Moisture conditions in rain exposed wood joints - Experimental methods and laboratory measurements

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Moisture conditions in rain exposed wood joints

Experimental methods and laboratory measurements

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Maria Fredriksson

CLIMATE
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PAPER

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Preface

This work has been performed at the Division of Building Materials, Lund University between 2008 and 2013 and is a part of the Woodbuild programme, funded by Vinnova (the Swedish governmental agency for innovation systems) and industries in the forest and building sector.

During my Phd-studies, guidance has been provided by my main supervisor Lars Wadsö and my assistant supervisor Peter Johansson whom I would like to thank for their clever comments as well as for believing in me and giving me the opportunity to become a Phd-student. I would also like to acknowledge Lars-Olof Nilsson for sharing his vision of how service life predictions should be performed.

This study would not have been the same without the material from the experimental forests at the Swedish University of Agricultural Sciences. I am very grateful to Thomas Ulvcrona who provided all wood used in this thesis and who also received me for visits at Svartberget research station and its surroundings. I would also like to thank Owe Lindgren for the co-authorship on Paper III and for helping me to perform the CT measurements at Luleå Technical University in Skellefteå. In addition, Johan Claesson is gratefully acknowledged for the invaluable help with the mathematics in Paper VII.

Special thanks go to Stefan Backe who has sawn all specimens used in this thesis and to Bengt Nilsson for ordering various components and patiently answering questions about pressure regulators. I would also like to thank my other colleagues for making the Division of Building Materials such a pleasant place to work at.

And finally, to Eric, thank you for always receiving me with a smile in the evenings (most often also with dinner ready on the table) also after too long working days. You're the best!

Abstract

This thesis concerns the moisture conditions in rain exposed wood structures, i.e. wood exposed to high moisture levels. The focus was on the microclimate (the climate at the wood surface) and the material climate (the wood moisture content) in joints. Methods for determination of microclimate, i.e. the duration of moisture on a wooden surface and the duration of water trapped in gaps between two boards, as well as a method for moisture content determinations close to surfaces and joints were developed. In addition, a theoretical study was performed to investigate the influence of the distance to a surface and specimen size on resistive moisture content measurements.

The relationship between microclimate and moisture content in wood joints was studied by exposing three different types of joints to artificial rain in the laboratory. The microclimate was varied by varying the size of the gap between the two boards. The measurements were performed on Norway spruce (*Picea abies* (L.) Karst.) heartwood and sapwood. Both slow grown wood from northern Sweden and fast grown wood from southern Sweden were used in the experiments. The duration of high moisture contents was evaluated for all joints. In addition, the measured moisture contents were used to evaluate differences in expected service life for the different joints using three decay models from the literature. End grain water absorption was also studied separately using computed tomography.

Modelling of moisture transport at high moisture levels requires knowledge of sorption properties also in the high moisture range. However, since the method used in the high moisture range was originally designed for desorption experiments there is a lack of absorption isotherm data in the high moisture range. A method for absorption experiments based on the pressure plate technique was therefore developed. Measurements were performed at one pressure level for Norway spruce sapwood and the results were compared to results from absorption experiments at lower relative humidity levels as well as a pressure plate desorption experiment.

Sammanfattning

Denna studie behandlar fuktförhållandena i regnexponerade träkonstruktioner, d.v.s. träkonstruktioner som når höga fuktkvoter. Särskilt fokus var på mikroklimatet (klimatet på träets yta) och materialklimatet (träets fuktkvot) i anslutningar. Metoder för att mäta mikroklimatet, d.v.s. våttider på en träyta och varaktighet av vatten i spalter, utvecklades liksom en metod för att mäta fuktkvot nära ytor och anslutningar. En teoretisk studie gjordes också för att undersöka hur avståndet till en yta samt en provkropps storlek påverkar mätningen av elektrisk resistans och därmed fuktkvotsmätningar.

Tre olika anslutningstyper vattenexponerades i laboratorium och mikroklimat och fuktkvotsprofiler mättes under uppfuktning och uttorkning. Mikroklimatet varierades genom att variera storleken på spalten mellan de två brädorna i anslutningen. Alla mätningar gjordes på kärnved och splintved av gran (*Picea abies* (L.) Karst.). Både material av långsamväxande gran från norra Sverige och snabbväxande gran från södra Sverige användes i försöken. Varaktigheten av höga fuktkvoter utvärderades för alla anslutningar. De mätta fuktkvoterna användes också för att utvärdera skillnader i förväntad livslängd mellan de olika anslutningstyperna. Ändträuppsugning studerades även separat med hjälp av datortomografi.

För att kunna modellera fukttransport vid höga fuktnivåer behövs sorptionsegenskaper också i det höga fuktområdet. Eftersom metoden som används i det höga fuktområdet ursprungligen är utformad för desorptionsförsök saknas dock data för absorption. Därför utvecklades en metod för absorptionsförsök baserad på ’pressure plate’ metoden. Mätningar gjordes för en trycknivå för splintved av gran och resultaten jämfördes med resultat från absorptionsförsök för lägre fuktnivåer samt resultat från desorptionsmätningar med ’pressure plate’.

Contents

Appended papers

This thesis is based on the following papers:

Paper I	Fredriksson M, Wadsö L, Johansson P, (2013), Methods for determination of duration of surface moisture and presence of water in gaps in wood joints. *Wood Science and Technology, 47(5):913-924*
Paper II	Fredriksson M, Wadsö L, Johansson P, (2013), Small resistive wood moisture sensors; a method for moisture content determination in wood structures. *European Journal of Wood and Wood Products, 71(4): 515-524*
Paper III	Fredriksson M, Lindgren, O, Computed tomography measurements of end grain water absorption and redistribution in Norway spruce (*Picea abies* (L.) Karst.) heartwood and sapwood. *Submitted.*
Paper IV	Fredriksson M, Johansson P, A method for determination of absorption isotherms at high relative humidity levels: measurements on Norway spruce (*Picea abies* (L.) Karst.). *Submitted.*
Paper V	Fredriksson M, Wadsö L, Johansson P, Ulvcrona, T, Influence of design on the moisture conditions in Norway spruce (*Picea abies* (L.) Karst.) joints. Part 1: Moisture content profiles and microclimate measurements. *Submitted.*
Paper VI	Fredriksson M, Wadsö L, Johansson P, Influence of design on the moisture conditions in Norway spruce (*Picea abies* (L.) Karst.) joints. Part II: Comparative evaluation of decay susceptibility. *Submitted.*
Paper VII	Influence of distance to surfaces and specimen size on moisture content measurements. *Manuscript.*

