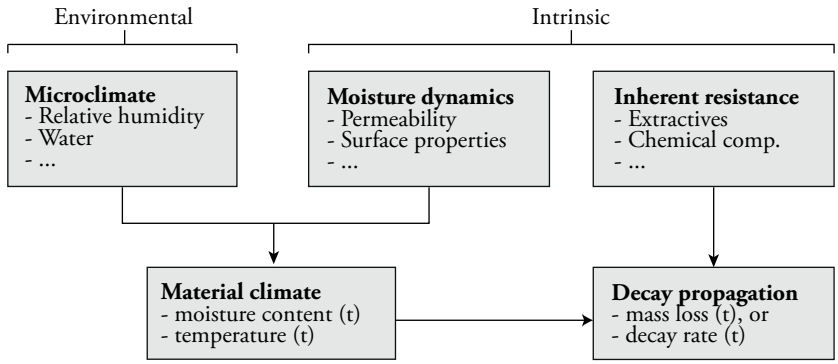


Figure 2.5: Conceptual illustration of an idealised design principle based on realistic physical and biological processes.

2.3 Idealized approach

Factors affecting the durability of wood can be separated into intrinsic properties and environmental influences. A conceptual overview of how environmental conditions and intrinsic properties relate to durability is provided in Figure 2.5. The intrinsic properties are properties strictly related to the material employed, such as chemical composition and moisture-related material properties. The environmental influences, in turn, involve most notably the moisture content and the temperature of the wood (Brischke *et al.*, 2006).

The wood moisture content and temperature are highly dependent upon the environmental conditions at the location where the material is employed. The durability of a material having a certain set of intrinsic properties thus varies, depending upon where and how it is used. Ideally, the effect of intrinsic properties are separated into those related to moisture and those related to chemical composition, so that the moisture-related properties can be used together with the environmental conditions to determine the actual material climate and the chemical composition can be used to estimate the corresponding impact in terms of decay propagation.

The idealized design methodology comes with a number of challenges, often rendering it difficult to employ in practice. One of the main problems is the dependency between the intrinsic properties and the environmental factors. Since the intrinsic moisture-related properties varies a great deal between species, the moisture content of different wood species can be vastly different under the same environmental conditions. The design guidelines employed tend to treat the environmental and the intrinsic factors independently, whereas they in fact are strongly interdependent.

Although convenient, treating the intrinsic properties and the environmental conditions

as being independent leads to certain pecularities. On the resistance side, the durability assessment of wood products follows predominately the EN 252 (2014) test protocol, where wooden stakes are driven into the ground and their loss in mass is then monitored over time. Obviously, a test of this sort does not provide a general measure of intrinsic durability and the results are known to transfer poorly to less severe exposure conditions (Brischke *et al.*, 2013). The moisture content of members that are in contact with ground can be considered as permanently above the critical moisture content level for decay to occur (EN 335-2, 2006) due to the low potential for re-drying that is involved (Kutnik *et al.*, 2014). As such, the intrinsic properties related to moisture performance have little effect on the rate of deterioration of the specimen tested. In addition, effects such as those involving the diffusion of metals from soil to wood (see e.g. Kirker *et al.*, 2017), which are only relevant to in-soil contact, are also included in the overall performance rating.

2.4 Performance based approach

Performance-based durability design aims at verifying quantitatively that a component retains its required performance throughout its service life. The performance requirement should be formulated as a limit state, beyond which the performance is regarded as being non-acceptable. This limit state may differ depending upon the performance which is intended. For example, since decay impairs the structural integrity of wood, the limit state for load-bearing members should be defined by the *onset of decay* whereas cladding and decking may provide satisfactory performance up until a certain level of decay.

A performance-based design process is illustrated conceptually in Figure 2.6. The concept involved is based on the original framework as developed in the European project WoodExter (2007-2011) and the Swedish project WoodBuild (2008-2013). Here, durability design is treated as being analogous to structural stability, where the material's resistance is related to an action of some sort. In the case of durability, the action is expressed in terms of the *exposure*, *S*, which is a function of moisture content and temperature. The exposure accounts for various environmental influences, such as the surrounding climate and the design of the member but is independent of material. The exposure can thus be regarded as a measure on the severity of the in-use conditions, a higher dose implying a lower service life level.

As previously mentioned, dealing with the exposure as being independent of the material involved is a practical but simplified representation of it. In reality, the exposure is a function of the moisture content and is thus dependent upon the characteristics of the specific material that is employed. Here, material-specific variations in moisture dynam-

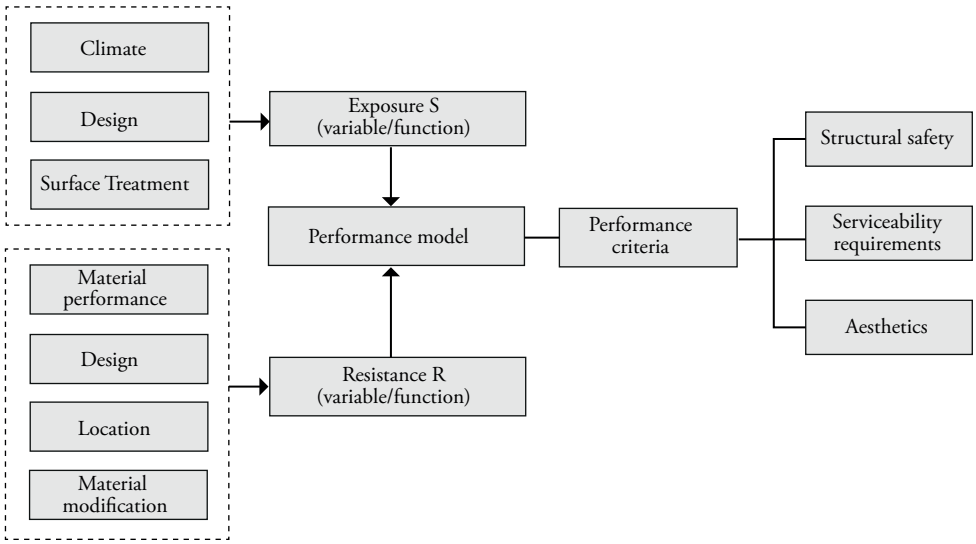


Figure 2.6: Performance based design concept, figure adapted from Thelandersson *et al.* (2011).

ics are treated instead as being on the resistance-side of the equation and the exposure model is calibrated for a single wood reference species: Norway spruce (*Picea abies*). The resistance of the material, R, is thus a function of both moisture-related properties of the wood and its decay inhibiting properties (Meyer-Veltrup *et al.*, 2017). A more detailed account of the design concept is given by Thelandersson *et al.* (2011).

The principle involved in the performance-based design framework is similar to the methodology proposed in EN 335 (2013), in which use-classes and natural or modified durability are used to characterize the exposure and the resistance involved, respectively. A key difference between the two methods lies in the operation where the two independent quantities, exposure and resistance, are connected through a common metric denoted *dose*. The exposure is expressed in terms of an exposure dose and the resistance of the material is expressed in terms of a resistance dose. Connecting the exposure dose to the resistance dose requires knowledge of how the moisture content and the temperature affect the decay rate.

2.4.1 Factorized design

The performance based design concept has been implemented as a factorized design methodology (see Meyer-Veltrup *et al.*, 2018). In short, an annual reference dose (d_{E0}) is determined on the basis of the geographical location (the regional climate) and is then adjusted for the expected degree of driving rain (k_{E1}), variations in the local climate (k_{E2}),

the effect of sheltering (k_{E_3}), the distance to the ground (k_{E_4}) and the design of details (k_{E_5}). The exposure dose, d_{Ek} is calculated as follows:

$$d_{Ek} = d_{E0} \cdot k_{E1} \cdot k_{E2} \cdot k_{E3} \cdot k_{E4} \cdot k_{E5} \tag{2.1}$$

The factors were established on the basis of numerical calculations or experiments in which the moisture content was evaluated under different conditions, such as under different degrees of exposure, and the relative decay rate was then estimated on the basis of a decay prediction model. As an example, values of k_{E_5} to be used for wooden decking are given in Table 2.1 with reference to examples given in Figure 2.7. The annual dose, d_{Ek} is a relative measure of the decay rate. The total dose accumulates over time until a limit state is exceeded. The limit state is expressed as a maximum dose, d_{Rd}, which corresponds to a certain level of decay, where the unacceptable level of decay reflects the performance criteria involved. The expected service life (*ESL*) can then be expressed as

$$ESL = \frac{d_{Rd}}{d_{Ek}} \tag{2.2}$$

Table 2.1: Exposure classes based on the WoodExter guideline (Thelandersson *et al.*, 2011), translated and interpreted by the author of the present thesis. Examples A-F are given by Figure 2.7

Exposure Class	Description	k_{E_5}
Excellent	No risk of standing water and ideal conditions for re-drying (example A)	0.9
Good	Horizontal element with potential re-drying from all four sides, facilitated by, for example, wide gaps between members (example B)	1.0
Mediocre	Risk of moisture trapping with some potential for re-drying	1.2
Poor	Considerable risk of moisture trapping with limited potential for re-drying (example C)	1.8
Appalling	Major risk of moisture trapping with extremely limited potential for re-drying (example D, E and F)	2.5

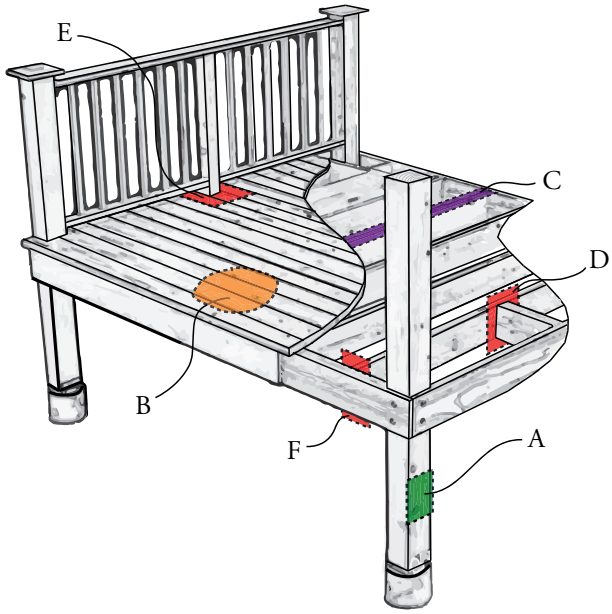


Figure 2.7: Wooden decking, details of different exposure level being referenced in Table 2.1.

In this thesis

One of the general objectives of the present thesis has been to develop models from which the factors of Equation 2.1 can be derived. Focus has been placed upon the effects of climate and detailing.

3 Decay prediction models

3.1 General

3.1.1 Decay fungi

Decay fungi (also called rot fungi) are a group of fungi specialized in extracting nutrients from wooden materials, a process which is basic to the recycling of wood biomass. Due to the loss of strength it results in, the process is of course undesirable for wood used structurally.

The body of decay fungi consists of a thread-like network of hyphae, collectively called mycelium. Most fungi spread via airborne spores that are produced by fruiting bodies of the fungi. The fruiting bodies are the part of the organism that are referred in casual terms to as fungi, whereas the mycelium is the part of them in which nutrients are collected and distributed (Schmidt, 2006).

The different species of fungi can be subdivided on the basis of the enzymatic process by which they operate into soft rot, white rot and brown rot fungi. The metabolic differences involved render the various subgroups suitable for different ecological niches. White rot is able to break down all three main components of the cell wall, namely cellulose, hemi-cellulose and lignin whereas the various species of brown rot are unable to break down lignin (Schmidt, 2006). Brown rot, however, is the more effective degrader of the energy-dense cellulose and hemicellulose and thus tends to produce the most aggressive type of decay. It is believed that brown-rot evolved initially from white-rot by discarding the energy-inefficient process of lignin degradation (Arantes & Goodell, 2014). Soft rot fungi is the least aggressive degrader of wood, yet it is able to operate under harsher conditions than white-rot and brown-rot can (Vane *et al.*, 2005), and is therefore prevalent in wood that is used in direct contact with the ground, such as in the case for poles.

Brown rot damage is most common in softwood whereas white rot is more common in hardwood (Schmidt, 2006). Brown rot is thus the cause of much damage in the northern hemisphere, where softwood is overwhelmingly used for structural applications. As stated earlier, brown rot is the most aggressive type of fungal decay. Although the loss of mass involved is very low in the early stages of decay, the corresponding loss of mechanical properties is large (Arantes & Goodell, 2014). For example, the compressive strength of wood has been shown to decrease by up to 45% already at a 10% loss of mass (Schmidt, 2006) and the bending strength has been shown to be able to decrease as much as 40% already at an only negligible loss of mass (Arantes & Goodell, 2014).

3.1.2 Material climate and decay

The specific chemical and enzymatic reactions governing the decomposition of lignocellulose materials are complex and not yet fully understood (Arantes & Goodell, 2014). However, it is widely known that the rate of decomposition is closely related to the moisture content and the temperature of the wood (Brischke *et al.*, 2006). The optimal, minimum and maximum conditions differ in terms of the type and species of the fungi involved (Viitanen & Ritschkoff, 1991).

Both oxygen and free water are imperative for enabling the chemical breakdown of the wood substrate by the decay fungi (Schmidt, 2006). The lowest moisture content needed for the growth of decay to take place is about 25-35% and the temperature generally needs to exceed the freezing point (Viitanen & Ritschkoff, 1991). The level of the minimum moisture threshold is subject to controversy, since several studies have shown that decay can occur at relatively low levels of moisture content (see e.g. Brischke *et al.*, 2017b) where the requirement of free water being present is not satisfied. The contrast between theory and the measurements obtained could partially be related to the methods involved in determining moisture content. In short, the moisture content as determined by use of gravimetric methods provides an inherently inaccurate indication of whether free water is present in the specimen or not, since possible local variations in the moisture content are not taken into account. Small variations in the moisture content of the wood can remain even after careful conditioning of specimens.

According to literature reviews by Brischke *et al.* (2006) and Viitanen & Ritschkoff (1991), the upper limit for brown rot is approximately 90% moisture content and about 35-45 °C, with large variations depending on the specific species of fungi involved. Exceeding the moisture threshold leads to oxygen deprivation, which inhibits fungal growth.

In summary, fungal growth occurs at a moisture content of 25-35% up to about 90% and at temperatures ranging from 0°C up to about 35-45 °C, provided that both conditions are satisfied simultaneously. Figure 3.1 shows the typical variations in wood moisture

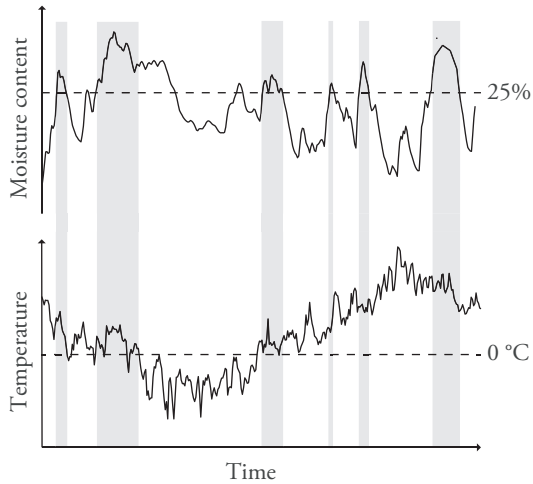


Figure 3.1: Illustration of the temperature and moisture conditions in a piece of wood over time, measured at a certain depth. The shaded areas mark the time-periods when the conditions for the growth of fungal decay are favourable. The dashed lines indicate the minimum values for temperature and moisture content, respectively.

content and temperature over time, the time periods representing favourable growth conditions being shaded. Temporary fluctuations outside of these maximum and minimums bounds are not immediately lethal to the fungi, since the mycelia can still survive for long periods of time under severe conditions (Viitanen & Ritschkoff, 1991). The amount of growth that occurs within a given period of time depends upon the length of the period and the conditions present during this period.

Since decay needs free water, wood that is used in above-ground applications is generally degradable only when exposed to wetting. This is a major difference as compared with the modelling of mould fungi, where wetting have been shown to be less critical for the growth of fungi, or even to inhibit their growth (Gobakken & Vestøl, 2012). Free water can appear through leakage, condensation or direct exposure to precipitation. It should be noted that dry-rot fungi (a subset of brown-rot fungi) have a unique ability of facilitating the transport of water from external sources (e.g. the soil) to dry wood (Schmidt, 2006). Dry-rot fungi is thus commonly found indoors where the conditions are otherwise too dry for the growth of fungi to occur.

3.2 Modelling decay

A variety of models have been developed for predicting the rate of deterioration produced by fungal decay. The level of deterioration is usually expressed in terms of either loss of mass or of the EN 252 (2014) decay rating, the latter being on a scale of 0 (com-

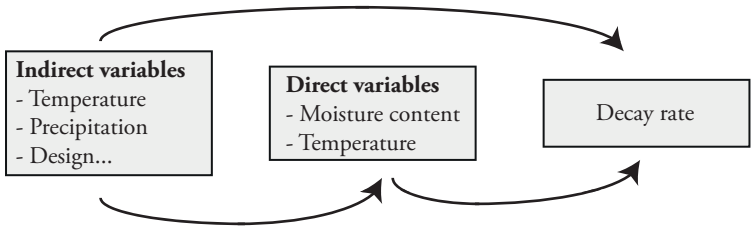


Figure 3.2: Decay prediction based on indirect or on direct variables.

pletely sound) to 4 (failure). All decay models are related in some way to the moisture conditions and to the temperature involved. Models can be divided, however, into those based on *indirect* and those based on *direct* environmental variables. The conceptual difference between the two categories is illustrated in Figure 3.2. Models based on indirect variables utilize the indirect causality that exists between macro-climate, local climate, design and the rate of deterioration. As can be understood, the growth of decay fungi is only indirectly affected by these factors through their effect on the climate of the wood material. Models based on direct environmental variables explicitly consider the effect of the moisture content and of the wood temperature on the rate of growth of fungal decay.

