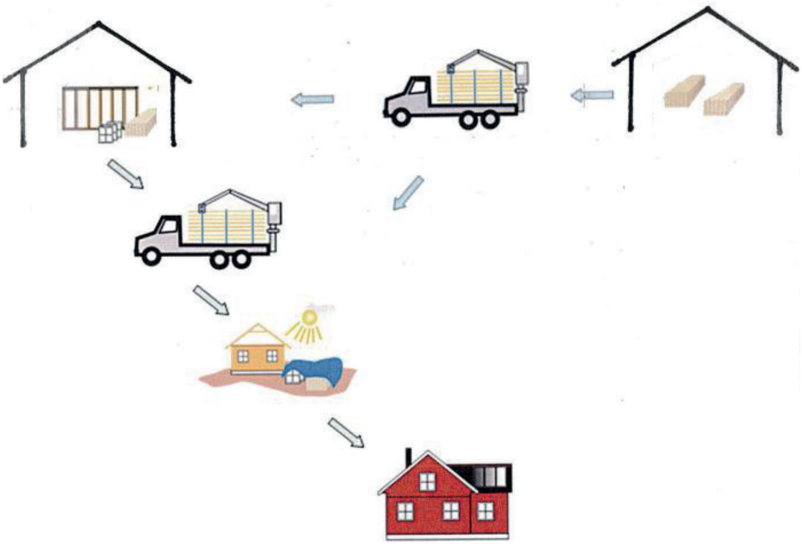
THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

# Moisture Conditions in Exterior Wooden Walls and Timber During Production and Use

LARS OLSSON



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Cover: Schematic diagram of the various phases of the construction process, from timber yards at the sawmill via production of wall elements and roof trusses at the factory to the construction site with assembly and finished houses in use.

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# Abstract

Thermal insulation of building envelopes has improved over the years. This means that building envelope have become more susceptible to defects, with an increased risk of moisture damage. The criteria for energy consumption have become more rigorous, but the shift should not lead to moisture problems. New knowledge about timber and wooden constructions is required in order to better meet these criteria. The purpose of this thesis has been to examine moisture levels in timber and external wooden walls during the construction and usage phases, as well as provide recommendations for good moisture safety.

The work is based on seven publications, listed in chronological order from the construction process, and covers timber stacks at sawmills, factory production of wall elements and roof trusses, transportation to the building site, assembly, as well as follow-up of finished houses and structures in the usage stage. Mainly three methods, field test, calculation and laboratory test, have been used for evaluation of moisture levels, temperature and mould growth.

The overall conclusion is that dry wooden structures and timber is required, which means that several minor adjustments need to be made to the construction practices, construction methods, products, materials, designs and structures currently being used, in order to achieve good moisture safety. In southern Sweden, there is a significant risk for mould growth on wooden studs in well-insulated north-facing external walls that lack external thermal insulation outside the wooden studs. In northern Sweden this risk is significantly lower or there is no risk at all. A small amount of rain that does not create running or dripping water on timber materials and which can dry out the same day should not lead to a risk of mould growth. In general, however, precipitation and material exposed to rain pose a high risk of mould growth. There is a risk of mould growth on timber surfaces that are exposed to an outdoor air in southern Sweden for more than a month, but not at all in the mountain areas or northernmost Sweden.

There also appears to be a major gap between product manufacturers, engineers and constructors with regard to ensuring overall functionality. For example, a large amount of products are not produced and tested to co-function or as part of a multi-component system in order to achieve an overall function, which means that not even the correct preconditions are generally available on the market in order to construct and assemble moisture safe.

**Keywords:** moisture, driving rain, precipitation, mold, mould growth, hysteresis, wood, timber, wall, façade, wind barrier, weather barrier, MRD-index, measurement, field test, laboratory test

# Summary

Thermal insulation of building envelopes has improved over the years. This means that building envelope have become more susceptible to defects, with an increased risk of moisture damage. The criteria for energy consumption have become more rigorous, but the shift should not lead to moisture problems. New knowledge about timber and wooden constructions is required in order to better meet these criteria.

The purpose of this work has been to examine moisture levels in timber and external wooden walls during the construction and usage phases, as well as provide recommendations for good moisture safety. The work is based on seven publications, listed in chronological order from the construction process and covers timber stacks at sawmills, factory production of wall elements and roof trusses, transportation to the building site, assembly, as well as follow-up of finished houses and structures in the usage stage.

The overall conclusion is that dry wooden structures are required, which means that several minor adjustments need to be made to the construction practices, construction methods, products, materials, designs and structures currently being used, in order to achieve good moisture safety. Several of the proposed adjustments are not exactly new ideas, but rather ones already expressed in the literature to a greater or lesser extent. Possible reasons for this not usually being applied could be that it is prevented by construction traditions, ignorance, insufficient demands set by the client and unclear building regulations. There also appears to be a major gap between product manufacturers, design engineer and contractors with regard to ensuring overall functionality. For example, a lot of products are not produced and tested to co-function or as part of a multi-component system in order to achieve an overall function, which means that not even the correct preconditions are generally available on the market in order to construct and assemble moisture safe.

In the studies, mould growth has been detected relatively often on delivered timber, albeit usually infrequently. Probable causes are, for example, that the timber has not been sufficiently dried, ≤16% moisture content, individual timber items have shown elevated moisture content and blue stained timber has not been rejected. Damp timber and timber with extensive mould growth has also been detected, which has rather been linked to incorrect storage or handling.

Timber items in timber stacks usually have relatively high moisture content differences in the cross-section, approximately 4% in the moisture content, despite the fact that the timber is at moisture equilibrium. The reason for the moisture content differences in the cross-section is the hysteresis effect. The fact that in reality there is a significant difference in the cross-section of a timber item at moisture equilibrium is not well known. This applies to timber that has not previously been in a drier state internally. This means that the timber stack could be considered to have an acceptable moisture content, e.g. 15%, but if the surface is in a humidifying process, the relative humidity could be around 80% RH with a risk of mould growth in favourable conditions, during the summer for example.

In a timber stack, there is a distribution in the moisture content between the timber items, and despite the entire stack being within an acceptable moisture content of, for example, 16%, there are timber items that are higher, and if these end up next to each other, there is a risk of mould growth during storage. However, it appears that the average moisture content is usually somewhat lower than the ordered target moisture content, which should mean that the proportion of timber with a higher moisture content is smaller than might be expected in a target moisture content class of 16%.

There is a risk of mould growth on timber surfaces that are exposed to an outdoor climate in southern Sweden for more than a month during the summer, but not at all in the mountain areas or northernmost Sweden. The lower the temperature and humidity, the lower the risk of mould growth. This means that timber storage should be limited during the summer if it is exposed to an outdoor climate, particularly in southern Sweden. An estimation of time can be based on calculations or general compiled tables.

It is common for wooden structures to become wet during the construction phase, during rainfall, and there is a high risk of mould growth. Better construction solutions, rainproof assembly methods or complete weatherproofing are required to prevent this. There appears to be a constant risk that wooden sills or plate will be wet, even inner wall sills both during the construction and the usage phase. This can be tackled, for example, by building up a plateau, level difference with a moisture resistant material onto which the sill or the lower edge of the wall are placed, whereby water absorption and thereby mould growth is prevented.

Outdoor humidity is generally not a problem in prefabricated timber frame building during construction phase, which involves short-term exposure, for example, for one month during the summer. During the winter there is no risk of mould growth, due to the low temperatures.

Rain splashes that do not create running or dripping water on timber and which can dry out the same day, should not lead to a risk of mould growth. In general, however, the occurrence of precipitation and water poses a high risk for mould growth on materials. A few days of exposure to water seem to be sufficient for the occurrence of microbial growth on damp timber.

Results from both laboratory and site measurements shows that leakage at windows and other penetrations and connections in façades or external walls is fairly common. It is also clear that the product combinations and solutions currently in use are not verified with regard to driving rain leakage. This is recommended in order to achieve rainproofing.

Nor do wind barrier products provide complete rainproofing protection in places like material joints, windows and other connections, thus creating a risk of inward water leakage. This has been established both in the laboratory and on site. One reason is that most products are not manufactured to fulfil an overall function. Therefore, it is recommended that entire systems are designed that ensure complete rainproofing.

External thermal insulation of the wooden frame with vapour-open and mould-resistant insulation should be used, which would protect the frame from a humid outdoor climate and increase the drying potential. There is a need for this in warmer, more humid areas of Sweden, but hardly at all in the most northerly areas of Sweden. In addition, it also provides a reduction of thermal bridges and reduced energy consumption, which applies throughout Sweden.

In cases with circumstances different from those examined in this study, moisture calculations should be applied and the anticipated outdoor climate or measured values be used, with evaluation using the MRD model, both for materials and for structures. Walls that are exposed to driving rain, are poorly ventilated or that face north, or shaded walls should be given special consideration. These structures should be followed up with moisture surveys, and this will provide verification of functionality, as well as generating knowledge and documented experience. Preferably a method to control and document the moisture resistance work in the construction process, for example ByggaF, should be used.

# Sammanfattning

Byggnadsskalet har genom åren blivit bättre isolerat. Det har inneburit att ytterväggar blivit känsligare för brister, med ökad risk för fuktskador. Kraven på energianvändning har skärpts men den omställningen får inte orsaka fuktproblem. Dessutom har kraven på fuktsäkerhet skärpts. Ny kunskap om virke och träbyggande behövs för att säkrare kunna svara upp till kraven.

Syftet med arbetet har varit att undersöka fukttillståndet i virke och träytterväggar under bygg- och bruksskedet, samt att ge rekommendationer för god fuktsäkerhet. Arbetet är baserat på sju stycken publikationer som redovisas i kronologisk ordning utifrån byggprocessen och omfattar virkespaket på sågverk, fabrikstillverkning av väggelement och takstolar, transport till byggplats, montage samt uppföljning av färdiga hus och konstruktioner i bruksskedet.

Den övergripande slutsatsen är att torrt träbyggande krävs, vilket innebär att flera mindre justeringar i byggpraxis, byggmetoder, produkter, material, montage och konstruktioner som används idag behöver göras för att uppnå god fuktsäkerhet. Flera justeringar som rekommenderas är egentligen inga nyheter utan är sådant som finns uttryckt i litteraturen i större eller mindre utsträckning. Möjliga orsaker till varför det ofta inte tillämpats kan vara att det hindrats av byggtradition, okunskap, otillräckligt kravställande från beställare och otydliga byggregler. Det verkar också finnas ett stort glapp mellan produkttillverkare, konstruktörer och entreprenörer i fråga om att säkersälla helhetsfunktionen. Exempelvis är många produkter inte framtagna och utprovade för att fungera tillsammans eller som ett system med andra produkter för att uppnå en helhetsfunktion, vilket innebär att inte ens rätt förutsättningar finns allmänt tillgängligt på marknaden för att konstruera och montera.

Det har i studierna relativt ofta påträffats mögelpåväxt på levererat virke, dock oftast i sparsam frekvens. Troliga orsaker är exempelvis att virket inte torkats tillräckligt torrt, ≤16% fuktkvot, enskilda virkesstycken har haft för hög fuktkvot och blånat virke har inte utsorterats. Det har också påträffats blött virke och virke med riklig mögelpåväxt som snarare har varit kopplat till bristfällig lagring eller handhavande.

Virkesstycken i virkespaket har vanligtvis relativt stora fuktkvotsskillnader i tvärsnittet, omkring 4%-enheter i fuktkvot, trots att virket befinner sig i fuktjämvikt. Orsaken till fuktkvotsskillnader i tvärsnittet beror på hystereseffekten som i sin tur är vedertagen kunskap. Att det i verkligheten blir en betydande skillnad i ett

virkesstyckes tvärsnitt vid fuktjämvikt i virkespaket förefaller inte vara vedertaget. Detta gäller för virke som inte tidigare befunnit sig i ett torrare tillstånd inuti. Detta innebär att virkesytan kan upplevas ha acceptabel fuktkvot, exempelvis 15 %, men om ytan befinner sig i en uppfuktningsprocess kan relativa fuktigheten ligga omkring 80 % RF med risk för mögelpåväxt vid gynnsam temperatur exempelvis sommartid.

I ett virkespaket finns det en spridning i fuktkvot mellan virkesstyckena och trots att hela paketet ligger inom acceptabel fuktkvot på exempelvis 16 % finns det virkesstycken som ligger högre och hamnar dessa intill varandra finns det en risk för mögelpåväxt vid lagring. Dock verkar det som medelfuktkvoten oftast blir något lägre än beställd målfuktkvot vilket torde innebära att andelen virkesstycken med förhöjd fuktkvot är färre än vad som kan förväntas i målfuktkvotsklass 16.

Det finns en risk för mögelpåväxt på virkesytor som exponeras för uteluft i södra Sverige under mer än en månad sommartid men inte alls i fjälltrakter och nordligaste Sverige. Ju lägre temperatur och fuktighet desto mindre risk för mögelpåväxt. Detta innebär att virkeslagring bör begränsas sommartid om det exponeras för uteluft särskilt i södra Sverige. Uppskattning av tiden kan baseras på beräkning eller generell framtagen tabell.

Det är vanligt att träkonstruktioner blir blöta under byggskedet i samband med regn och risken för mögelpåväxt är stor. Bättre konstruktionslösningar, regnsäkra montagemetoder eller heltäckande väderskydd behövs för att undvika detta. Det förefaller finnas en ständig risk för uppfuktning av träsyllar, även innerväggsyllar både i bygg- och bruksskedet. Det kan man komma till rätta med genom att exempelvis bygga upp en nivåskillnad med fukttåligt material som syllen eller nederkant vägg ställs på varvid vattenuppsugning och därmed mögelpåväxt undviks.

Luftfuktigheten ute är generellt sett inget problem vid prefabricerat trähusbyggande, vilket innebär kortvarig exponering exempelvis under en månad sommartid. Vintertid finns ingen direkt risk för mögelpåväxt, på grund av låg temperatur.

Regnstänk som inte skapar rinnande eller droppande vatten på trämaterial och som kan torka ut samma dag torde inte vara någon risk för mögelpåväxt. I allmänhet utgör i emellertid förekomst av nederbörd och vatten stor risk för mögelväxt på material. Några dagars exponering för vatten verkar vara tillräckligt för uppkomst av mikrobiell påväxt på blött virke.

Riklig påväxt är ofta osynlig för blotta ökat varför bestämning behöver göras med mikrobiologisk analys.

Både resultat från provningar i laboratorium och fältmätningar pekar på att det är ganska vanligt med inläckage vid fönster och andra anslutningar i fasader eller ytterväggar. Det kan också konstateras att de produktkombinationer och lösningar som används är inte verifierade med avseende på slagregnstäthet. Det rekommenderas för att uppnå en god fuktsäkerhet.

Vindskyddsprodukter ger inte heltäckande regntäthet vid t.ex. materialskarvar, fönster och andra anslutningar vilket utgör risk för vatteninläckage. Detta har konstaterats både i laboratorium och i fält. En orsak är att de flesta produkter inte är framställda för att ta en helhetsfunktion. Därför rekommenderas det att hela system tas fram som säkerställer regntäthet.

Utvändig isolering av stommen med ångöppen och mögelresistent isolering, bör användas, vilket skyddar stommen från fuktig uteluft samt ökar uttorkningspotentialen. Behovet av detta finns i varmare och fuktigare delar i Sverige men knappast alls i nordligaste Sverige. Dessutom ger det också en minskning av köldbryggor och minskad energianvändning vilket gäller för hela Sverige.

I de fall med andra förutsättningar än vad som studerats i studien bör det tillämpas fuktberäkningar och att förväntat uteklimat används eller använd uppmätta värden från flera års mätningar och att detta utvärderas med MRD modellen både för material och konstruktioner. Väggar som är slagregnsutsatta, dåligt ventilerade eller orienterade åt norr samt skuggutsatta väggar bör särskilt beaktas. Dessa konstruktioner bör följas upp med fuktmätningar vilket ger en verifiering av funktion, skapar kunskap och dokumenterad erfarenhet. Använd gärna en metod för att styra och dokumentera fuktsäkerhetsarbetet i byggprocessen, exempelvis ByggaF.

# Preface

This thesis has been financed by SP and Chalmers. The thesis is mainly based upon the studies carried out in the research programmes "Framtidens Trähus" Wood Frame Buildings of the Future and WoodBuild. The main financier for the research programme is Vinnova. In addition, financing has been provided by the Swedish Forest Industries Federation and in various ways by many contributors associated with the timber and construction industries, along with travel contributions from the Maj and Hilding Brosenius Research Foundation.

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I should also like to thank colleagues at SP and colleagues within the research programmes for contributions and collaboration.

My penultimate thanks go to supervisor Professor Carl-Eric Hagentoft and assistant supervisor Paula Wahlgren, both at Chalmers, and to assistant supervisor Adjunct Professor Kristina Mjörnell, SP and LTH. Kristina was involved to plan main research programs and has been responsible for parts of the programs. So, finally, thank you, Kristina, for all your encouragement and support in all of the sub-projects, as well as the big, final step in summarising them for this thesis.

Lars Olsson

Borås, May 2014

# List of publications

This licentiate thesis is based on the work in the following publications and consist of papers presented at peer-reviewed conferences and research reports published at SP Technical Research Institute of Sweden.

Appended:

I. Olsson, L. (2012a). *Omfördelning av fukt i virkesstycken och risk för mögel på virkesstycken i virkespaket* (SP report 2012:60). Borås: SP Technical Research Institute of Sweden.
II. Olsson, L., Mjörnell, K., Johansson, P. (2011a). *Moisture and mould in prefabricated timber framed constructions during production until enclosure of the house*. NSB 2011, Proceedings of the 9th Nordic Symposium on Building Physics, Tampere, Finland.
III. Olsson, L. Mjörnell, K. (2012b). *Laboratory investigation of sills and studs exposed to rain*. IBPC 2012, Proceedings of the 5th International Building Physics Conference, Kyoto, Japan.
IV. Olsson, L. (2012c). *Laboratoriestudie av träfasaders täthet mot slagregn* (SP report 2012:45). Borås: SP Technical Research Institute of Sweden.
V. Olsson, L. (2012d). *Laboratory investigation of timber frame walls with various weather barriers*. Proceedings of the 5th Nordic Passive House Conference 2012, Trondheim, Norway.
VI. Olsson, L. (2011b). *Fuktmätningar under två år efter byte av putsfasad* (SP report 2011:67). Borås: SP Technical Research Institute of Sweden.
VII. Olsson, L. (2013). *Fuktmätningar i fyra trähus* (SP report 2013:33). Borås: SP Technical Research Institute of Sweden.

Work on Papers II and III has been partially planned by Kristina Mjörnell. Pernilla Johansson has been responsible for the microbiological analyses in Paper II.

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# Abbreviations

| | |
|---|---|
| ByggaF | Industry standard ByggaF – method for moisture safety of the construction process |
| CPD | EU's construction product directive |
| CPR | EU's construction products regulation |
| $D_{crit}$ | Critical dose, depending on the material, RH, T and time |
| EPS | Expanded polystyrene |
| ETICS | External Thermal Insulation Composite System |
| KTH | Royal Institute of Technology |
| LTH | Lund University |
| MC | Moisture content [%] |
| MRD | Mould Resistance Design |
| MRD index | index $\geq 1$ means a risk of established growth |
| MW | Mineral wool |
| Pa | Pascal, unit of pressure |
| RH | Relative humidity [%] |
| $S_d$ | Equivalent air layer thickness [m] |
| Sill | or plate is the bottom part of the wall framing or structure |
| SP | SP Technical Research Institute of Sweden |
| T | Temperature [°C] |
| U | Thermal transmittance, U-value [$W/m^2K$] |
| VTT | Technical Research Centre of Finland |
| WUFI | Software tool for hygrothermal building envelope simulations |
| XPS | Extruded polystyrene |

# 1 Introduction

## 1.1 Background

Thermal insulation of building envelopes has improved over the years (see Figure 1) (Byggforsk 1990). This has meant that the envelopes have become more susceptible to defects, with an increased risk of moisture damage (Samuelson 2008), (Hagentoft 2009). Older structures have very little thermal insulation (Björk et al. 2002) by today's standards, because heat from indoors often has a good drying effect on the walls. When they began insulating wooden houses in the US in the 1930s, damp problems arose (Rose 2011). It was discovered that partly vapour from indoor air was working its way out in the construction to a greater extent than before, mainly because the insulation was more vapour open and porous than the uniform timber, and partly because the indoor air was leaking out, encountering significantly colder areas way before it reached the outside. However, poorly insulated or uninsulated structures can reach significantly lower surface temperatures internally than the indoor air temperature, which can give rise to condensation and microbial growth on internal surfaces in the event of poor indoor ventilation (Samuelson 1985).

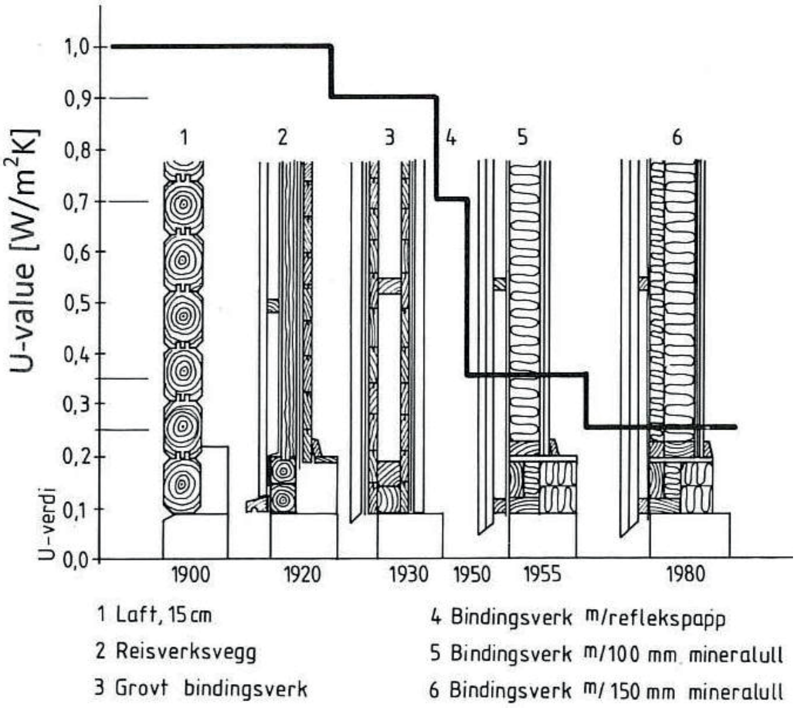


*Figure 1. Thermal loss through external walls has decreased considerably over the years, from U values of 1.0 W/m$^2$K for timber walls to 0.25 W/m$^2$K for 150 mm stud walls (Byggforsk 1990).*

During the energy and oil crisis of the 1970s, thermal insulation of structures was increased in order to keep energy costs down.  This of course led to a decrease in energy consumption, but at the expense of higher moisture levels in the external parts of structures (Samuelson 2011). No significant thermal impact from indoors occurs above standard insulated attic floor or ceiling these days, because extremely well insulated structures, for example in passive houses, are unlikely to be worse off, damp-wise (Samuelson 2008). Nevander and Elmarsson (1991) demonstrate using diffusion calculations in external wooden stud walls with internal vapour barriers that the risk of mould growth increases tenfold if the insulation thickness is doubled, but the increase seems to subside at 300-400 mm thickness at which point the moisture level is determined mainly by the outdoor climate. Furthermore, their calculations demonstrate that the risk of mould growth increases if the vapour barrier's vapour resistance is reduced.