The contribution of the authors to the papers included in this thesis was as follows:

Paper I	MF did the laboratory work, evaluated the data and wrote the majority of the paper. Methodical aspects were discussed with LW and PJ who also commented on the manuscript.
Paper II	MF did the laboratory work, evaluated the data and wrote the majority of the paper. Methodical aspects were discussed with LW and PJ who also commented on the manuscript.
Paper III	MF did the laboratory work (CT-scanning was performed together with OL), evaluated the data and wrote the majority of the paper except some parts concerning CT which were written by OL.
Paper IV	MF did the laboratory work and wrote the paper. PJ had the initial idea and the authors discussed methodical aspects during the development of the method.
Paper V	MF planned the study together with LW and PJ. MF did the laboratory work, evaluated the data and wrote the majority of the paper. TU provided the material and wrote parts of the material section. LW and PJ contributed with comments on the manuscript.
Paper VI	MF planned the study together with the co-authors who also commented on the manuscript. MF did the laboratory work, evaluated the data and wrote the paper.
Paper VII	JC derived the equations and MF did the calculations and wrote the paper. LW had the idea and commented on the manuscript.

Introduction

Durability and service life prediction

All materials degrade with time but different materials are subjected to different degradation mechanisms; low temperatures in combination with high moisture contents can cause frost damage on materials such as concrete or bricks. Metals (e.g. the reinforcement in concrete structures) corrode if conditions such as pH and relative humidity are favourable and organic materials, for example wood, are degraded by decay fungi and insects. Knowledge of these mechanisms is important in order to design durable structures and to know which service life to expect when choosing certain materials and designs.

One approach that can be used to understand which service life to expect of a structure is to compare the exposure of a material to its resistance (see e.g. Sarja 2000). This approach is similar to the one used in structural engineering where a load (exposure) is compared to the bearing capacity (resistance) of a structural element; the bearing capacity should be higher than the load, otherwise the structure will fail. Applied to service life prediction, this means that the structure should be able to withstand the exposure at the location where it is situated throughout the wanted service life. That is, for severe climate conditions a material with a high resistance is needed, but for less severe conditions it is possible to use a material with a lower resistance to obtain the same service life. Since different materials are degraded by different degradation mechanisms relevant exposure and resistance parameters need to be identified for the material that a structure consists of. For example, reinforcement corrosion in concrete is induced when the chloride concentration at the depth of the reinforcement exceeds a certain threshold value or when the pH-value is lowered due to carbonation (a reaction between the concrete and carbon dioxide) (e.g. Ahmad 2003; Luping et al. 2012). Relevant exposure parameters in this case are therefore the chloride concentration and the carbon dioxide concentration at the surface and corresponding resistance parameters are the permeability of the concrete as well as the thickness of the layer that covers the reinforcement. These two parameters determine how fast the chloride and carbonation fronts will reach the reinforcement and thereby also the service life.

The relevant exposure and resistance parameters are not only material specific but also depend on the application; for wood in the building envelope, the exposure parameter is primarily a combination of relative humidity and temperature and the resistance parameter is the resistance to mould growth. However, for rain exposed wood outdoors that reaches high moisture contents, resistance to decay by rot fungi is the main resistance parameter of interest and the relevant exposure parameter is therefore a combination of wood moisture content and temperature.

Scope of this thesis

This thesis concerns the exposure conditions of wood outdoors above ground, i.e. rain exposed wood structures. The main focus is on the relation between the moisture conditions at the surface (the microclimate) and the wood moisture content (the material climate). Methods for determination of microclimate, i.e. duration of surface moisture and water trapped in gaps (*Paper I*), as well as moisture content (*Paper II*) were developed and used for an experimental study of the relation between microclimate and moisture content for different wood joints (*Paper V* and *VI*). End grain water absorption was also studied separately by computed tomography (*Paper III*). Moisture transport models for high moisture levels require sorption properties also in the high moisture range. Therefore, a method for determination of the absorption isotherm, i.e. the relation between the relative humidity and the moisture content, at high moisture levels was developed (*Paper IV*). In addition, a theoretical study of the influence of specimen size and distance to a surface when the moisture content is measured by the resistive method was performed (*Paper VII*). All studies were performed on Norway spruce (*Picea abies* (L.) Karst.).

Service life prediction of outdoor wood structures above ground

Historically, various approaches have been used to determine the durability or service life of wood structures. Even though wood is mainly used for above-ground applications the durability has generally been tested by in-ground field tests (Bergström and Blom 2005). However, the above ground durability is also commonly tested by exposing specimens outdoors on racks (e.g. Bergström et al. (2004)) or in double layer tests (e.g. Brischke and Rapp 2008b). The design of specimens exposed on racks varies but does often include a water trap in order to accelerate the experiment. Examples of common specimen types are L-joints (e.g. Miller and Boxall

1987), lap-joints (e.g. Lindegaard and Morsing 2003), boards with overlap (e.g. Blom and Bergström 2006), T-shaped specimens (e.g. Sell 1982) and rectangular boards (e.g. Bergström et al. 2004). Reviews of the most common methods used in above-ground field tests are given by Råberg et al. (2005) and Bergström and Blom (2005).

The above type of field tests mainly gives the comparative performance of different materials, e.g. it is possible to determine that wood species A is more durable than wood species B. The service life of the specimen can be determined by waiting until the specimens fail, but the determined service life of the component is then only valid if it is exposed in the same way as in the field test; if the exposure is changed, e.g. if there is no water trap in the actual structure where the wood is used, if the climate at the location where the structure is situated is different from the climate where the field test was performed etc. the service life is most probably different from the service life of the specimen in the field test. Since it is time consuming to test durability by exposing specimens outdoors for several years, methods to forecast the performance in a long term field test have been suggested (e.g. Rapp et al. 2000).

The service life of a wood material partly depends on the surrounding climate. Therefore, Scheffer (1971) made a first attempt to find a correlation between climate and the decay rate in different parts of the United States. He developed a climate index that described the potential for decay in above ground structures based on temperature and rainfall data. However, this climate index, often referred to as the Scheffer climate index, has been criticised: De Groot (1982) found that this index was not precise enough since other factors such as detail design and surface treatments etc. are not taken into account, Beesley et al. (1983) found only a weak correlation between the Scheffer climate index and the decay rate for specimens exposed at various test sites in Australia. In addition, Brischke and Rapp (2008a) found no correlation between the Scheffer climate index and the decay rate in their field tests at 27 sites in Europe.