Models based on indirect environmental variables are easy to use, since they are based on input variables that are readily available and that usually require only a simple algorithm for processing purposes. In contrast, the utility of models based on direct environmental factors is inhibited by the need for material climate data. For predictive purposes, such data can be obtained through use of a numerical model in which indirect environmental variables are used as input. Although more complex, the direct approach holds certain advantages. Most notably, a model based on direct environmental variables can predict non-linear effects such as the synergy and the combined effects of various indirect environmental variables. For example, it is well known that decay is accelerated by (1) increased amounts of precipitation and (2) poor detailing. However, poor detailing alone may put the wood in a state of permanent wet conditions, in which case increasing the amount of precipitation has no negative effects on the rate of decay.

The following sections describe some of the most frequently used decay models, based on indirect and on direct environmental variables, respectively. Models that have been used in the present thesis are presented in depth, whereas others are described only briefly.

3.2.1 Indirect environmental variables

Scheffer Climate Index

The first attempt to examine the relationship between indirect environmental variables and the deterioration by fungal decay was undertaken by Scheffer (1971), who established an empirical equation, the Scheffer Climate Index (SCI), relating the macro climate to the rate of decay. The relationship is based on decay ratings of flooring boards and of post-rails and weather data from different locations of the US. The resulting equation was described as follows:

$$Climate\ index = \sum_{Jan}^{Dec} \frac{(T-2)(D-3)}{16.7} \tag{3.1}$$

where T (°C) and D (days) are the mean monthly temperature and the number of days in a month in which there is more than 0.25 mm of precipitation. The monthly contribution to the cumulative decay hazard goes down to zero when the mean monthly temperature reaches 2°C, this accounting for the lower temperature limit of some species of brown-rot (Morris & Wang, 2011). Likewise, the minimum number of days in which precipitation occurs was set to 3 so as to be able to rate the driest climates risk-free. Figure 3.3 shows the regional variation of SCI as mapped over Europe as a whole.

It is noteworthy that the SCI does not consider the relative humidity of the site. More recently, efforts to improve the SCI have been made. Fernandez-Golfin *et al.* (2016) modified the original equation to incorporate effects related to condensation on wood surfaces. An unpublished study referenced by Morris & Wang (2011) aimed at improving the SCI by accounting for the drying potential of the air. Although this attempt was unsuccessful, it was argued that differences in drying potential are already implicitly included in the original equation through days involving low amounts of precipitation being weighed in the direction of zero decay.

The reliability of the SCI has been subject to much discussion. The Scheffer index was originally believed to be linearly proportional to the decay rate, yet more recent studies have obtained results inconsistent with this idea. Tropical locations having extreme precipitation appear to be problematic, since the relative decay rate there deviates from the SCI (Preston *et al.*, 2011), the actual decay rate being lower than the predicted one. The Scheffer index has also been criticised for being too coarse for use in building applications, since it is based solely on macro-climate (Cornick & Dalgliesh, 2003). Studies by Morris & Wang (2011) argue, however, with empirical support, that the SCI is able to parse the effects of climate and has some merit in assessing decay risk above ground.

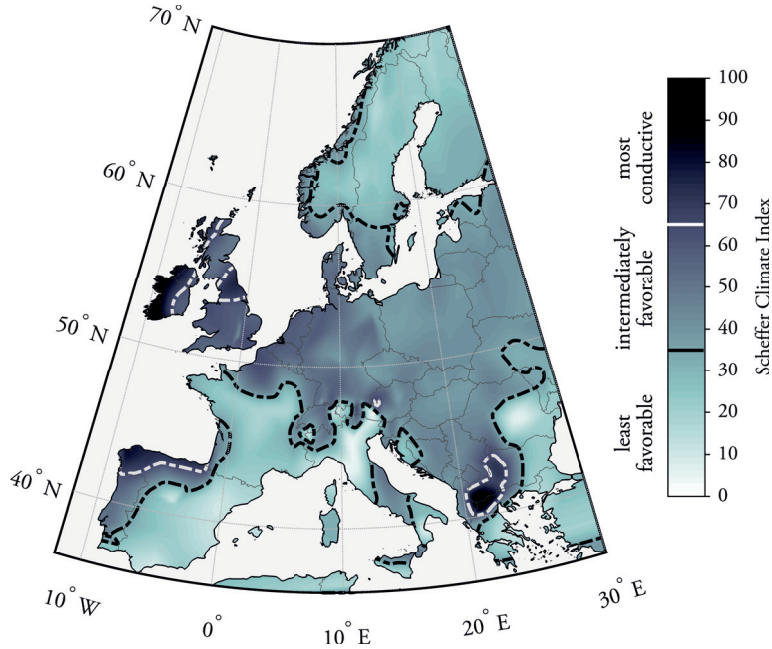


Figure 3.3: Scheffer Climate Index mapped across Europe. The three different hazard zones defined by Scheffer (1971) have been divided by dashed lines. Figure adapted from Paper V.

Moisture Index, MI

Cornick & Dalgliesh (2003) developed a moisture index, MI, for building applications, one that is expressed as a function of the normalized wetting index, WI, and the normalized drying index, DI, in equation 3.2. The DI can be described as *the capacity of the air to take up water*. It is calculated as the difference in vapour content of the air and the saturation vapour content. As such, the DI is a function of the temperature and the relative humidity. The MI is a measure of precipitation, for example the annual precipitation or the annual driving rain. Unlike the SCI, the MI explicitly considers the drying conditions that are present.

$$MI = \sqrt{WI^2 + (1 - DI)^2} \tag{3.2}$$

TimberLife

The "TimberLife model" is a comprehensive multiple-parameter decay prediction model for Australia developed by Wang *et al.* (2008). The model is based on a comprehensive dataset concerning the progression of decay over time, based on examination of multiple

locations in coastal areas of Australia. The decay process is modelled as a bilinear function, there being an initiation period (t_{lag}) that is followed by an extended period having a constant decay rate, r (mm/year). The latter, r, is described as follows:

$$r = k_{wood} k_{climate} k_p k_t k_w k_n k_g \tag{3.3}$$

where the factors involved take account of the effects of the wood species (k_{wood}), the macro climate ($k_{climate}$), the paint employed (k_p), the thickness of the member (k_t), the width of the member (k_w), the use of fasteners (k_n) and the geometry (k_g), respectively. Furthermore, t_{lag} is assumed to be dependent upon the decay rate r, according to:

$$t_{lag} = 8.5 r^{-0.85} \tag{3.4}$$

As can be seen from equation 3.3, each factor describes the relative effect of a given variable on the decay rate. As such, the model provides valuable information on the relative effects of various decay-influencing factors. The effects of the detail design and of the climate are two of the main features of what the present thesis takes up. Accordingly, the values concerning the effects of the details involved are shown in Table 3.1. Interestingly enough, Wang *et al.* (2008) found there to be no correlation between the decay rate and the temperature. Consequently, the factor taking the effect of macro climate into consideration ($k_{climate}$) is a single-parameter function of precipitation calculated as follows:

$$k_{climate} = 0.03 t_{rain}^{-0.85} \tag{3.5}$$

where t_{rain} is the cumulative duration of precipitation. An equation relating the amount of precipitation to the duration of rain falling, in 3-hour increments, is also provided: see work by Wang *et al.* (2008) for details.

Table 3.1: The relative effect of geometry, k_g^a, on the decay rate according to Wang *et al.* (2008). See Figure 3.4 for two examples of different detailing.

Effect contact	k_{g1}	Contacted material	k_{g21}	Contact face	k_{g22}	Gap factor	k_{g23}
No contact	0.3	Wood	1.0	Top	2.0	Continuous to continuous	1.0
Contact	0.6	Steel	0.7	Otherwise	1.0	Continuous to butted	1.2
Embedded contact	1.0	Concrete	1.0			Butted with $< 1mm$ gap	2.0
						$> 2.5mm$ gap	1.3
						otherwise[b]	$\frac{3.7}{1.5} - \frac{0.7x}{1.5}$

[a] $k_g = k_{g1}k_{g2} = k_{g1}k_{g21}k_{g22}k_{g23}$
[b] where x is the gap size in units of mm

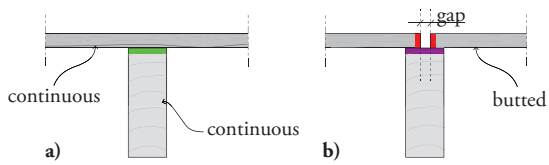


Figure 3.4: Continuous member joined to another continuous member (a) and to two butted members (b). The coloured surfaces describe locations where k_{g23} is equal to 1.0 (green), 1.2 (purple) and dependent on gap-size (red). Figure adapted from Wang *et al.* (2008).

3.2.2 Direct environmental variables

Damage functions based on laboratory data

Viitanen & Ritschkoff (1991) and Viitanen (1997) measured the loss in mass of pine and spruce wood over time under conditions of different levels of relative humidity and temperature. On the basis of this data, empirical bilinear functions of mass loss over time were established, with an initial period of zero loss followed by a linear increase in mass loss over time, as shown in Figure 3.5 (Viitanen, 1997). The functions are empirical in nature and were fitted to experimental results obtained under constant moisture- and temperature conditions. The data has, nevertheless, been used to develop damage functions involving variable conditions.

Viitanen *et al.* (2010) and Nofal & Kumaran (2011) used the experimental results of Viitanen (1997) to develop damage functions for variable climate conditions. The two models are rather similar in their approach, both of them being built on a two-step process in which the decay process is described in terms of an activation process and a subsequent process in mass loss. The mass loss can be either active or inactive, depending

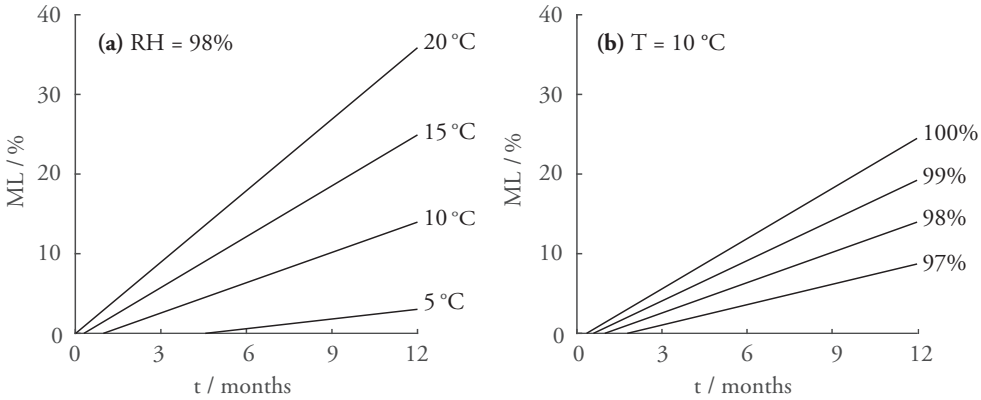


Figure 3.5: Mass loss of spruce over time at different temperatures (left) and relative humidities (right), based on damage functions from Viitanen (1997).

upon the activation function involved. The loss in mass is irreversible, yet the fungi can return to an inactive state after being activated. It should be emphasized that, as Viitanen *et al.* (2010) state, some of the parameters are not supported by empirical evidence, in particular those related to deactivation and reactivation of the decay fungi. Both models were integrated through use of hygrothermal software so as to enable risk assessment of decay in building envelopes. The pioneer work in this area of Viitanen *et al.* (2010) is one of the first attempts to model the risk of decay on the basis of direct environmental variables. Later attempts to develop similar models for hygrothermal analysis include the work by e.g. Saito *et al.* (2012).

Damage functions based on outdoor data

Brischke & Rapp (2008) established a relationship describing the change in decay rating over time as a function of the daily average moisture content and the temperature of the wood in question. The model was developed from a data set in which the daily average moisture content and temperature, as well as the annual decay rating of double-layer setups (standard accelerated decay design) were measured over a 7 year period at 23 different geographical sites across Europe. The decay activity was modelled by transforming the daily moisture content and temperature of the wood in question into so-called moisture- and temperature-induced *doses* (hereafter denoted d_{u} and d_{T}), a dose being a value between 0 and 1, the latter figure representing optimal conditions for growth of decay. The two doses are then combined to a daily dose, d_{day}, as follows:

$$d_{\mathrm{day}} = f(d_u(u), d_T(T)) \tag{3.6}$$

where d_{day} describes the normalized decay activity (0 = no activity; 1 = maximum activity) as a function of the daily moisture content and temperature. Brischke & Rapp (2008) calculated d_{day} as the product of d_u and d_T, but Isaksson *et al.* (2013) later revised the model and used different weights for the two doses. The dose accumulates over time, with the dose after n days being described as follows:

$$d_n = \sum_{i=1}^{n} d_{\text{day},i} \tag{3.7}$$

The dose is related to the decay rating, $DR(d)$, via an empirical relationship determined as the regression between the cumulative dose and the decay rating.

The functions $d_T(T)$ and $d_u(u)$ are shown in Figure 3.6 (a) together with the equation combining the two doses to a daily dose. The function describing the decay rate, DR, as a function of the accumulated dose is shown in Figure 3.6 (b). The functions $d_T(T)$ and $d_u(u)$ are based on cardinal points from the literature representing the minimum, the maximum and the optimal conditions for growth of decay fungi at different moisture and temperature levels. The minimum threshold is based on the premise that the decay fungi requires liquid water in order to thrive. Consequently, the decay activity equals zero when the moisture content is below about 25-30% and when the temperature is below 0°C due to freezing. The maximum and optimum differ from one type of decay fungus to another. However, on the average the optimum level is at around a 50% moisture content and a 30°C temperature, whereas the maximum temperature is around 40°C. The maximum moisture content is less certain, but is also less important, since it rarely occurs in above-ground applications.

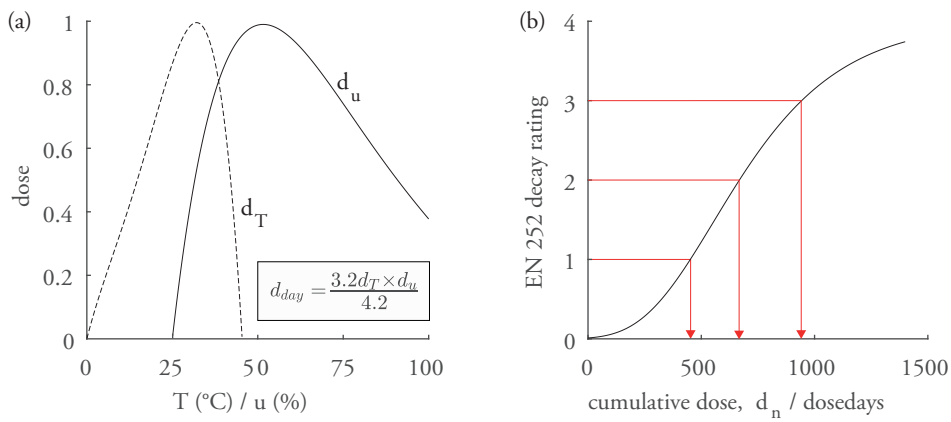


Figure 3.6: A set of functions describing the moisture- and temperature induced dose as functions of the daily average moisture content and temperature (left) and the damage function (right) used by Isaksson *et al.* (2013). The dose corresponding to decay ratings 1, 2 and 3 have been marked in the right figure.

Several different dose-response models have been developed from the same dataset, including the *simplified logistic model*, the *two-step model*, the *set-back model* (Isaksson *et al.*, 2013) and a specific model for the subset of specimens that were attacked by brown-rot (Brischke & Meyer-Veltrup, 2016). Although the new models developed by (Isaksson *et al.*, 2013) do not provide better accuracy than the original one does, they have proven to be useful under certain circumstances.

One of the main problems in modelling decay on the basis of electrical measurements under variable conditions is the inconsistency between the location of the moisture sensor and the point at which decay is observed. Under stable conditions, the moisture content of the wood is more or less uniform and can easily be calculated on the basis of gravimetric measurements. Under variable conditions, however, the wood moisture content is subject to considerable fluctuates near the surface of the specimen. Figure 3.7 shows the simulated response at different depths in a wooden board exposed to five one-hour spray cycles. The peaks near the surface (1.5 mm) temporarily exceed the critical threshold for decay, whereas the response in the core of the specimen (depth $>$ 3 mm) gives no indication of critical conditions. In consequence, the depth or location at which the measurements are taken has a strong effect on the resulting decay prediction.

Non-uniform moisture distributions were not a major problem with the original data set, from which the logistic equations were originally developed, since the specimens were more or less permanently wet due to the severe moisture-trapping effect of the experimental configuration employed. The validity of these equations for specimens with large moisture gradients is questionable however. More realistically, these equations are valid when the measurements are obtained from locations at which decay is likely to develop, i.e. near the surface of the wood, in cracks or near joints.

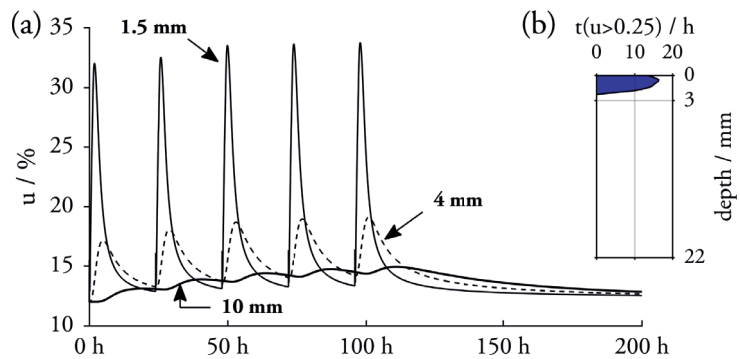


Figure 3.7: Simulated moisture content (a) and distribution of *duration above 25% moisture content* (b) of a wooden board subjected to five 1-hour spray cycles based on the model from Paper IV.