There does not appear to be convincing evidence that only more thermal insulation has caused general moisture damage. There are however incidents of damage where defects and incorrect solutions have occurred, for example air leakage, overestimation of the material's moisture resistance, built-in or residual moisture, insufficient residential ventilation which create excess air pressure or internally thermal insulated structures. Several structures that became common during the energy crisis were modified solutions with historic origins, for example, foundation slabs and backfilled external walls that were insulated internally, brick façades with underlying wooden studs and increased insulation or additional insulation of structures such as external walls, roofs and timber-frame floors. To some extent this created extensive moisture problems (Samuelson 1985), (Samuelson 2011) which is why the latter began recommending underlying thermal insulation below the foundation slabs (Harderup 1993) and external thermal insulation of cellar walls (Sandin 1999) and for ventilated external walls with brick façades, the wooden studs began being protected with weather barrier, external mineral wool insulation that was capillary breaking and thermally insulating (Sandin 1993). When it comes to foundation crawl spaces, there are also several different improvements (Åberg 1995). However, this will not necessarily resolve the entire problem, as the crawl space borders ground that generates more or less microbial odour, which can affect the building (Olsson 2006). With regard to attic structures, visible growth on the underside of the roof underlay or tongue and groove boards has continuously been reported since the energy crisis (Samuelson 2011), (Ahrnens and Borglund 2007). Nevertheless, no general construction changes have been made apart from better air-tightness and negative pressure ventilation becoming more common in residential buildings, which means less risk of moisture convection, which could be crucial for good moisture safety.

With regard to wooden façades with wooden structure, there are relatively few reports here, partly because they are not accessible for inspection, partly because no general and extensive damage has occurred. However, Nevander and Elmarsson (1991) demonstrated a high risk of mould growth on the inside of wind barriers with calculations. Insulated north-facing walls, 200 mm, in the far south of southern Sweden were particularly susceptible during the month of September. At the same time, they point out that this does not correspond with experience in practice. Furthermore, they demonstrate that in the northernmost parts of Sweden, the risk of mould growth was very low.

During the 1980s, unventilated rendered external walls and external insulation on existing heavy external walls became increasingly common, which improved the structures from both an energy and a moisture perspective. When the same solution began being used outside a wooden stud wall, it produced extensive moisture problems (Samuelson et. al 2007), as wooden stud were moisture sensitive. The reason was that penetrations and detail connections (see Figure 2) in the façade were leaking and rainwater could penetrate and reach as far as the wooden structure (Jansson 2011). Even leakages in window and door structures have been shown to let in rainwater (Samuelson and Jansson 2009). Similar problems have been reported in Canada, in addition to problems in external walls with wooden panelling façades (Canada Mortgage and Housing Corporation 1998).

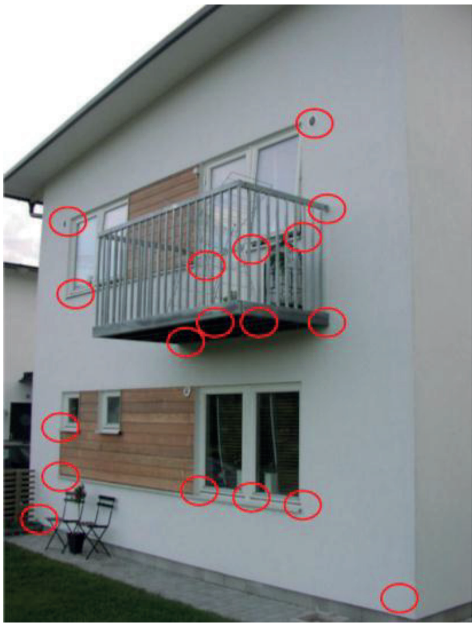


*Figure 2. Examples of sensitive areas at high risk of inward leakages (Jansson 2011).*

When it comes to timber, there has been a practice in the industry that it is not abnormal for timber to have a certain level of microbial growth during construction (Samuelson & Wånggren 2002). This means that it could be difficult to determine the cause of the growth on discovery of old damage in buildings (Esping et al. 2005). In addition, it could be difficult to entirely prevent this type of construction material from having a negative affect on the indoor environment (Nilsson 2009). When it comes to causes of damp timber in construction scandals, there is a ranking list (Esping et al. 2005) as follows:

1. "Incorrect handling of timber at construction sites – both during storage of the timber and during the construction process.
2. Incorrect covering at the supplier's storage area or during transportation.
3. Other causes such as: incorrect wrapping, incorrectly dried or stored timber at the sawmill, incorrect moisture content, MC, stated in the order."

There are no timber standards that cover microbial growth which is invisible to the naked eye. There is however a visual method in which, during the timber sorting process, the area of biological infestation should be presented for assessment of appearance or mechanical properties in accordance with SS-EN 1311 (SIS 1997). This means that on the one hand there are no set standards to ensure that timber is delivered free from invisible microbial growth, and on the other, sawn or planed timber surfaces should be free from both visible and invisible growth thereafter, with the exception of blue stain, which has deep penetration, if it is not subjected to unfavourable conditions (Nilsson 2009).

In the Swedish National Board of Building, Planning and Housing regulations (2006), the criteria for energy consumption have been tightened, but that shift should not lead to moisture problems. In addition, criteria on moisture safety have been tightened. One requirement is that critical moisture levels for materials should be provided. If this is unknown, a critical moisture level of 75% RH (relative humidity) should be applied. Exactly how long timber can be exposed to really humid conditions is unclear (Nilsson 2009). This is why in 2006-2007 two research projects were initiated, called WoodBuild and "Framtidens Trähus" Wood Frame Buildings of the Future for the forestry and timber industries, with the aim of increasing knowledge in this area. In addition, lifecycle and durability issues have become more prominent in recent years. One main reason for this is that the EU's construction product directive (CPD) and construction products regulation (CPR) outline seven essential criteria that construction products should meet during an economically reasonable lifecycle. This in turn means criteria on declaration of aspects like durability and lifecycle. New knowledge about timber and wooden construction is required in order to better meet these criteria.

## 1.2 Former work

*Moisture in timber*

Timber has natural variations in, for example, appearance, strength, density, shrinkage properties, warping properties, moisture content and susceptibility to microbiological infestation. These properties vary longitudinally and transversely within each item of timber, and above all between each item of timber. (Esping et al. 2005).

Timber can become infested with microbial growth from a moisture level of 75% RH, when combined with a favourable temperature and sufficient time (Johansson et al. 2005). This is equivalent to a moisture content, MC, of approximately 15-18% for timber material, depending on whether the material is in a humidifying or drying out phase (Nevander and Elmarsson 1994). Microbial growth can be prevented if one or more of the above three parameters are limited, such as moisture, temperature or storage time (Block 1953), (Johansson 2006). The safest way to prevent microbial growth is probably to limit the MC, as both the storage temperature and storage time can vary during storage and delivery. However, many structures are subjected to outdoor climatic variations or other variations that deviate from the above conditions, making it difficult therefore to assess the risk of mould growth. There is therefore a major need for a calculation model that can handle variations (Nilsson 2009).

Mould fungi generally grow on the surface of timber. These can be pigmented so that growth can be seen with the naked eye, but they can also be unpigmented with the result that heavy growth of mould fungi cannot be seen with the naked eye. Some pigmented fungi are able to grow deeper into the timber and cause discolouration, also known as blue stain. These fungi generally require a lot of moisture and if there is blue stain inside structural timber, you can conclude that at some point it has been exposed to a large amount of moisture or free water. Blue stain can occur as early as the felling phase, and consequently before sawing and drying at the sawmill, and is therefore in the timber during production from the very start. In this case, the fungi that caused blue stain will not be active. (Johansson 2006)

Handling timber correctly, with regard to preventing mould, requires knowledge of the timber's susceptibility. Data about exactly which limits should be exceeded in order for mould to grow on Swedish timber has been lacking (Hässler and Henningsson 1990) (Esping et al. 2005) as varying climactic conditions are representative of the real world. This probably explains why there has been uncertainty about the MC that timber should be dried to before it is stacked. In 2009, the risk of microbial growth on stacked timber was found to be relatively high in a status report (Nilsson 2009), but there was no evidence of whether that was true in practice. Some claim that artificially dried timber remain dry on the surface for a long time in timber stacks and the moisture levels never reach a critical point for microbial growth before use. There are older studies (Hallenberg and Gilert 1986), (Hyppel 1989) that indicate the existence of growth on timber. In order to determine whether there is growth on timber surfaces, a microbiological analysis is required, as heavy growth is usually not visible to the naked eye (Samuelson et al. 1999), (Esping et al. 2005), (Johansson et. al 2005). Some do not consider microbial growth on timber to be a problem, as the users would react if that was the case. This could explain why some people do not believe that microbial growth on timber stacks occurs, as it cannot be determined with the naked eye whether seemingly clean, unblemished, non-discoloured timber is infested with microbial growth.

Sawmills can control the timber drying process to the desired MC. After which it can be dried or humidified further, depending on the surrounding climate prior to planing, stacking and wrapping. According to Svensk Byggtjänst (1998) "General material and workmanship specifications 98”, timber during construction was permitted to have a MC equivalent to MC class 18 according to SS 23 27 40, which means that 84% of the timber should be within a 14.0-22.0% MC. In 2011, according to Svensk Byggtjänst (2011) “General material and workmanship specifications 11”, a target MC of 16% and drying quality standard according to SS-EN 14298:2004 (SIS 2004) were introduced for the supply of construction timber. This means that the actual MC named in the average MC is permitted to be within 13.5-18%, and that 93.5% of all timber items should be within a 11.2 to 20.8% MC. This is measured at a timber depth of 0.3 x thickness and 0.3 x breadth, which should represent the average MC in a timber item, as directly after drying it is driest on the surface and most humid in the centre of the timber item (Esping et al. 2005). In addition, timber stacks could be supplied with an average MC of max. 18%, which is higher than the critical value for microbial growth on timber on the basis of the above argument. Microbial growth on the timber, however, requires further conditions, for example, the timber must be exposed to favourable temperatures for a sufficient duration and the timber surface must adopt almost entire moisture equilibrium with the timber in the centre in order for there to be microbial growth on the timber.

An accelerated drying process in a chamber drier causes major MC differences in the timber cross-section (Esping et al 2005). This means that the MC will be higher inside the timber than on the surface of newly dried timber items. In addition, MC differences can occur between and within each individual timber item in the timber stack, depending on things like density differences in the timber. Redistribution of moisture occurs in stacked and wrapped stacks, only stacked stacks (Esping et al. 2005) or in the timber’s longitudinal direction (Segerholm 1998) and timber items stored far apart with different MC, but the redistribution takes a very long time.

There is an uncertainty as to how fast moisture is redistributed in the cross-section of a timber item and between timber items stored together after the drying process. How long does it take a timber item to start reaching moisture equilibrium on the timber surface at the point that adjusts fastest? This is interesting if the estimated time can be used to enable a potentially longer storage time when the average MC of timber is elevated after the chamber drier with regard to microbial growth risks.

In a study by students from the University of Borås (Malmgren et al. 2005), MC were measured in all timber items in a timber stack. The stack was wrapped on five sides and the timber had a dimension of 45x70 mm. The results show that there was a concentration of timber items with higher MC adjacent to each other. It can therefore not be ruled out that timber stacks could contain timber items with higher MC adjacent to each other rather than evenly distributed.

The quantity used to describe critical moisture levels in materials, with regard to microbial growth, is relative humidity (Johansson 2005). Determining the timber's RH through MC measurement requires the use of desorption and absorption curves for that timber variety, i.e. different curves depending on whether the material is in the drying or humidifying curve, which is known as hysteresis (see Figure 3). In addition, the curves change somewhat if the timber has been exposed to repeated drying and humidifying phases (Nilsson 1988). This makes it fairly difficult to determine the exact RH in the timber and its surfaces using MC measurement, particularly if the timber's humidity has been varied or if its humidity history is missing (Nilsson 1988).

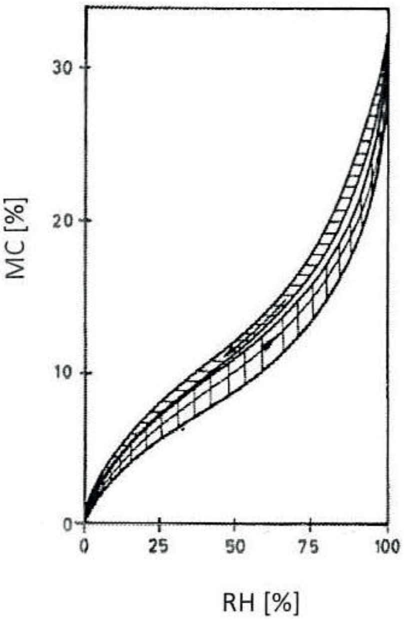


*Figure 3. The variation area in MC and RH for desorption (upper area) and absorption isotherms (lower area) for pine and spruce at approximately 20°C (Nilsson 1988).*

### *Moisture during the construction process*

During the construction stage, there is always a risk of the timber becoming damp, thus enabling micro-organisms to start to grow (Hansson 1989) (Esping et al. 2005). Before 2009, it was not known with certainty how long timber can be exposed to damp climactic conditions before microbial growth starts, nor was it known to what extent it is possible to dry out timber that has become damp without microbial growth starting (Nilsson 2009).

Segerholm (1998) has shown high MC in sills and that wetting is rapid if exposed to rain. Heavy absorption occurs at the ends of the timber and where nails penetrate the material.

Many buildings, old and new, have damp problems and many of the problems could have been prevented if moisture safety control had been used throughout the construction process for the production of structures and solutions, as well as material choices and assembly (Mjörnell and Arfvidsson 2008). Many construction materials must be applied humid, others are humid from the manufacturing process and are supplied humid to the construction site or humidified by precipitation or water during construction at the site, which means moisture damage can occur during the construction phase. Moisture damage can also occur if structures, materials or products do not work or are not used correctly, or if the installation of materials and structures does not provide the expected function. In Sweden for at least five years it has been possible to work systematically with moisture control according to a method called ByggaF (Fuktcentrum 2013), with training in the method also being offered. However, it is still not very common to use ByggaF. The method became an industry standard in 2013, which will hopefully increase the use.

### *Measurements in external walls*

Increasing the protection of exterior walls against inward leakage reduces the risk of moisture and durability problems arising from driving rain. Earlier studies have found that one of the areas in which there is a risk of inward leakage due to rain is between walls and exterior windows (Gustavsson 2009), (Nevander and Elmarsson 1994). This may be due to poor workmanship in fitting details, poor designs or leaks in the wooden façades and windows themselves. Similar conclusions have been drawn in Canada (Canada Mortgage and Housing Corporation 2003) and during laboratory tests on ventilated rendered stud walls (Samuelson and Jansson 2009). In three of four objects, water had penetrated at the detail connections and penetrations past the rendering layer. Other studies also show inward leakage to the timber frame due to defects at window detail connections (Umeno and Hokoi 2011), (Canada Mortgage and Housing Corporation 2003).

In British Columbia, Canada, the external walls of 37 houses were examined, all with reported moisture problems in the form of rot and mould growth in the external walls, along with nine reference houses without any reported moisture problems prior to the examination (Canada Mortgage and Housing Corporation 1998). Various different façade materials were encountered during the survey, such as plaster, timber panelling and plastic panelling, as well as various types of wind barrier, such as OSB, plywood and wind fabric. The main reasons appear to be rainwater penetration via leakages in the façades, mainly at window and balcony connections, and through window frames. All types of façade had problems, but the biggest problem was with plaster rendering. The conclusions show that even the reference houses had poorly built detail solutions, but that the façades and houses were not as exposed to direct driving rain. Better solutions, clear assembly instructions and well executed assembly is recommended.

There are quite a few published site surveys of external wooden stud walls (Kurkinen et al. 2009), see example of this below. In a lot of older studies, moisture levels have been measured in MC, which makes it difficult to determine whether there was a risk of mould growth, as the critical moisture levels are given in RH quantities. It is only in recent years that it has been measured using RH instruments. In addition, there is a general lack of evaluations with results of mould analyses that detect invisible growth, which is necessary in order to actually determine occurrence. In addition, there has not previously been dimensioning software for microbial growth that detects moisture and temperature variations, or indeed a verifiable way of confirming the risk of growth (Nilsson 2009). In recent years, several calculation models have been developed that can take into account variations, for example WUFI-Bio (Sedlbauer and Krus 2003), (Sedlbauer 2001), (Sedlbauer 2002), (Krus et al. 2010), VTT's model (Viitanen and Ojanen 2007), (Hukka and Viitanen 1999), (Ojanen et al. 2010), m model (Togerö et al. 2011), MRD model (Thelandersson and Isaksson 2013) which probably makes it possible to assess the risks of growth better than before. A comparison of the two latter models was carried out by Kjellberg (2011), which showed relatively good conformity. A comparison was also carried out between the WUFI-Bio and MRD model by Nilsson et al. (2012) and in that comparison, it was highlighted that WUFI-Bio had no recovery function during cold and dry periods, which could give an implausible result or one that is difficult to interpret. A comparison has also been carried out between VTT's model and WUFI-Bio by Viitanen et al. (2010), (Vereecken and Roels 2012) which shows similar outcomes to the previous comparison, i.e. that WUFI-Bio lacks recovery function, but VTT's model does not.

In southern Finland, surveys have been underway for 18 months, including the survey of a wooden stud wall, 150 mm mineral wool insulation, with internal plastic film or vapour- and air barrier and asphalt impregnated fibreboard as a wind barrier, as well as ventilation gaps and wooden panelling façades (Käkelä and Vinha 2002). The results show at most 70-75% RH monthly average on the inside of the wind barrier.

Surveys have been underway in Denmark for 2½ years in a test house, with twelve different wooden stud walls designs, exposed to the south and the north (Hansen et al 2002). The designs had 285 mm mineral wool insulation and internal plastic film, and different wind barrier combinations, such as gypsym board and asphalt impregnated woodbased board, with and without a ventilation gap, as well as different façade materials. The results show MC at around 17% at most inside the wind barrier in ventilated north-facing façades. MC were somewhat lower to the south. The highest MC behind the wind barrier, 18-19%, occurred in several of the unventilated façades. Ventilation appears to have had a positive effect if moisture has been transported to the ventilation gap, such as inward rain leakage, capillary transportation through the façade material, residual moisture, etc.

In Stockholm, Sweden surveys have been underway for at least two years in well insulated wooden stud walls with 300 mm mineral wool insulation (Elmroth 1988). Measurement of MC shows no particular difference in the MC between inside the wind barrier and the ventilation gap, and the MC was at its highest during the winter at approximately 20%.

In southern Sweden, momentary measurements of RH have been carried out in ten houses in May and June and of MC in January (Örtengren-Sikander 1993). Measurements were taken from both the north-facing and south-facing walls. Wall structures consisted of a wooden frame, 120-145 mm mineral wool insulation, and internal plastic film and 50-80 mm EPS slab as a weather barrier. The façades were ventilated and consisted of brickwork or wooden panelling. The results showed RH at most around 65% behind the wind barrier in May and June, and the MC were at most around 9-11% in January behind the weather barrier. No difference in humidity could be established between the north and the south or between the various façade types.

Levin and Gudmundsson (2000) have measured MC in north-facing wooden stud external walls with 250 mm cellular insulation in Stockholm over a two-year period. Internally there were vapour-open air barriers, and the wind barrier consisted of gypsym board and a façade of wooden panelling with an underlying ventilation gap. The MC had been converted to RH and showed values just over 80% RH at most inside the wind barrier.

In Norway, surveys have been underway for three years in a test house in east and west-facing wooden stud external walls with various vapour barriers or vapour retarders and various wind barriers such as gypsym board, wind fabric and porous wood fibre board (Uvsløkk et al. 1999). One wall was well insulated with 300 mm mineral wool insulation and had an internal vapour resistance of Sd=0.5 m and a wind barrier with a vapour resistance of Sd=0.08 m, the results showing a MC of 17% at most inside the wind barrier.

In Madison, Wisconsin, USA surveys have been underway over two winter periods in a test house in south-facing wooden stud external walls with 100 mm mineral wool insulation. Internally there were vapour barriers of plastic film and wind barriers consisting of plywood and façades of horizontal wooden panelling (Duff 1968). The results show a 13-14% MC at most in the outer section of wooden studs without air leakage in the internal plastic film.

## 1.3 Aim

The purpose of the work is to provide recommendations as to how good moisture safety can be achieved and to demonstrate moisture and temperature conditions in timber and external wooden stud walls during the construction and usage phases. The work includes handling of the timber from the timber yard to the finished external wall in the usage phase. Good moisture safety means that harmful humidification, wetting and mould growth is prevented.

## 1.4 Scope

The work includes measurements och evaluation of moisture and temperature conditions in external wooden walls in houses with internal air and vapour barriers and for timber stacks within Sweden. It also includes observations from the construction process and reporting of construction practices. Also included is a risk assessment for mould growth, mould resistance tests of timber or wood and mould analyses of timber and wooden structures.

The houses studied are mostly prefabricated timber frame houses with production of external stud walls and roof trusses in house-building factories. However, a certain degree of loose timber construction has taken place on site. Single-storey detached houses have often been assembled by local contractors and multi-storey buildings have mostly been assembled by major building contractors.

The sort of wood studied is spruce.

## 1.5 Methods

The RH, MC and temperatures have been measured both momentarily and continuously during the various phases of the construction process, and over several years in the external walls of finished houses (see Figure 4). Surveys to detect rain penetration to the wooden structure have also been carried out. Sampling and microbiological analysis, according to methods described by (Hallenberg and Gilert 1988), have been carried out on timber and in structures at accessible sample points or by opening the structures during the various phases of the construction process or in finished houses. Moisture surveys and observations during visits to house-building factories and construction sites have been documented and photographed.

Tests and comparisons of different structures have been carried out in laboratories with simulated indoor and outdoor climates in a climate chamber. Driving rain leakage of wooden panelling façades has been tested in a laboratory. Moisture redistribution in timber stacks has been studied in a laboratory. Testing of mould growth or mould resistance on timber or wood has been carried out in a laboratory, according to methods described by (Johansson and Bok 2011).

Computer simulations of moisture and temperature in timber and structures have been carried out using one- or two-dimensional calculation software. Calculation of mould risk in timber both during timber storage and in finished houses has been carried out using a mould model.

## 1.6 Outline of the work

The work is based on seven publications, listed in chronological order from the construction process (see the following list), and covers timber stacks at sawmills, factory production of wall elements and roof trusses, transportation to the construction site, assembly, as well as follow-up of finished houses in the usage stage (see Figure 4).

The report about mapping moisture conditions during the construction process forms the basis for several other studies.

Paper I. *Redistribution of moisture in timber items and the risk of mould in timber items in the timber stack.* The study shows moisture redistribution in timber items after drying at the sawmill and packaging, MC differences in a cross-section of the timber items and the risk of mould growth. The study was carried out on the basis that a need for new knowledge had emerged, partly based on results in Paper II and partly based on a knowledge summary by Nilsson (2009).