Brischke and Rapp (2008a) emphasize the importance of relating decay progression to material climate since different wood species, in their case Scots pine sapwood and Douglas fir heartwood, have different moisture contents under the same macroclimate conditions. In order to determine the relationship between the material climate and the decay rate Brischke and Rapp (2008a) monitored wood moisture content, wood temperature and decay progress in specimens exposed in double layer tests at 27 sites in Europe during 7 years. The daily average precipitation and average daily temperature were also recorded. The wood moisture content and the temperature were used to estimate a dose consisting of a moisture induced dose and a temperature induced dose. These dose functions were based on moisture content and temperature limits for growth of decay fungi from literature; the minimum and maximum moisture contents and temperatures for growth were assumed to give no dose while the optimum moisture content and temperatures were assumed to give dose 1. The accumulated daily dose was calculated for the specimens in the field tests and was correlated to the decay ratings. The data from these field tests were also used by Isaksson et al. (2012) who present and evaluate different decay models. All models are based on the same approach as in Brischke and Rapp (2008a); a temperature and a moisture induced dose are calculated and a total dose is determined. This total dose is then used to calculate the decay rating index according to the standard EN 252 (European Standardization Committe1990). Here, decay is rated from 0 to 4 where 0 means sound and 4 means failure.

Viitanen et al. (2010) presented a model for growth of decay fungi exposed to variable environmental conditions. The model is based on data from laboratory experiments by Viitanen and Ritschkoff (1991) and Viitanen (1996) and the decay is modelled in two steps: an activation process and a mass loss process. The state of the decay fungi is described by a parameter α which initially has the value zero. The value of α increases during conditions favourable for decay, when the temperature exceeds 0 °C and RH exceeds 95%, and decreases during dry conditions. Mass loss starts to occur when $\alpha = 1$, but only takes place when the temperature exceeds 0 °C and the relative humidity (RH) exceeds 95%. Unlike the models in Isaksson et al. (2012) and Brischke and Rapp (2008a) this model is based on RH instead of moisture content.

Another decay model similar to one of the models presented by Isaksson et al. (2012) is used in an engineering design guideline (Thelandersson et al. 2011a; Thelandersson et al. 2011b). This design guideline concerns not only the relation between material climate and decay, but also the exposure. The exposure is determined by multiplying a basic exposure index, which depends on the geographical location, by factors depending on the local climate, sheltering, distance to the ground, detail design and a calibration factor. These factors were determined either from experimental data, best practise guidelines or expert judgements. More detailed information is given in Thelandersson et al. (2011b).

Work with durability design models has also been performed in Australia (e.g. Leicester 2001; Foliente et al. 2002; Wang et al. 2008) and a service life design guide with background documents (e.g. Wang et al. (2007) concerning decay above ground) is available.

Methods for determination of moisture conditions at high moisture levels

Determination of moisture content

The gravimetric method

The moisture content (u) is a measure of the amount of water present in a material and is defined as:

$$u = \frac{m - m_{\mathrm{dry}}}{m_{\mathrm{dry}}} \qquad (1)$$

where m is the equilibrium mass at a certain moisture content and m_{dry} is the oven dry (103±2 °C) mass (Skaar 1988). The moisture content of a specimen can thus be determined by weighing the specimen before and after drying. This is generally called the gravimetric method or the oven-dry method. In the present work, the moisture content was also determined by measuring the wood electrical resistance and by computed tomography (CT). Both these methods are further described below.

Resistive moisture content measurements

The most common method for determination of the wood moisture content is to use the moisture dependence of the wood electrical resistance. This method is commonly used by moisture content meters (James 1988) but is also widely used in research, both in field tests (Gaby and Duff 1978; Derbyshire and Miller 1997b; Geving et al. 2006; Brischke and Rapp 2008b; Sandberg et al. 2011; Gellerich et al. 2012; Meyer et al. 2012; Isaksson and Thelandersson 2013; Mundt-Petersen 2013) and in laboratory tests (Hjort 1996; Derbyshire and Miller 1997a). The electrical resistance of wood decreases with increasing moisture content (Stamm 1927), but this relation is different in different moisture content ranges; the largest decrease in resistance occurs below the fibre saturation point, i.e. when the water is bound in the cell wall.

Apart from moisture content, a variety of other factors, wood variables as well as experimental variables, affect the wood resistance and consequently also moisture content measurements. Examples of such factors are temperature (Stamm 1927; Takechi and Inose 1953; Keylwerth and Noack 1956; Davidson 1958; Brown et al. 1963; Lin 1965), wood species (Skaar 1988), lignin content (Venkateswaran 1974; Vermaas 1983) and electrode design (Forsén and Tarvainen 2000; Jacobsson 2003). Skaar (1988) claimed that the size of the sample is of little importance since the resistance is concentrated to the vicinity of the electrodes. However, Nore and Thue (2008) found that wood moisture content measurements were affected by the distance to the surface in their measurements in wooden claddings.

Generally, simple uninsulated or insulated pin electrodes are used in wood resistance measurements, but attempts have been made to improve the electrode design. To enable moisture content measurements at different depths Forrer & Vermaas (1987) used electrodes consisting of an insulating material with stainless steel rings. These electrodes were however rather large (diameter 8 mm) which is a problem if the specimens are small. Derbyshire & Miller (1997a) used small electrodes consisting of hypodermic needles (diameter 1.27 mm) insulated with PVC-tubing in their laboratory measurements.

A problem, particularly during long term measurements, is to ensure that the contact between the electrode and the wood remains (Skaar 1988; Dai and Ahmet 2001). This problem is caused by the dimensional changes that occur during drying or wetting of wood. If the contact resistance increases, the measured wood resistance becomes apparently higher which means that the wood is believed to be dryer than it is (Skaar 1988). This problem can possibly be prevented by using screws (Hjort 1996; Derbyshire and Miller 1997b; Norberg 1999) or glued electrodes (Brischke et al. 2008).

In the present study, electrodes that enabled measurements of moisture content profiles and moisture content close to a surface were needed. This required small electrodes and to enable contact between the electrode and the wood, the electrodes were fastened with electrically conductive adhesive. These moisture content sensors are described in *Paper II*. Since a variety of factors other than moisture content may influence the wood resistance, the relationship between moisture content and resistance was determined for the wood material and the electrodes used in the present study. Specimens of the two types used in these experiments are shown in Fig. 1. As the results from a previous study (Nore and Thue 2008) indicated that the measured moisture content might be influenced if measurements are made close to a surface, a theoretical study of the influence of specimen size and distance to a surface was performed. This study is presented in *Paper VII*.