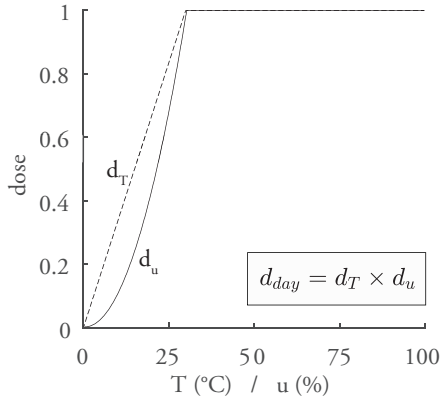


Figure 3.8: Simplified logistic model describing the moisture- and temperature induced dose, respectively, as functions of daily average moisture content and temperature (Isaksson *et al.*, 2013).

Other dose-response functions address this issue by manipulating the cardinal points for obtaining the minimum, the optimum and the maximum level of decay, respectively. In the so-called *simplified logistic model*, SLM, the minimum moisture content for decay activity to occur is effectively removed (Isaksson *et al.*, 2013). A moisture-induced dose, as such, is always generated when the temperature exceeds 0°C. The functions involved are shown in Figure 3.8. The lack of threshold introduces another problem, however. Assessment of wood which is not subject to decay (e.g. wood used indoors) results in a finite lifetime since doses, albeit small, are produced even at low moisture contents. Accordingly, the application of such functions is generally limited to their use on rain-exposed wood, as is argued in Paper V.

In this thesis

The logistic model and the simplified logistic model were used as a measure of the rate of decay in Papers I & V. The relative Scheffer climate index was used as an indicative metric of the relative rate of decay in Paper V.

3.3 Classification of resistance to fungi

Although the focus of the present thesis is heavily skewed towards the exposure side of the performance based methodology, certain basic knowledge of durability classification and resistance modelling is important for being able to appreciate the concept as a whole. This section thus briefly considers the standard methodology involved, as described by EN 350-1 (1994), and its shortcomings as well as new approaches that may possibly address some of those shortcomings.

3.3.1 Standard durability classification

Traditionally, the natural resistance of wood is rated on a scale between 1 (very durable) and 5 (perishable) in accordance with a durability classification scheme given by EN 350-1 (1994). The durability class is determined on the basis of the performance of a wood product relative to a reference species, either through laboratory testing or through long-term in-ground field testing (EN 350-1, 1994). The relative performance, also denoted as the x-value, describes the loss in mass relative to a reference species subjected to the same conditions. EN 350-2 (1994) includes a durability classification table of several hundred species of wood, with spruce being rated as slightly durable (class 4). The traditional methodology for durability classification is subject to two major shortcomings.

First, it can be argued that a single test for evaluating the durability class of timber is not desirable, since the ranking is strongly dependent upon the fungi that are employed for testing (Van Acker *et al.*, 1999). Since different fungi are prevalent in different use-classes, no single metric can accurately describe the performance of wood of a particular sort. This is a matter discussed by Van Acker *et al.* (2003), who proposed an end-use-specific durability classification, similar to the methodology already established for wood treated with preservatives.

Secondly, the effect of the moisture-related wood properties is strongly affected by the use-class involved. For example, moisture-related properties are more decisive in above-ground applications than in-ground applications (Stirling *et al.*, 2016). In between periods of frequent precipitation, wood used in above-ground applications can remain dry for long periods of time, whereas wood in contact with ground retains water, due in part to the water-holding capacity of the soil. Since fungi in the ground experience an abundance of water, the moisture-related properties of the wood is of lesser importance. On the contrary, the moisture-related properties are closely linked with the period of time during which the moisture conditions facilitate the growth of decay in above-ground applications.

3.3.2 Classification based on moisture dynamics

It is clear that the durability of wood depends upon both moisture-related properties and inherent resistance, whereas traditional classifications, as described in the previous section, primarily capture the effects of the latter. There have been several attempts to develop metrics for the classification of wood and wood-based products with respect to their moisture-related properties. Rapp *et al.* (2000) developed a moisture-induced risk index (MRI) for the classification of treated and untreated wood. The MRI is calculated on the basis of laboratory testing in which the weight-changes in wooden specimens is monitored during periods of liquid absorption and a consecutive desorption phase. Windt *et al.* (2018) developed a similar index for wood-based panels (plywood). Both those studies found reasonably close correlations between the respective indices and the moisture behaviour evident during outdoor exposure.

3.3.3 Classification based on critical dose

Meyer-Veltrup *et al.* (2017) used the distinction between moisture-related properties and inherent resistance for the classification of various wood species. That study provides a promising alternative to the standard natural durability classification described by EN 350-2 (1994). The resistance dose, d_{Rd}, which is a measure of resistance of the material in question, is calculated as follows:

$$d_{\mathrm{Rd}} = d_{\mathrm{crit}} \cdot k_{\mathrm{inh}} \cdot k_{\mathrm{wa}} \tag{3.8}$$

where d_{Crit} is a reference value describing the resistance dose for Norway spruce and k_{inh} and k_{wa} are factors accounting for differences in decay inhibiting properties and moisture dynamics, respectively. It should be emphasized that the resistance is still described under a fixed set of conditions and it is questionable whether the resistance model should be applied to exposures of any and all types, such as in-ground, moisture trap and freely exposed member types. However, the distinction between moisture dynamics and decay inhibiting properties makes this approach rather flexible.

In theory, one could apply different weights to the two factors, depending upon the exposure situation involved. For example, for members that are permanently wet, the contribution of k_{wet} could be reduced. This is a matter that was not discussed in the Paper by Meyer-Veltrup *et al.* (2017).

4 Moisture conditions of wood

4.1 General

Wood constantly interacts with water. In a living tree, water is transported from the roots of the tree to the foliage where most of the water evaporates back into the atmosphere. Once inside the trunk of the tree, the water is transported upwards through an interconnected network of hollow cells. Only a certain part of the trunk, however, actively facilitates moisture transport, namely the sapwood. The sapwood is located between the bark and the core of the trunk, where latter is comprised of heartwood. In many wood species, the sapwood can be visually distinguished from the heartwood by color. For other species, such as Norway spruce, the heartwood and sapwood appear identical after drying (Sandberg & Sterley, 2009).

The cell type governing the water transport in softwood, having an open diameter of about 10 µm to 50 µm and a length of a few mm, is called tracheid (Fredriksson & Thygesen, 2017). The cell structure of hardwood is more complex with more cell types such as vessels which are typically about 50 µm to 200 µm in diameter (Forest Products Laboratory, 2010). In softwood, water flows between tracheids in the transverse direction via pit openings, or radially through rays. The transformation from mature sapwood to heartwood involves the closing of pits, a process that is termed pit aspiration, which is the reason for heartwood being less permeable than sapwood. In general, earlywood has a larger open diameter than latewood but also a larger portion of aspirated pits (Sandberg, 2009).

Due to the structure of the tree trunk, wooden members are highly anisotropic with the conductivity parallel to the fibres being considerably higher than perpendicular to the fibres. This can be understood by the path of a single droplet of water having to pass through a network of narrowed pit openings when travelling through the material. The number of pit openings encountered per unit length travelled is comparatively high in the transversal direction, thus the conductivity in this direction is lower.

4.2 Moisture sorption

As a hygroscopic material, wooden members also interact with water vapour present in the air. The moisture content of wood in outdoor applications is thus constantly subject to variations, with the average moisture content varying between about 10 and 25%, depending on the season and the dimensions of the member. Diurnal variations in moisture content are pronounced in the surface layer but diminish with increasing depth. Whereas ambient fluctuations in the relative humidity do not generally lead to decay during outdoor storage, corresponding variations in the moisture content can lead to difficulties related to moisture induced stress or cracking and mould growth (Forest Products Laboratory, 2010).

Moisture uptake (absorption) and release (desorption) are referred to collectively as sorption. Moisture exists in wood in three different phases: as bound water, as water vapour and as liquid water (Forest Products Laboratory, 2010). Bound water is chemically bound to the cell walls through hydrogen bonding, whereas water vapour and liquid water exist within the cell cavities.

A term frequently used in wood science is the fibre saturation point FSP. The term was originally introduced by Tiemann (1906), where it was defined as the point on the drying curve where the strength begins to increase with decreasing moisture content (see Figure 4.1). Tiemann (1906) hypothesized that the wood cell cavities had, at this point, been completely emptied of water while the cell walls remained saturated, hence the term *fibre saturation* point. It has later been shown that this is not entirely correct, as the separate events do not necessarily occur at the same point. To clarify, the cell wall is not necessarily saturated because water is present in the cell cavities (see review by Engelund *et al.*, 2013).

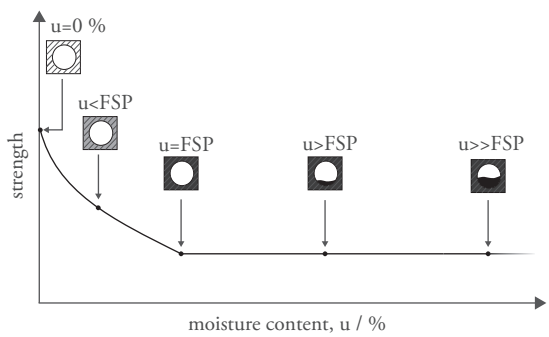


Figure 4.1: Relationship between wood moisture content and strength. The boxes show, conceptually, the state of moisture in the cell wall (striped area) and the voids (circular area) at different moisture levels.

In the present section, the moisture concentration below the FSP is denoted hereafter as w_b (kg/m^3), and any excess free water above this point is denoted as w_f (kg/m^3). The total moisture concentration is then equal to $w = w_b + w_f$ and the moisture content, u (kg/kg), is $u = w/\rho_o$, where ρ_o is the density of the dry wood. This distinction is necessary because the transport mechanisms involved are vastly different, depending on the phase the water is in.

The exchange of moisture with the external environment depends on the conditions on the surface of the wood. While in contact with air, the surface of the wood tends towards a state of equilibrium with the ambient relative humidity. The relationship between the relative humidity of the air and the moisture content of the wood is described by the sorption isotherm, which is commonly described as the function $u(\phi)$, where ϕ is the relative vapour pressure ($= RH/100$). Figure 4.2 provides an example of a typical sorption isotherm obtained through absorption. The equilibrium moisture content also depends on the temperature and the moisture history of the material. The equilibrium moisture level is higher when equilibrium has been attained through desorption. The discrepancy between the equilibrium levels attained through absorption and desorption is termed sorption hysteresis and is particularly pronounced in the over-hygroscopic region (Cloutier & Fortin, 1991). In addition, the equilibrium moisture content is temperature dependent and generally decreases with increasing temperature.

Liquid water can enter the pore system through either capillary condensation inside the pore system or via wetting of the surface. The relative vapour pressure at which capillary condensation occurs depends on the pore size of the porous material. Since the cell

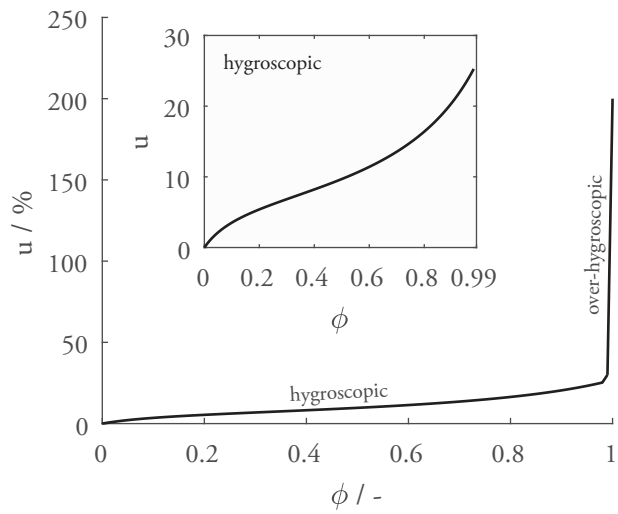


Figure 4.2: A typical absorption isotherm.

cavities enclosed by the wood cell walls are in the µm-scale, a very high relative vapour pressure ($\phi > 0.99$) is necessary for capillary condensation to occur there (Engelund *et al.*, 2010). This part of the sorption isotherm is termed the over-hygroscopic region and is characterised by the fact that small changes in the relative humidity lead to large changes in the equilibrium moisture content (Fredriksson *et al.*, 2013b). Under practical conditions, free water is most frequently absorbed via wetting of the wood surface through precipitation, splash or surface condensation. When a wooden member is exposed to free water, the moisture content near the exposed surface temporarily exceeds 20-25%, thus enabling the growth of decay fungi. The duration of the moisture content exceeding this level, as well as the level of the moisture content involved, are both important decay indicators.

In this thesis

The shape of the over-hygroscopic segment of the sorption isotherm was not considered explicitly in the present thesis. Exposure to free water was dealt with by assigning a fixed moisture content to the wood surface. In Paper I, this value was disconnected from the sorption isotherm and could not be attained without free water (condensation not included) being present on the wood surface. In papers IV and V, the value in question was connected to the sorption isotherm at $u_{\text{eq}}(\phi = 1.0)$ using linear interpolation from $u_{\text{eq}}(\phi = 0.99)$. Both of these methods provide highly simplified representations of the moisture-behaviour in the over-hygroscopic range.

4.3 Moisture transport

Matters of moisture transport in wood has been the subject of considerable investigation, not least within the field of drying technology where the primary objective has been to simulate the migration of water from green lumber. The literature offers a variety of models for describing moisture transport in solid wood and its interactions with the environment. Many such models are limited, however, to either a particular range of moisture contents, such as above or below the FSP, or to a particular set of boundary conditions, such as constant wetting or drying. Models employed in the field of wood drying are not easily applicable to problems related to re-wetting, for example, due to the lesser degree of pit aspiration of green wood (Comstock & Côté, 1968) and effects related to air trapping (Virta *et al.*, 2006).

A few models have been developed specifically for wetting of dried wood, however. In the sections that follow, certain basic concepts used for modelling moisture transport

of this type are described. The transport of hygroscopic moisture is described by Fick's second law of diffusion, whereas liquid water is as described by Darcy's law of fluid flow through porous media. More sophisticated models, such as those involving stochastic modelling of single-fibre flow paths (e.g. Salin, 2008; Sandberg & Salin, 2012), are not described here.

4.3.1 Hygroscopic moisture transport

In steady state, a diffusive flux can be expressed in terms of a diffusion coefficient and a concentration gradient, according to Fick's first law of diffusion. If the gradient of moisture concentration, w_b (kg/m^3), is seen as the driving force, it can be written as follows:

$$q_b = -D_w \frac{dw_b}{dx} \tag{4.1}$$

where q_b (kg/m^{2}s) is the mass flux over time per unit area and D_w (m^2/s) is the diffusion coefficient. The gradient of moisture concentration, as opposed to moisture content, is used here as the driving force since the units then become easier to relate to the relevant physics involved. The equation for mass conservation is given by

$$\frac{\partial w_b}{\partial t} = -\frac{\partial q_b}{\partial x} \tag{4.2}$$

Equations 4.1 and 4.2 can be combined to obtain Fick's second law of diffusion, which can be described in one-dimensional terms as follows:

$$\frac{\partial w_b}{\partial t} = \frac{\partial}{\partial x}\left(D_w \frac{\partial w_b}{\partial x}\right) \tag{4.3}$$

The special case when $dw_b/dt = 0$ represents a steady state, which yields a linear concentration profile in the case of a constant diffusion coefficient.

The rate of moisture transport generally decreases with decreasing temperature. The effects of the temperature can be taken into account by adjusting the diffusion coefficient in accordance with the Arrhenius equation (Simpson, 1993):

$$D(T) = D_o \, e^{-E_A/(RT)} \tag{4.4}$$

where D_0 is a base value obtained at a certain moisture content and temperature, D is the temperature-adjusted diffusion coefficient, E_A is the activation energy, R is the universal gas constant and T is the temperature. The ratio E_A/R is similar for many wood species (Simpson, 1993) and values for it can be obtained from the literature (e.g. Stamm, 1964; Koponen, 1985). The parameter D_0 can be derived from Equation 4.4 by inserting into it the diffusion coefficient and the temperature at which it was originally determined.

It should be noted that non-fickian effects have been reported for moisture transport within the hygroscopic range (Wadsö, 1993a). Recently, sophisticated multi-fickian models have been developed to address the shortcomings of the traditional single-fickian approach (Krabbenhoft & Damkilde, 2004; Frandsen *et al.*, 2007). Nevertheless, the accuracy of Equation 4.3 remains sufficient for many engineering applications, such as those involving creep (Toratti, 1992; Honfi *et al.*, 2014) and moisture induced stresses (Fortino *et al.*, 2009; Angst & Malo, 2010), and it is used throughout the present thesis (Papers I, II, IV & V).

4.3.2 Liquid moisture transport

Building materials located above ground come in contact with liquid water in the form of precipitation and condensation, as well as exposures of other types. When a water film is formed on a wood surface, capillary forces pull water into the cavities. The free water flow through a generic porous medium, q_f (kg/m^{2}s), depends on the intrinsic permeability of the medium K_s (m^2), the viscosity of water μ_w (Pa s), the density of water ρ_w (kg/m^3), and the pressure gradient $\frac{dP}{dx}$ (Pa/m), as described by Darcy's law:

$$q_f = -\frac{K_s \rho_w}{\mu_w} \frac{dP}{dx} \tag{4.5}$$

Together with the one-dimensional equation for mass conservation, the change in free water concentration over time can be expressed as follows (Hall & Hoff, 2011):

$$\frac{\partial w_f}{\partial t} = \frac{\partial}{\partial x}\left(\frac{K_s \rho_w}{\mu_w} \frac{\partial P}{\partial x}\right) \tag{4.6}$$

Permeability is strongly dependent on the direction of flow relative to the fibres. For example, the permeability is 10^2–10^4 times greater parallel to the fibres than perpendicular to the fibres (Perre *et al.*, 1993). On a micro-scale, the transverse transport of liquid through softwood can be described by the physical model proposed by Comstock (1970). In short, water migrates between adjacent cells through pit openings, an extremely slow

process which is governed by the permeability of the cell wall (in the transverse direction). After sufficient liquid has bypassed the pit to establish a liquid phase inside of the adjacent lumen, moisture can then distribute itself throughout the lumen (in the longitudinal direction) with relatively little resistance. The permeability is also highly dependent on the wood species involved, the permeability of pine sapwood being considerably greater than that of Norway spruce, for example, a matter that can be explained by its lower degree of pit aspiration.