Paper II. *Moisture and mould in prefabricated timber framed constructions during production until enclosure of the house.* The study shows measurements and observations during the construction process of approximately 30 houses and also shows experiences from site visits.

Paper III. *Laboratory investigation of sills and studs exposed to rain.* The study shows moisture levels, drying times and mould growth on sills that have briefly been exposed to rain or water. The study is based on the conditions sills are often exposed to water, according to site experiences summarised in Paper II.

Paper IV. *Laboratory study of wooden façade leakage during driving rain.* The study shows driving rain leakage in wooden panelling façades and façade details, such as window connections.

Paper V. *Laboratory investigation of timber-frame walls with various weather barriers*. The study shows comparisons with and without insulation of the frame and its effect on moisture levels.

Paper VI. *Moisture surveys over two years after replacement of plaster façade*. The study shows moisture and temperature conditions as well as detection of driving rain penetration in ventilated and unventilated wooden stud external walls with a plaster façade.

Paper VII. *Moisture surveys in four timber houses*. Moisture and temperature conditions as well as detection of rain penetration in ventilated timber stud walls. It also includes mould analysis of materials from structures and calculations of mould risk. Shows which moisture conditions and possible mould growth occurs on site in well-insulated structures.

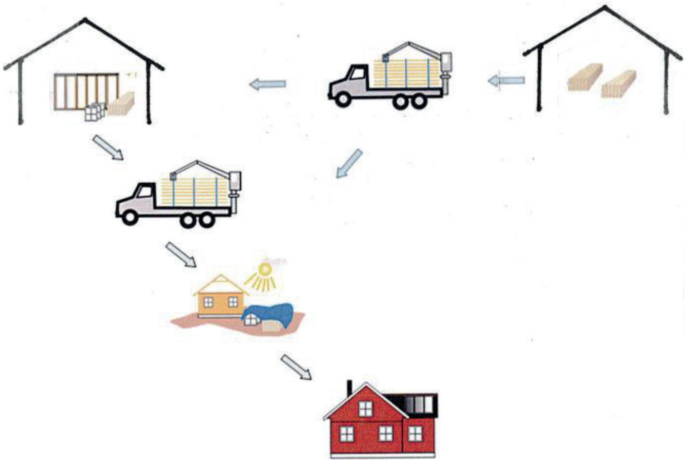


*Figure 4. Schematic diagram of the various phases of the construction process, from timber yards at the sawmill via production of wall elements and roof trusses at the factory to the construction site with assembly and finished houses in use.*

## 1.7 Limitations

In several of the reported attempts, at least two and often three of the methods described by Vinha (2007) have been used to describe the moisture and temperature conditions and mould growth. There are both advantages and disadvantages with the three methods used, though they do complement each other fairly well. Within building physics, there are a number of different factors of significance, which is why it could be difficult to demonstrate the accuracy of the results or draw far-reaching conclusions unless several methods were used.

There have been a limited number of construction projects, houses and structural designs and it has not always been possible to take material samples in walls. This is why laboratory testing and calculations have been carried out to study specific issues and to provide a more comprehensive picture of what the conditions have meant. Given each stage of the construction process, different structures, different objects, different locations and different designs, which overall basically accommodate an infinite number of specific situations and conditions in reality, the results reported cannot be relevant for everything. Each report applies to reported cases and conditions but all reports together should hopefully act as a sufficient basis in order to provide recommendations.

# 2 Timber stacks

Timber is generally dried artificially, for example in a chamber dryer. After which the timber is processed through planing, to then be stacked and wrapped before storage and delivery. The following issues need to be addressed in order to determine if there is a risk of growth on the timber. How dry should the timber be when stacked at the sawmill in order to store timber? How long can timber surfaces be exposed to an outdoor climate? What MC can be expected in timber stacks? Does dried timber normally exceed critical moisture levels during storage due to its overall MC despite the surface being relatively dry after drying? When does microbial growth occur on timber?

## 2.1 Measured moisture content in timber stacks

In this study, MC were measured 7-8 days after the timber had been removed from the chamber drier at a sawmill in Västra Götaland on 12-13 September 2012. Measurements were taken from three timber stacks with timber dimensions of 47x200, 47x150 and 47x100 mm before planing. In addition, measurements were taken from a wrapped timber stack that was ready for delivery with timber dimension of 21x88 (planed tongue and groove), which had been dried in the chamber a month earlier.

The MC has been measured using Protimeter Timbermaster instruments as well as hammer electrodes with insulated pins that measure electrical resistance. Measurements were taken at timber depths of 0.3 x thickness and 0.3 x breadth in the timber item in accordance with SS-EN 13183-2 (SIS 2003). Measurement uncertainty of the MC is estimated at less than ±1%. Temperature compensation was carried out for the MC values. The measuring instruments were calibrated with traceability to normal and the national standards laboratory, SP. Temperature compensation was performed according to (Esping and Samuelsson 1994).

A quantity of timber items as stipulated in the standard was selected from each timber stack, in accordance with EN 12169:2011 (SIS 2011) for MC measurement. For timber stacks with the dimensions 47x150 and 47x200 mm, the upper layer has also been admissible during selection, which is not included according to EN 12169:2011. In addition, the number of timber items for the dimensions 47x100 mm were limited to approximately half of the timber stack. For the timber dimensions 21x88 mm, the number of timber items was limited to three, and the selection began in the fourth layer of the timber stack in order to avoid direct impact.

MC measurements of timber from four different timber stacks were taken at the same sawmill on 12-13 September 2012, refer to Table 1.

*Table 1. The average MC for a timber stack for each dimension, along with minimum and maximum values for each individual timber item.*

| **Timber stack with timber dimensions [mm]** | **Average MC in the timber stack [%]** | **Min MC in the individual timber item [%]** | **Max MC in the individual timber item [%]** |
|---|---|---|---|
| 47x100 | 16.5 | 14.5 | 19.3 |
| 47x150 | 15.3 | 12.5 | 19 |
| 47x200 | 16.7 | 13.9 | 20.1 |
| 21x88 | 17.5* | 16.5* | 18.9* |

*Based on only three timber items.

The surveys show an average MC in the timber stack of 16.7% at its highest; the MC for individual timber items was 20.1% at its highest and 12.5% at its lowest. These timber stacks can therefore be regarded as meeting the target MC of 16% and drying quality standard in accordance with SS-EN 14298:2004 (SIS 2004) for the supply of construction timber.

A comprehensive study by Källander and Scheepers (2013) demonstrates that sawmills generally meet the standard (SIS 2004). The study covered more than 3,000 timber items, 184 drying batches from 13 sawmills distributed across what amounts to the whole of Sweden. One drying batch can consist of many timber stacks. MC were measured using the resistance method (SIS 2003) and the dry weight method, however, there is no information on which dry weight method was used. The 16% target MC results from a total of 1,939 measurements, shows an average MC of 14.8% using the dry weight method and 16.0% using the resistance method. It was clear that the resistance method produced an elevated value of approximately 1%, as the dry weight method is significantly more accurate. There were occasional MC values of up to 24%, however, 95% of all values were below 17.6% using the dry weight method and below 19.3% using the resistance method. The 18% target MC results, from a total of 1,203 timber measurements, shows an average MC of 15.7% using the dry weight method and 17.4% using the resistance method. There were occasional MC values that exceeded 24%, however, 95% of all values were below 19.4% using the dry weight method and below 20.6% using the resistance method.

The measurements were taken by the sawmill staff, so there are probably differences in handling and measurement uncertainty, mainly in the resistance method (for example different brands of measuring equipment). There is also a degree of unclarity when it comes to temperature compensation and calibration, uninsulated or poorly insulated pins, insufficient length of pins, variations in measuring depth, etc.

The standard allows a certain amount of deviation from the target MC, which could involve critical factors if this is utilised to the limit. However, it appears that the sawmills remain significantly below the target MC in this study. The reason the sawmills remain below the target MC could be because they use the resistance method which may overestimate the MC, or because they remain well within the drying limit to ensure that they meet the standard.

## 2.2 Moisture redistribution in timber inside timber stacks

How long does it take a timber item inside a timber stack to start reaching moisture equilibrium on the timber surface at the point that adjusts fastest? The timber achieves MC differences in the cross-section in the chamber drier. After which moisture redistribution begins in the timber item, i.e. the centre of the timber will continue to dry whereas the surface or outer areas will humidify from the moisture in the centre, which means a transition from the desorption to the absorption curve. If the timber surface is drier than the centre of the timber when the timber is stacked, the question is whether a longer storage time can be permitted for timber that has an elevated average MC with regard to microbial growth risk. Below are results of moisture redistribution in calculations as well as measurements.

If the timber is not packaged, but is included in a timber stack, the surrounding air can humidify the timber or contribute to drying. The significance of the surrounding air with regard to mould growth is studied in chapter 2.4.

### 2.2.1 Calculation results

Calculations of moisture redistribution in timber have been carried out by Professor Lars-Olof Nilsson and the aim was to demonstrate how long moisture redistribution takes along with RH and MC. Calculations have been made in the vertical cut in the centre of the timber item with a dimension of 45x195 mm where moisture levels too are already near the final equilibrium MC (see Figure 5). It has been possible to do this with a one-dimensional program called KFX (Rodhe 2003). Input data for the calculation has been selected according to a qualified estimate of moisture distribution in timber items after chamber drying. In addition, it is assumed that nearby timber items have the same MC of 18% and temperature of 15°C and moisture distribution as calculated, which is why moisture exchange between timber items does not need to be taken into consideration. Calculations have been made in a one-dimensional direction in order to take into account hysteresis, transition between sorption curves (Nilsson 1988). In addition, the impact from the edges is marginal in the centre of the timber, which has been demonstrated in a preliminary two-dimensional calculation with the VaDau software (Hedberg 1988) and is presented in (Olsson 2012d).

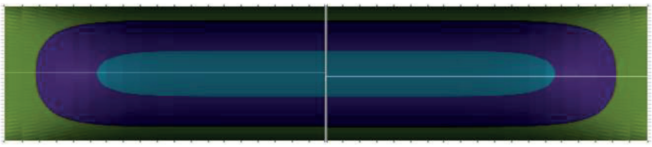
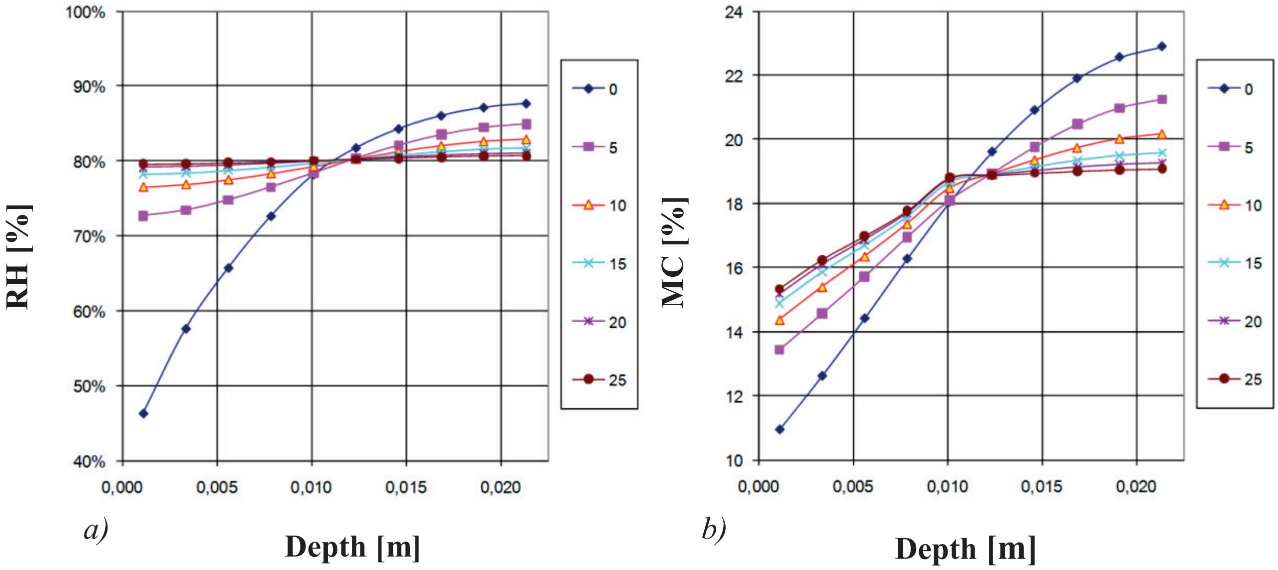


*Figure 5. 2-D caluculation of timber item with dimensions 45x195 mm that has dried in the same climate on all surfaces. The MC is highest in the centre and lowest at the surface.*



a)

b)

*Figure 6. Diagrams a and b show calculation results of RH and MC at various depths from the surface for timber dimensions 45x195 mm with an average MC of 18%. Each curve represents the redistribution time in days (one day is 24-hours) after chamber drying for a timber item inside a timber stack. It is assumed in the calculation that adjacent timber items have the same MC.*

The calculation results show that it takes approximately two weeks for the timber surface to reach a level approaching moisture equilibrium (see Figure 6a). Redistribution is therefore relatively fast. The two last percentage points in RH required to basically achieve moisture equilibrium appear to take a further two weeks. Ultimately there will be about 4% difference in the MC value between the centre (19%) and the surface (15%) at total moisture equilibrium, despite the same RH (80%) in the entire cross-section, refer to Figure 6. The difference is due to hysteresis (Nilsson 1988). This means that a relatively low surface MC (15%) can correspond to fairly high humidity (approximately 80% RH).

### 2.2.2 Survey results

Measurements have been taken to demonstrate moisture redistribution in timber for various timber dimensions in timber stacks. Samples in the form of two specimens from each timber stack were taken on 12 and 13 September 2012 at a sawmill in southern Sweden, from three relatively recently dried timber stacks. The timber was dried artificially in a chamber drier, with timber dimensions of 47x200, 47x150 and 47x100 mm. These samples were taken before final processing and planing of the timber studs. Dimension 21x88 mm (planed tongue and groove) had dried for a month prior to sampling. The specimens were cut into lengths of 600 mm. The specimens were sealed at the time of sampling and were stored in a temperature stable room at 23°C for five days, and subsequently in a temperature stable room at a constant temperature of 15°C with a RH of 30-40% for approximately two months. Moisture redistribution was examined by measuring RH (capacitive sensors from Vaisala HMP44) in the centre of the timber item and on the wide and the narrow surfaces (see Figure 7). The measurements were taken more frequently at the beginning and less frequently towards the end of the survey period. The MC was measured at the time of sealing and after two months with a Protimeter Timbermaster resistance meter as well as hammer electrodes with insulated pins. Measurement uncertainty for RH is estimated to be less than ±3.5% and less than ±0.2ºC for temperature. Measurement uncertainty of the MC is estimated to be less than ±1%. The measurement instruments were calibrated with traceability to normal and national standards laboratory, SP. Temperature compensation was performed according to Esping and Samuelsson (1994).

The specimens consisted of spruce timber that had been chamber dried and laid scattered under covering for 7-8 days before samples were taken. The planed tongue and groove timber was stacked and wrapped on five sides and was dried for approximately four weeks before samples were taken.

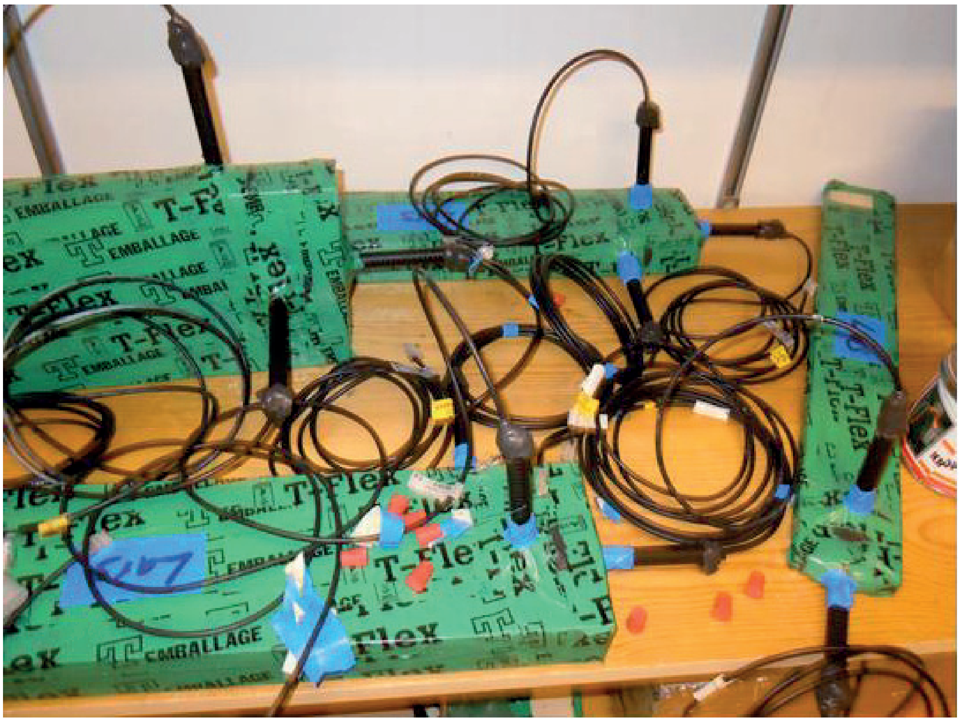


*Figure 7. Sealed specimens with measuring tubes, 12 mm inner diameter, assembled on surfaces and in the centre as well as an installed RH sensor.*

Figure 8 and Figure 9 show the results for one of the specimens, 47x200 mm. A summary of all of the measurements is presented in Table 2.

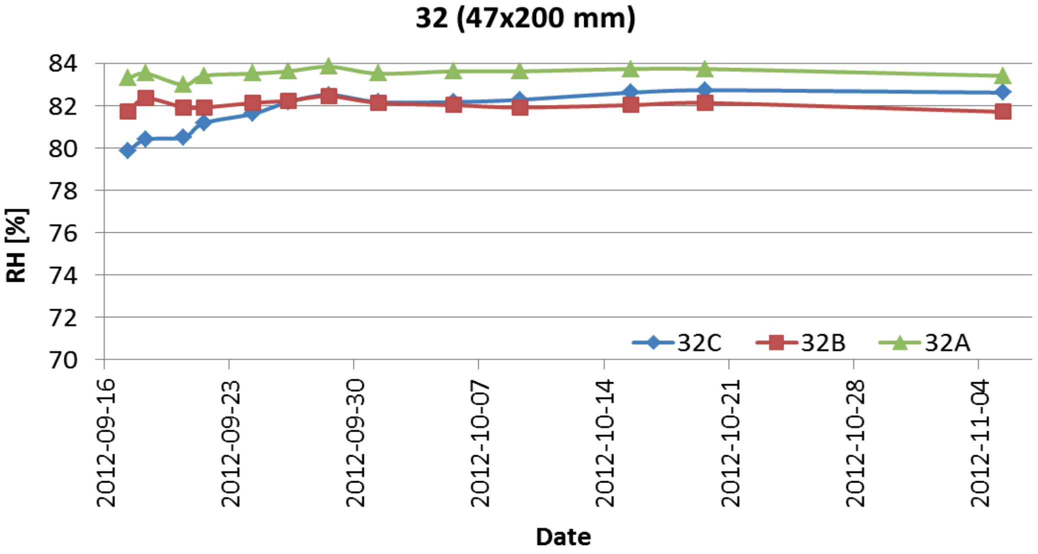
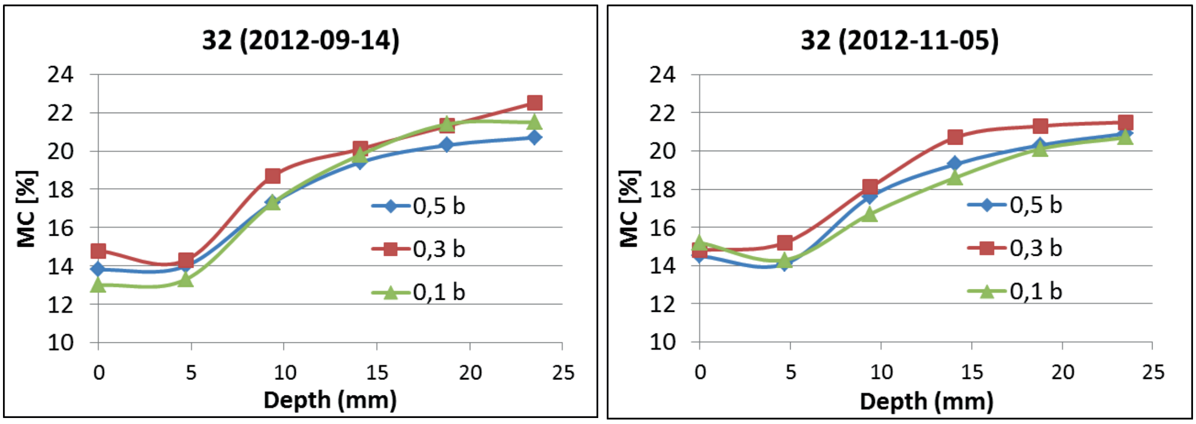


*Figure 8. Measured RH over approximately two months of follow-ups of sealed specimens (no. 32) timber dimension 47x200 mm. The curves represent different measurement depths in the timber (A is in the centre of the timber, B is in the middle of the wide side's surface and C is in the middle of the narrow side's surface/edge).*



*a)* *b)*

*Figure 9. Diagrams a and b show measured MC at six different depths and for three different distances from the narrow side/edge (e.g. 0.3 x b). The diagrams are split into measurements taken before (14 Sept 2012) and after (5 Nov 2012) long-term follow-ups for timber items (no. 32) with dimensions of 47x200 mm. Note that the points of measurement before and after have been kept separate at a mutual distance of approximately 100 mm to avoid impact from the pinhole, and that the points of measurement for MC were kept separate by 300-400 mm within the specimen.*

*Table 2. Summary of moisture redistribution in timber items. Comparison between before and after two months of follow-ups of sealed samples. Measurement point A is in the centre of the timber and B is in the middle of the wide side's surface.*

| **Timber no. and dimension in [mm]** | **MC Before *(before sealing)* [%]** | **MC After [%]** | **RH Before *(5 days after sealing)* [%]** | **RH After [%]** |
|---|---|---|---|---|
| 79A (47x100) | 17 | 16 | 72 | 68 |
| 79B (47x100) | 13 | 12 | 72 | 68 |
| 121A (47x100) | 17 | 16 | 69 | 65 |
| 121B (47x100) | 12 | 12 | 69 | 65 |
| 99A (47x150) | 17 | 16 | 70 | 66 |
| 99B (47x150) | 14 | 13 | 69 | 64 |
| 147A (47x150) | 19 | 17 | 75 | 70 |
| 147B (47x150) | 11 | 13 | 73 | 70 |
| 32A (47x200) | 20 | 19 | 83 | 83 |
| 32B (47x200) | 14 | 15 | 82 | 82 |
| 67A (47x200) | 17 | 19 | 74 | 71 |
| 67B (47x200) | 12 | 13 | 74 | 72 |
| 40A (22x88) | 18 | 17 | 76 | 75 |
| 40B (22x88) | 15 | 15 | 76 | 75 |

Measurement of the moisture redistribution in a timber item (sealed specimen no. 32) with timber dimensions 47x200 mm showed that the RH and MC were close to equilibrium even when tested at the sawmill (see Figure 8 and Figure 9). Both the RH and MC before and after the survey period show a relatively small difference. Some of the moisture has probably been redistributed during the 7-8 days of storage after drying, which the calculations confirm to a certain extent. The ambient climate has probably also speeded up 'redistribution', as the timber was scattered after drying, which can also be established from the measured RH, which has decreased or remained at the same level for two months of follow-ups. As with the above calculations, a significant variation of approximately 4% was also obtained here in the difference in MC between inside and on the surface at moisture equilibrium. A comparison for all specimen samples mostly suggests an approximate difference of

4% (see Table 2). MC differences in the cross-section of the timber after moisture redistribution and moisture equilibrium are mainly due to hysteresis (Nilsson 1988). In an earlier site study, MC differences in the cross-section have been discovered in timber in timber stacks after several months of storage (Segerholm 1998).