Figure 1. The two specimen types used in *Paper II*.

Summary of Paper II

Small resistive moisture content sensors were developed in order to enable moisture content measurements close to joints and surfaces and at different depths. The sensors were fastened by electrically conductive adhesive to reduce the risk of the sensor loosing contact with the wood during fluctuating moisture conditions. To determine the relationship between electrical conductance and moisture content, small specimens of Norway spruce (*Picea abies* (L.) Karst.) heartwood and sapwood with moisture content sensors were prepared. The relationship between moisture content and electrical resistance was determined for a wide range of moisture conditions by equilibrating specimens both over saturated salt solutions and by the pressure plate method. The moisture content was then determined both gravimetrically and by using the moisture content sensors. The error, i.e. the difference between the gravimetric moisture content and the moisture content from the regression equation, increased with increasing moisture content.

Summary of Paper VII

A theoretical study was performed in order to determine whether moisture contents measured by the resistive method are affected by the specimen size and the distance to the specimen surface. According to the model, higher resistances are measured in small specimens and close to surfaces, and the magnitude of the error depends on the equivalent radius of the electrodes. The error increases with increasing moisture content.

Computed tomography (CT)

Computed tomography has been used in wood science for several applications; for example, to study wood drying (e.g. Wiberg and Morén 1999) or end grain water absorption (Johansson and Kifetew 2010; Sandberg and Salin 2012), to identify defects such as knots (see e.g. Longuetaud et al. 2012), and to study the performance of welded wood joints (Vaziri et al. 2011). In a CT-scanner, the X-ray source rotates around the specimen and the detectors on the opposite side of the X-ray source detect the attenuation (Fig. 2). After a complete rotation, the X-ray linear attenuation coefficient (also called the absorption coefficient) is calculated in small volume elements (voxels) and is then normalized to the X-ray absorption coefficient of water in order to enable comparison between results from different CT-scanners (Lindgren et al. 1992). This normalized value is called the CT-number and is related to the density of the specimen. Since the wood density is closely related to the moisture content, the moisture content can be calculated from CT-measurements if a measurement on the dry specimen is also made. Equations for calculation of the wood moisture content from the CT-number were presented by Lindgren (1992).

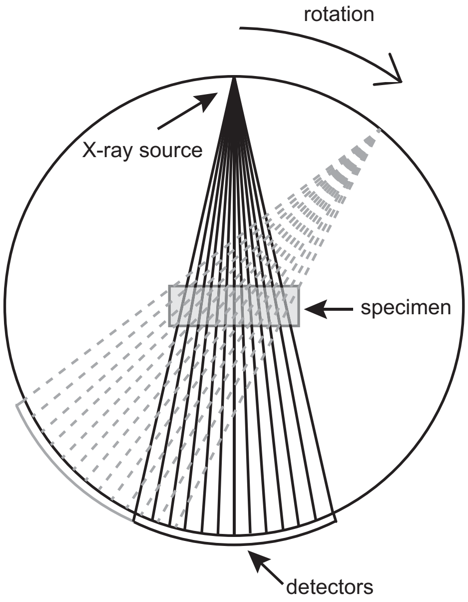
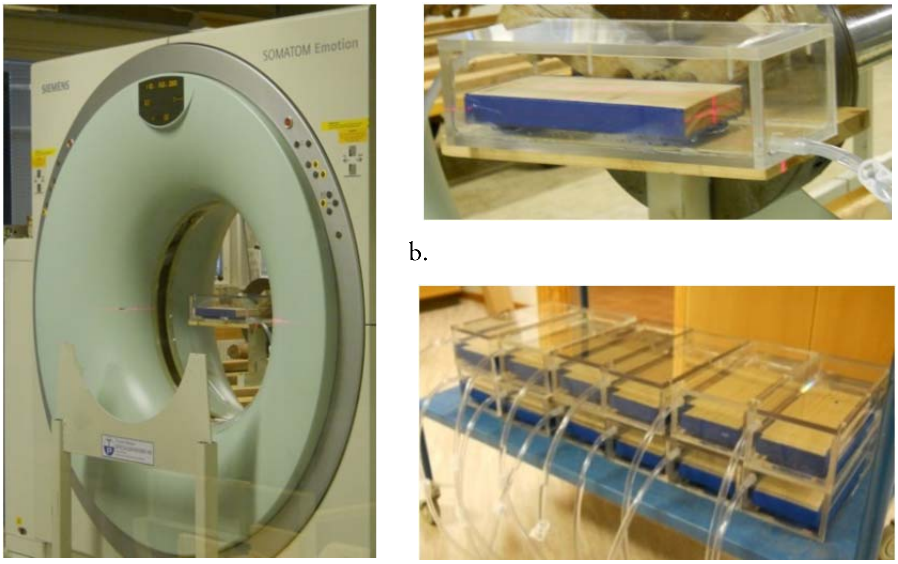


Figure 2. Schematic illustration of a CT-scanner.

In the present work, CT was used to study end grain water absorption and redistribution in Norway spruce (*Picea abies* (L.) Karst.) heartwood and sapwood of both slow grown and fast grown wood. Specimens were placed in individual climate boxes (Fig. 3c) and were scanned individually (Fig. 3a,b) both during water absorption and during redistribution. This study is further described in *Paper III*.



b.

a.

c.

Figure 3. The CT-scanner (a), a specimen in a climate box inside the CT-scanner (laser beam is used for specimen alignment) (b) and all boxes with specimens during the water absorption (c).

Summary of Paper III

End grain water absorption and redistribution in Norway spruce (*Picea abie*s (L.) Karst.) heartwood and sapwood of two provenances (slow grown and fast grown wood) was studied using computed tomography (CT). Specimens were conditioned to 65% relative humidity (RH) and were placed in individual climate boxes. Each box with a specimen inside was then scanned by a medical CT-scanner. Water was let into the boxes and remained there during 6.5 hours. The water was then let out and the specimens were kept in their boxes in which the climate was 100% RH since droplets of water were left in the box. The boxes with the specimens inside were scanned individually both during absorption (water in the box) and during redistribution (100% RH in the box). The water absorption was higher and the redistribution was generally more pronounced for the sapwood specimens than for the heartwood specimens. Generally, the growth ring width did not have a significant influence on the end grain water absorption, probably because the density was similar for the slow grown and the fast grown wood despite the large difference in growth ring width.