Transport driven by capillary pressure behaves as a diffusive process in the sense that, when in contact with liquid water, the volume absorbed is proportional to the square root of time (Hall & Hoff, 2011). Spolek & Plumb (1981) further found that capillary pressure can be expressed as a function of saturation, S (-), which is a measure on the fraction of filled voids. The saturation is calculated as follows: (Spolek & Plumb, 1981):

$$S = \frac{w_f}{w_{f,max}} = \frac{w - w_{FSP}}{w_{max} - w_{FSP}} \tag{4.7}$$

where w, w_{FSP} and w_{max} are the actual moisture concentration, the moisture concentration corresponding to the FSP, and the moisture concentration at complete saturation, respectively, where w_{max} is determined on the basis of the porosity of the material.

The relationship between liquid water content and capillary pressure can be used to express moisture transport in the over-hygroscopic range with moisture gradient as the driving force (Spolek & Plumb, 1981). This is practical in character, since it implies that the transport of liquid water, dw_f/dt, and the transport of hygroscopic water, dw_b/dt, can both be expressed with the gradient of moisture content being the driving force: dw/dx. The diffusion coefficient governs the flow of moisture below the FSP, whereas the capillary transport coefficient governs the flow of liquid water above the FSP. Assuming that there is no overlap between the hygroscopic- and over-hygroscopic regions, the transport coefficient can be described by a single continuous function over the entire moisture range.

The inherent physical differences between the two modes of transport are expressed by the shape and the dependencies of the transport coefficient below and above the FSP, respectively. In the transverse direction, the rate of transport through combined vapour and bound-water diffusion has been found to increase with increasing moisture content (Angst & Malo, 2010). Koponen (1984) and Nilsson (1988) found that the rate of transport to peak at a moisture content of around 15-20%, after which it tends to decrease with increasing moisture content. Reports of the shape of the capillary transport coefficient have, however, not been entirely congruent (Kumaran, 1999). For example, Kang *et al.* (2009) found the diffusivity in the longitudinal direction of spruce to increase with increasing moisture content within the over-hygroscopic moisture range, whereas

Koponen (1984) found the exact opposite to be the case.

4.3.3 Moisture exchange with the environment

The wood surface tends towards equilibrium with the ambient air, and the equilibrium moisture content is described by the sorption isotherm. The exchange of moisture between the wood surface and the external environment can be described in terms of a surface flux, q_n (kg/m^{2}s), which is driven by some potential, $\Delta\xi$, together with a corresponding mass transfer coefficient, k_ξ, which can be described as follows (Wadsö, 1993b):

$$q_n = k_\xi \Delta\xi = k_\xi(\xi_s - \xi_a) \tag{4.8}$$

where $\Delta\xi$ or $(\xi_s - \xi_a)$ is the difference in some potential, ξ, between the ambient air (ξ_a) and the wood surface (ξ_s). There are several different potentials commonly employed in wood science for describing wood-air interactions, such as the difference between wood moisture content and the equilibrium moisture content of the air (Δu (kg/kg)) or the corresponding difference in vapour pressure (Δp_v (Pa)) (Wadsö, 1993b). When the wood surface moves from a known moisture state towards a known exterior relative humidity, the difference in potential is given by the sorption isotherm, as shown in Figure 4.3.

Differences between various potentials are expressed in terms of their degrees of dependency on the mass transfer coefficient. It is well-established that the mass transfer

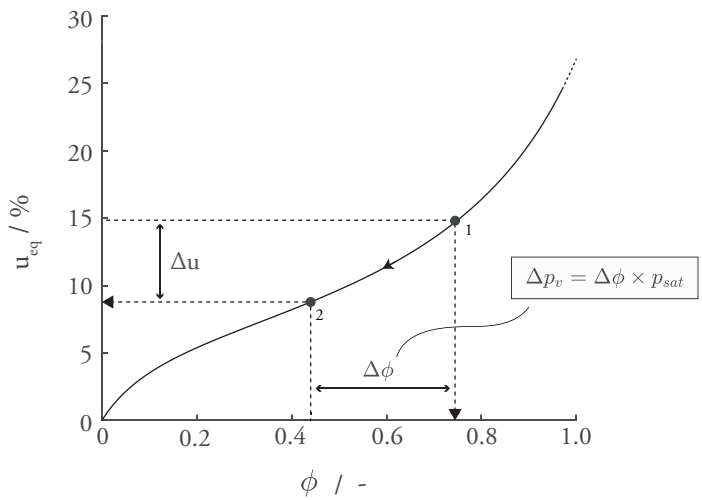


Figure 4.3: The hygroscopic part of a sorption isotherm fitted to data from Fredriksson & Thygesen (2017), showing the difference in potentials when a wood surface moves from state 1 towards state 2.

coefficient, independent of the potential that is employed, depends on the air velocity. At a fixed air velocity, the exchange of moisture between a free water surface and the air can be described by a constant k_p (Wadsö, 1993b) with the difference in vapour pressure, Δp_v, as the driving force. Assuming that this also applies to wood surfaces, then the transfer coefficient with Δu as the driving force, k_u, becomes a function of u, since conversion of k_u to k_p involves the non-linear slope of the sorption isotherm. An approach using a constant k_p with the difference in vapour pressure serving as the driving force is thus to be favored over use of a constant k_u with the difference in moisture content serving as the driving force (Wadsö, 1993b). Experiments have shown, however, that even k_p actually increases with increasing wood moisture content, due possibly to the increase in the area of the exposed cell wall containing liquid water (Siau & Avramidis, 1996; Tremblay *et al.*, 2000). Tremblay *et al.* (2000) also showed that the function $k_p(u)$ can be quite difficult to describe numerically.

In the drying of wet wood, the surface temperature of the wood decreases due to evaporative cooling. As the wood dries, the surface temperature gradually increases towards the temperature of the air. Evaporative cooling affects the moisture flux, since the reduced surface temperature tends to reduce the vapour pressure on the wood surface, thus leading to a reduced vapour pressure differential. The same effect is not considered when using the difference in moisture content as the driving force and is much weaker when using the difference in water potential, for example, as the driving force (Tremblay *et al.*, 2000).

In this thesis

In Paper I, Δu was used as the driving force with k_u as mass transfer coefficient. In paper II, III and V, Δp_v was instead used as the driving force, with k_p as mass transfer coefficient. In this case, the wood surface temperature was assumed equal to the temperature of the air, so the reduced p_{vs} due to evaporative cooling was not considered. The mass transfer coefficients were always assumed to be constant.

In dealing with precipitation on porous materials, the absorption rate is limited by the volume of water striking the surface. For many materials, the moisture content at the surface can remain below the saturation level for a significant length of time before the surface becomes saturated and water begins to run off of the surface (Hall & Kalimeris, 1982). When the surface has become saturated, the boundary conditions are basically equal to those of a material being in direct contact with a water reservoir. The mass of absorbed water is then proportional to the square-root of the time involved, i.e.:

$$\Delta m = A_w t^{1/2} \tag{4.9}$$

where the coefficient of proportionality, A_w (kg/(m$^2\sqrt{s}$)), is commonly referred to as the capillary absorption coefficient. The rate of absorption is the first derivative of Eq. 4.9:

$$q = 0.5 A_w t^{-1/2} \tag{4.10}$$

For surface saturation to be sustained, the flux of water into the material, q (kg/(m^{2}s)), must be greater or equal to the volume of precipitation striking the surface. Moisture transport in spruce is a relatively slow process, however, so the wood surface becomes saturated quite rapidly. For Norway spruce, the capillary absorption coefficient in the tangential direction is about $2 - 4$ g/(m$^2\sqrt{s}$) (Niemz *et al.*, 2010). Assuming $A_w = 3$ g/(m$^2\sqrt{s}$), Equation 4.10 gives an absorption rate of $q = 0.7$ (kg/(m^2 h)) after about one minute of capillary absorption, a level that can be sustained by a rain-intensity of less than 1 mm/h. As a simplification, it can thus be assumed that the exposed spruce surface becomes saturated instantly when rain strikes the surface. The slow absorption rate serves as a plausible explanation as to why the duration and the frequency of precipitation is more critical than the total amount of precipitation in predicting the wood moisture content under outdoor conditions (Lisø *et al.*, 2006).

As described in the previous paragraph, it can be assumed that most precipitation is in fact not absorbed by the wood surface. The amount of absorbed water over the course of a rain event therefore depends on its duration. Duration and intensity of rain events are, however, rarely available through meteorological databases. In fact, meteorological data on precipitation is generally limited to accumulated precipitation of hourly temporal resolution at best. Therefore, it becomes necessary to estimate the duration of rain events based on their precipitated volume.

When the sampling interval is frequent within a typical rain event, then the rain-history itself can be seen as a relatively accurate representation of when the wood surface is wet. For example, if rain is recorded under four consecutive 5-minute periods, then it can be assumed that the surface is wet for 20 minutes. The related uncertainty and error increases with increasing sampling interval. For example, a small volume of precipitation recorded over an hour is unlikely to describe a one-hour rain event. In similar studies it is frequently assumed that any sampling period when the accumulated amount of rain exceeds a defined threshold corresponds to an uninterrupted sequence rain (see e.g. Frühwald Hansson *et al.*, 2012). With this method, the duration of many rain events are overestimated while those falling below the threshold are neglected.

In this thesis

Precipitation was considered by assuming that a water film was instantly established and maintained on the wood surface over the course of the rain event. The duration of the rain event was estimated on the basis of hourly precipitation. The relationship employed was developed from 3 years of measured precipitation with a sampling interval of 10 minutes and 2500 hours with recorded precipitation. Figure 4.4 shows the hourly precipitation against the cumulative time when rain was being recorded. The scattered data shows that it is rather difficult to estimate the length of a rain event based solely on the precipitated volume.

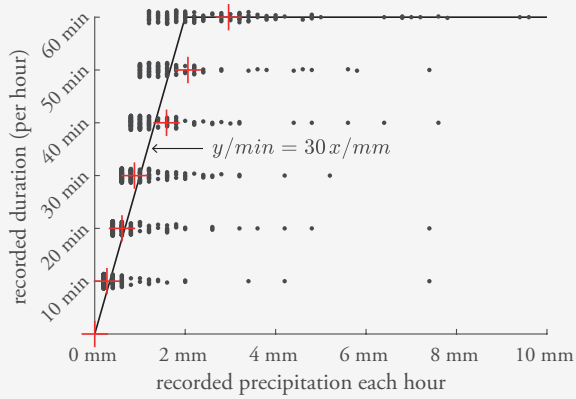


Figure 4.4: Cumulative hourly precipitation plotted against cumulative time when rain was recorded (based on 10-minute records). The red cross marks the mean precipitated volume for each duration.

4.3.4 Diffusion coefficients and surface moisture content

Equation 4.9 does not provide any information regarding the spatial distribution of the moisture that is absorbed, $\Delta m(t)$, which depends on the diffusion coefficient. The value of A_w is often used as a basis for calculating an *average* diffusion coefficient, assuming that the resistance to moisture flow is uniform over the moisture range as a whole. An order-of-magnitude approximation can be obtained from the following equation (Kumaran, 1999):

$$D_w \approx \left(\frac{A_w}{w_{max}} \right)^2 \tag{4.11}$$

where D_w (m^2/s) is the diffusion coefficient and w_{max} is the moisture concentration at the

surface. Equation 4.11, although somewhat simplistic, shows that the resulting diffusion coefficient is closely associated with assumed moisture content on the wood surface.

Motivations for selecting the boundary moisture content varies in the literature. Derbyshire & Robson (1999) attempted to model the moisture distribution by assuming the boundary moisture content to be equal to the maximum moisture content corresponding to fully saturated wood. They showed, however, that when $w_{\max}$ is set to the theoretically maximum moisture content, as calculated from the porosity, then the diffusion coefficient becomes extremely small and the slope of the corresponding moisture profile becomes too steep. Other researchers have used a value $w_{\max}$ that is much lower than that of saturated wood (see Mounji *et al.*, 1991; El Kouali & Vergnaud, 1991; Fakhouri *et al.*, 1993; De Meijer & Militz, 2000; Sivertsen & Vestøl, 2010), generally around 30% and 60% for Norway spruce (Sivertsen & Vestøl, 2010). For example, De Meijer & Militz (2000) modelled moisture profiles of Norway spruce using a value of 30% for the moisture content, assuming that most of the subsurface transport occurs via vapour and bound water diffusion, capillary action being limited to the surface. Indeed, they were able to model the moisture distribution with a rather high degree of accuracy, although the moisture content near the surface they obtained experimentally was higher than what they had predicted.

More realistically, the diffusion coefficient is described as dependent on moisture content. Several authors have used a moisture-dependent diffusion coefficient to study the absorption and distribution of moisture in wood subjected to wetting. The moisture-dependency of the diffusion coefficient within the over-hygroscopic moisture range can be determined indirectly by measuring the permeability of the wood (see e.g. Derbyshire & Robson, 1999; Virta *et al.*, 2006). In both of these studies, the moisture distribution of cladding boards was also modelled using the theoretical maximum of the moisture content as a boundary condition. Alternatively, the diffusion coefficient can be determined directly from the moisture distribution at different times during wetting or drying (see Koponen, 1984, 1985; Kang *et al.*, 2009). Figure 4.5 shows some diffusion coefficients for transversal moisture transport in Norway spruce as reported in the literature (Koponen, 1984; Nilsson, 1988). Note that the values reported by Nilsson (1988) are based on data from the literature and include both Scots pine and Norway spruce.

As a final note on the maximum moisture content of wood obtained under short-term wetting conditions, it should be mentioned that it is difficult to determine experimentally the actual moisture content *at* the surface, since there is a need of defining some representative volume over which the moisture content is measured. Some measuring techniques, however, are capable of measuring the moisture content very close to the surface. For example, Dvinskikh *et al.* (2011) obtained moisture content measurements of 30-60% at a distance of 0.5 mm from the exposed side-grain of Norway spruce after

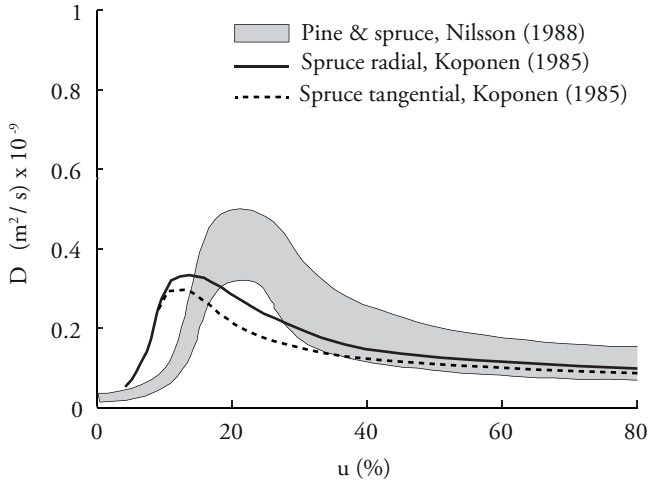


Figure 4.5: Transport coefficients from the literature. Note that the values reported by Nilsson (1988) are based on the literature and are given as a range (max/min).

24 hours of wetting, using nuclear magnetic resonance spectroscopy, whereas Fredriksson *et al.* (2016) obtained moisture content values greater than 50% at a distance of 3 mm from the surface after 6 hours of wetting, employing small resistance-type moisture sensors. Using tomography, Lindgren (1991) measured the moisture content of Norway spruce to about 30-60% at a distance of about 1.5 mm from a radial surface. Using the same method, Fredriksson & Lindgren (2013) and Lindgren (1991) measured values of about 120% moisture content near an end-grain after 6.5-48 hours of water absorption.

In this thesis

In paper I, the diffusion coefficient from Nilsson (1988) was used. In papers IV & V, the coefficient from Koponen (1984) was used instead.
The moisture content at the boundary was set to 100% in paper I and to 120% in papers IV and V. It is emphasized that the shape of the diffusion coefficient and of the corresponding moisture profiles are deemed uncertain in the capillary region.

4.4 Factors affecting the boundary conditions

4.4.1 Short-term wetting

Wood used in above-ground applications is subject to short-term wetting e.g. due to precipitation, splash or condensation. If the exposed wood surface is sufficiently ventilated, the response to precipitation is limited, with large fluctuations being limited to the exposed surface layer. Conceptually, short-term wetting can invoke a response such as shown in Figures 4.6 (a-d), which can be described as follows:

a) During wetting of the surface, liquid water is absorbed into the surface and a steep gradient is developed. For short-term wetting (<24 h) of less permeable wood species, only the outermost parts of the side-grain (<3 mm from the surface) show a moisture content that lies above the FSP (see measurements by Lindgren, 1991; Virta *et al.*, 2006; Dvinskikh *et al.*, 2011).

b) As drying begins, water that is present in the outermost cavities evaporates, resulting in a reversed gradient and the migration of moisture towards the surface.

c-d) The migration of water towards the surface continues while water is also redistributed deeper into the core through diffusion. For thin specimens, the response may reach the opposite surface, at which point two-sided drying begins.