## 2.3 Mould growth inside timber stacks

Based on calculations and measurements of moisture redistribution in an earlier chapter, it can be assumed that the surface MC of the timber items inside the timber stack will relatively soon achieve a reasonable degree of equilibrium if nearby items have almost same MC. In addition, there will barely have been any significant change in the moisture level after six months of storage in the middle of a timber stack, particularly if it is wrapped on five sides. If the timber is unwrapped, changes to the overall moisture level are probably very slow, in the middle of the stack at least (Segerholm 1998) (Esping et al. 2005). The question is, at which MC or RH is there a risk of mould growth inside timber stacks – above all during a longer storage period?

Presented below are the results from calculations and laboratory tests.

### 2.3.1 Calculation of the MRD index

The calculations demonstrate at which RH level there is a risk of mould growth inside timber stacks, above all during a longer storage period. Calculations were made by Tord Isaksson at LTH. Calculations were made using the MRD model (Thelandersson and Isaksson 2013), where MRD stands for Mould Resistance Design. The model calculates a dose based on climate exposure and time. The dose can both increase and decrease, depending on climactic variations. If the dose reaches a critical dose, $D_{crit}$, a value of one or higher is obtained, which means a risk of established growth.

This calculation is based on planed stud timber which, according to the model, has $D_{crit}$ in 17 days. Furthermore, the calculation has been based on three RH levels: 78, 80 and 82%, which is equivalent to a MC in the timber stack of around 17, 18 and 19% respectively. Temperatures in the calculation are taken from site measurements of ambient air (see Figure 11) in three timber yards in southern Sweden during the period between October 2008 and October 2009.

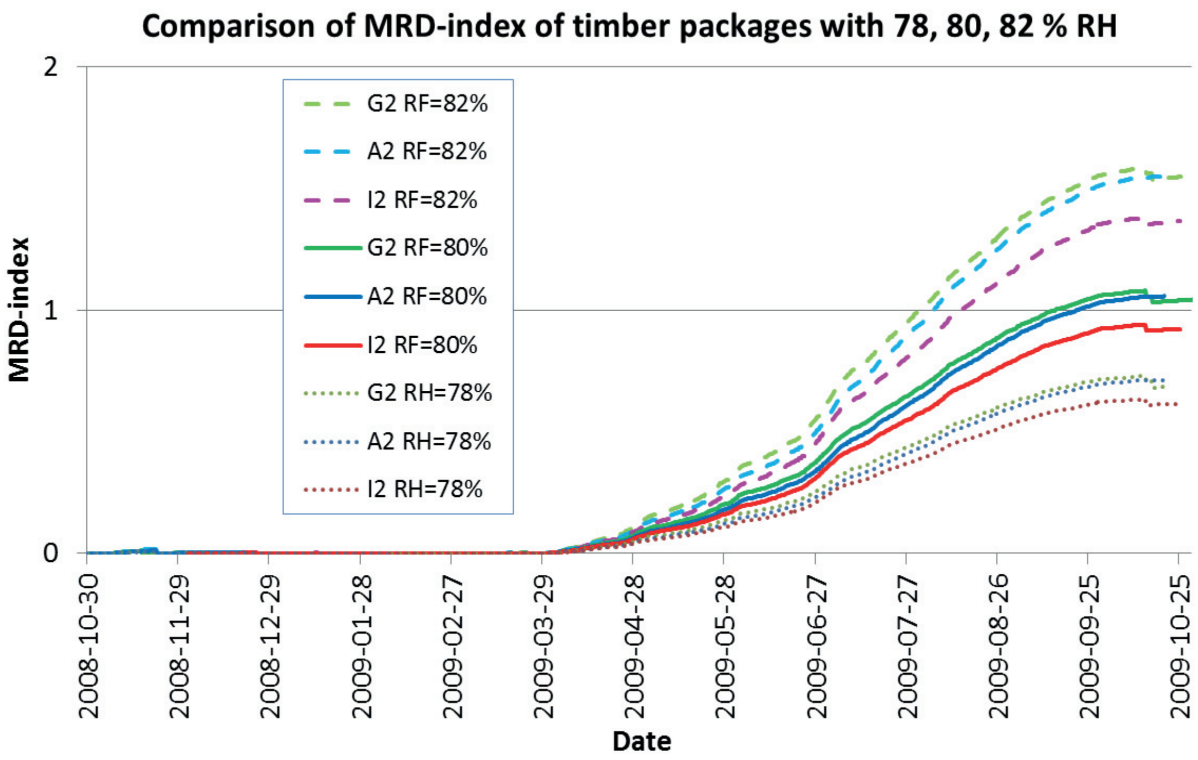


*Figure 10. MRD index in timber stacks or packages with a confirmed RH of 78%, 80% and 82% and measured temperature adjacent to the timber stack. The calculations have been made for three different timber yards for a year between 29 Oct 2008 and 21 Oct 2009.*

Calculations show an MRD index of 1 to 1.5, which means that established growth could have occurred in timber stacks with 80% RH and 82% RH that have been stored for three summer months (see Figure 10). Growth may have occurred in timber stacks with a RH of 78%, however, not enough for growth at the temperature in question. Generally, the temperature has been somewhat lower in outdoor storage facilities (I2) which has produced a slightly lower MRD index. During the colder months, no microbial growth appears to have been possible in any storage facility. It appears as though the microbial growth is at its prime during the three summer months of June to August, due to a higher temperature during these months.

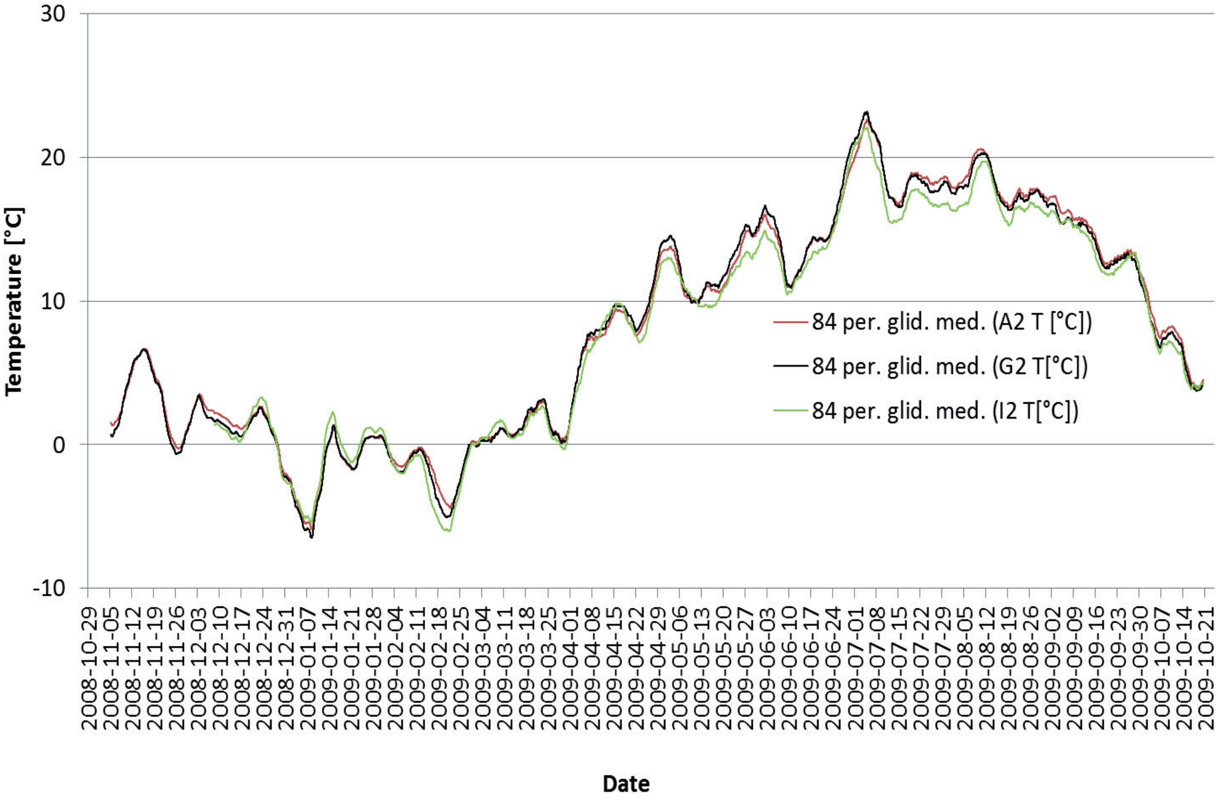


*Figure 11. Sliding average for a week based on measurements every two hours. Temperature of the ambient air around the timber stack, were logged and continuously measured at all times of the year for three timber house factories in southern Sweden. Timber stacks A2 and G2 were stored in unheated areas indoors and I2 was outdoors under roof (Olsson 2010).*

### 2.3.2 Survey results

For the delivery of construction timber, the average MC in an entire timber stack may not exceed 18% with a target MC of 16%, according to current industry regulations in AMA Hus 11 (Svensk Byggtjänst 2012). How long can this type of timber stack be stored during the summer before there is a risk of microbial growth inside the stack, assuming it is stored away from moisture, e.g. under cover or in an unheated storage space?

The moisture level in this type of timber stack with an 18% MC is probably equivalent to approximately 80% RH. The average temperature in southern Sweden in the summer is estimated to be around 15°C (see Figure 12) based on historical climate data of average temperatures (Nevander and Elmarsson 1994). Temperature variations in the ambient air over a 24-hour period are unlikely to produce any significant temperature variations inside a timber stack, due to the timber's inertia, both in mass and thermal conductivity. Therefore a constant temperature of 15°C probably reflects the approximate temperature inside a timber stack during the months of June to August.

In order to examine representative timber, samples have been taken in timber yards at three house-building factories in southern Sweden. The timber consisted of planed tongue and groove board and planed studs in spruce. Clean timber without visible damage was selected. Each original full timber length was divided into smaller samples with a surface area of approximately 50 cm². They were stored in an indoor climate until they were to be used in the test. Material sampling and testing of mould growth has been carried out by Gunilla Bok and Pernilla Johansson at SP.

The specimens (23 planed tongue and groove boards and 13 planed stud timber items) in the test were exposed to mould spores by placing them outdoors under cover on 6 July 2011 between 8 am and 4 pm. The samples were then incubated in a climate chamber at 80% RH and 15°C. The samples were analysed on four occasions (days 41, 49, 64 and 110) using a stereo microscope with a magnification of 40 and classified according to a five-point scale. Established growth is defined as ≥2 on the classification scale, according to (Johansson et al., 2012).

*Table 3. The overall number of samples with microbial growth for each house-building factory. Classification of class 2 microbial growth means established growth.*

| | Planed tongue and groove board | | Planed studs | |
|---|---|---|---|---|
| Factory | Total number of samples | Number of sample with growth of at least class 2 after 110 days | Total number of samples | Number of sample with growth of at least class 2 after 110 days |
| A | 10 | 4 (3 after 41 days) | 3 | 0 |
| B | 7 | 0 | 6 | 0 |
| C | 6 | 0 | 3 | 1 |
| Total | 23 | 4 | 12 | 1 |

The test demonstrates, for example, that 13% of planed tongue and groove board was infested with microbial growth during a 41 day test period (see Table 3). The growth appeared at some point between 1 and 41 days, as the analyses were carried out after 41, 49, 64 and 110 days. All samples with growth came from the same factory (A). All samples classified as class 2 after 41 days had class 3 growth after 110 days. The results show that 8% of the stud samples were infested during a test period of 110 days and growth appeared at some point between 65 and 110 days. The results show that the growth differs between the timber from different factories, which is more or less to be expected according to Johansson and Bok (2011), Hyppel (1989) and Hallenberg and Gilert (1986), and could be due to different conditions during storage, such as spores, dirt, humidity levels, different timber suppliers, timber quality, etc. In the calculations in chapter 2.3.1, established growth was found on planed stud timber with a storage time of around three summer months, which is consistent with this test.

## 2.4 Calculation of mould growth on timber exposed to an outdoor climate

How long can timber surfaces be exposed to an outdoor climate if they are shielded from precipitation and direct sunlight before mould growth occurs? Surfaces that can be directly exposed to ambient air during outdoor storage include the surface of unwrapped timber stacks, the underside of 5-sided wrapped timber stacks, scattered timber and well ventilated wooden stud walls.

Calculations were made using the MRD model (Thelandersson and Isaksson 2013). The calculations were made by Tord Isaksson at LTH. The model calculates a dose based on climate exposure and time. The dose can both increase and decrease, depending on climactic variations. If the dose reaches a critical dose, $D_{crit}$, a value of one or higher is obtained, which means a risk of established growth. This calculation is based on planed stud timber which, according to the model, has $D_{crit}$ in 17 days.

Furthermore, the calculations are based on RH and temperature observations from SMHI for the period between 27 Nov 2008 and 18 Dec 2011 for three Swedish locations, namely Falkenberg, Växjö and Skellefteå, which represent the south coast, southern interior and northern coast of Norrland. Some survey data was missing, which is why it has been supplemented using a method described by (Hägerstedt 2012).

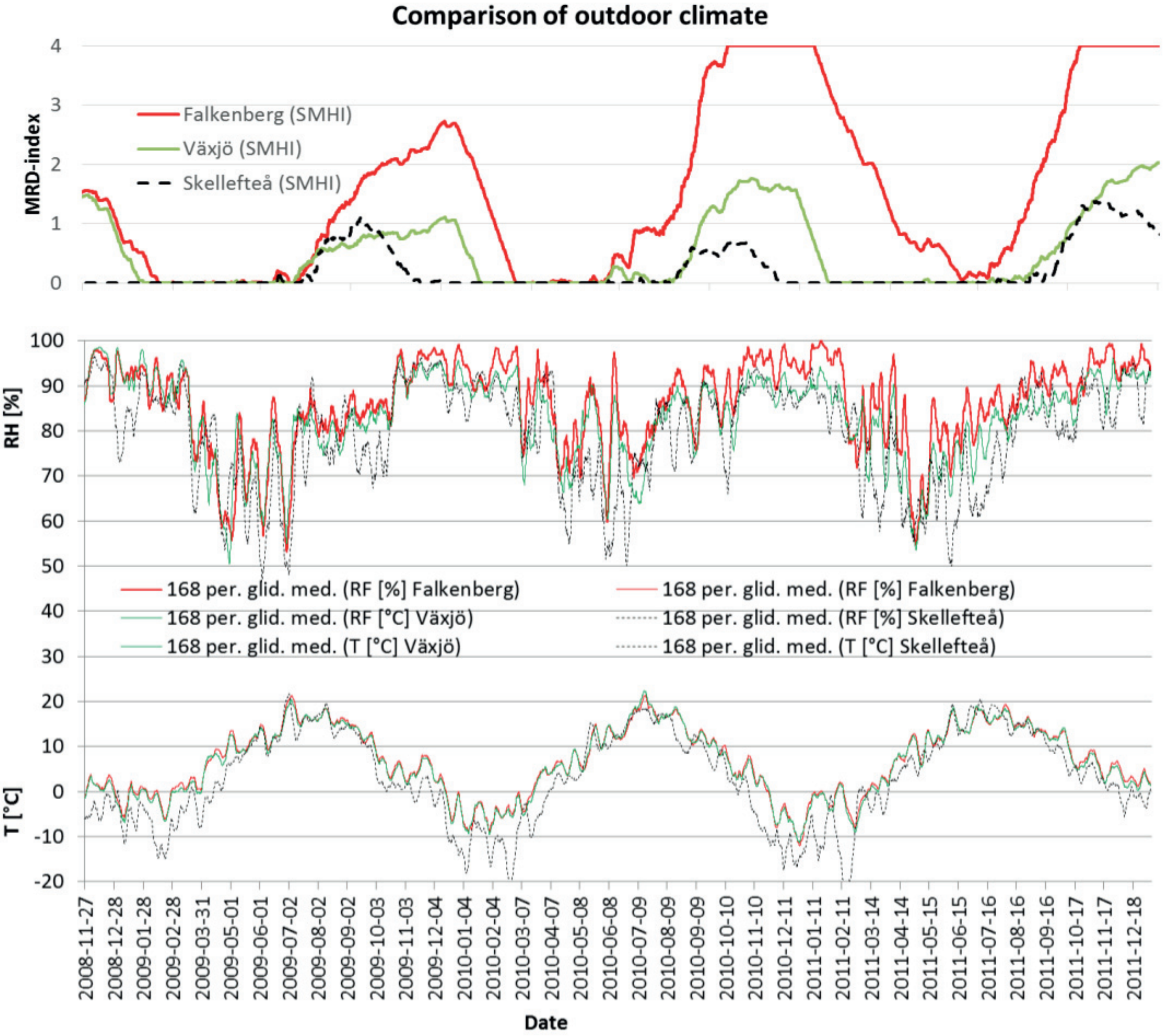
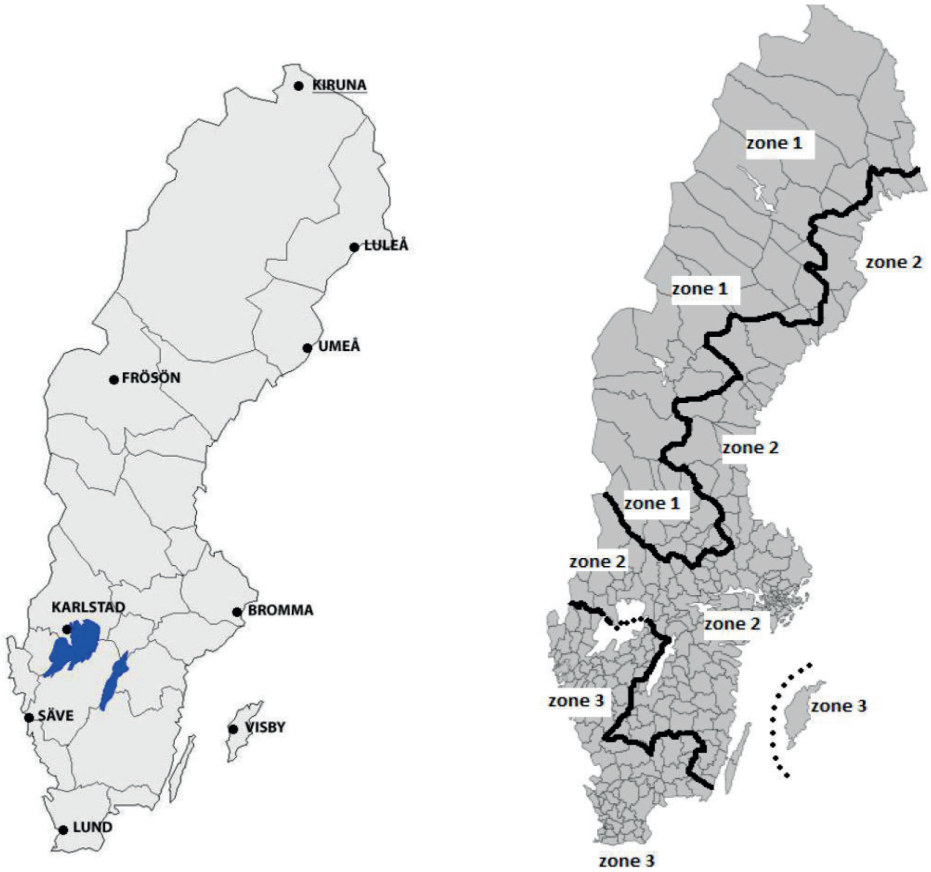


*Figure 12. The curves in the lower diagram demonstrate sliding weekly average values (168 hours a week) of RH and temperatures, according to SMHI data for Falkenberg (Torup), Växjö and Skellefteå during the period between 27 Nov 2008 and 31 Dec 2011. The upper diagram shows the MRD index (note that all values greater than 4 are shown as 4).*

Based on this comparison, it has generally been most humid in Falkenberg and coldest in Skellefteå. The MRD index was considerably higher than 1 every year in Falkenberg. In Växjö the MRD index just reached 1 in the first year and around 2 in the following years. The MRD index barely exceeded 1 in Skellefteå in the first year, and reached 0.7 in the second year and was up over 1 again in the third year. Based on this data, there could be growth on timber that is exposed to an outdoor climate, both in Falkenberg and Växjö, in all three years, assuming the timber is not exposed to a heat supply, e.g. direct sunlight, and in at least one of the years in Skellefteå. The average temperature in Skellefteå was considerably lower than in Växjö and

Falkenberg, which would explain the lower MRD index. Note that this evaluation is representative of timber material that has been exposed to an outdoor climate and has nothing to do with climate envelope in standard heated houses. However, it does provide an understanding of whether there are any conditions at all which promote growth on timber exposed to an outdoor climate. The results suggest that there is a likelihood for growth on material, mainly between June and September, in structures that end up in what is more or less an outdoor climate in Falkenberg and barely any risk at all in Skellefteå. This is fairly consistent with the table drawn up by Frühwald-Hansson et. al (2013). There is a risk of growth on timber material exposed to an outdoor climate (RH and temperature) according to Frühwald-Hansson et. al (2013) in much of southern Sweden, but none at all in the far north (see Figure 13 and Table 4). A zonal division of Sweden has been compiled according to recommended outdoor under-cover timber storage times, with regard to growth on standard planed timber that is exposed to an outdoor climate (Frühwald-Hansson et. al 2013).



a) b)

*Figure 13. Map (a) showing locations modelled. Map (b) showing the Swedish municipalities and zones for different mould risk. Zone 1 has no mould risk and Zone 3 has highest mould risk. Coastal municipalities in the north are assigned to Zone 2 (Frühwald-Hansson et. al 2013).*

*Table 4. Recommendation on maximum storage time in weeks for Zones 1 to 3 based on climate data from Meteonorm recurring about every 10th year (which covers 90% of 47 years of data). (Frühwald-Hansson et. al 2013)*

| **Storage starting on day 1 of month** | **Zone 3** | **Zone 2** | **Zone 1** |
|---|---|---|---|
| January | 20 | 30 | Unlimited storage possible |
| February | 20 | 30 | |
| March | 20 | 30 | |
| April | 10 | 20 | |
| May | 10 | 20 | |
| June | 5 | 10 | |
| July | 5 | 10 | |
| August | 5 | 5 | |
| September | 5 | 5 | |
| October | 30 | 40 | |
| November | 30 | 40 | |
| December | 30 | 40 | |

Table 4 shows that there could be growth on timber that is exposed to an outdoor climate for 5 weeks in Zones 2 and 3, under favourable conditions during August and September. This covers the most humid years during the period between 1961 and 2007. In other words, Table 4 is based on the climate over a period of 42 historic years out of 47 years, and storage time may need shortening for the other 5 years (extreme years).