Microclimate measurements: surface moisture and presence of water in gaps

There is an interest in measuring the time during which surfaces are wet in several fields of science and technology. Much work on this has been done in research related to plant disease since water on a leaf surface is favourable for bacteria and fungi (Wallin 1963). Monitoring of duration of leaf wetness, i.e. when water is present on the leaf surface, is therefore, for example, useful for making the use of fungicides more efficient (Wichink Kruit et al. 2008). Thus, a large number of leaf wetness sensors have been developed (see e.g. Huber 1992). In addition, similar sensors exist in corrosion science since surface wetness is an important parameter also here (see e.g. Sereda et al. 1982). In building science, duration of surface moisture is an important factor that influences for example growth of algae and mould on facades (e.g. Johansson et al. 2010). A review on different surface moisture sensors used in building science is found in the introduction to *Paper I*.

In many published measurements the duration of surface moisture is monitored on a sensor surface rather than on the material surface itself. The surface of the sensor should then have similar surface properties as the material on which the measurements are made, for example a leaf (Davis and Hughes 1970; Griffioen et al. 1992). If these sensors are placed on another material, surface properties such as thermal absorbance or water absorption of the material are different from the surface properties of the sensor. Another factor that needs to be considered is the risk that the sensor itself traps water which would make the measured duration of surface moisture longer than if no sensor were present.

In wood structures, decay often starts in joints where water gets trapped after rain episodes (e.g. Gaby and Duff 1978; Hjort 1997). To be able to study the relation between the duration of water in such water traps and the moisture content in wood joints a method to determine the presence of water in a gap was developed. This method as well as a method for measuring the duration of moisture on wood surfaces is presented in *Paper I*.

Summary of Paper I

This paper presents two methods; one for determination of duration of surface moisture on wood surfaces and one for determination of duration of water trapped in gaps in wood joints. Both sensor types consist of insulating tubing, electrically conductive adhesive and copper wire. The sensors were mounted on a specimen similar to joint A in *Paper V* . Water was poured on the specimen and visual observations of when there was water on the surface and in the gap were made. These observations were compared with the measured conductance and a good correlation was found. However, the surface moisture sensors sometimes gave a low conductance reading a short time after no liquid film was visible on the surface. Surface moisture sensors were also mounted on two wood specimens exposed outdoors in a field test in Lund, Sweden. Here, the sensors were connected to a wireless logger intended for moisture content determinations in wood. The output from the surface moisture sensors in the field measurements corresponded well to rainfall data.

Sorption properties of wood at high moisture levels

The relationship between the moisture content of a material and the relative humidity (RH) in the ambient air is shown in a sorption isotherm. In the hygroscopic range (up to about 98% RH) the sorption isotherm is commonly determined by using a sorption balance (see e.g. Anderberg and Wadsö 2008) or by equilibrating specimens above saturated salt solutions (see e.g. Wadsö et al. 2004). However, above the hygroscopic range, the change in moisture content is often large for small changes in RH. Sorption isotherms in this high moisture range are sometimes called suction curves. To equilibrate specimens to RH-levels in the high moisture range the pressure plate or pressure membrane method can be used. Here, samples are conditioned by applying a pressure and this pressure corresponds to a certain relative humidity level and moisture content. Since the change in RH is small for a larger step in pressure (see Table 1) the specimens can be equilibrated to a certain RH-level with a high resolution. For wood, the pressure plate/membrane method has been used for several wood species (Penner 1965; Fortin 1979; Cloutier and Fortin 1991; Cloutier and Fortin 1994; Cloutier et al. 1995; Tremblay et al. 1996; Defo et al. 1999; Zhang and Peralta 1999; Kumaran et al. 2002; Almeida and Hernandez 2007; Almeida et al. 2008; Thygesen et al. 2010) as well as for acetylated and furfurylated wood (Thygesen et al. 2010).

Tabell 1. The relative humidity (RH) levels that correspond to pressures between 1 and 90 bar.

pressure (bar)	pressure (MPa)	RH (%)
1	0.1	99.93
2	0.2	99.85
4	0.4	99.70
6	0.6	99.56
8	0.8	99.41
10	1.0	99.26
12	1.2	99.12
14	1.4	98.97
30	3.0	97.81
60	6.0	95.66
90	9.0	93.57

In the hygroscopic range, both the desorption isotherm and the absorption isotherm can be determined by starting either with wet or dry samples. However, the pressure plate/membrane equipment is designed for desorption experiments and modifications are necessary to perform absorption experiments. The main issue is to ensure that all parts of the specimen reach equilibrium state from absorption. The ceramic plate (pressure plate) or the cellulose membrane (pressure membrane) needs to be water saturated before a measurement is started. However, if a dry specimen is put in contact with a water saturated ceramic plate, there is a risk that a higher moisture content than the intended equilibrium moisture content is reached initially in the lower parts of the specimen. If that is the case, the lower parts of the specimen reach equilibrium state from desorption and the upper parts of the specimens reach equilibrium state from absorption. The moisture content of the lower part of the specimen then becomes higher than that of the upper part (see Fig. 4) and the moisture content will not be uniform through the specimen.

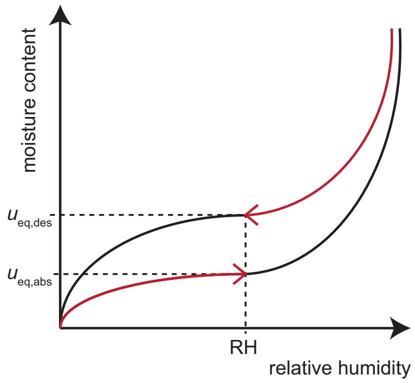


Figure 4. A schematic illustration of a sorption isotherm. The equilibrium moisture content during desorption ($u_{eq,des}$) is higher than the equilibrium moisture content during absorption ($u_{eq,abs}$) at the same relative humidity (RH).

Another issue that needs to be addressed in absorption experiments is that an inflow of water is necessary for absorption to take place and this requires modifications of the pressure plate cell. Previous work concerning pressure plate absorption experiments is reviewed and discussed in *Paper IV*.