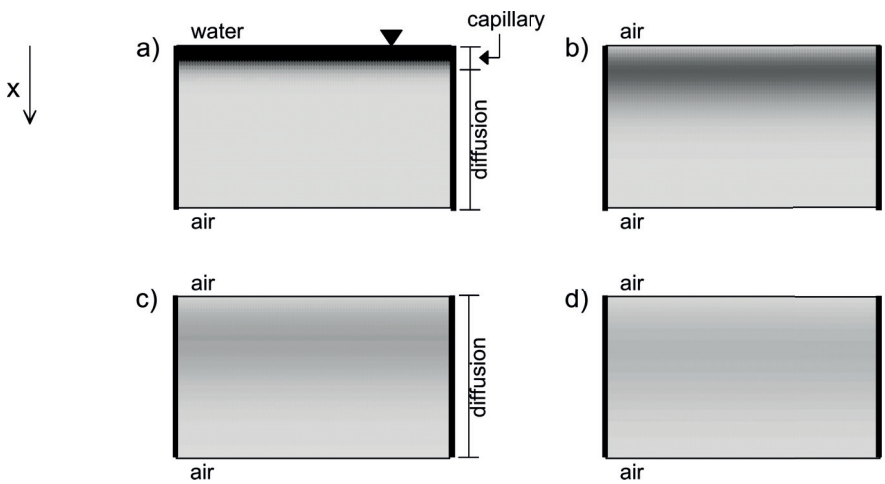


Figure 4.6: Conceptual visualization of different moisture profiles during single-sided short-term wetting of wood under free drying conditions. The images are based on simulated results obtained through use of the model described in Paper IV.

In this thesis

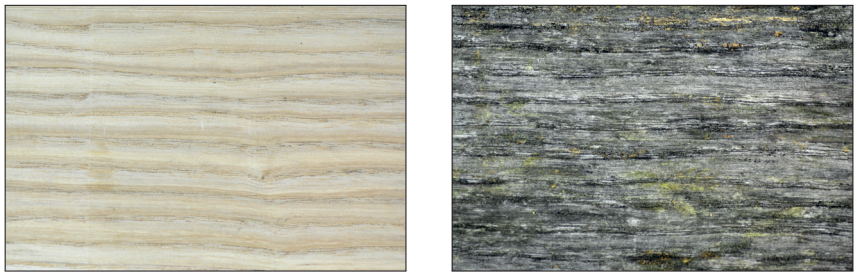
The objective of paper I was to describe the moisture conditions of wood without constraints being placed on drying. In the present work, a simple diffusion model for estimating the spatial distribution of moisture in the cross-section was employed. This model is of limited use in itself for assessing durability, since biological deterioration tends to begin in areas where drying is constrained. However, being able to predict in the simplest case is of course imperative for moving towards the modelling under more complex boundary conditions. The model employed was later expanded in paper IV to include certain types of moisture traps.

4.4.2 Long-term changes of material properties

Wood exposed to outdoor conditions is subject to various environmental effects related to heat, radiation and moisture. Changes in the material due to cracks, checks, photo-deterioration and staining fungi alter the surface characteristics, either by making the surface less hydrophobic or by creating passageways for moisture to migrate deeper into the subsurface (Evans *et al.*, 2008; Žlahtič & Humar, 2016).

The cell walls of the wood are mainly composed of cellulose, hemicellulose and lignin. The cellulose and the hemicellulose are hydrophilic, whereas the lignin is more hydrophobic and thus limits the rate of absorption (Forest Products Laboratory, 2010). Lignin is also photo-degradable and deteriorates when exposed to UV- and visible light. Subsequent to its breakdown, the residue is washed away by run-off water. As a result, wood exposed to UV-radiation develops a greyish cellulose-rich hydrophilic surface layer (see Figure 4.7). The damaged layer is generally very thin, since UV- and visible light only penetrate about 0.5 and 1 mm, respectively, into the subsurface (Evans, 2013). Colour changes have been detected, however, at depths of about 2.5 mm (Browne & Simonson, 1957). Whereas photo-deterioration is mostly superficial, moisture-induced checking can extend to depths of several millimeters (Evans *et al.*, 2003) and can serve as potential pathways of liquid water into the subsurface of the wood (Gaby & Duff, 1978; Ekstedt, 2002).

Most of the photo-deterioration and checking occurs within a couple of weeks of being exposed to natural sunlight, however the process can continue for several months before developing to continuous slow erosion (Evans, 2013). Later changes in moisture-related characteristics are likely to be related to the occurrence of decay fungi, staining fungi or deeper cracks. Modelling the wood moisture conditions after the onset of decay is extremely difficult, since properties such as chemical composition and porosity begin



(a) (b)

Figure 4.7: Surface of a piece of freshly planed Ash (a) and a piece of weathered Ash (b).

to change continuously. In addition, moisture production by decay fungi should be taken into account (see Viitanen & Ritschkoff, 1991; Saito *et al.*, 2012). It can be argued, however, that the post-decay-process is of little relevance to the assessment of durability, since the limit state is exceeded already when the wood begins to decay. The effects, as such, of decay fungi on the moisture balance of wood are not considered in the present thesis.

In this thesis

The aim of paper II was to investigate how weathered surfaces affect the moisture conditions of wood exposed to cyclic rain. The study was initiated for investigating the causes of long-term trends that were observed in modelling variations in moisture over long periods of time.

4.4.3 Constrained drying due to joints

The mass transfer coefficient dealt with in Equation 4.8 depends on the air velocity over the wood surface, an obstructed air flow being associated with reduced rate of evaporation. Areas of contact are particularly vulnerable to moisture accumulation due to the air flow over the contact area being inhibited. At the same time, wetting generally still can occur through the presence of small gaps or slits. Such areas are often referred to as moisture traps. Many types of joints in timber structures serve as potential moisture traps and are thus sensitive to being exposed to free water. In fact, decay-related damage of timber bridges is found predominantly at the joints (Brischke *et al.*, 2008a; Kleppe, 2013; Pousette & Fjellström, 2016).

Several research studies have been concerned with the moisture conditions in moisture traps. Gaby & Duff (1978) measured the moisture content at different locations in pre-

existing decks and railings and found the moisture level to be elevated near joints and end-grain. Isaksson & Thelandersson (2013) monitored the moisture content of various details under exposure to the same environmental conditions, observing significantly increased moisture content in connecting members and exposed end-grain areas. Fredriksson *et al.* (2016) studied the effects of gap-size on the moisture conditions present in joints of three different types through measuring the moisture distribution during and after exposure to artificial rain.

Figures 4.8 (a-d) show conceptually the moisture distribution at different points in time after the wetting of wood. Exposure to water wets the entire wood surface, including the interface area between two connecting members (a). During wetting, the moisture distribution is thus identical to that shown in Figure 4.6 (a). Free surfaces dry relatively quickly after a rain event has ended (b). In areas where drying is obstructed, moisture redistributes instead through the wood towards the drier areas. After those parts of the board that are unaffected by the moisture trap have returned to equilibrium, a distinguished patch having higher moisture content can be seen in the vicinity of the moisture trap (c-d). For a given duration of wetting, the response in terms of moisture content is both higher in amplitude and more extended in time near moisture traps, as compared with free surfaces.

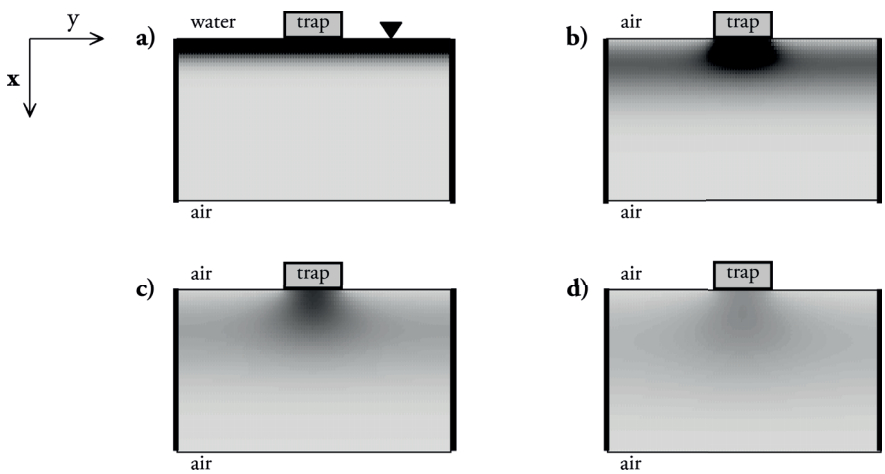


Figure 4.8: Conceptual figure of different moisture profiles during single-sided short-term wetting of wood with locally constrained drying occurring along the length of the moisture trap. The moisture profiles are based on simulated results obtained through use of the model described in paper IV.

In this thesis

The objective of the study reported in Paper III was to collect empirical field data and quantify the effects of drying constraints on the moisture behaviour of beams and columns. Examples of these data are shown in Figure 4.9. A semi-empirical model for describing these effects was also developed.

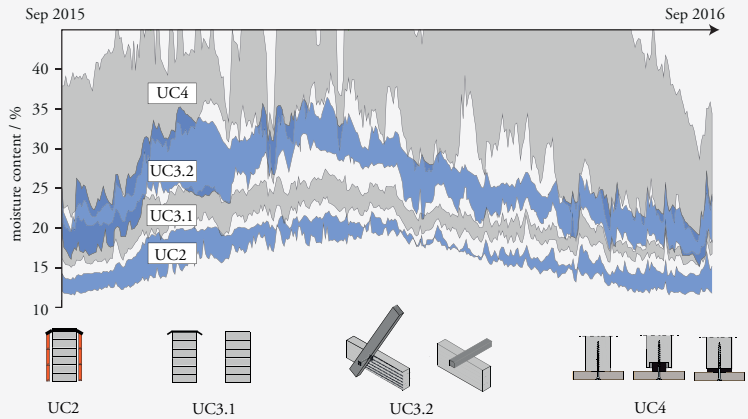


Figure 4.9: Experimental results from Paper III showing the effect of detail design on moisture conditions in wooden members.

The objective of Paper IV was to describe numerically the moisture conditions of wood subjected to drying constraints. In this work, the model developed previously in Paper I was extended to include moisture transport in two directions. Through use of the model it was shown that the moisture conditions near joints can be described by setting the surface transfer coefficient over the contact faces to zero (i.e. no wood-air interaction taking place), the absorption of liquid water remaining unaffected by the connecting member.

4.5 Coupling moisture transport and decay models

4.5.1 Choice of models and interpretation of output

The direct decay models described in chapter 3 express the decay rate as a function of temperature and some quantity of moisture. In the present work, two different models decribed by Isaksson *et al.* (2013) were employed: the logistic model (LM) and the simplified logistic model (SLM). Note that the LM was originally developed by Brischke

& Rapp (2008), but the function describing the daily dose was later revised by Isaksson *et al.* (2013). As opposed to the SLM, the LM has a distinct cut-off limit (u=25%) below which the decay activity equals zero.

The equations governing the LM are based on empirical functions relating material climate to decay rate, so the model can be expected to deliver realistic results under a wide variety of conditions, granted that the moisture content and temperature conditions are known. The cutoff limit, however, makes it sensitive to the nature and accuracy of its input. The SLM is less sensitive, since the governing equations are gradual and lack a lower threshold. On the other hand, the SLM tends to yield unrealistic results under use-class 1 (indoor) and use-class 2 (sheltered) conditions, the moisture content there either rarely or never exceeding 25%. In general, the SLM is subject to greater constrains but is less sensitive to the nature of its input, which is reflected by how it is employed in the present thesis.

The numerical moisture model yields the moisture variation in the entire cross-section of the wood involved. In addition, the spatial distribution of the growth of decay over time can be estimated by coupling the moisture model with a decay model. Figure 4.10 shows the moisture distribution at a given point in time (a), the moisture content over time in two different sections and at two different depths (b), and the spatial distribution of doses after a certain period of time has elapsed (c). The LM yields a steep gradient near the exposed surface, and involves zero doses being produced at the opposite, sheltered face. The steep gradient is due to the fact that only the outer layer is exposed to moisture content fluctuations exceeding 25%. In contrast, the SLM yields a comparatively smooth dose distribution due to the absence of any moisture threshold.

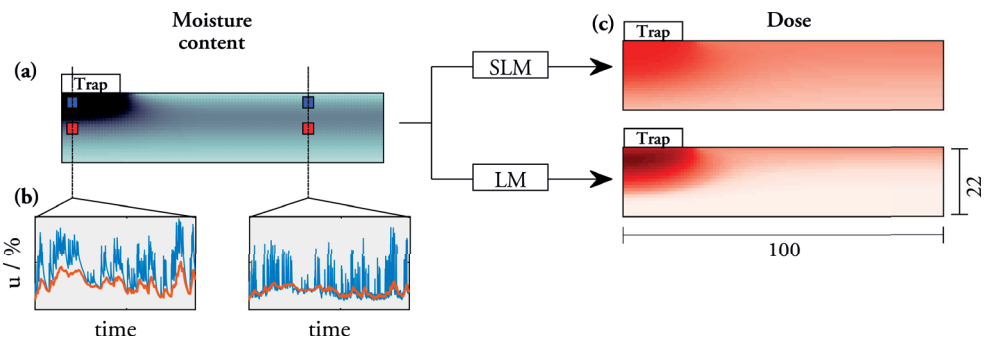


Figure 4.10: Simulated moisture distribution at one point in time (a), moisture content over time at four coordinates and (b) distribution of accumulated doses at the end of the time-period in question.

4.5.2 Mapping decay hazard

Combining moisture and decay models enable quantitative assessment of the relationship between meteorological data and the decay hazard. Meteorological data was obtained through use of the commercial software *Meteonorm*. The Meteonorm database includes 8000 weather stations worldwide, the majority of them being located in the European and North American regions. In addition, the software provides sophisticated models for spatial interpolation between weather-station results and the stochastic modelling of *typical years*.

In this thesis

Two different decay models, the logistic model (LM) and the simplified logistic model (SLM), were employed in Paper V. Due to the underlying features of the two models, the decay hazard was defined as follows:

- LM – the decay hazard was defined here by the highest dose found in the specimen, since this is the point at which, according to the model, decay is first established.
- SLM – the decay hazard was defined here by the maximum dose given at a distance of 10 mm from the exposed surface, since the model was developed under similar conditions.

The decay hazard in over 300 European climates was calculated. Decay hazard maps for use-classes 3.1 and 3.2 were developed on the basis of this data set. A example of a decay hazard map is shown in Figure 4.11.

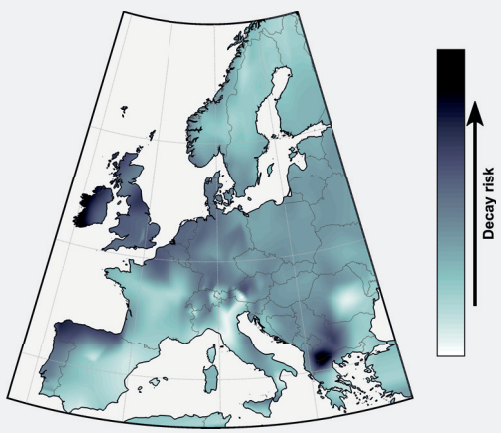


Figure 4.11: A decay hazard map for use-class 3.1, based on the results presented in Paper V.

5 Data acquisition

5.1 General

There are a variety of different methods for determining the moisture content of wood, ranging from simple gravimetric techniques to sophisticated spectroscopy that maps the spatial distribution in three dimensions (Thybring *et al.*, 2018). Each method is subject to drawbacks of some sort, such as low spatial and/or temporal resolution, limited accuracy or a need for sensitive instrumentation that makes the method unsuitable for use outside of a laboratory environment. Thus, the measurement technique to be employed should be selected with regard to the specific application involved. The main focus of the present thesis is on temporal variation, reliability under harsh conditions and the possibility of obtaining local, non-invasive measurements. On the basis of these criteria, the electrical-resistance-type technique was deemed most suitable. Measurements obtained by use of this method are presented in Papers I to IV.

Certain basic theory is necessary in order to accurately interpret resistance-type measurements. The present section intends to provide a brief overview of the functionality, the main features and the uncertainties of this technique. In addition, methods for assessing surface conditions, including those not based on electrical resistance, are discussed.

5.2 Electrical moisture measurements

Figure 5.1 shows a wooden member having a constant cross-section and uniform moisture content being clamped between two plates of equal cross sectional area. The electrical resistance of such a system can be described as follows:

$$R_w = \rho \frac{L}{A} \tag{5.1}$$

where ρ, L and A are the resistivity (Ωm), the length (m) and the cross-sectional area (m^2), respectively, of the wooden member. The resistivity is sensitive to changes in moisture content and decreases with increasing moisture content (Stamm, 1927). The empirical relationship connecting the resistance to the moisture content is here referred to as the calibration curve. The resistivity ρ is extremely moisture-dependent within the hygroscopic moisture range, in which it decreases several orders of magnitude between a moisture content of 7% and the FSP (25-30%) (Stamm, 1929). Above the FSP, the resistivity decreases further, although its moisture-dependency there is far less pronounced (Stamm, 1929; Brown *et al.*, 1963). The ratio L/A is termed the cell constant of the system and depends on the experimental setup and the electrode configuration (Tamme *et al.*, 2012). The empirical relationship found between the electrical resistance and the moisture content are thus related both to the experimental setup and to the material properties involved. These are discussed separately in sections 5.2.2 and 5.2.3, respectively. In addition, all measurements used in the present thesis were obtained under variable external conditions. Accordingly, the effects of non-uniform moisture content are also discussed in the sections that follow.