Vinha (2007) has analysed the risks of growth on material that has been exposed to an outdoor climate in Finland with a mould model by (Hukka and Viitanen 1999). The results also show a relatively high risk of growth in southern Finland, but none at all in northern Finland.

# 3 Production, delivery and assembly of prefabricated wall elements and roof trusses

The following questions need to be answered in order to determine whether the construction process is moisture safe. What is the situation in reality and what moisture conditions occur in prefabricated wood frame buildings? Are there any critical stages and what needs to be improved?

## 3.1 On site measurements and observations

In order to investigate the climate that the wood is exposed to during the production and erection phase, 24 prefabricated detached houses, three timber-house factories and two apartment buildings were studied. The investigations were performed as consecutive phases (as also shown in Figure 14b):

1. RH and temperature of the air in the factory timber store were continuously measured every two hours over a year. In addition, each company's timber store and factory production has been visited at least once. As a minimum, three stacks of timber, several roof trusses and completed wall elements were inspected visually, looking for dirt and staining. Five to fifteen scattered MC measurements were made, and material samples taken for microbiological analysis, in most cases. A limited assessment was also made of the extent of any non-compliances.
2. The RH and temperature of the ambient air around the wall elements were logged/continuously measured each hour from the factory, during transport and until completion of the building. After erection of the main structure, and erection/fitting of enclosing surfaces, these measurements represent the ambient climate inside the building. For each building, the logger was attached to a stud near the window on one of the wall elements. Apart from purely practical aspects, the choice of this position is interesting, as the inside surface of exterior walls is not intended to be exposed to outdoor conditions for any substantial length of time. Material samples for microbiological analysis were taken twice from interior studs (as visible in the window reveal), at the factory and at the construction site in order to provide

information on how the wood withstands the climate during the construction process.

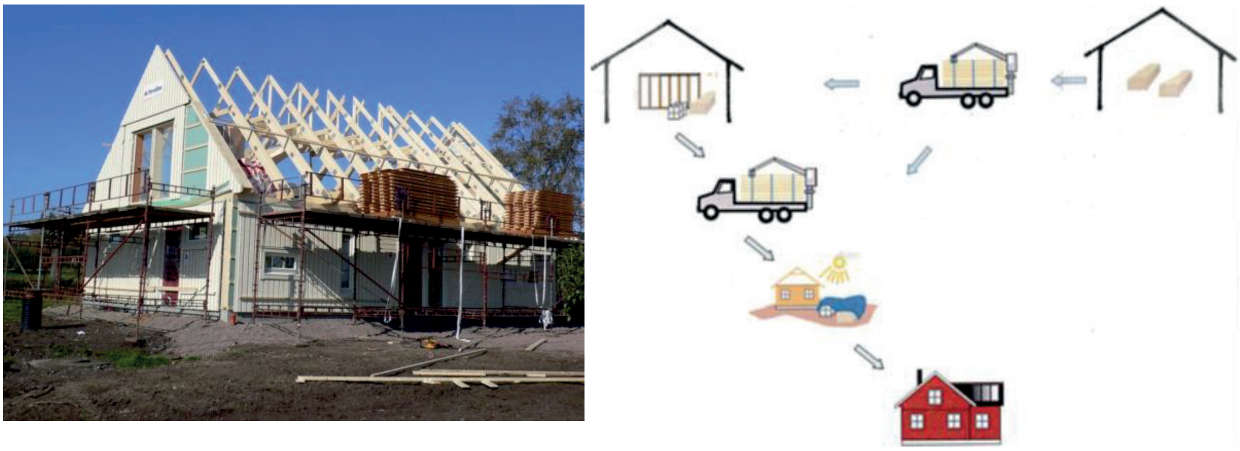
3. Sixteen of the buildings were visited at the construction sites. The various parts of the buildings and/or surfaces were given a general visual inspection for dirt, staining or defects. Material samples were taken for microbiological analysis and measurement of MC. The sampling strategy was that each part of the structure should provide at least five distributed test points. Any stacks of timber, or storage areas, were inspected in essentially the same way as during the corresponding visits to the factories.

MC in wood was measured momentarily by resistance measurement (Protimeter Timbermaster), electrodes of steel pins which measure 0-10 mm deep. Uncertainty of measurement is estimated as being less than ±1.5 percentage points over a MC range of 8 to 25%. Uncertainty is assumed to be greater for MC over 25%, and so any measured values above that limit are shown as 25%. Temperature compensation was performed.

RH and temperature was continuously measured by electrical instrument (Testo 175-H2). Uncertainty of measurement is estimated as better than ±3.5 percentage points for relative humidity, and ±0.7°C for temperature. The instruments were calibrated with traceability.

Samples of wood materials were taken by using a chisel and hammer to take a thin piece of surface material (2-5 mm thick). The size of these samples varies, but was normally in the range 5 to 10 cm². The samples taken in the field were examined under a microscope by the method described in (Hallenberg & Gilert, 1988), using a stereo-microscope at 10 to 40 times magnification. To quantify this growth, a preparation from the material surface is made, which is studied at magnifications of up to 400 times. The preparation is made by scraping part of the surface with a sharp preparation nail or by taking a tape impression of the surface. These are then placed in a drop of lactic acid with cotton blue or alternatively a drop of potassium hydroxide solution on a microscope slide and then covered with a cover glass. Microorganisms were classified as hyphae or actinomycetes. Micro-organisms were classified as hyphae based on the following scale: no growth, slight growth, modest growth and extensive growth. Any occurrence of blue stain fungus was noted separately (require high moisture levels, or free water, for growth).

The results from this investigation consist of data on exposure climates, MC in wood and microbiological analyses of wood as well as observations at all stages from storage at the factory until assembly at site.



a) b)

*Figure 14. a) Erection of a prefabricated single-family house, in progress, stage 2. b) Schematic diagram of the investigated phases in the building process.*

Microbial growth was found on almost one third of all the samples that were taken (see Figure 15). Elevated or high MC were found in one third of all the samples (see Figure 16). The results show that growth was just as likely to be found on dry wood or materials as on damp wood or materials. Blue stain growth was found on two fifths of the samples having some form of growth, and particularly on dry samples (see Figure 15). As blue stain requires free water for growth, this indicates that it probably occurred before the wood reached the factory.

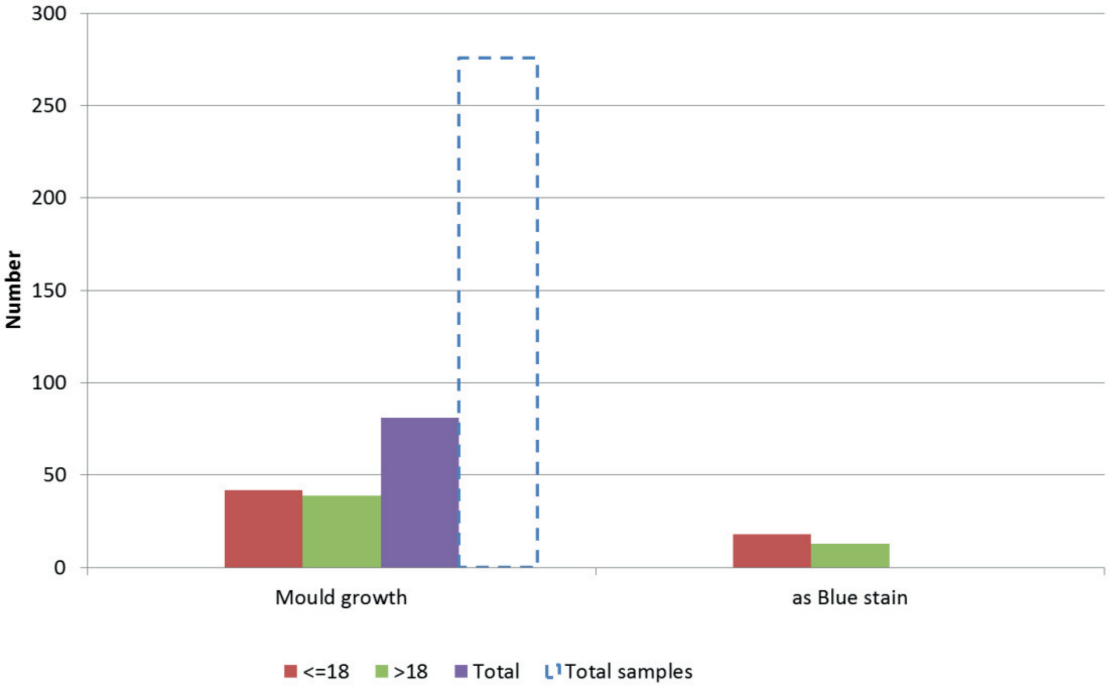


*Figure 15. The red bar shows the number of samples with a MC below or equal to 18%. The green bar shows the number of samples with a MC above 18%. The purple bar shows the total number of samples with growth. The dashed bar shows the total number of samples, 276, that were taken in this study.*

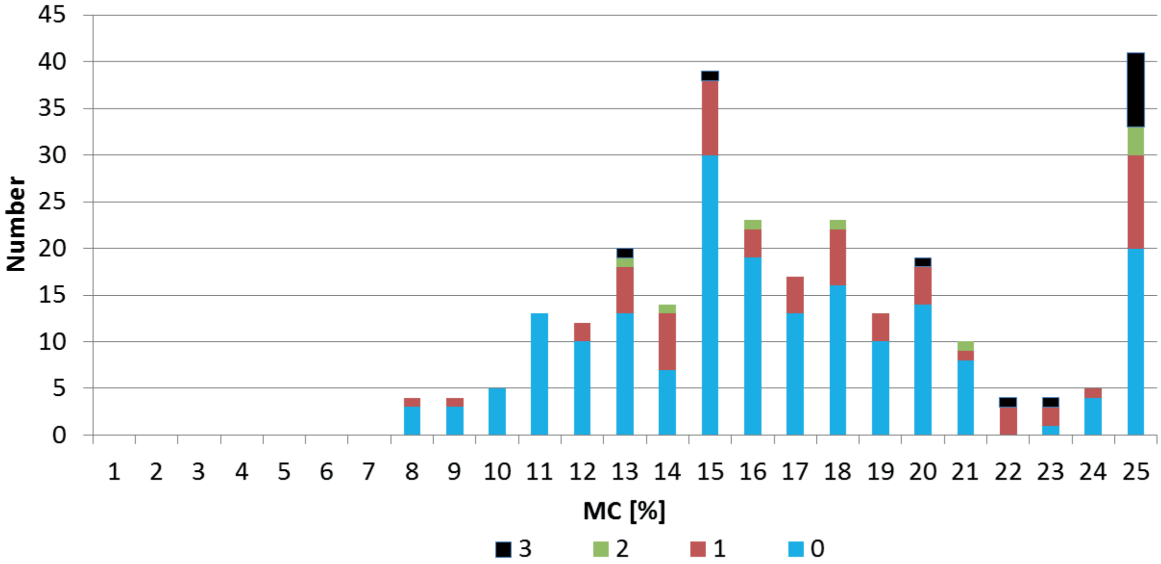


*Figure 16. The bars are grouped to show measured MC. Those showing MC of 25% represent all samples with actual MC above 24%. Each bar indicates the number of samples and the proportion of samples with the respective growth levels: 0 = no growth, 1 = slight growth, 2 = modest growth, 3 = extensive growth.*

In four of the 24 buildings, the local RH remained essentially over 80% RH for a month, while the temperature remained below 13°C (see results in Figure 17 for one of the four buildings). In the other 20 buildings, the RH never, or only briefly, exceeded 80% RH. In general, temperatures were low, at about 10°C, during those times when the local RH exceeded 80%. Material samples for microbiological analysis were taken twice from studs (these studs were exposed to ambient air but never free water) on elements/walls at the factory and at the construction site in order to provide information on how the wood withstands the climate during the construction process. No microbiological growth was found on these studs. We have not found any indication of growth on material due to ambient air, despite the time to fully enclosed house ranging from one week to a few months, depending on level of prefabrication. However, it is clear that in many cases growth has occurred on materials and elements that were exposed to free water in the factory or at the building site (see Figure 18). The main structures of houses, for example, are generally erected regardless of the weather conditions, apart from strong winds.

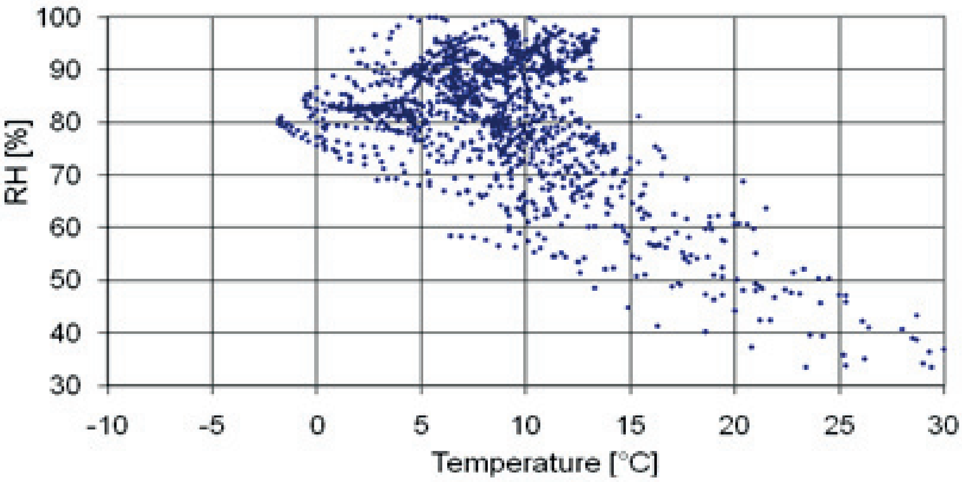


*Figure 17. Climate conditions were logged each hour (i.e. each point represents one hour) from 24 September 2008 to 21 November 2008 on wall element/building, building H, in southwestern Sweden.*

*a) b) c)*

*Figure 18. Observations from outdoor storage of wall elements. One of the house manufacturers stored completed wall elements outdoors in the factory area for several weeks, see (a). They were wrapped in plastic, although parts were found that were not wrapped. In some cases, the plastic was torn in several places, see (c). As a result, some parts of the elements were extremely wet behind the plastic, see (b), while others had microbial growth on them.*

a) b) c)

*Figure 19. Observations from erection stage.*

Wet sills or plates were found in six buildings in interior and exterior walls, as shown in Figure 19a-b and Figure 20. These sills also have microbiological growth. If it was raining while buildings were being erected at the site, there was no way the sills would not get wet. In several cases (from all manufacturers) the sills were found to be still wet several weeks after the building had been erected. There is a need for changes to design and production methods. Hansson (1989) made the same recommendation around 25 years ago.

Exterior wall designs from all three manufacturers were found in which the sill was partly visible diagonally from below or from the outside and exposed to outdoor air (see Figure 19b). Figure 19c shows the exterior of an outer wall, with poor joints in wind barrier and gaps around windows. The wind barrier was exposed to rain in at least six of the buildings over longer periods of time, despite having leaking joints and connections. Better solutions are needed, for example verified wind barrier systems. One of the manufacturers supplied a roof underlay consisting only of impregnated plywood, which was assessed as not being resistant to direct rain. Microbial growth was also found on the underside of this roof. Dirt was found on timber and parts of the structure in five buildings. Small leaks in the roof in the store buildings were found at two manufacturers' premises.

*Figure 20. Observations from erection stage.*

## 3.2 Laboratory experiment of moisture in sills

Wooden sills frequently become wet due to rain during the construction stage (Olsson and Mjörnell 2012b), (Hansson 1989). The question is, how well can wooden sills or studs withstand being briefly exposed to water before or during integration in the structures, and is there a risk of mould growth?

The investigation was carried out in the laboratory, with appropriate conditions being created through conditioning of materials and simulation of expected air exposure in climate chambers. Six of seven sill designs in this study represent ordinary sill designs and were selected by Swedish forest-based industries and SP. One new sill design with a raised level of XPS (see Figure 21), extruded polystyrene under the wall, was also investigated. All wood material was Swedish spruce.

In order to be able to get five different wall sections into the climate chamber, the sills were sawn into 600 mm sample lengths. In addition, one end of each sill was sealed with adhesive, in order to simulate the conditions in the centre of long sills.

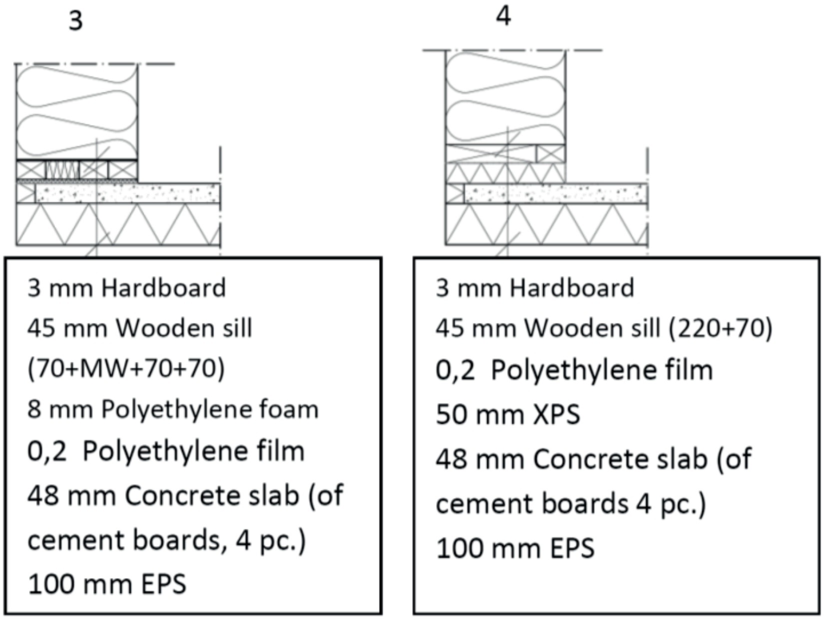


*Figure 21. The figure shows sill design 3 and 4. Installation sill and mineral wool insulation are incorporated in the middle of the sill design 3. The wall will compress polyethylene foam that is there to make it airtight.*

Selected test exposure is based on field experience (Olsson et al. 2011a). The sill designs were placed in a shallow water bath, containing a water depth of 1-2 mm of distilled water for one (sill design 1, 5) or three (sill design 2, 3, 6, 7) days (see sill design 3 and 4 in Figure 21). The wooden sill, sill design 4, is placed on 50 mm XPS, create level difference, whereby water absorption is prevented. Assembling the prefabricated timber-frame detached house generally takes one to two days, and requires the use of a crane. After the wall elements and roof trusses have been lifted into position and secured, the underlay of the roof can usually be applied within three days of starting to erect the structure. The concrete foundation slab will usually have been prepared by mounting both the installation sill and moisture proof membrane under the sill a day or two before the elements or house are delivered and mounted. The connection between the bottom edge of both interior and exterior wall, sill, installation sill and the concrete slab are usually exposed to rain water that often collects on the concrete slab (see Figure 19 and Figure 20).

Sill designs (1-5) that were to be built into the test wall were incorporated within 25 minutes of the end of simulated rain. It took about eight hours from installing the first sill until the internal plastic film/moisture barrier and external wind barrier were fitted. The other two sill designs (6 and 7) were located in the outdoor climate area of the climate chamber. The outside of the wall was exposed to 10°C and about 70% RH for one week; then about 90% RH for the next week, and these changes continued for three months. The inside face of the wall was exposed to 20°C and naturally varying indoor humidity. Climate simulation continued for about three months, with continuous measurement of RH, MC, and temperature.

The RH and temperature were measured with capacitive sensors hourly throughout the test period. The sensor lengths were 25 mm and diameter 6 mm. Uncertainty of measurement was estimated as lower than ±3.5% for relative humidity and ±0.5°C for temperature. The instruments were calibrated with traceability to normal and national test site at SP. The MC was measured with a resistive method at many points and presented in more detail by (Olsson and Mjörnell 2012b), (Olsson 2011c).

Samples of wood materials were taken before and after the test. The samples were examined under a microscope by the method described in (Hallenberg & Gilert 1998) (see chapter 3.1).

The results show that all the sill designs (whether built-in or non-built-in) that were exposed to water for one or three days were attacked by extensive mould growth (see Figure 22) with the growth occurring mainly on those surfaces facing the direction in which drying-out was restricted, such as against moisture barriers, steel parts or items, or materials that were damp or more or less vapour-proof.

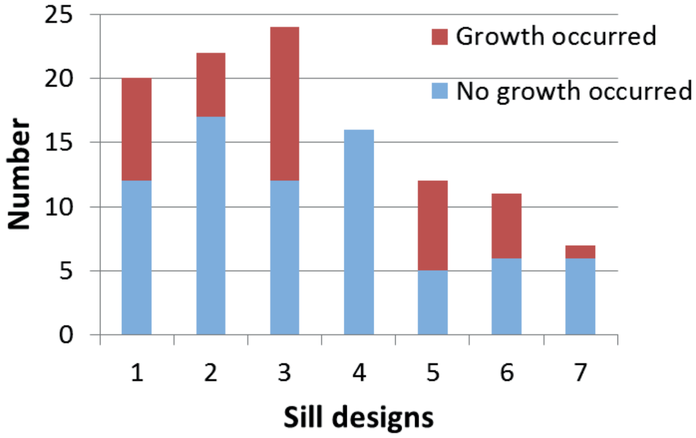


*Figure 22. The columns represent the total number of samples with and without microbial growth. The growth column includes values for all test points for which we clearly know that growth has occurred. The occurred growth was mainly modest or extensive.*

Sill design 4 was not exposed to a water bath. In addition, it seems as if water absorption by end faces of the wood is highly critical in terms of the risk of mould growth. Moisture levels were lower at measurement points well away from end faces, with lower values being reached more quickly. At many of these positions, no mould growth occurred at all, although there were some test points in all of the sections that were well away from end faces and some not in contact to free water but which were attacked by mould growth.

Our assessment is that there is a high risk of mould growth on sills, installed sills, and studs that have been exposed to rain and water under field conditions. However, based on the results of this study, brief exposure to rain splash that does not involve dripping or running water, and which dries off during the same day, ought not to present any direct risk of growth of mould on wooden surfaces. In addition, Johansson and Bok (2011) have shown in laboratory tests that mould growth can occur on damp timber at 95% RH in a time shorter than four days. In principle, the drying-out time from enclosure until RH had fallen to 80-85% ranged from three to six weeks for all the wall sections that had been exposed to water (see Figure 23). Drying takes a relatively long time in the field, which has been shown previously (Olsson et al. 2011a), (Hansson 1989). Specific drying-out times varied from design to design.