In the present study, a method to perform absorption experiments using the pressure plate technique was developed. To prevent contact with the water saturated ceramic plate before it had equilibrated, the specimens were suspended in magnetic clamps. In addition, the pressure plate cell was modified and water was circulated by peristaltic pumps to supply the specimens with water during the absorption experiment. This method is further described in *Paper IV*.

Summary of Paper IV

This paper presents a method to determine absorption isotherms at high RH-levels using the pressure plate technique. Two main modifications were made compared with the procedure in desorption experiments. The specimens were suspended in magnetic clamps and were released when the ceramic plate had reached equilibrium with the applied pressure. In addition, the pressure plate cell was modified in order to enable a water flow through the cell. The water flow was achieved by peristaltic pumps and since water evaporated through the silicone tubing used in the peristaltic pumps, this leakage was determined in order to define the equilibrium state. For comparison, a desorption experiment was performed at a similar pressure level. The moisture contents obtained from the absorption experiment were significantly lower than the moisture contents from the desorption experiment. In addition, the moisture contents from the absorption experiment agreed well with moisture contents at lower RH-levels. The measurements were performed on Norway spruce (*Picea abies* (L.) Karst.) sapwood.

Moisture conditions in wood exposed to rain

Decay in outdoor rain exposed structures often starts in joints since high moisture contents are generally reached in such positions. This is well known, both because wood structures frequently fail close to joints (e.g. Gaby and Duff 1978; Hjort 1997) and because specimens with some type of joint are generally used to accelerate outdoor field tests. Therefore, the focus of the present study was on the microclimate and moisture conditions in wood joints. A review of previous studies on moisture conditions in rain exposed structures is given in Fredriksson (2010).

All joints that consist of two pieces of wood can be classified as belonging to one of three general joint types where the angle, the contact area and the distance between the two surfaces can be varied. Any joint found in a structure can be ascribed to one of these three joint types (Fig. 5):

A. Two end grain surfaces facing each other.

   Examples: a horizontal butt joint in a cladding, two boards in a decking or two boards in a hand rail.

B. An end grain surface facing a side grain surface.

   Examples: a post and the handrail in a railing or a sill and a stud.

C. Two side grain surfaces facing each other.

   Examples: two decking boards lying parallel to each other or a beam and a decking board.

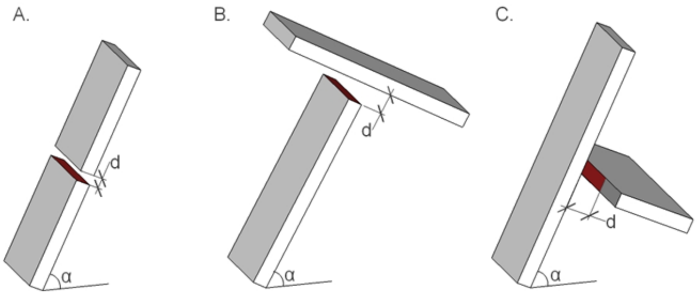


Figure 5. Three general joint types

The grouping into end-grain surfaces and side grain surfaces was used since the moisture transport is significantly faster in the longitudinal direction; the duration of surface moisture on an end grain surface should therefore be shorter than on a side grain surface. Consequently, the boundary conditions are different in these two cases. The joints that were included in the present work were chosen from these three general joint types.

To study the relationship between microclimate and moisture content, joints of Norway spruce (*Picea abies* (L.) Karst.) were exposed to artificial rain in the laboratory. Specimens of joint types A and B used in these experiments are shown in Fig. 6. The microclimate, i.e. the duration of surface moisture and presence of water in gaps as well as the moisture content were monitored using the methods presented in *Papers I* and *II*. Heartwood and sapwood were separated and both slow grown and fast grown wood were included. The experimental set-up is further described in *Paper V* along with results from the moisture content and microclimate measurements. In *Paper VI*, the duration of high moisture contents was evaluated in the various joints as well as the influence of heartwood/sapwood and joint design on the service life.

Figure 6. Specimens of joint type A (left) and B (right) from the experiments presented in *Papers V* and *VI*.

Summary of Paper V

Joints of Norway spruce (*Picea abies* (L.) Karst.) were exposed to artificial rain in the laboratory. Three joint types were included: joint A with two end grain surfaces facing each other, joint B with an end grain surface facing a side grain surface and joint C with two side grain surfaces facing each other. Specimens of both fast grown wood from southern Sweden and slow grown wood from northern Sweden were included and heartwood and sapwood were separated. For each specimen type, three different gaps between the boards were used (0, 2 and 5 mm). Moisture content profiles as well as duration of surface moisture and water in gaps were logged every five minutes using the methods described in *Papers I* and *II*.

Summary of Paper VI

Joints of Norway spruce (*Picea abies* (L.) Karst.) were exposed to artificial rain in the laboratory as described in *Paper V*. The duration of high moisture contents was evaluated as time above 20%, 25% and 30% moisture content. In addition, the measured moisture content data was used in three decay models in order to investigate whether the differences in moisture content also influenced the service life. The duration of high moisture contents was generally lower for the heartwood specimens than for the sapwood specimens, but no significant influence of growth ring width was seen. A gap of 5 mm between the boards lowered the duration of high moisture contents in many cases but the magnitude of the reduction varied. The decay models gave similar results if a relative comparison was made, but the absolute values of the service life differed.

Concluding remarks

Towards modelling of the material climate of wood outdoors

A schematic overview of a service life prediction model based on the exposure-resistance approach for above ground wood structures is shown in Fig. 7. The decay progression is highly dependent on the material climate, which needs to be determined from weather data at the location where the structure is situated (the macroclimate). However, the climate close to a structure (the mesoclimate) is not necessarily the same as the macroclimate since it is influenced by factors such as sheltering from wind, shading etc. For example, the wind distribution around a building affects the amount of wind driven rain and extensive research has been performed on this subject, see for example Blocken and Carmeliet (2004). The climate at the material surface (the microclimate) is not the same as the mesoclimate since it is affected by factors such as detail design, surface treatment, colour etc.