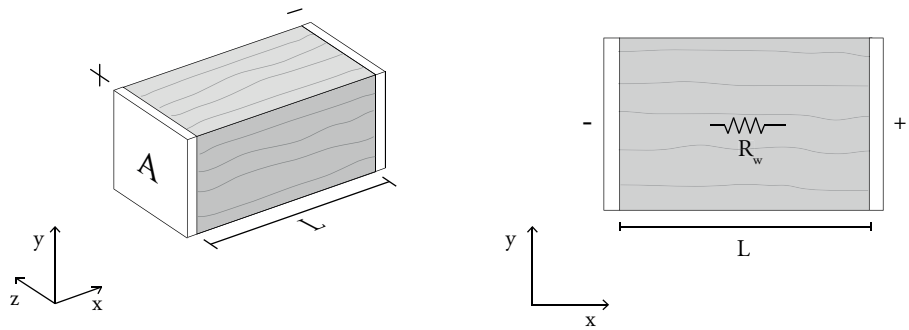


Figure 5.1: A wooden member clamped between two plates of equal cross section.

5.2.1 Effects of gradients

Figure 5.2 shows two different types of moisture gradients: (a) a gradient between the electrodes and (b) a gradient parallel to the plane of the electrodes. The wooden specimen in the figure has been divided into fictitious laminations of uniform moisture content in order to illustrate the differences between the separate cases, where case (a) is a system of laminations connected in series and case (b) is a parallel system. The total resistance of the first system can be calculated as the sum of the separate resistances, i.e. $R_{\text{tot}} = R_1 + R_2 ... R_n$ (Stamm, 1927). Due to the logarithmic relationship between the moisture content and the electrical resistance, the moisture content reading obtained under this type of gradient tends to be considerably lower than the arithmetic mean (Stamm, 1927).

The resistance, in turn, of the parallel system illustrated by case (b) can be calculated as $R_{tot}^{-1} = R_1^{-1} + R_2^{-1} \ldots R_n^{-1}$, which means that the conductance is equal to the sum of the individual conductances, the conductance and resistance being reciprocals (Stamm, 1930). In contrast to the previous case, the measured moisture content here is much greater than the arithmetic mean. Resistance-type measurements, as such, are often said to indicate the highest moisture content bridging the entire distance between the two electrodes (Björngrim *et al.*, 2017). Although this is often a good rule-of-thumb, in a situation involving a gradient resistance-type measurements always measure below the highest moisture content that is in contact with the electrode. The difference between the measured value and the actual moisture content can be significant in the presence of steep gradients, an issue that was highly relevant in the study of Paper II where moisture content was measured close to the exposed wood surface.

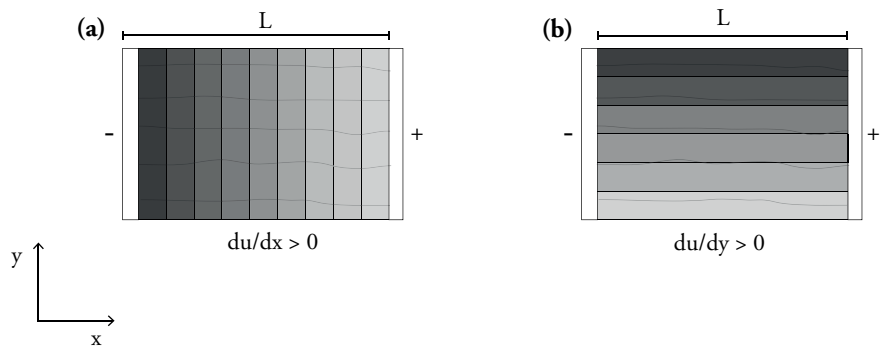


Figure 5.2: Two different types of moisture gradients: (a) a gradient between the electrodes and (b) a gradient along the electrodes.

5.2.2 Effects of electrode configuration

In practice, the resistance of wood is rarely measured by plates having the same cross sectional area as the specimens involved. Figure 5.3 shows a more practical electrode configuration, one in which two partially insulated pin-type electrodes have been driven into a wood sample. Here, the area of the conducting path is variable, so Equation 5.1 is no longer applicable. Instead, the resistance needs to be integrated over the path of conduction (Norberg, 1999):

$$R = \rho \int_0^L \frac{1}{A(x)}\, dx \tag{5.2}$$

It can be understood, on the basis of geometrical considerations, that the region covered by the conducting path is small in the vicinity of the electrodes. According to Norberg

(1999), the total resistance of the system can be simplified to the summed contribution of three separate components, R_1 and R_2 describing the fractions of the total resistance related to the electrodes and R_w describing the resistance of the wood between the electrodes, as illustrated in Figure 5.3. In a situation in which the wood volume is large relative to the surface area of an electrode, then it follows that $R_1 = R_2 >> R_w$ and the resistance of the system is thus governed by the moisture content of the small volumes of wood near the electrodes. Accordingly, the effect of the distance between the electrodes is small, the cell constant instead being governed either by the geometry of the electrode or by the contact area between the wood and the electrode (Skaar, 1964; James, 1988; Norberg, 1999; Tamme *et al.*, 2012; Zelinka *et al.*, 2015). Experimental results have confirmed that the electrical resistance is instead primarily affected, at a certain moisture content, by the electrode length (Hjort, 1996; Björngrim *et al.*, 2017) and the diameter of the electrode (Hjort, 1996) and that the distance between the electrodes is of lesser importance (Li *et al.*, 2018).

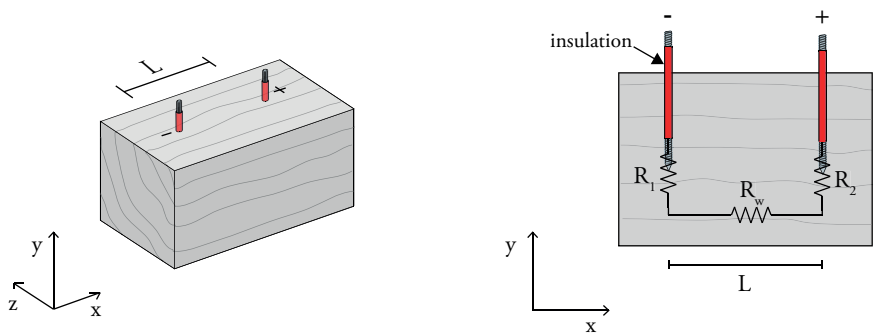


Figure 5.3: A pin-type electrode configuration. Figure adapted from Norberg (1999).

The reasoning in section 5.2.1 regarding gradients also applies to pin-type measurements, the difference between the two cases being that the moisture content *between* the electrodes has a negligible impact on the reading. Instead, the electrical resistance here is governed by the highest moisture content that connects *both* pins to the surrounding woody material (James, 1988). To clarify, in a situation when the two electrodes of a single pair are embedded in two wood volumes having 10% and 15% moisture content, respectively, then the sensor measures a value of about 10%.

5.2.3 Effects of material

The resistivity, ρ, depends upon a variety of properties. The empirical function relating resistivity to moisture content is usually adjusted for the temperature and the species

involved (Otten *et al.*, 2017). However, on a smaller scale the resistance also depends on the direction of the fibers (Stamm, 1927), the density of the wood (Vermaas, 1984), if the specimen is comprised of heartwood or sapwood (Forsén & Tarvainen, 2000) among several other factors listed by Stamm (1927) and Fredriksson (2010).

5.2.4 Uncertainty in the over-hygroscopic moisture range

Electrical resistance depends upon a variety of factors, including those related to the resistivity of the material, $\rho(u)$, and to the experimental setup (cell constant). Within the hygroscopic moisture range, however, most of these effects are outweighed to a large extent by the moisture dependency. This makes resistance-type measurements relatively insensitive to variations in material properties and changes in the measurement system employed, such as changing the type of electrodes.

In the overhygroscopic range, however, careful calibration is a requried for avoiding large errors. Any calibration curve developed for a single measurement system is generally not transferable to a differet system without invoking large errors in the moisture reading. Figure 5.4 shows two calibration curves for Norway spruce determined by two separate research groups (see Fredriksson *et al.*, 2013b; Otten *et al.*, 2017). Consider, hypothetically, that the difference between the two curves is explained solely by differences between the respective measuring systems, which actually appears quite likely, since the curve reported by Otten *et al.* (2017) was determined by comparatively large electrodes and their curve yields lower resistance values at a given moisture content. Consider too what would happen if the two calibration curves were swapped, so that the measuring system developed by Fredriksson *et al.* (2013b) was used together with the calibration curve obtained by Otten *et al.* (2017). Due to the nature of the two curves, the error would be much greater in the over-hygroscopic range than in the hygroscopic range. In addition, large variations in moisture content that are confined to the over-hygroscopic moisture range would *appear* to be only minor, a characteristic that was exploited in Paper II in estimating the duration of surface wetness.

To summarize, minor errors in the calibration curves can invoke very large errors within the over-hygroscopic range. Despite large errors occurring, variations in electrical resistance within the over-hygroscopic range tend to be indicative nevertheless of changes in moisture content.

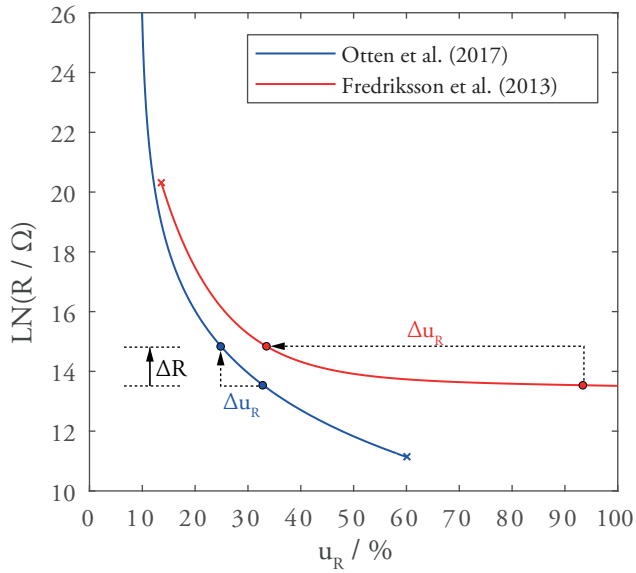


Figure 5.4: Electrical resistance shown as a function of the moisture content as reported in the literature.

In this thesis

Measurements obtained through use of resistance-type sensors are reported in Papers I to IV, but only those included in Papers II and III were obtained as part of the present thesis work. The monitoring system employed in the present work was not calibrated for the over-hygroscopic moisture range.

5.3 Monitoring of surface conditions

Surface conditions and the length of exposure to liquid water are important indicators of the durability of wood material. There are basically two types of surface measurements in this case, those monitoring the presence of water on the surface and those measuring the surface moisture content. The special case in which a liquid film is formed on the wood surface is particularly important in connection with matters of durability.

There are a variety of measurement techniques for measuring surface moisture content. Yamamoto *et al.* (2013) used a special kind of electrode configuration consisting of two metal rings of differing diameter that are pushed against the surface of the wood. The smaller ring was placed inside of the larger one, the electrical resistance between these two rings thus being measured. Scheepers *et al.* (2017) measured the surface moisture content

of wood indirectly via the surface temperature, by utilizing a relationship between surface temperature and moisture content stemming from evaporative cooling. Both of these techniques are generally limited to the hygroscopic range. Yamamoto *et al.* (2013) noted, however, that the point at which the surface transitions between the over-hygroscopic and the hygroscopic moisture ranges could be identified on the basis of the abrupt change in the rate of change in the resistance that occurred there.

In order to detect and monitor the presence of a water-film on the wood surface, the water on the surface needs to be distinguished from the water inside, or enclosed by, the surface layer of the wood. Fredriksson *et al.* (2013a) developed a resistance-based detection technique where surface electrodes were completely separated from the wood substrate by capillary tubing, thus the system only connecting with the wood electrically when water bridges the capillary tubing. Another method for detecting water on wood surfaces was used by Nore *et al.* (2016), who evaluated the difference between two sensors, one being located in the surface layer and another one being located at a small distance below the surface of the wood, a large difference between the two outputs thus indicating the presence of water on the surface of the wood.

In this thesis

In Paper II, a colorimetric approach was developed for measuring the time during which free water is available in the surface layer of a wood specimen. The method is based on the change in optical appearance caused by wetting of the surface, this change in appearance stemming from the lower refraction index of water as compared to air. Wood essentially appears darker when liquid water occupies the otherwise air-filled cavities in the surface layer of the wood, or when the surface is covered by a water film. This method is taken up further in Chapter 6.

6 Data sets included

6.1 Overview

In the present thesis work, two different experiments were designed and conducted. Additional data from two further publications have also been used in several of the publications included in the thesis. Table 6.1 provides an overview of these data sets, that either are included in the papers that are appended or represent part of additional data that is presented in the thesis. All of these data sets were obtained using resistance-type moisture sensors. The following sections describe each of those data sets in brief. In addition to the data sets presented here, the numerical model has been tested against data concerning the long-term wetting of large members (data reported in De Meijer & Militz, 2000) and small members exposed outdoors over long time-periods (data reported by Brischke *et al.*, 2017b), however these data are not presented here.

Table 6.1: An overview of the experimental data used in the present study, including the author's original data sets as well as data sets from the literature.

Reference	Dimension	Depth[a]	Papers
Fredriksson *et al.* (2016)[b]	22×90 mm^2	0/3/11/19 mm	I & IV
Niklewski *et al.* (2018b)	270×115 mm^2	0/11 mm	III
Niklewski *et al.* (2018a)	18×100 mm^2	0/10 mm	II
Isaksson & Thelandersson (2013)	22×90 mm^2	0/11 mm	I & IV

[a] Distance from the surface exposed to rain. Zero refers to measurements taken directly at the surface, either in the outermost wood layer or on the surface itself.

[b] Includes two different rain sequences á 300 h

6.2 Data sets from the literature

6.2.1 Fredriksson et al. (2016)

Fredriksson *et al.* (2016) conducted laboratory experiments aimed at exploring the effects of detail design on the moisture distribution in several types of wood-to-wood joints (additional data given by Fredriksson, 2013). The full data set includes data concerning three joints in which measuring points were located in all of the joint members. In the present study, any data points that were affected by end-grain absorption were discarded from the dataset. The remaining data is limited to that concerning a single joint consisting of a horizontal board (22×90 mm^2) connected to a vertical board of equal dimensions with the end-grain of the latter facing the side-grain of the former. The same type of joint was designed with variable gap sizes of 0, 2 and of 5 mm, respectively (see Figure 6.1). The material used included both slow-grown and fast-grown Norway spruce sapwood. One specimen of each material was tested for each gap-size, resulting in a total of six employable data sets.

The two-dimensional spatial moisture content distribution over time was obtained by measuring the resistance continuously at three different depths (3, 11 and 19 mm) located at several different positions along the boards (see Figure 6.1), using a measurement system employing small electrodes ($1 \times 1 \times 1$ mm^3) developed in another study (Fredriksson *et al.*, 2013b). The test procedure included two different sequences of artificial rain: (1) a single extended spray and (2) short cyclic sprays. The controlled environmental conditions that were present, the multiple relevant rain sequences that were used, the thoroughly calibrated measurement system and the rigorous control of material properties rendered the data ideal for calibrating the numerical model.

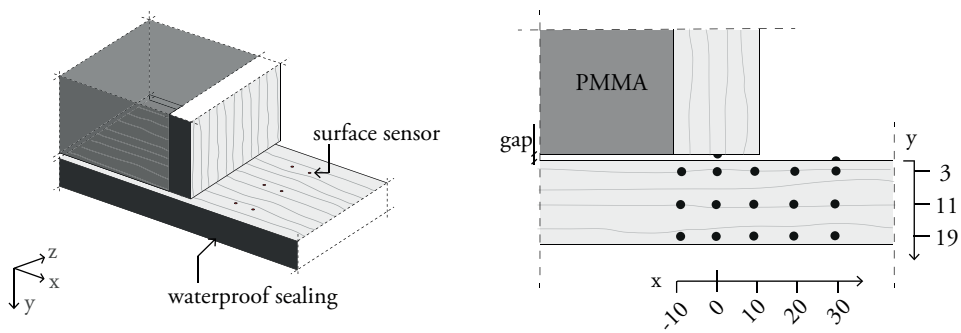


Figure 6.1: An experimental setup designed by Fredriksson *et al.* (2016). A plastic box (PMMA) was attached to the backside of the vertical board that is shown so as to avoid wetting of the sensors that were inserted from the same side. Units in (mm).

Paper I is limited to one-dimensional moisture transport with only the measuring points at x=30 mm in Figure 6.1 being employed for model calibration, the points closer to the vertical board being more susceptible to two-dimensional effects due to their proximity to the connecting board. Axial symmetry and waterproof sealing of the short sides ensured zero transport in the z-direction. The moisture content being higher in the vicinity of the joint created a gradient in the x-direction. However, analysis of the data set as a whole indicated that this gradient had no more than a negligible impact on the moisture conditions at x=30 mm. For example, whereas the moisture content at the measuring points closest to the joint was notably higher, there was practically no difference between the points located at x=20 and x=30 mm. Paper IV extends the model developed in Paper I and includes all the measuring points shown in Figure 6.1, including those of electrodes located on the wood surface.

6.2.2 Isaksson & Thelandersson (2013)

Isaksson & Thelandersson (2013) conducted outdoor experiments aiming at exploring and modelling the effects of detail design on the moisture content of specimens made of Norway spruce sapwood ($22\times90\times500$ mm^3). The testing carried out included various types of wood-to-wood joints (two replicates per type) and different reference specimens, the one pair being sheltered and the other being exposed to one-sided wetting. A number of details included in their study are shown in Figure 6.2. A system for detecting the presence of surface moisture (described by Fredriksson *et al.*, 2013a) was used to monitor the exposed reference specimens. The reference specimens were exposed for almost three years, whereas the measurements in the joints were terminated already after a year. Hourly weather data was obtained at the site and missing data was replaced by data from the Swedish meteorological institute (SMHI).

For Paper I, the reference boards were ideal for verifying the previously calibrated model under realistic environmental conditions. Paper III used the data concerning details to develop the empirical model. Paper IV used data regarding the reference board and data concerning some of the details to test the numerical model.