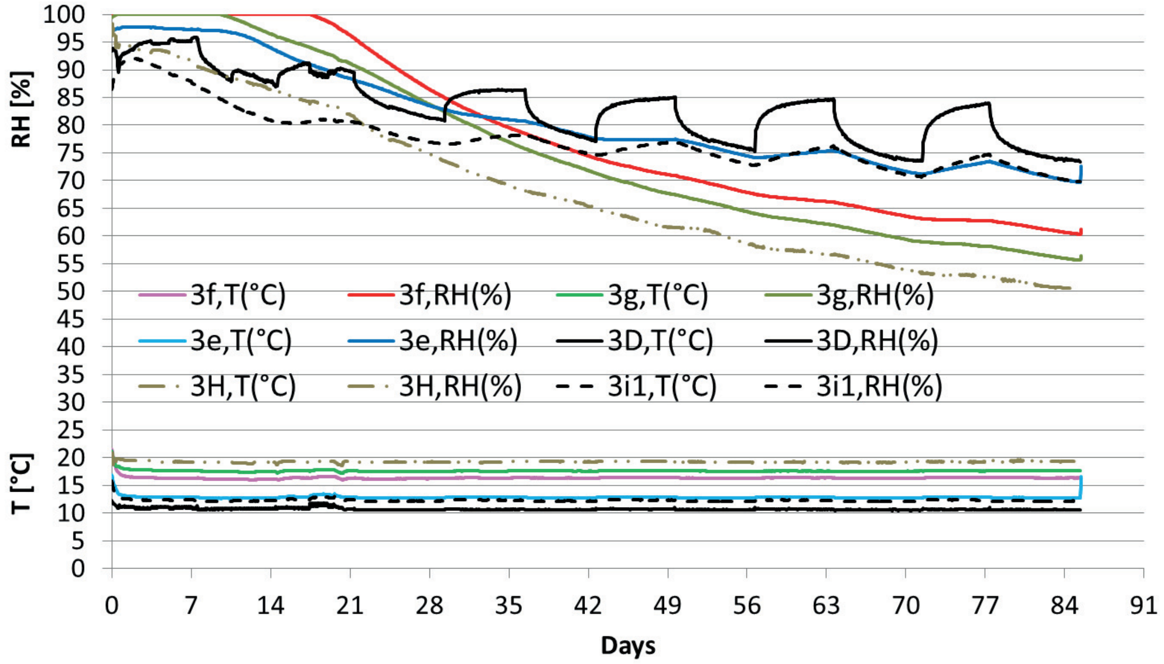


*Figure 23. Measured values of RH and temperature over 86 days, for sill design 3. Positions e, f, g were placed under the sill, H inside the surface of the sill, D outside the surface of the sill and (i) between the sill and stud.*

The study has not shown any tendency for materials to have less growth at lower temperatures, 11-13 °C, in the outer part of the wall than materials in the inner parts of the walls at higher temperatures, 16-19 °C. Moisture levels have been high and relatively long-lasting in both cases. Similar results were obtained for Hallenberg and Gilert (1988), showed that mould growth was significantly lower at 7°C compared to 23°C, but the same quantitative reduction could not be seen for 14°C.

At many of the measuring points where growth was extensive, the growth was not actually visible to the naked eye. This confirms that microbial analysis by microscope is necessary in order to be able safely to decide whether the wood material has been attacked by mould. Several of the measuring positions showed slight growth before exposure to water or climate simulation, with the material having presumably become infected with the growth before it was delivered at the laboratory.

Based on the results, we might advance the following conclusions and recommendations. The wall's connection to the concrete slab should be designed so that it will not be exposed to water during precipitation. Possible solutions could be replacing timber sills with non-moisture-absorbing and moisture-resistant material, or installing a plateau on the concrete slab made from a non-moisture-absorbing and moisture-resistant material on which to place the wall. Wall studs can be protected from water absorption if they are part of a finished wall element that has been weatherproofed. Complete weatherproofing of the entire building element is another alternative. New solutions should be tested and evaluated before being used.

# 4 External walls during the usage phase

The purpose of this chapter is to examine moisture levels and mould growth in external wooden walls during the usage, as well as provide recommendations for good moisture safety. The question is, how well do wood structures survive the climate conditions or is there a need for changes in designs?

## 4.1 Effect of different wind barrier types

How important is the weather barrier for the exposure of outdoor RH in the wall behind the barrier, on the outer part of the timber frame? The work has been performed in the laboratory, with appropriate weather conditions being created in a climate chamber. Work has also included a general comparison of measured results and two-dimensional calculated results.

Four different weather barrier designs in the form of wind barrier fabric, 30 mm and 70 mm stiff mineral wool slab (MW), and 50 mm expanded polystyrene slab (EPS) (see Figure 24) were built and tested in a climate chamber. The thickness of the structure was 290 mm and the height was 1500 mm. The wall consisted of five sections, of which four were insulated with mineral wool and one with loose-fill cellulose insulation. The total wall thickness varied between 290 mm and 360 mm, depending on the type of weather barrier. In addition, one of the sections incorporated two different wooden studs: solid or massive and lightweight.

The study has been limited to exclude the façade, rain and solar radiation. The climate exposure on the outside was intended to represent that to be expected in a well-ventilated air gap of a north-facing wall. The most critical period is usually during late summer and autumn due to exterior RH and temperature. The climate conditions were created in a climate chamber, intended to represent an autumn climate in terms of weekly average values of RH and temperature. The outside of the wall was exposed to 10°C and about 90% RH for one week; then about 70% RH for the next week, and these changes continued for 3 months. The fourth month saw constant RH of 90%. The inside face of the test wall consisted of plastic film as air and moisture barrier, and was exposed to 20°C and naturally varying indoor humidity. Residual moisture in material has had a chance to dry out for 2 months in a normal laboratory environment during summer before the wall was closed up and simulation started.

The specific designs of the test wall sections were selected in conjunction with the Swedish Forest Industries' Federation. All the timber was spruce. Where a solid or massive wooden stud was required, this was arranged by adding a 70 mm stud to a 220 mm stud to give 290 mm wall thickness.

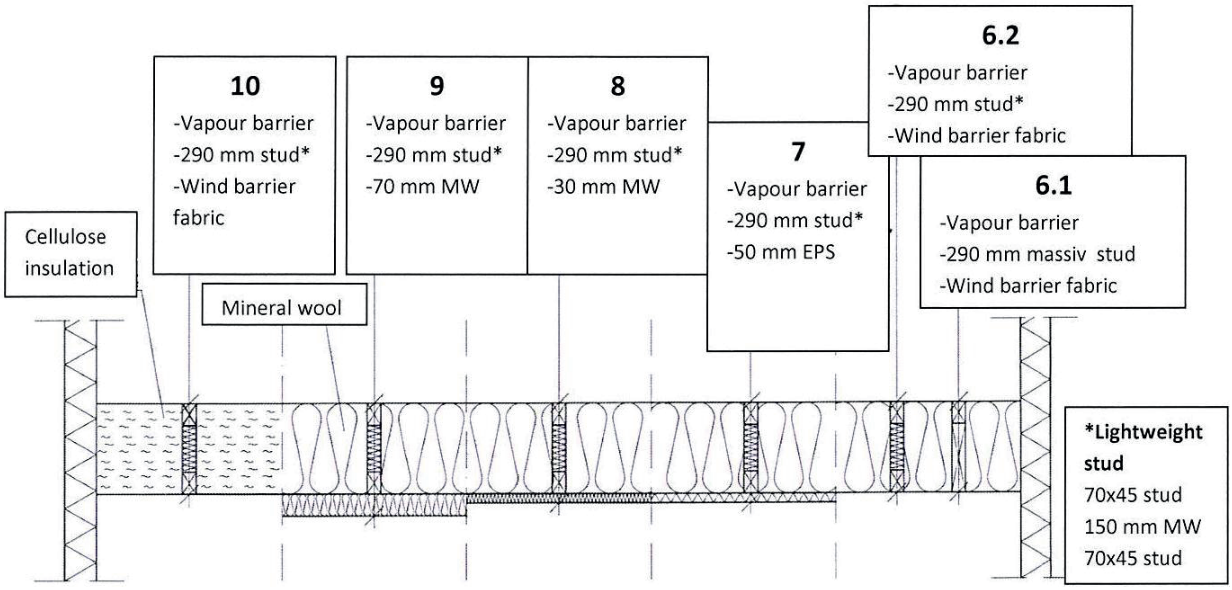


*Figure 24. Horizontal cross-section through the test wall, showing the different structural constituents. The inside face of all designs consisted of plastic film as an air and moisture barrier.*

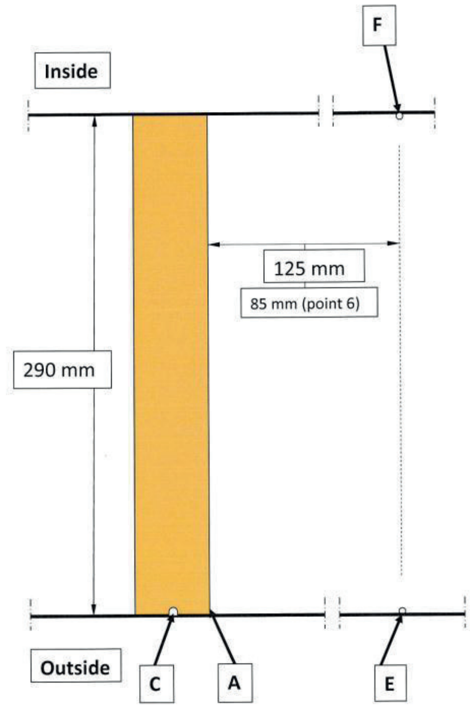


*Figure 25. Horizontal cross-section showing the position of measurement points on and beside the wooden stud. RH and temperature sensors are 6 mm in diameter, which means that the centre of the sensor is about 3 mm inboard of the exterior stud and 3 mm inboard of the weather barrier.*

The RH and temperatures at the specified measurement points in each section were measured hourly throughout the test period. The sensor lengths were 25 mm, and diameter 6 mm. Uncertainties of measurement for sensors were estimated as less than ±3.5% for RH and ±0.5°C for temperature (for sensors), and ±0.2°C for temperature (for thermo-element). The instruments were calibrated with traceability to normal and national test site at SP.

The result showed an RH value on the outside part of the stud of less than 75% in wall section no. 9, with 70 mm MW as weather barrier (see Figure 26). In the other sections, RH values on the outside of the wooden stud exceeded 75%. According to Swedish National Board of Housing (2008), the critical moisture condition for wood needs to be investigated for these cases.

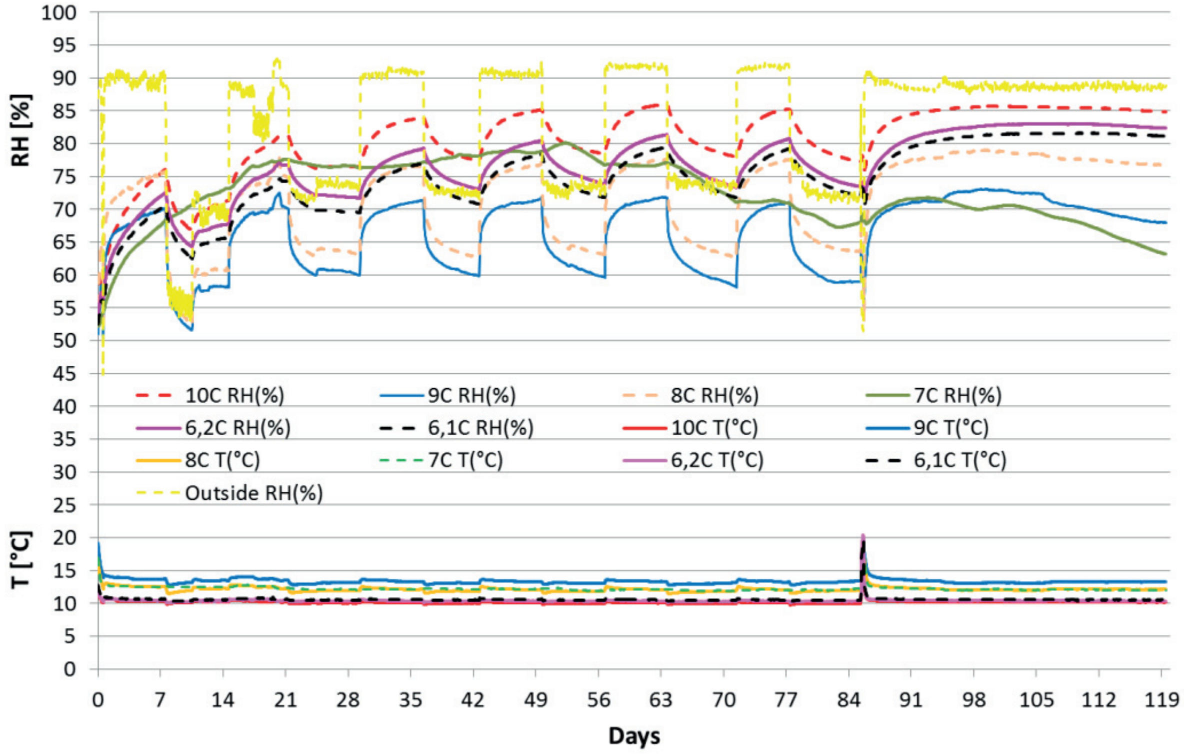


*Figure 26. Measured RH on the outside part of the studs, measurement point C, and at position outside of the climate chamber, over 119 days.*

The temperature at point 6.1C (solid stud) was about 0.4°C higher than at point 6.2C (lightweight stud), which explains why the RH in the outside solid stud was somewhat lower (see Figure 26). The reason for the lower moisture value at point 6.2C than at point 6E (inside the wind barrier) can be partly explained by the temperature difference and by the fact that the heat flow is greater through a lightweight stud than through insulation. Note that these temperature measurements were made using RH and temperature sensors, which do not indicate exact surface temperatures. For this reason, surface temperatures have also been measured using thermo-elements, which show somewhat lower temperature differences (Olsson 2011d).

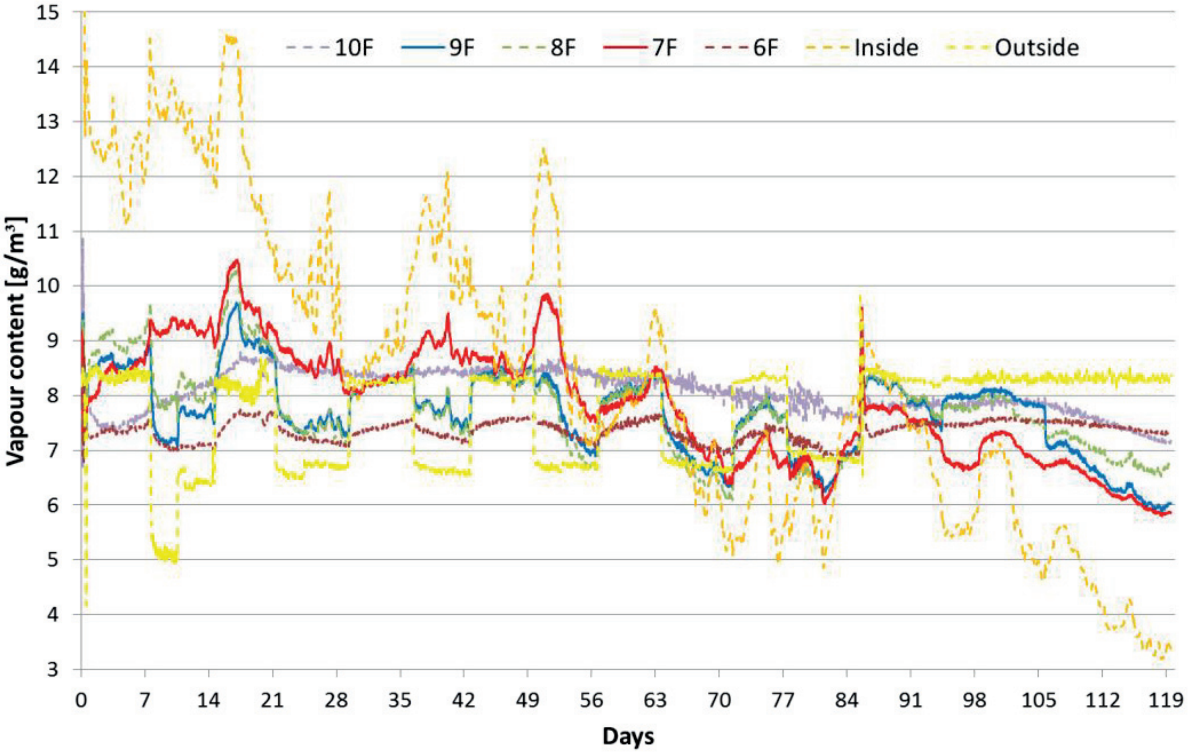


*Figure 27. Vapour content over 119 days, as calculated from measured temperature and RH at position F on the inside of the weather barrier and at position inside and outside of the chamber.*

The reason for the initial higher RH at point 7C (see Figure 26) and then its lower value at the end of the test, was probably that moist air from the inside and later on dry air from the inside penetrated through small air leaks in the vapour barrier, e.g. through cable penetrations that had actually been sealed with butyl mastic and joints that had been sealed with tape. The vapour content at point 7F (see Figure 27) on the outside of the vapour barrier was the same as that in Section 8, and partly the same as Section 9, during the first month, and so all of them are thought to have suffered from minor air leaks from the interior. However, there was a substantial difference in RH between positions 7C and 8C-9C during the first two months (see Figure 26). One explanation for this difference may be that moisture gets into Section 7, which seems to have difficulty in drying out due to lower vapour permeability in EPS-slab compare to MW-slab.

Section 10 also seems to have suffered from moist air from the interior, but it is more difficult to be certain of this, as the cellulose insulation is hygroscopic and tends to smooth out variations. At the end of the climate simulation, the vapour content falls in Sections 7, 8, 9 and 10, despite the outdoor moisture remaining at about the same value. The reason for this is probably the effect of dryer indoor air causing the moisture level to fall. It is also possible that there is some driving force that compels indoor air to leak out through small gaps, as the temperature difference between the interior and exterior was about 10°C, giving rise to a pressure difference of about 0.4 Pa. Another possibility is due to local wind gust created from fans in both warm and cold part of the climate chamber.

Comparison of laboratory measurements and calculations have been made. The purposes of the comparison (see Table 5) are to provide an overview of the approximate moisture levels that can be expected in reality in each of the types of structure, and to check how well the calculation results agree with the measured results and climate exposure in the climate chamber.

Tomas Forsberg, who was a student at KTH, performed calculations in his student thesis using the WUFI-2D program, which provides two-dimensional analysis (Forsberg 2011). Complete calculation results are given in (Olsson 2011d). Calculations started from an MC of 15% in wooden studs and cellulose insulation. The effects of moisture convection have not been included. The façade and the effects of rain were also excluded, with the climate outside the weather barrier intended to represent a well-ventilated wall. The model was simulated as being north-facing, with the climate being that of a statistically average year in Stockholm, with the exception that the RH peaks are rounded to around 95% during almost the entire year, in accordance with the Swedish climate data in WUFI.

*Table 5. Comparison of laboratory measurements and calculations.*

| **Point** | **Laboratory measurement RH [%]** | **Calculation RH [%]** | **Notes** |
|---|---|---|---|
| 6.1A | - | 85-90 | - |
| 6.1C | 79-82 | 80-85 | Close |
| 6E | 85 | 90-95 | Fairly close (difference of 5-10 percentage points in RH, which can be partly explained by high RH peaks in the outdoor climate parameters used for calculation modelling) |
| 6.2C | 81-83 | - | - |
| 7A | - | 75 (83 Year 1) | - |
| 7C | 70 (77-80 at the start) | 70 (77 Year 1) | Close. (In both cases, additional moisture at the start gave higher values.) |

| **Point** | **Laboratory measurement RH [%]** | **Calculation RH [%]** | **Notes** |
|---|---|---|---|
| 7E | 75-80 (90 at the start) | 80-89<br>(90-95 in year 1) | Fairly close. (In both cases, additional moisture at the start gave higher values.) It seems as if moisture level is declining in the calculation case. |
| 8A | - | 70-80 | - |
| 8C | 77-79 | 70-80 | Close |
| 8E | 82-83 | 70-83 | Close |
| 9A | - | - | - |
| 9C | 72-73 | - | - |
| 9E | 75-77 | - | - |
| 10A | - | 85-90 | - |
| 10C | 85 | 80-87 | Close |
| 10E | 87-90 | 95 | Fairly close (difference of 5-10 percentage points in RH, which can be partly explained by high RH peaks in the outdoor climate parameters used for calculation modelling) |

The calculated results are very similar to the measured results, particularly in respect of the RH values on the outside of the studs at point C, as shown in Table 5. The calculated values also mirror the differences between sections seen in the measured values. The measured values agree quite well with the calculated values in terms of showing to what extent the different designs react to outdoor air and additional moisture (residual and convection moisture).

Slight mould growth was only detected after the test period outside of the cellulose insulation. Because no samples were taken before the measurement period, it is unclear whether it occurred in the experiment.

In general, the more vapour-permeable and the better-insulating weather barrier, the less the risk of moisture accumulation in the wall structure from air vapour from inside and/or outside. The choice of weather barrier and any substandard quality of workmanship can have a significant effect on the moisture conditions in the wall.

High moisture levels can build up in the wooden structure if it is externally insulated with a more vapour-proof weather barrier, such as EPS-slab in combination with moisture permeating into the wall from the inside or with residual building moisture. The moisture level was somewhat lower in solid studs than in lightweight studs, which can be explained by the fact that heat-conductive material achieves higher temperatures and lower moisture levels in the outer parts of the wall. Measurements and calculations both show high humidity, and there is a risk of mould growth in the wall section containing cellulose insulation if the material is moisture- sensitive.

Similar results have been obtained in a Finnish laboratory study (Vinha et al. 2002). Sixteen different wall constructions, about 200 mm of insulation, with different combinations of vapour barriers and wind barriers have been studied. A combination of interior plastic film and a weather barrier of mineral wool slab showed the lowest humidity and fastest drying.

## 4.2 Laboratory test of resistance to driving rain

The objective of this laboratory test has been to obtain better knowledge of the protection against driving rain provided by present-day wooden façades, whether prefabricated or constructed in situ, by investigating how well the exterior of the façade, penetrations and detail connections withstand rain. This has been done with the assistance of two prefabricated house manufacturers, who have each supplied two exterior wooden stud wall elements; one with vertical façade panels, and one with horizontal façade panels (see Figure 28 and Figure 29). All panels were constructed with overlap, groove and tongue. Manufacturer A had both battens and laths behind the vertical cladding and only battens behind the horizontal façade panel. Manufacturer B had battens behind both horizontal and vertical panels. The vertical and horizontal façade panels were designed with overlapping panels. The façades also included common façade details such as windows, fastenings and penetrations. Manufacturer B incorporated a layer of stiff mineral wool slabs outside the wind barrier fabric. Manufacturer A had only a wind barrier fabric behind the ventilation gap. All test items had a plastic film, air- and vapour barrier mounted on the inside.

*Figure 28. The two test items, manufacturer A, with horizontal and vertical wood panelling respectively.*

*Figure 29. Ongoing testing of two test items, manufacturer B, with horizontal and vertical wood panelling respectively in the rain chamber.*

The test method used was SS-EN 12865 (SIS 2001) “Determination of the resistance of external wall systems to driving rain under pulsating air pressure”, procedure B, with 300 minutes of total test time. The test starts with the test item being exposed for 60 minutes to simulated rainfall of 1.5 l/($m^2$, min). Pulsating pressure also then starts for 60 minutes for each step 0-150 Pa, 0-300, 0-450 and 0-600 Pa. The moisture indicators were checked after each pressure level; indicators consisted of absorption paper and thin electrodes for resistance measurement (see Figure 30 and Figure 31). At the end, the wall was opened in order to investigate any further leakage.