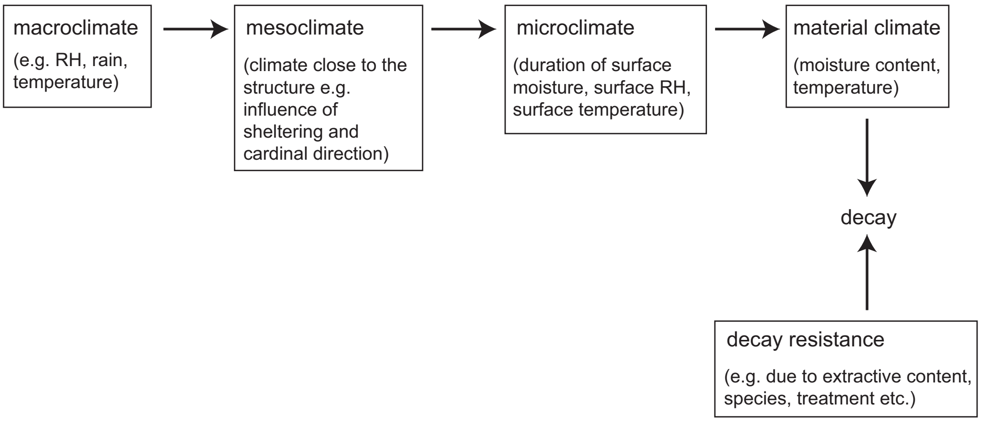


Figure 7. A schematic overview of different parts in a service life prediction model for outdoor wood structures.

From microclimate to wood moisture content

The microclimate is the boundary condition for the moisture transport further into the wood material. Since wood structures outdoors are exposed to rain, a model concerning the relationship between microclimate and moisture content for outdoor structures requires moisture transport models in the high moisture range. Since the moisture transport is significantly faster in the longitudinal direction than in the radial/tangential directions, models that describe end grain water absorption are of special importance. Such models have been suggested by for example Salin (2008), Mounji et al. (1991) and Johansson and Kifetew (2010).

Moisture transport models describing transport at high moisture levels require moisture sorption properties for the full moisture range, but there is currently a lack of data in the high moisture range. This is because the method used in this range (the pressure plate method) was originally designed for and is mainly used for desorption experiments. However, the method described in *Paper IV* makes it possible to determine also absorption isotherms in the high moisture range and the results from the first measurements show that there is a large hysteresis in the high moisture range as also has been indicated in previous studies (Penner 1965; Fortin 1979; Cloutier and Fortin 1994). Because of this large hysteresis it is important not only to have the full absorption/desorption isotherms, but also the scanning curves. The scanning curves link the desorption and the absorption isotherms and describe the moisture state of a material changing from absorption to desorption and vice versa. The knowledge of scanning curves is therefore important to describe the moisture conditions in wood exposed to a fluctuating climate. Cloutier and Fortin (1994) used different hypothetical scanning curves as well as the desorption isotherm in their model for wood drying and found that the calculated drying time as well as the average moisture content was significantly different if the desorption isotherm or if a scanning curve was used. In addition, the choice of scanning curve had a large influence on the results. Also Salin (2011) emphasizes the importance of including hysteresis in drying models and Nilsson and Sandberg (2011) conclude that inclusion of hysteresis and the knowledge of scanning curves are important when modelling wood end grain absorption. The new method presented in *Paper IV* enables determinations of the absorption isotherm in the high moisture range so that it is possible to determine the full absorption/desorption isotherms. In addition, this method should enable determination of scanning curves.

In the study presented in *Papers V* and *VI,* both the microclimate and moisture content profiles were monitored in several joints. Since both the boundary conditions (the duration of surface moisture and water in gaps) and moisture content profiles were measured these measurements can be used to verify a model describing the relation between microclimate and moisture content. The measurements were performed successfully using the methods described in *Papers I* and *II*. However, a disadvantage with these methods and the experimental setup used in *Paper IV* is that the specimen preparation and the mounting of the measuring equipment are very time-consuming and the amount of measurements and replicates were therefore limited. The moisture content profiles in these measurements consist of only four points, but instead the resolution in time is high since measurements were made every fifth minute. On the other hand, the moisture content profiles measured with CT have a high spatial resolution (the moisture content profiles), but here the time between the measurements was several hours.

Influence of some wood properties on the water uptake

Slow grown spruce is traditionally considered to be more durable than fast grown spruce and is thus preferred for outdoor structures such as claddings (Sivertsen and Vestøl 2010). Water uptake is one of the factors that influence the wood durability, but the results presented in the present thesis show no significant difference in water uptake between slow grown and fast grown Norway spruce (*Paper III*, *IV* and *V*). Despite the large difference between the growth ring width of the slow grown and the fast grown spruce used in the present study, there was no significant difference in density. This is shown in Fig. 8 which includes the densities of all boards used in this study. However, the density of softwoods is related to the latewood percentage rather than the growth ring width (e.g. Tasissa and Burkhart 1998; Shmulsky and Jones 2011), which implies that the latewood percentage was similar for the specimens in the present study. The latewood cells are the dominating pathway for liquid water uptake (Siau 1984; Almeida et al. 2008; Sedighi-Gilani et al. 2012) and similar latewood percentage would therefore give similar water uptake.

Bendtsen (1978) claims that there is a misunderstanding that wood with wide growth rings always has lower density, and that this is due to the fact that the tree age is not taken into account. He gives the example that if two trees, one slow grown and one fast grown, with the same diameter are compared, the fast grown tree is younger. This younger tree has a larger proportion of juvenile wood which has different properties than mature wood, for example lower density (Thörnqvist 1993). However, if the density of slow grown and fast grown wood of the same age, i.e. at the same annual ring number counted from the pit is compared, the density is similar (Bendtsen 1978). It is therefore not possible to conclude that the density of a board sawn from a slow grown tree has a higher density than a board from a fast grown tree only because it has more narrow growth rings.

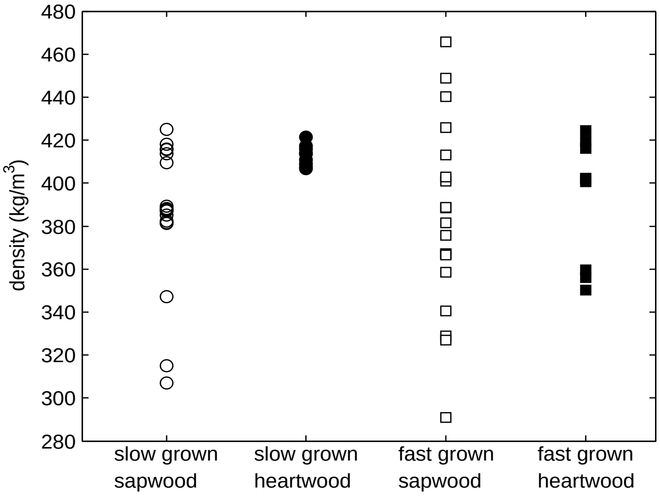


Figure 8. The density of the wood boards included in the studies in the present thesis. Note that the number of replicates is lower for the heartwood specimens.