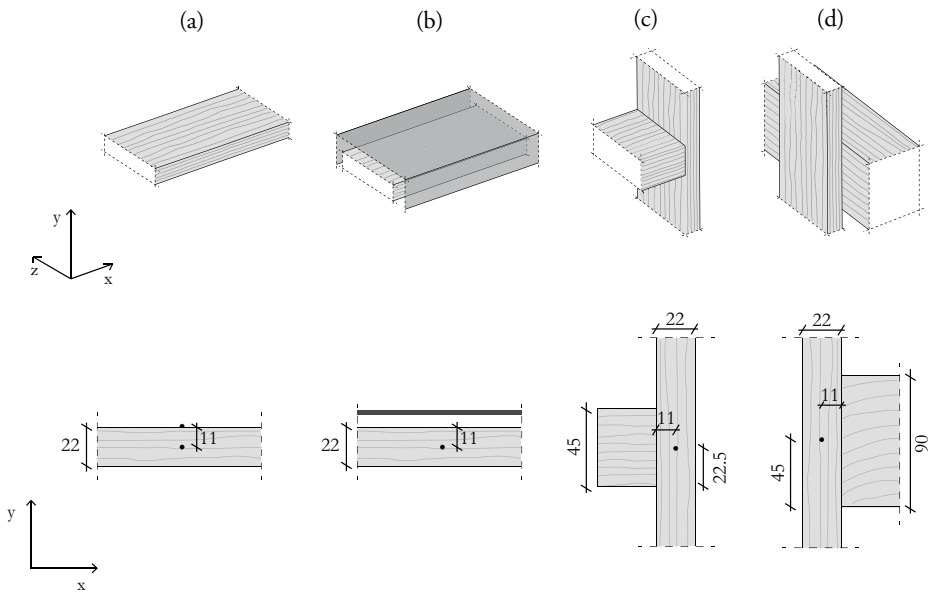


Figure 6.2: Some details involved in the experiment reported by Isaksson & Thelandersson (2013), units in (mm).

6.3 New data sets

6.3.1 Niklewski et al. 2018b

The purpose of the experiment was to investigate the effects of detailing on the wood moisture content and to relate these effects to the relevant weather parameters. The study is similar, methodologically, to the study reported by Isaksson & Thelandersson (2013). Original aspects of it include the size of the members involved, the type of detailing employed and the model used for generalizing the results.

The experimental setup was designed in collaboration with two major actors in timber bridge design and construction who are active in Sweden. The design details included in the study are frequently used for pedestrian bridges, usually together with conventional salt-based treatments. The wood members and other materials were obtained from these same actors.

The final design included 15 different types of different configurations, involving a total of 18 measuring points with some of the configurations having multiple measuring points. The measurements were taken by use of the resistance-type method with pin-type electrodes being pushed to a depth of 10 mm beneath the exposed wood surface. Figure 6.3 provides an overview of the test setup and Figure 6.4 shows some photographs of

the beams and columns involved in the experiment. The following configurations were included:

1) Free beams
   - Rubber sealing on the top face and ventilated cladding on the sides (B1a-b)
   - Rubber sealing on the top face (B2a-b)
   - Freely exposed beams (B3a-b)
2) Steel fasteners connected to the wood
   - A circular anchoring plate ($B4_d$)
   - A square anchoring plate ($B5_d$)
   - A common type of nail plate ($B6_d$)
   - A slotted-in steel-plate with dowels ($B7_d$)
3) Wood on wood connections
   - A vertical contact area, with three different gap-sizes ($B8_d$-$B10_d$)
   - A horizontal contact area, with two different sizes of the connecting area ($B11_d$-$B12_d$)
4) Column connected to concrete
   - A polythene distance located between the end-grain and the concrete and a drip-nose protecting the end-grain from run-off water ($C1_d$)
   - A polythene distance located between the end-grain and the concrete ($C2_d$)
   - The column end-grain and the concrete being in direct contact ($C3_d$)

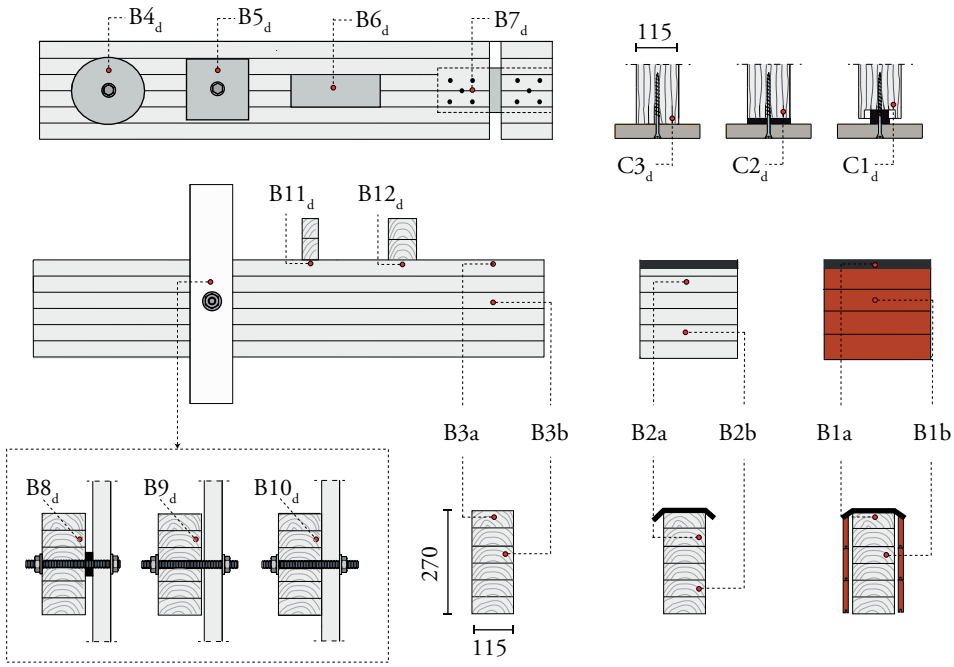


Figure 6.3: An experimental setup designed by Niklewski *et al.* (2018b), the measuring points being indicated by red dots. Units in (mm).

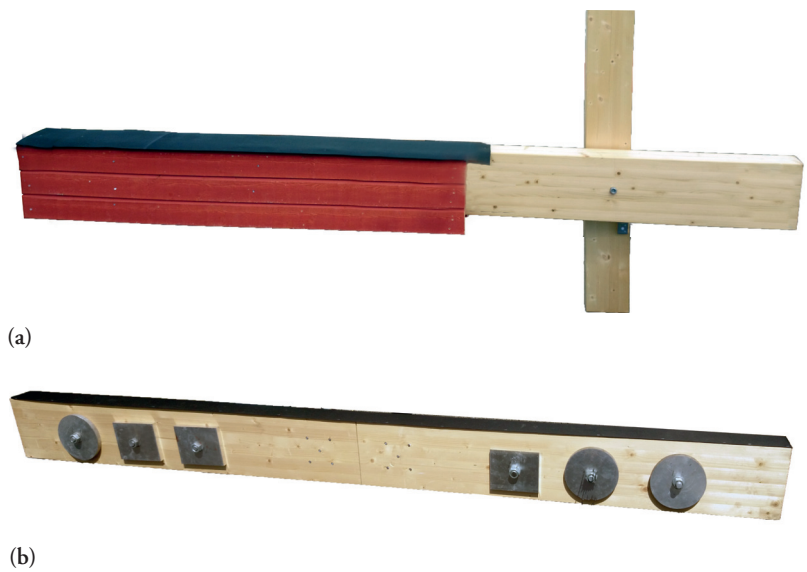


Figure 6.4: A fully sheltered beam and a wood-to-wood vertical contact area (a) and a beam to which various pressure plates and a slotted in steel plate with dowels have been attached (b)

Measuring points were placed at locations that were deemed critical to the details in question. Altogether, 54 measuring points were included (3 replicates of each 18 unique measuring points).

One of the downsides of the methodology involving use of pin-type moisture sensors is the lack of spatial resolution concerning the wood volume close to the details. Ideally, the pins should capture the highest moisture content in the area around the joint, granted that the point having the highest moisture content is the point that is most susceptible to decay. Assuming that water is able to wet the entire interface area between the connecting members, this point is generally located in the center of the area at which point the distance to the evaporating surface is the greatest. However, some details consist of two members that are held together by force, thus limiting the size of the gap and the possibility for water to penetrate between the members. It is thus possible that the moisture content is higher closer to the edges of the contact area than at the center of it. From the results obtained it was clear that this was also the case, as discussed in Paper III.

Additional measurements include:

1) Monitoring of the surface wetness at measuring points B2a, B2b, B3a and B3b (unpublished).
2) Monitoring of the relative humidity, the precipitation, the wind velocity and the air temperature.
3) Monitoring of wood temperature in one of the sheltered beams (B1b) and in one of the exposed beams (B3b)

The surface measurements revealed a few interesting differences between the top surfaces, the side surfaces and the partially sheltered side surfaces. These observations have previously not been published and are therefore briefly discussed here. Due to the pins in question being uninsulated, their response peaked at times when a water film was present on the wood surface and subsequently declined as the wood surface layer dried out. Figure 6.5 (a) shows the response of a top surface and a side surface, respectively, where the most distinct peaks (height greater than 8%) having been counted by use of the MATLAB signal processing toolbox. The width of each peak at half-height has also been calculated, as shown in Figure 6.5 (b). As can be seen from Figure 6.5 (a), certain wetting sequences were only present on the top surface, whereas there were basically no peaks that were present only on the side surface. Over the entire year involved, a total of 212 peaks were counted on the top surface (B3a), as compared with the 135 peaks that were counted on the side surface (B3b). Partial shelter was found to reduce the number of peaks to 117 (B2b) and 67 (B3a), depending on the angle between the measuring point and the overhang. Interestingly enough, the decrease in wetting sequences due to the

shelter that was provided did not yield a significant decrease in the moisture content as measured at a depth of 10 mm from the exposed surface. Another interesting finding was that the top surface and the side surface differed primarily in terms of frequency of wetting, or number of peaks, whereas the duration of wetting, or peak width, was very similar when comparing those peaks that were common in both time-series (see Figure 6.5 (a)).

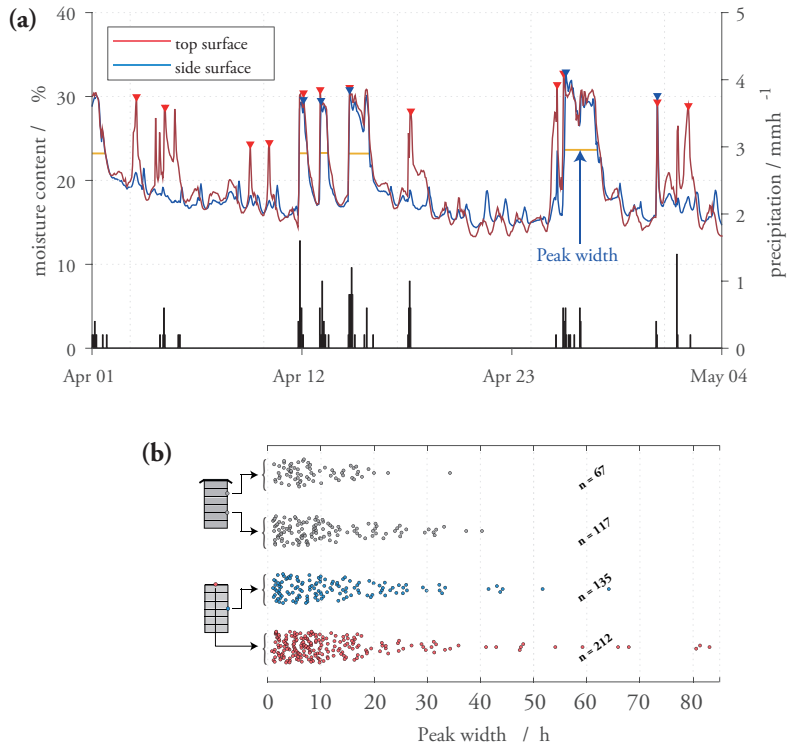


Figure 6.5: In (a): Surface conditions measured with uninsulated pins. Peaks having a prominence exceeding 8 % moisture content have been marked and counted by the MATLAB signal processing toolbox. The widths at half-peak height on the side surface have been marked. In (b): Peak counts and their width.

6.3.2 Niklewski et al. 2018

The purpose of this study was to investigate the effects that weathering of the surfaces has on the moisture conditions of wood. The decision to investigate this stemmed from a set of discrepancies observed during the simulation of long-term data sets (covering periods of 2-3 years) during which the nature of the modelling error exhibited a notable increase over time. Figure 6.6 shows such a data set. If the experimental data is evaluated alone, the increasing long-term trend that is evident can be attributed to variations in the weather, for example due to there being greater amounts of precipitation during the final

year. Such variations were already considered, however, in the numerical model. Thus, the variation of the errors involved provide some indication that the material properties themselves are in fact changing over time.

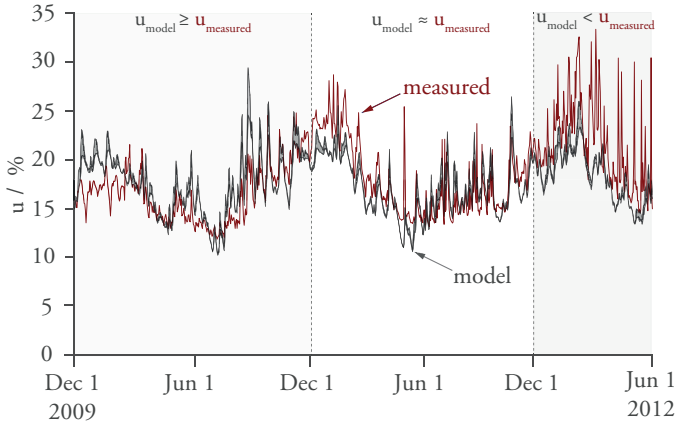


Figure 6.6: Measured and calculated moisture content in the middle of a horizontal Norway spruce board ($22 \times 100 \times 500$ mm^3) over a period of three years, using the model described in Paper I.

There is rigorous literature available on changes in wood characteristics over time, as discussed earlier in Chapter 4. There has been only limited interest, however, in the question of how such changes affect the moisture content of wood and consequently of how it can facilitate the growth of decay fungi. In line with this, an experiment was designed to investigate how changes in the surface characteristics of wood affect the moisture variation of wood exposed to outdoor conditions. The testing involved specimens which had been pre-weathered for 7 years and a set of axially matched control specimens. Both sets of specimens were exposed to cyclic single-sided spray. The spray sequence was intended to induce large differences between the two sets of specimens by initiating the next spray cycle shortly after, or shortly prior to, the weathered surface having dried out.

Two different methods were used to study the surface conditions, one of them based on electrical resistance and the other based on colorimetric analysis. Although the accuracy of resistance-type sensors is rather limited under conditions of high moisture content, the point in time when the wood changes from being wet to dry (around the FSP) could be determined on the basis of the distinct change in the slope of the drying curve that occurs when the surface layer transitions between the hygroscopic and over-hygroscopic moisture range (Yamamoto *et al.*, 2013). The locations of the electrodes are shown in Figure 6.7. The colorimetric method exploits the change in optical appearance that wetting brings about, stemming from the lower refraction index of water than of air.

Exposure to water changes temporarily the perceived color of the wood surface. The cumulative duration during which the color deviates from its initial value was used for estimating the period of time during which the surface was wet. Although none of the methods were able to determine the actual moisture content within the over-hygroscopic moisture range, the point in time at which the surface transitioned from being wet to dry appeared in both of the time-series. Combined with one another, the two methods provided a clear picture of the surface conditions, including (1) the patterns of surface drying that could be noted, (2) the duration of time during which liquid water was present on as well as within the surface of the wood, and (3) a local measure of the moisture content on the surface below the FSP.

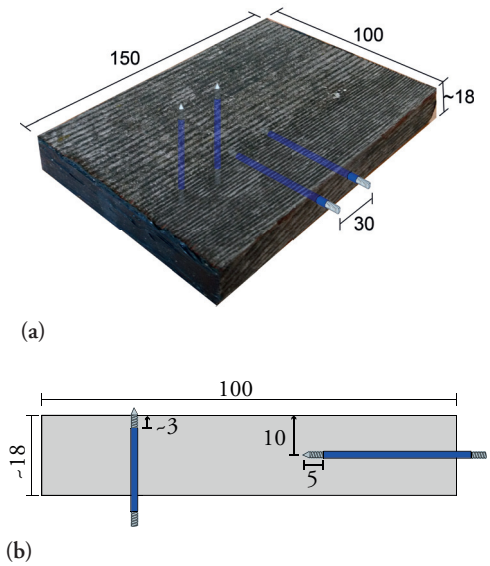


Figure 6.7: A specimen with a weathered surface layer (a) and cross-section of the wood showing the locations of the electrodes (b).

Figure 6.8 shows the optical and the electrical response when a wood specimen is exposed to a one-hour sequence of being sprayed. A reference image was taken prior to the test carried out (1) and the change in optical appearance over time was then calculated for each consecutive image. When the wood was wetted, the electrical resistance increased instantly as the water connected the two electrodes. The reflectance of the wood surface was at the same time reduced, as indicated by the abrupt peak in ΔE^* (2). The resistance then increased slowly with a corresponding slow decrease in the measured moisture content while the color remained more or less constant (3). Finally, the color began returning to its original value (4), at the same time as the electrical resistance began increasing rapidly, with a corresponding rapid decrease in the measured moisture content.