*Figure 30. Indicators were positioned just below all details in the ventilation gap and behind the façade; test item A with vertical façade panel.*

*Figure 31. Indicators were positioned just below all details in the air gap and behind the façade; test item B with horizontal façade panel.*

The result shows that significant leakage into the ventilation gap occurred in three of the four test items (see Table 6).

*Table 6. Information as to where water had leaked in behind the façade panelling and where it was completely sealed for each test item. The test items have been given a letter, A or B, for each manufacturer and either vertical or horizontal façade panelling. In addition, there is a note about water absorption in panel ends.*

| **Detail** / **Test item** | **Centre plate** | **Ventilation duct/ Small pipe** | **Window** | **Lightweight fixture** | **Heavy fixture** | **Note about water absorption in panel ends** |
|---|---|---|---|---|---|---|
| A Vertical | Leakage | Leakage | Leakage | - | - | Yes |
| A Horizontal | - | Leakage | Leakage | Sealed | Leakage | Yes, behind the external window trim |
| B Vertical | Sealed | Sealed | Slight leakage | - | - | Yes |
| B Horizontal | Leakage | Sealed | Leakage | Sealed | Sealed | Yes, behind the external window trim |

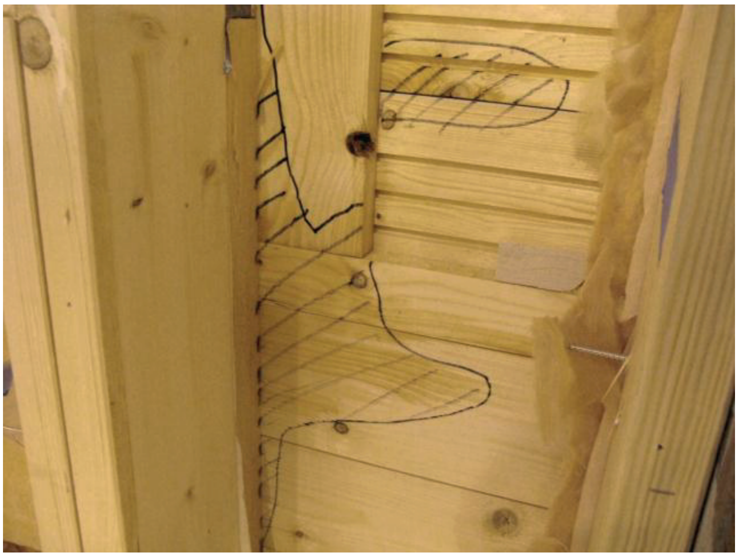


*Figure 32. Photo of the back of the wooden façade panel (test item B) after the wall was opened from the inside. Highlighted areas indicate wet areas behind the façade/horizontal panel, battens and underlay board for the horizontal metal plate.*

Connections, penetrations and joints in wood façades may increase the risk of leakage, at least into the ventilation gap, despite the fact that, in principle, the ventilation gap acts to equalise pressures on each side. Much of the inwardly leaking water was absorbed by the rear panel, laths, battens etc (see Figure 32). On the whole, and regardless of manufacturer, the study shows several defects or shortcomings in both workmanship and design features, such as:

- Substantial leaks between horizontal panels and external window trim, where water found its way in.
- In one case, water penetrated all the way in to the wooden studs.
- Inward leakage occurred, despite the use of sealing mastic.
- Some panel ends were found to be unpainted, where water could be absorbed, with risk of rot.
- One manufacturer incorporated a layer of thermal insulation outside the wind barrier fabric, which is beneficial for the stud and structure inside it, as it keeps the framework warmer and drier. On the other hand, it is a drawback as, to all intents and purposes, the ventilation gap was blocked, preventing drainage and ventilation.

It is likely that water is penetrating behind the façades, unless otherwise demonstrated. Furthermore, an inward leakage passing the façade can flow across the wind barrier, and if it reaches a leaky connection to window, balcony, joint or other penetrations in the wind barrier further down, the water can be diverted into the timber frame. If the façade has several floors with façade details, the number of leakage points increases the further down the façade the water flows and the greater the surface area that is covered by water on the wind barrier/weather barrier. This could mean that the risk of inward leakage through gaps in the wind barrier increases further down the wall. It is not feasible to carry out laboratory tests that involve that many floors, due to the limited height of the laboratory. It is therefore probably more suitable to test the wind barrier/weather barrier for leakage separately with common joints, connections and fixtures to safely determine its function. There are currently no European harmonised standards, Swedish construction regulations or Swedish industry standards that refer to system testing of products, which could explain leakage problems.

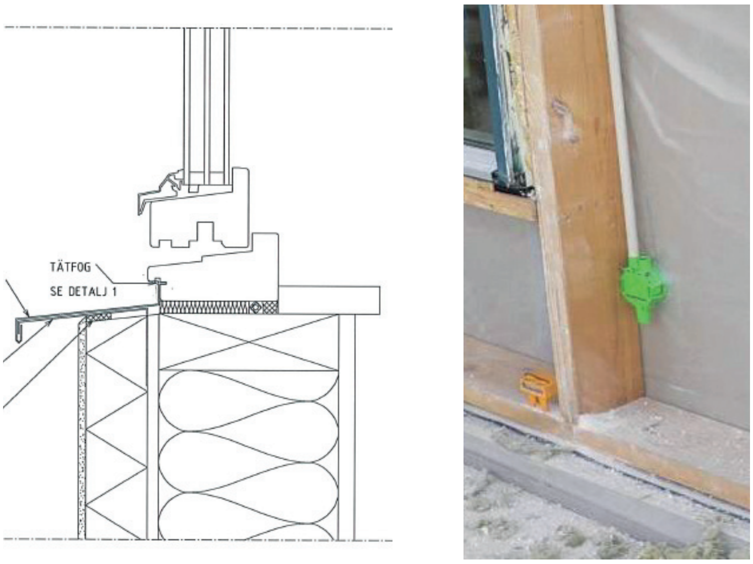
## 4.3 Site measurements behind plaster façades with and without a ventilated gap

Moisture damage has been found in houses having well-insulated, rendered (ETICS – External Thermal Insulation Composite System) wooden stud walls that are unventilated and undrained. A national survey has been carried out in order to determine the extent of the problem (Samuelson and Jansson 2009). It became clear during the survey that it would be important to monitor the moisture conditions in walls that were built or rebuilt, in order to check that moisture performance was as intended. However, there is no documented experience from subsequent monitoring of moisture conditions in such wall structures in Sweden. Representatives of contractors and materials manufacturers were asked during the survey to make renovated or new buildings available for monitoring of moisture conditions behind the rendering of exterior walls. Buildings in two areas of Helsingborg in south western Sweden, where the façades were in need of rebuilding, were made available for monitoring.

The resulting field study has continuously monitored RH, MC and temperature conditions over a two-year period 2009-2011 in houses that were rebuilt, but which retained the ETICS design and wooden stud walls, although with improved detailing (see Figure 33a). It has also monitored these parameters in one house that was rebuilt to incorporate a ventilated façade outside the stud wall design, with stiff mineral wool slabs mounted outside the wind barrier board (see Figure 34a).

The sensors were distributed over all four façades, with 12-13 measurement points per house and more sensors on south-facing and west-facing façades that were expected to be more exposed to driving rain. Measurements were taken using wireless sensors (Protimeter HygroTrac), which measure the MC, RH and temperature. These were attached with two stainless steel screws into timber and also acted as electrodes to measure the MC. The screws penetrate the timber material to a depth of 10 mm, and measure at a depth of 0-10 mm. The RH and temperature sensor is at a distance of 30 mm from the timber surface and inside the plastic casing (see Figure 33b). The RH and temperature are measured approximately 15 mm inside the wind barrier, due to the sensor's placement in the yellow plastic casing. The MC is measured approximately 5 mm inside the exterior of the stud with measurement points under windows, balcony fixtures, awning fixtures, near wall corners, on sills and under roof connections. In addition, reference sensors were placed far from façade details, near the internal air and vapour barrier, inside and outside. This means that the temperature will be somewhat higher and the RH will be somewhat lower than the point inside the wind barrier. As wooden studs form a thermal bridge from the interior to a certain degree, a slightly higher temperature probably occurs there also and, as a result, a lower RH at its exterior than inside the wind barrier adjacent to studs (Olsson 2011d).

Approximately 40 sensors in total have distributed over three buildings, being calibrated prior to construction with traceability to normal and national standards laboratory at SP. They have not, however, been calibrated afterwards, as they were built in. The MC has been adjusted for Swedish spruce and current temperatures. Measurement uncertainty is estimated to be less than ±1.5% in MC, less than ±5% in relative humidity (RH) and less than ±0.5ºC throughout the entire measurement period. Our experience of these sensors is that the MC and temperature appear to be relatively stable over time, but the RH may possibly have a slight drift that has been included.



a) b)

*Figure 33. (a) Vertical cross-section of wooden stud wall with new ETICS. (b) Position of measurement point 6 (building B) in the outer part of the sill, façade facing southeast.*

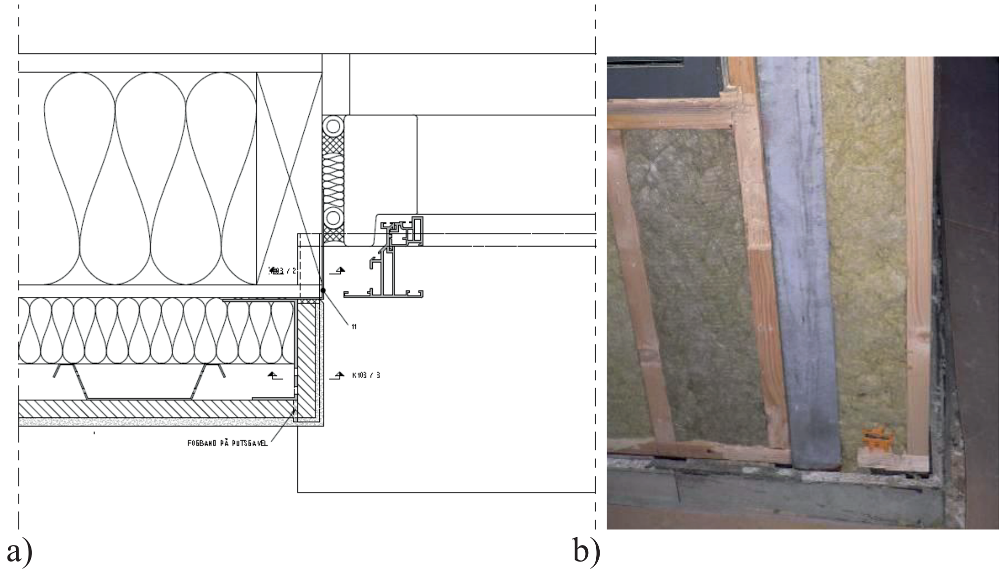


*Figure 34. (a) Horizontal cross-section of wooden stud wall with new ventilated rendered façade. (b) Position of measurement point 1 (building C) in the outer part of the sill, façade facing southeast.*

The measurements behind the ETICS in the stud walls show normal values: at most, about 75 % RH, i.e. not elevated moisture values that could result in moisture damage. But there were some exceptions: the measurements indicating high MC of 25% (see Figure 35) on 12 November 2010 when there was particularly heavy rain and wind load on this façade (see Figure 36). Additionally, there were some additional points where there was a hint of leakage. Bearing in mind their relatively short durations, these measured moisture conditions ought not to result directly in moisture damage.

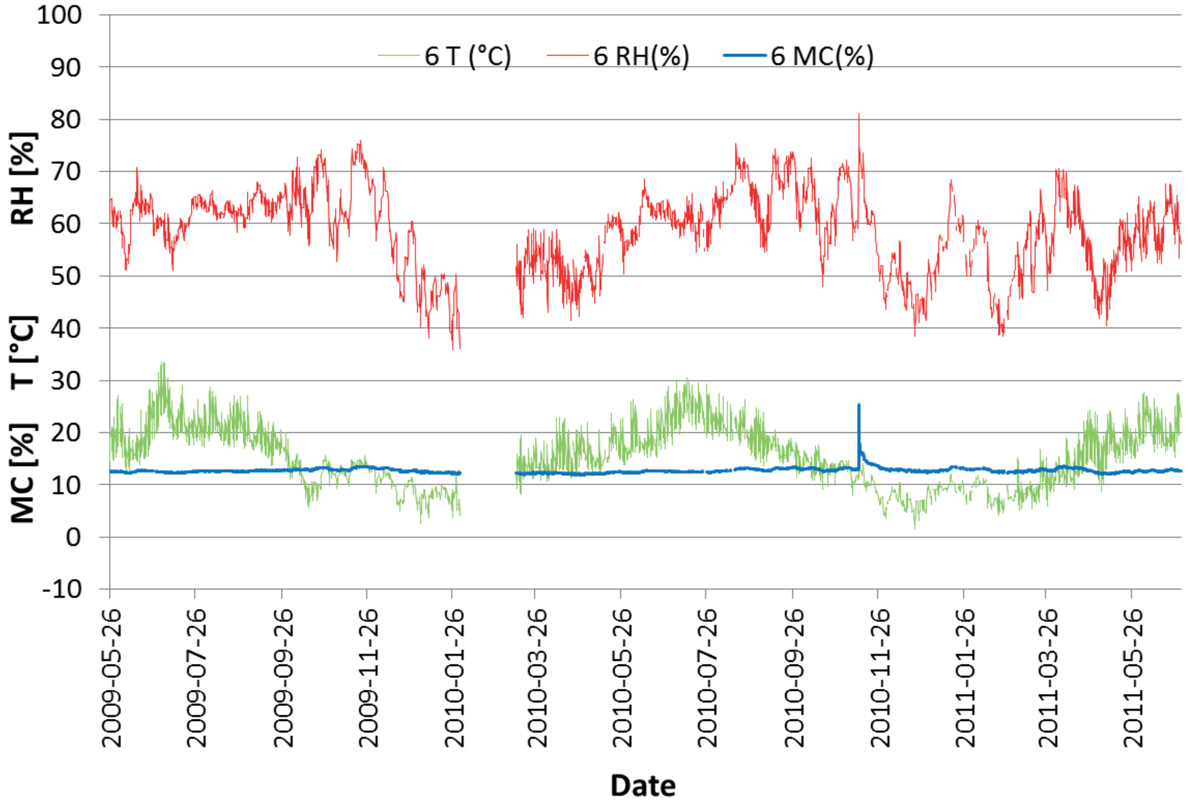


*Figure 35. Measured RH, temperature and MC, measurement point 6 and building B, during the period 2009-05-25 to 2011-06-30.*

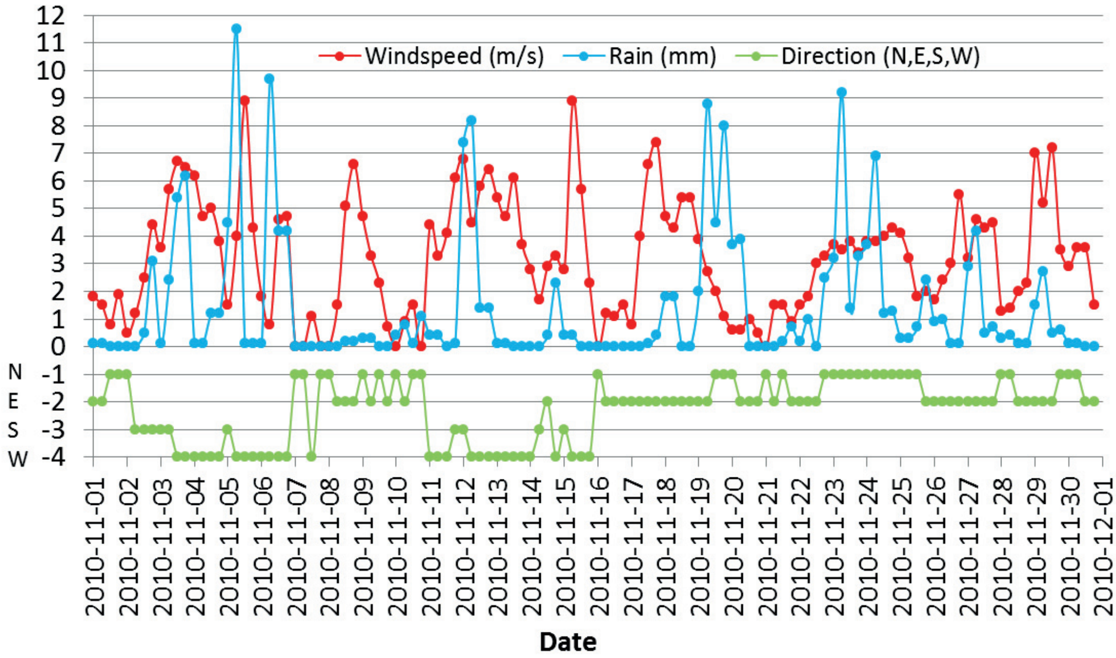


*Figure 36. Wind speed, precipitation and wind direction for the period between 1 November 2010 and 1 December 2010 (SMHI). Each point represents the average value for a period of 6 hours for precipitation and 3 hours for wind speed.*

In general, measurements behind the ventilated façades show normal values, at most of about 75-80% RH. One exception showed brief high moisture values of over 90% RH (see Figure 37), on 19 November 2009 and 12 November 2010 when there was particularly heavy rain and wind load on this façade (see Figure 38 and Figure 36).

Additionally, there was one additional point where there was slight leakage. Again, and with the relatively short duration, these measured moisture conditions ought not to result directly in moisture damage.

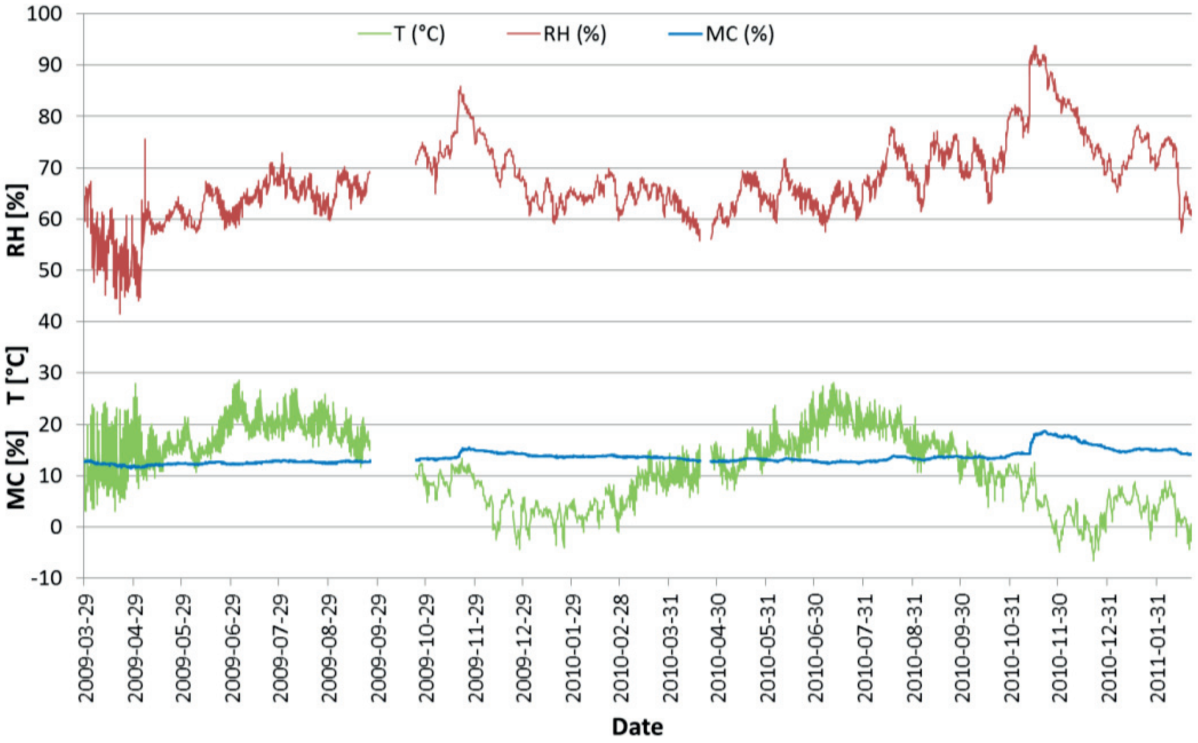


*Figure 37. Measured RH, temperature and MC, measurement point 1 and building C, during the period 2009-03-29 to 2011-02-20.*

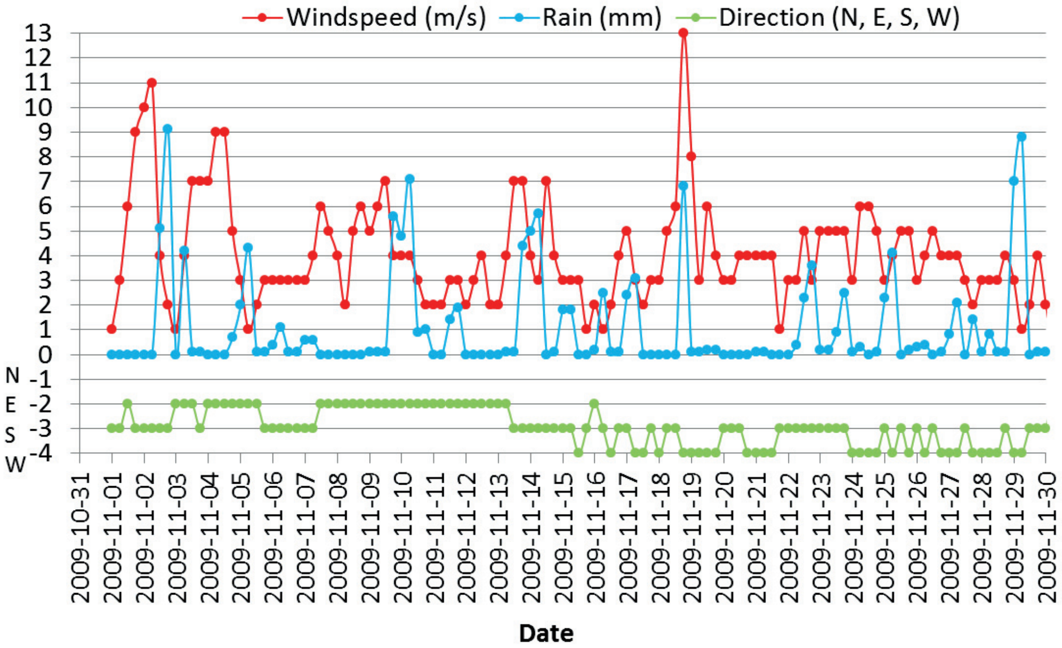


*Figure 38. Measurement data from SMHI, wind speed, precipitation and wind direction for the period between 31 October 2009 and 30 November 2009. Each point represents the average value for a period of 6 hours for precipitation and 3 hours for wind speed.*

We recognize that all penetrations and connections were specifically designed and particularly carefully constructed using mastic. Even so, inward leakage has occurred. The actual reason for these exceptions has not been identified, which should be done.