In dried condition, there is no visible difference between Norway spruce heartwood and sapwood. This is probably the reason why heartwood and sapwood are seldom separated for Norway spruce. Several recent studies (Metsä-Kortelainen et al. 2006; Sandberg 2006; Sivertsen and Vestøl 2010; Sandberg and Salin 2012) as well as the present study (*Paper III*, *V* and *VI*), have shown that there is a difference between the moisture uptake of Norway spruce heartwood and sapwood. Since the heartwood content of older trees is higher than that of younger trees this can be one explanation why the slow grown wood is considered to be more durable, again an age effect. Sivertsen and Vestøl (2010), who also found no difference in water uptake between slow grown and fast grown Norway spruce, suggest that the heartwood content can be the explanation why slow grown Norway spruce has a good reputation as a cladding material in Norway. Other possible explanations might be that fast grown wood has a lower extractive content (Kimland and Nordin 1972) and is thereby possibly more susceptible to decay, or that softwoods that grow rapidly during the juvenile period tend to have a higher proportion of juvenile wood, partly because of the wider growth rings close to the pith, but also because rapid early growth may extend the juvenile period (Shmulsky and Jones 2011).

From material climate to decay

Several models describing wood degradation due to decay fungi exist to date (Brischke and Rapp 2008a; Viitanen et al. 2010; Thelandersson et al. 2011b; Isaksson et al. 2012). Both the model by Brischke and Rapp (2008a) and the models by Isaksson et al. (2012) are based on extensive field tests (Brischke and Rapp 2008a). The novelty of these field tests was that the moisture content and the decay were monitored continuously as well as the climate at the field test site. This enabled the development of models describing the relation between decay and material climate. A drawback is however that due to the experimental setup, the moisture content in many of the specimens was almost always at a high level and the influence of for example long dry periods on the decay is therefore not included. An attempt for a model including a set-back parameter was presented in Isaksson et al. (2012), but was not complete since data under fluctuating moisture conditions was missing. The model by Viitanen et al. (2010) takes into account dry periods since mass loss is inhibited when the RH and temperature are below certain limits. However, the model is based on results from laboratory measurements under constant conditions.

In *Paper VI*, moisture content data from *Paper V* was used to compare the expected service life of the different joints. Even though the absolute values of the calculated service life were substantially different, the relative results, i.e. if results within and between joints were compared, were similar. It may therefore be possible to use the models to compare different structural designs to decide which is more or less suitable. This is supported by the fact that the models pointed at the same weak points in the joints even though the model by Viitanen et al. (2010) is based on different data than the other two models that were used (the two-step response model (Isaksson et al. 2012) and the similar model in Thelandersson et al. (2011b)).

Future research

The new method for absorption experiments using the pressure plate technique (*Paper IV*) makes it possible to measure both absorption and desorption isotherms in the high moisture range for wood. In addition, it should enable determination of scanning curves. Scanning curves link the desorption and the absorption isotherm and describe the moisture state of a material going from drying to wetting and vice versa. Cloutier and Fortin (1994) tried different hypothetical scanning curves in their model of wood drying and found that the choice of scanning curve has a significant influence on the results. In addition, Salin (2011) emphasizes the need to include hysteresis in wood drying models and Nilsson and Sandberg (2011) found that the knowledge of scanning curves is needed in order to model wood end grain water absorption. Determination of scanning curves would therefore contribute and possibly improve models describing moisture transport in wood.

The knowledge of desorption and absorption isotherms as well as scanning curves in the high moisture range is useful also for other materials than wood. The method for determination of absorption isotherms in the high moisture range presented in *Paper IV* is applicable also for other materials. An additional example of a rain exposed material where the high moisture range is important is render. Render is often applied in layers that have different functions and structure. The understanding of moisture transport between the different layers as well as between the render and the underlying material is important in order to design rendering systems that inhibit water penetration.

In *Paper V*, the moisture conditions at the surface as well as moisture content profiles were measured. A model that describes these measurements, i.e. the relation between microclimate and moisture content, is one of the components needed in a service life prediction model for outdoor wood structures. Such a model would contribute to determinations of which moisture contents that are reached in structures with different design and materials.

A service life prediction model for wood structures outdoors also requires more knowledge about growth of decay fungi. There is currently a lack of knowledge concerning growth under fluctuating moisture and temperature conditions and how the decay fungi respond to for example long dry periods.

Moisture transport in wood can be further studied using new techniques such as neutron radiography or X-ray tomography and 3D imaging. These techniques make it possible to study moisture transport in wood with a higher resolution than the computed tomography technique used in the present thesis. First work on wood using neutron radiography was performed by Sedighi-Gilani et al. (2012) who found that moisture content distributions in wood could be quantified and visualized with a high resolution (0.07 kg/m^3).

Additional publications by the author

(not included in the thesis)

Papers in scientific journals:

Fredriksson, M., Wadsö, L.& Ulvcrona, T., (2010), Moisture sorption and swelling of Norway spruce (*Picea abies* L. Karst.) impregnated with linseed oil, *Wood Material Science and Engineering* 5: 135-142

Conference papers:

Fredriksson, M., Johansson, P., (2013), A new method for determination of absorption isotherms in the high moisture range – first results for Norway spruce (*Picea abies* (L.) Karst.), presented at the 9th Meeting of the Northern European Network for Wood Science and Engineering, Hannover, 11-12 September 2013

Fredriksson, M., Wadsö, L., Johansson, P., (2013), The influence of microclimate on the moisture conditions in a Norway spruce (*Picea abies* (L.) Karst.) joint exposed to artificial rain, presented at the IRG-WP Annual Meeting 2013 Stockholm, Sweden, 16-20 June 2013, IRG/WP 13-20505

Fredriksson, M., Wadsö, L., Johansson, P., (2012), The effect of moisture content of water trapped in wood joints, presented at IUFRO 2012 All Division 5 Conference Estoril, Portugal, 8-13 July 2012, IRG-WP 12-40613

Other publications:

Fredriksson, M, (2010), Methods for determination of moisture conditions in wood exposed to high moisture levels, TVBM-3157, Licentiate thesis, Division of Building Materials, Lund University

Fredriksson, M., (2010), A critical literature review of moisture and temperature conditions in wood exposed outdoors above ground, TVBM-3152, Division of Building Materials, Lund University

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