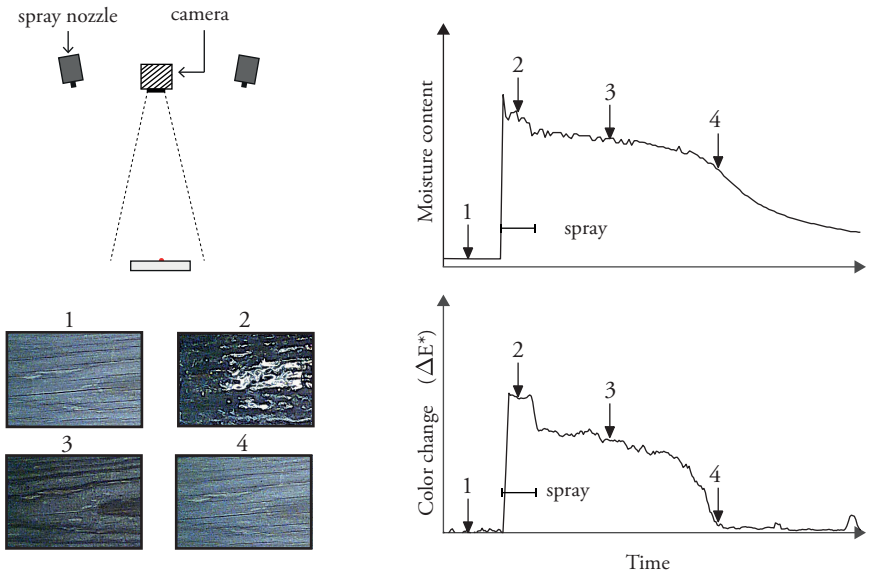


Figure 6.8: Monitoring surface wetness through use of a conventional digital camera.

The method just described was successfully used to detect both the presence of liquid films and the duration of surface wetness. Although more sophisticated and accurate optical methods exist, such as those based on surface temperature (Scheepers *et al.*, 2017), the method based on visible light is simple to use, requires no calibration and no sophisticated instruments. The images utilized in Paper II were captured by a medium-resolution (720 p) commercial digital camera in order to limit the hard disk space and computational time required for image processing. Nevertheless, the spatial distribution of the surface wetness was captured rather accurately.

Figure 6.9 shows a selection of typical results obtained using the colorimetric method. The intensity of the grayscale images signifies the length of the time period during which the surface remained wet when exposed to a 1-hour spray sequence. The resulting images revealed several interesting features, including the following:

- Weathered wood maintained a state of surface wetness about twice as long as freshly planed wood.
- Earlywood dried more quickly than latewood, as seen in Figure 6.9 (d).
- Cracks closed and re-opened due to volumetric changes associated with water absorption, as indicated by the elongated dark patches that can be seen in Figure 6.9 (b).

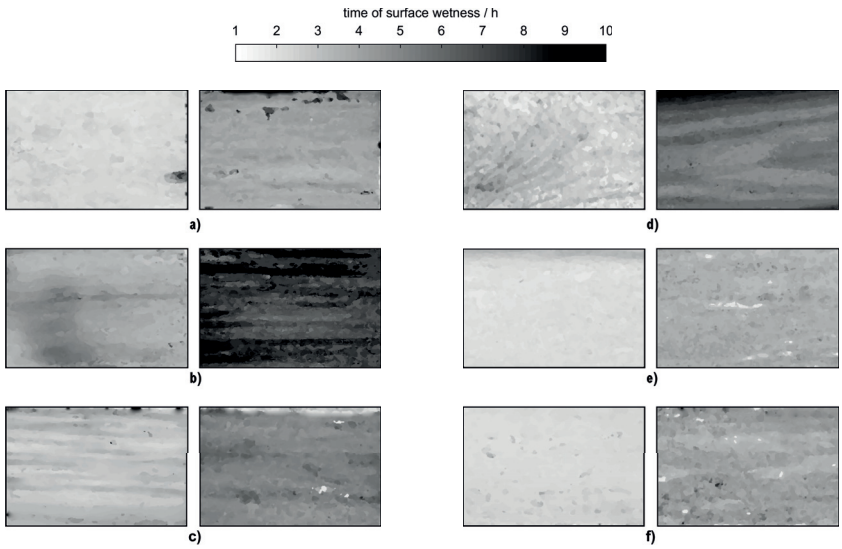


Figure 6.9: The duration of surface wetness as assessed by time-lapse digital imaging, including pairs of weathered (left) and re-surfaced specimens (right). Spruce (a), Western red cedar (b), and Beech (c), Pine sapwood (d), Oak (e) and Ash (f).

Summary and conclusions

Performance-based durability design is a quantitative framework for estimating the service life of timber members. The framework is largely comprised of two parts:

1. A model for estimating the effect of various environmental exposures on the moisture conditions of wood
2. Another model for predicting how the material responds to the conditions in question.

The core objective of the present thesis was to develop a new exposure model to enable more accurate assessment of the various environmental exposures and their effect on the durability of wooden members. Key contributions of the present thesis involve studies on the effects related to detailing and weather history as well as their interdependency.

The first two papers dealt with *the effect of climate on the moisture conditions of exposed members without drying constraints*, with the aim to evaluate the reference situation (a horizontal board) and possible long-term effects that may evolve over time. Paper I highlights an interesting aspect that was not considered in the existing performance-based design framework, namely the spatial variation of durability conditions in the member. Apart from the fact that the numerical model gave a relatively accurate account of climatic effects, the following points summarize some of the core findings:

- Service life assessments in above-ground conditions are strongly affected by the depths at which the moisture conditions are probed.
- The conditions for decay growth are most favourable near the wood surface, thus implying that decay is most likely to establish here first.
- The two decay models that were evaluated gave inconsistent service life estimates, despite them originally being developed from the exact same data set.

The discrepancy mentioned in the last point above is quite likely related to the models

being applied under less severe conditions than those of the accelerated decay set-ups that they were originally calibrated for. Although it can not be concluded whether one model is more correct than the other, the general inconsistency implies that service life assessments of this sort should be interpreted with caution, since the results are dependent on the nature of the decay model employed.

Paper II *investigated possible long-term effects involved in the moisture behaviour of the reference situation*. For durability applications, it is imperative that the accuracy of the exposure model remains stable over long periods of time. At the same time, effects that evolve over time, such as photodegradation and cracking, are known to affect the absorption of moisture into wood. A method was developed for studying the magnitude of this effect through comparing specimens having weathered surfaces with a control set of specimens having freshly planed surfaces. Core findings include:

- Weathering exhibits a pronounced effect on the wood moisture content.
- The effect of weathering on the moisture content fluctuations is primarily confined to the surface layer of the wood, yet a noticeable increase in moisture fluctuations should be expected also deeper in the core of the wood samples.

It remains unclear exactly how these effects evolve over time. It is, however, quite likely that the conditions become stable, at least to some extent, after 1-2 years as this is the time frame when the majority of the physical surface degradation takes place.

Papers III *and* IV *provides two different contributions for dealing quantitatively with the moisture conditions of details*. The aim of Paper III was to refine and improve the pre-existing method for dealing with the effect of detailing. A comprehensive experimental study on the moisture variation of structural wood members was conducted as part of the study presented in Paper III. One of the core findings was that the increase in moisture content due to detailing, or *moisture trapping*, could be connected to the weather history at the test site through an empirical model. To the authors knowledge, this is the first time a model has been used to describe the moisture conditions in details as a function of weather data, although the model presented in Paper III was used for exploratory rather than predictive purposes.

Paper IV goes on to give a more detailed account of the moisture conditions in a few selected details. *A numerical predictive approach was employed so as to be able to relate weather parameters (relative humidity, temperature and precipitation) to the moisture distribution of a set of details*. Moisture trapping was considered by setting the drying rate through contact faces equal to zero, effectively leading to pockets of moisture being formed subsequent to wetting. The spatial distribution of the moisture content over time was then used to calculate the spatial distribution of decay activity. The main findings include

- The effects of detailing on the moisture content, and by extension the durability, are quite possible to assess quantitatively.
- The model is able to capture possible non-linear effects between frequency and duration of precipitation and decay activity.
- Accurate predictions require precise and reliable input in terms of the boundary conditions involved.

The model is sensitive to the boundary conditions involved, and the boundary conditions of joints are inherently difficult to describe. Yet, in a design context it is quite possible to estimate the moisture content of details by approaching uncertainties with a conservative philosophy, assuming for example that contact faces of rain-exposed details are completely and consistently wetted when exposed to precipitation and that zero drying may occur through the contact face. The resulting conditions, and the corresponding decay assessment, does not necessarily comply with the real situation but may still serve as an adequate conservative basis for determining the design life or the minimum time between inspections.

Paper V is an extension of Paper IV where the numerical model was used to *investigate the relative variation of decay hazard over different European climates*. The numerical model was used to develop two sets of decay hazard maps, one set of maps for free members and another set for joints. The objectives were twofold, first to evaluate the differences in projected dose between two different decay prediction models, and secondly to evaluate the dependence of relative performance on climate. The two decay models provided quite different results with respect to the dependency between precipitation and the effect of detail design. Most notably, the logistic decay model indicated that the relative effect of detailing and the relative effect of climate were interdependent, which is significant since the the relative effect of detailing has previously been assumed to be more or less independent of the climate. Specifically, the relative increase in exposure due to detailing decreased with increasing amounts of precipitation. At the same time, the simplified logistic decay model, that is currently used in the performance-based design framework, did not show a dependency of this sort.

The ability to predict the spatial distribution of the moisture content over time, as opposed to the global average moisture content or the moisture content at a given depth, has a number of advantages in predicting the service life of members. Most notably, the output of the moisture model was found to be compatible with decay models that are based on the inherent biological relationship between decay activity and the material climate. It is reasonable to assume that, in the event of non-uniform moisture distribution, decay fungi favour regions in which the material climate is most fitting for fungal growth. This means that the colonization of decay fungi on the surface of a specimen can perhaps best be described through use of the variation in moisture content that oc-

curs on the same surface, as opposed to other metrics such as the global average moisture content. Global averages and similar measures can be used to assess softer metrics such as the relative decay risks, but they are less suitable for predicting actual decay rates.

Ultimately, the results presented as part of the present thesis are intended for use in connection with service-life planning and risk assessment of wood structures. The results of the present thesis have already, in part, been implemented as part of a performance-based service life guideline for timber bridges. However, as discussed in the section that follows, there is still a great deal of work to be done before the performance based framework can be considered as part of the standardized design methodology, an effort that would certainly involve both further model development as well as verification of its performance.

Further research

The aim of the present thesis has been to refine and expand the existing performance-based design framework for wood, strong emphasis being placed on *one* of the aspects of durability assessment, namely the prediction and assessment of the moisture conditions. The results obtained suggest that the moisture content of spruce wood, which is used as a reference species, can be predicted with fair accuracy. The step from accurate moisture content prediction to accurate assessment of durability is however a significant one, its involving the relationship between moisture content, temperature and wood decay. Although the present framework enables such assessment to be made, the reliability of the predictions obtained remains largely unverified. In order to establish confidence in and credibility of the design methodology as a whole, future efforts should be aimed at verifying its performance in real applications. This task involves reality checks as well as verification through long-term monitoring, where moisture content, temperature and decay progression are carefully monitored under realistic conditions, and not simply in accelerated trials.

Another important step is to expand the current methodology with respect to potential *missing features*. For example, it is believed that cracks and other imperfections, that are currently not considered here, may serve as important catalysts for decay on transverse surfaces. Another feature that is also largely missing is knowledge of how local conditions (such as terrain, vegetation and proximity to water as well as shading) affect the microclimate present at the surface of the wood.

Finally, even a reliable design methodology is virtually useless if it fails to reach the hands of practitioners. It is thus imperative to explore the possibilities for the implementation of design standards and for making user-friendly guidelines. There is currently a pending grant proposal (*Forest Value*) for developing an open-source design-tool for practitioners. One of the work packages is also set to deal with *missing features*.

Other publications

Scientific contributions not included in the present thesis:

I **Effect of density and cracks on the moisture content of coated Norway spruce (Picea abies (L.) Karst)**
T. Sjökvist, **J. Niklewski**, Å. Blom
Submitted to Wood and Fiber Science

II **Durability of rain-exposed timber bridge joints and components**
J. Niklewski, E. Frühwald Hansson, A. Pousette, P.A. Fjellström
Presented at the World Conference on Timber Engineering 2016, August 22-25, Vienna, Austria

III **Performance based service life design of timber bridges. In: Durable timber – final report and guidelines. Chapter 2.**
S. Thelandersson, **J. Niklewski**, C. Brischke. L. Meyer-Veltrup
SP Report 2017:25, Skellefteå, 2017.

IV **Design and performance prediction of timber bridges based on a factorization approach**
L. Meyer-Veltrup, C. Brischke, **J. Niklewski**, E. Frühwald Hansson
Wood Material Science and Engineering, 13(3)167–173

Summary of appended papers

Paper I

A numerical model was used here to describe the moisture conditions in wooden boards made of Norway spruce (*Picea abies*). Numerical solutions were first compared with laboratory measurements obtained from the literature. The model was then used to model rain-exposed and sheltered boards subjected to outdoor weathering conditions over a period of two years. The moisture content in the middle of the specimens and the duration of surface wetness were reproduced rather accurately. Finally, the model was coupled with two different decay prediction models, these enabling service life predictions of wooden boards under different climate conditions to be obtained.

Paper II

An experimental study of the effects of weathering (of surfaces) on the moisture conditions within and on wooden boards was carried out. The moisture conditions of eight different species of wood were monitored in conjunction with exposure to a cyclic spray sequence. Each test specimen was cut in half, whereby the superficial damage on one of the halves was removed by planing. The two sets were then compared on the basis of the duration of surface wetness, the moisture content in the surface layer and the moisture content in the core of the samples. A novel technique for estimating the areal distribution of surface wetness was developed specifically for this study.

Paper III

This paper deals with the effects of different types of detailing on the moisture conditions of wooden beams and columns. An experimental setup including various beam and

column details was designed, built and subsequently exposed to outdoor conditions for a year while the moisture content was being monitored at critical points. The variation in moisture level was strongly affected by the type of moisture absorption involved and the potential for post-wetting and re-drying, the latter being inhibited primarily in contact areas. An initial attempt at assessing the variations in moisture level in exposed details was then undertaken, based on a semi-empirical model that was developed. By integrating that model with a decay prediction model, the results of the study could be utilized for durability assessment.

Paper IV

A numerical model was used to describe the moisture behaviour of joints subjected to precipitation. The numerical model developed in Paper I was adapted to longitudinal moisture transport, the effects of wood-to-wood contact areas being studied by prescribing a complete lack of wood-to-air interaction for the surfaces in question. Just as in the first paper, the model was initially tested by use of high-quality data obtained in a laboratory setting, and was then tested in an outdoor environment. The model was found able to describe with reasonable accuracy the general moisture behaviour of wood near the joint. The results are of considerable interest since the model allows the moisture content to be predicted in problematic locations in which decay is known to develop.

Paper V

The numerical model employed in Paper IV was then used to develop decay-hazard maps for joints of specific types as well as for free boards. Annual variations in the moisture content of a joint and of a free board were calculated for 300 European sites, the results being presented as heat maps showing the areal intensity of decay hazard. Overall, the tendencies evident on both maps were found to be consistent with the Scheffer climate index (SCI).

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Scientific publications

Author contributions

The names of the authors are abbreviated by use of their initials. It is implied that all of the co-authors have read the manuscript and been able to provide valuable feedback on it. The first authors was the corresponding author for each of the published papers.

Paper I: Moisture content prediction of rain-exposed wood. Test and evaluation of a simple numerical model for durability applications.

JN did the modelling and data analysis. MF provided data and wrote part of the methods section. TI provided data.

Paper II: The effect of weathered surfaces on the moisture conditions of wood. Measurements and modelling.

CB and LMV provided the samples used in the experiment. JN designed the experiment, conducted the trials, analysed the data and did the numerical modelling.

Paper III: Moisture conditions of rain-exposed glue-laminated timber members: the effect of different detailing.

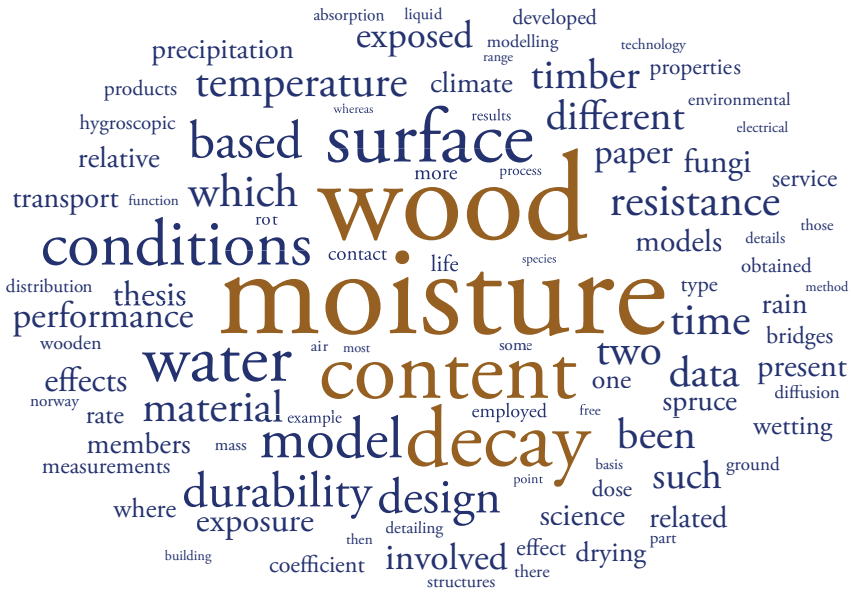
JN designed the experiment, conducted the trials and analysed the data.

Paper IV: The effects of joints on the moisture behaviour of rain exposed wood

JN did the modelling. MF provided the experimental data. MF contributed significantly to the analysis of the results and wrote the methods section describing the experiments.

Paper V: Numerical study on the effects of macro climate and detailing on the relative decay hazard of Norway spruce

JN did the modelling and the visualisation of the hazard maps. The authors came up with the idea behind the paper collectively.



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