We would recommend that façade plaster systems using present façade details should be tested and evaluated, and that façade systems and designs should be constructed to incorporate additional moisture safety design aimed at tackling commonly encountered weaknesses.

## 4.4 Site measurements in newly built external wooden walls with ventilated façade

What moisture conditions can be expected in today's well insulated external wooden walls and is there a risk of mould growth in the timber frame?

Site measurements have been taken at approximately 130 measurement points over three years in four new production timber-frame houses, two of which were single-storey detached houses and two of which were apartment buildings, spread over three locations in Sweden. Falkenberg and Växjö are both located in southern Sweden and Skellefteå is located in northern Sweden. These measurements have previously been presented without calibration correction and have been compared to one-dimensional moisture and temperature calculations (Mundt-Petersen 2013a-e). The evaluation of these timber- frame structures continues below.

Site measurements have been taken of RH, MC and temperature, as well as microbiological analyses from material in both roofs and walls facing all four directions. Measurements have been taken continuously between 2009 and 2011, for approximately three years, depending on when construction of the buildings began. The measurements have been registered continuously once an hour. In addition, all buildings except those in Skellefteå have been monitored by momentary measurements of the wooden material and continuous measurements of the surrounding RH and temperature during the construction phase (Olsson & Mjörnell 2011a) (Olsson et al. 2010). Measurements have then formed the basis for evaluation of risks of mould growth, mainly in the measurement points that have not been accessible for sampling, using a calculation model known as the MRD model (Thelandersson and Isaksson 2013). In the structures that have been examined, the timber frame's external section ought to be the most moisture-sensitive part with regard to outdoor climate and in the event of leakage in façades and wind barriers. As the actual façade and ventilation gap are exempt from the Swedish National Board of Building, Planning and Housing regulations (2006) with regard to standards for the highest permitted moisture level of component material, the façade has been excluded from the evaluation in this respect.

Placement of the sensors was carried out in cooperation with S. Olof Mundt-Petersen, LTH with two aims. On the one hand, it has to be possible to determine roof and wall moisture and temperature differences in order to verify the calculation software and evaluate the conditions with regard to mould and, on the other, it has to be possible to intercept any inward leakage that might occur from, for example, potential façade and wind barrier defects. Simon Dahlqvist has been responsible for measurement data collection for the database and Per-Anders Fjällström has been involved in procuring the measuring equipment and installation. Both work at SP.

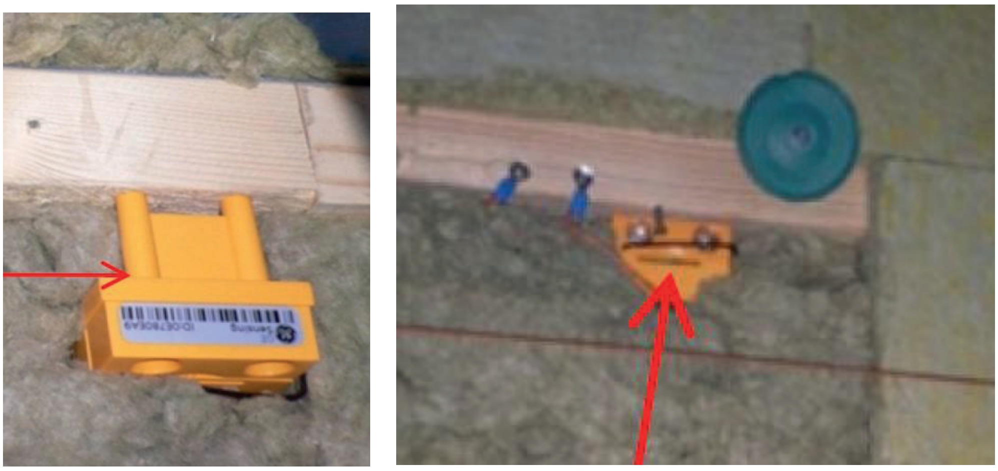

a) b)

*Figure 39. The images show installed sensors at the outer section of wooden studs. (a) shows a bolted-on sensor near the outside of a stud. (b) shows a sensor with extension cables for MC bolted onto the outside of a stud.*

Measurements were taken using wireless sensors (Protimeter HygroTrac), which measure the MC, RH and temperature (see Figure 39). These were attached with two stainless steel screws into wooden material and also acted as electrodes to measure the MC. The screws penetrate the wooden material to a depth of 10 mm. The RH and temperature sensor is at a distance of 30 mm from the wooden stud surface and 15 mm from the barcodes outside the yellow plastic casing. The MC is mostly measured approximately 5 mm inside the exterior of the stud and the sill and at a timber depth of 0-10 mm (see Figure 39). The RH and temperature are measured approximately 15 mm inside the wind barrier, due to the sensor's placement in the yellow plastic casing. This means that the temperature will probably be somewhat higher and the RH will be somewhat lower than, for example, a point inside the wind barrier. As timber studs form a thermal bridge from the interior to a certain degree, a slightly higher temperature probably occurs there also and, as a result, a lower RH at its exterior (Olsson 2011d) than inside the wind barrier adjacent to studs. It is probable that the temperature on the underside of the tongue and groove board might be somewhat lower than the temperature sensor, particularly in attic structures, however, in roofs with well ventilated ventilation gaps, the surfaces around the gap and the temperature sensor are likely to have relatively similar temperatures. In order to be able to measure the outside of wooden studs in external walls, the MC at some measurement points has been measured with extended electrodes with a greater contact surface, which might therefore have produced a somewhat higher reading than the true MC (Figure 39b).

The MC has been adjusted for Swedish spruce and current temperatures (Samuelsson 1990). A general deviation was detected during spot checks of sensors prior to construction and was caused by a general misalignment by the manufacturer. All RH sensors probably had a deviation in the RH, which was adjusted prior to presentation of the results in this evaluation. Measurement uncertainty at the start of the survey is estimated to be less than ±1% in MC, less than ±3% in RH and less than ±0.5ºC. Our experience of these sensors is that the MC and RH appear to be relatively stable over time, but the sensor that measures RH may possibly have a slight drift. As most of the sensors were built into structures, it has not been possible to calibrate them afterwards. However, the following points: 18, 19, 20, 24, outside, and inside in Falkenberg as well as 43, 46, 47, 51, 52, 54 and outside in the multi-storey building in Växjö, have been calibrated afterwards. The drift for these measurement points has been within ±2% at 85% RH. In addition, the RH has been adjusted for this final drift for the entire measurement period, which then generated an equivalent deviation at the beginning. The measuring instruments were calibrated with traceability to normal and national standards laboratory at SP. However, a few sensors that have been outdoors have shown larger drifts and some have ceased to function, for example due to splashes of paint, which is why the measurement data from SMHI has also been presented. With regard to SMHI data, there has occasionally been a lack of data, which has been supplemented using a method described by (Mundt-Petersen 2013f).

The exact RH of wooden surfaces can be difficult to determine purely from measuring the MC, without knowing the timber item’s drying and humidifying history and when treatment was carried out, etc., due to hysteresis. The problem is that there can be approximately 4% difference in the MC in the timber’s cross-section (between the surface and centre) despite the entire timber being in equilibrium (Olsson 2012a). A timber surface in equilibrium with, for example, 80% RH could have a surface MC of between approximately 15% and 18% depending on whether the surface comes from a humidifying or drying phase.

By measuring the MC or electrical resistance of the material surface, inward leakage or free water can be detected. This is particularly important in structures with good drying possibilities, as local moisture accumulation is difficult to detect through RH measurements alone.

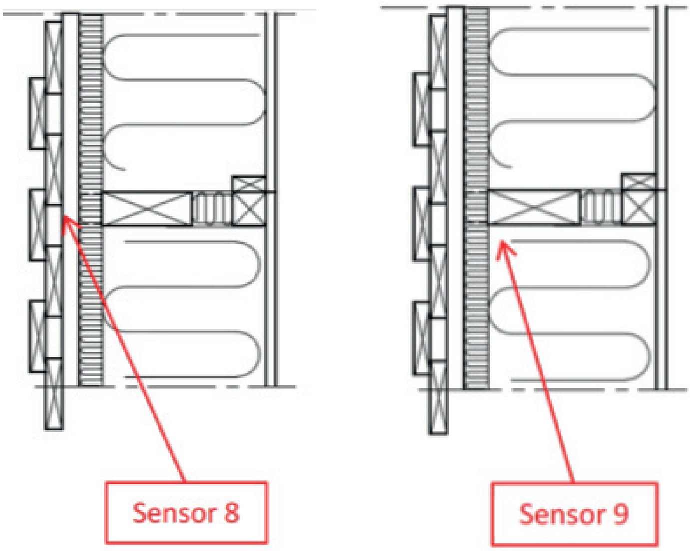
Timber material samples were taken before and after the test. The samples were examined under a microscope by the method described in (Hallenberg and Gilert 1998) (see chapter 3.1).

Calculations were made using the MRD model (Thelandersson and Isaksson 2013). The calculation is based on tongue and groove board or planed wooden stud which, according to the model, has $D_{crit}$ in 10 and 17 days respectively. With regard to underlay roofing, in the calculations it is assumed that it has always been tongue and groove board, despite the fact that the underlay roofing in detached houses in Falkenberg was impregnated plywood. This is because there was no $D_{crit}$ for impregnated plywood, and at the same time the aim was to study how wood or tongue and groove board withstands the climates in question.

### 4.4.1 Survey results – Comparison of climates between inside the wind barrier, ventilation gap and outside

Below is a comparison of inside the wind barrier, ventilation gap and outside for three of four buildings in façades with little or no direct sunlight. The multi-storey building in Växjö is not included in the comparison, as large quantities of measurement data are missing in measurement point 7, which is the only location with sensors on both sides of the wind barrier near each other.

The building in Falkenberg is a single-storey detached house with a concrete floor slab and attic space in the roof structure. The house is ventilated using mechanical extraction ventilation. Beneath the concrete floor slab is 300 mm of thermal insulation. The external walls consist of wooden studs with lightweight studs and are protected externally by 30 mm high density mineral wool slab and internally by plastic film, with a vapour resistance of at least $S_d$=40 m, the overall wall insulation thickness is 250 mm (see Figure 40). The façade consists of wooden panelling and has an underlying ventilation gap. The thickness of the ceiling or attic floor insulation is approximately 400 mm. There is a system in the attic space that draws in dry air or outdoor air when possible, while heating the attic space when necessary (TrygghetsVakten 2009). According to data, the air inlet at the eave has been blocked in order to prevent involuntary ventilation of the attic. There is, however, a large air outlet in the attic that was connected to the outdoor climate near the main entrance to the house, which may have affected the function of the system. According to data, the fan has a capacity of 400 m$^3$/h and the overall effect of the heating cables is 500 W.



**External wall seen from outside**

-Vertical wooden panel
-24 mm ventilation gap
-30 mm mineral wool slab
-220x45 mm lightweight stud and a MW infill layer
-Plastic film
-13 mm gypsum board

*Figure 40. Horizontal cross-section of external wall with placement of sensors 8 and 9 in detached house in Falkenberg.*

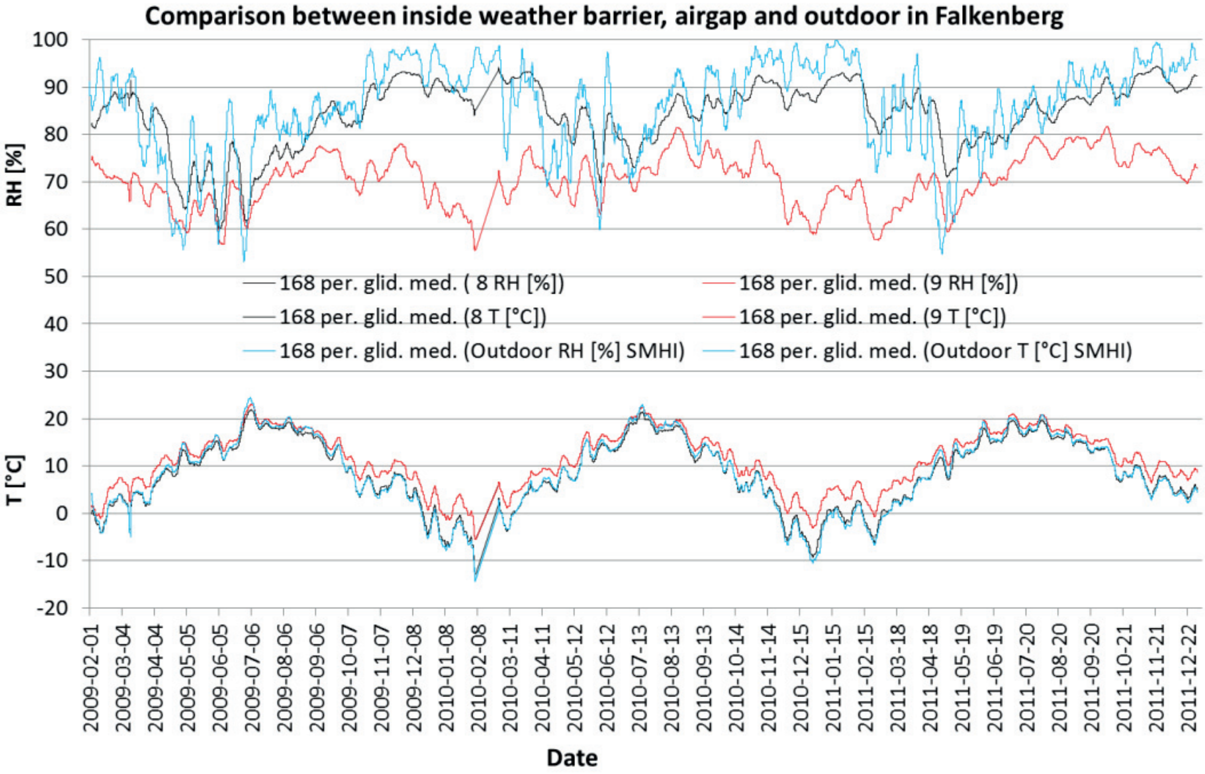
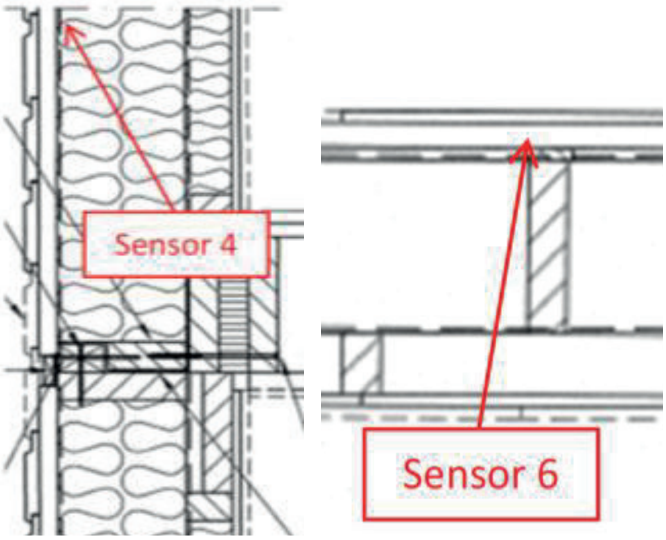


*Figure 41. The curves demonstrate sliding weekly average values (168 hours a week) of measured RH and temperatures near the outside wall stud (9), in the ventilation gap behind the façade (8), both facing northeast and outside (outdoor air by SMHI), all during the period between 1 February 2009 and 31 December 2011 for detached house in Falkenberg.*

The measurements show a RH around 75-80% at most on the outside of wooden studs. The temperature between the inside of insulated wind barriers and ventilation gaps demonstrates a difference of 1.5 to 2.5°C at 10°C in the ventilation gap (see Figure 41), which corresponds fairly well with the temperature difference between the outside of studs and outdoors in the laboratory measurements (Olsson 2012d). The temperature at the sensor (probably equivalent to outside of studs) compared to outdoors produced an RH approximately 15% points lower at most in wooden studs, based on the Mollier diagram. This difference also occurs in the above diagram as well as in laboratory measurements (Olsson 2012d). Therefore, the climate on the outside of studs and sensors is likely to be relatively similar in this site survey. Furthermore, it can be assumed that the MRD index carried out for measurement point 9 is likely to be representative of the outside of studs (see Table 7).

The detached house in Växjö is a two-storey single family house with a concrete foundation slab and flat roof. The house is ventilated using mechanical extraction ventilation. Beneath the concrete slab is 250 mm thermal insulation. The external walls consist of 195 mm thick wooden studs, plastic film and 70 mm internally, which provides an overall thermal insulation thickness of 265 mm (see Figure 42). The wind barrier fabric has a vapour resistance of $S_d$=0.2 m and the plastic film has a vapour resistance of at least $S_d$=40 m. The façade is ventilated and consists of wooden panelling. The roof consists of 400-700 mm insulation thickness and between the insulation and the roof underlay there is a ventilation gap.



**External wall seen from outside**

-Vertical tongue and groove wooden panel
-28 mm ventilation gap
-Wind barrier fabric
-195x45 mm wooden stud and a MW infill layer
-Plastic film
-70x45 mm wooden stud and a MW infill layer
-13 mm gypsum board

*Figure 42. (a) Vertical cross-section of external wall on second floor with placement of sensor 4. (b) Horizontal cross-section of external wall on first floor with placement of sensor 6 in the ventilation gap.*

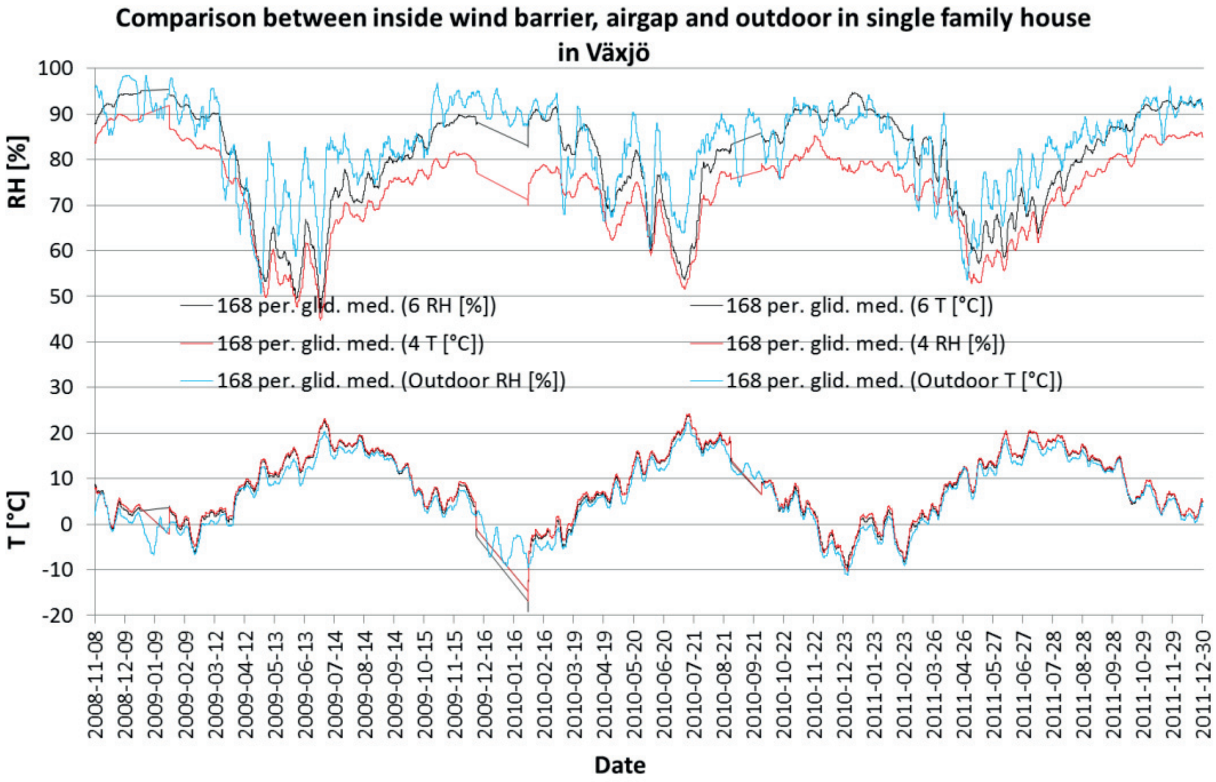
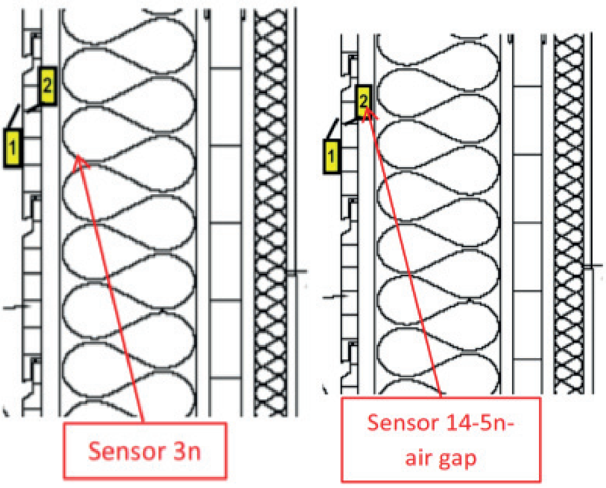


*Figure 43. The curves demonstrate sliding weekly average values (168 hours a week) of measured RH and temperatures near the outside wall stud (4), in the ventilation gap behind the façade (6), both placed in the façade facing northwest and outside (by SMHI), during the period between 8 November 2008 and 31 December 2011.*

The measurements show a RH around 80-85% at most on the outside of wooden studs.

The temperature between the inside of wind barriers and ventilation gaps demonstrates a difference of 0.5 to 1.0°C at 10°C in the ventilation gap (see Figure 43), which corresponds fairly well with the temperature difference between the outside of studs and outdoors in the laboratory measurements (Olsson 2012d), (Olsson 2011d). The temperature at the sensor (probably equivalent to outside of studs) compared to outdoors produced an RH approximately 6% points lower at most in wooden studs, based on the Mollier diagram. This difference also occurs in the above diagram as well as in laboratory measurements (Olsson 2012d), (Olsson 2011d). Therefore, the climate on the outside of studs and sensors is likely to be relatively similar in this site survey. Furthermore, it can be assumed that the MRD index carried out for measurement point 4 is likely to be representative of the outside of studs (see Table 8).

The apartment building in Skellefteå is a seven-storey building with a timber element structure and wooden studs. The roof consists of a roof truss or parallel chord flat roof. The external walls consist of a 83 mm thick timber element as load-bearing structure and 45 mm of thermal insulation inside and 195 mm of thermal insulation outside (see Figure 44). There is plastic film on the inside of the timber element. The façade is ventilated and consists of glulam panelling. The wind barrier fabric has a vapour resistance of $S_d$=0.2 m and the plastic film has a vapour resistance of at least $S_d$=40 m.



**External wall seen from outside**

-Glulam timber panel
-25 mm ventilation gap
-Wind barrier fabric
-195x45 mm wooden stud and a MW infill layer
-83 mm solid timber element
-Plastic film
-45x45 mm wooden stud and a MW infill layer
-15 mm gypsum board

*Figure 44. Two similar vertical cross-sections of external walls with placement of sensors 3n and 14-5n.*

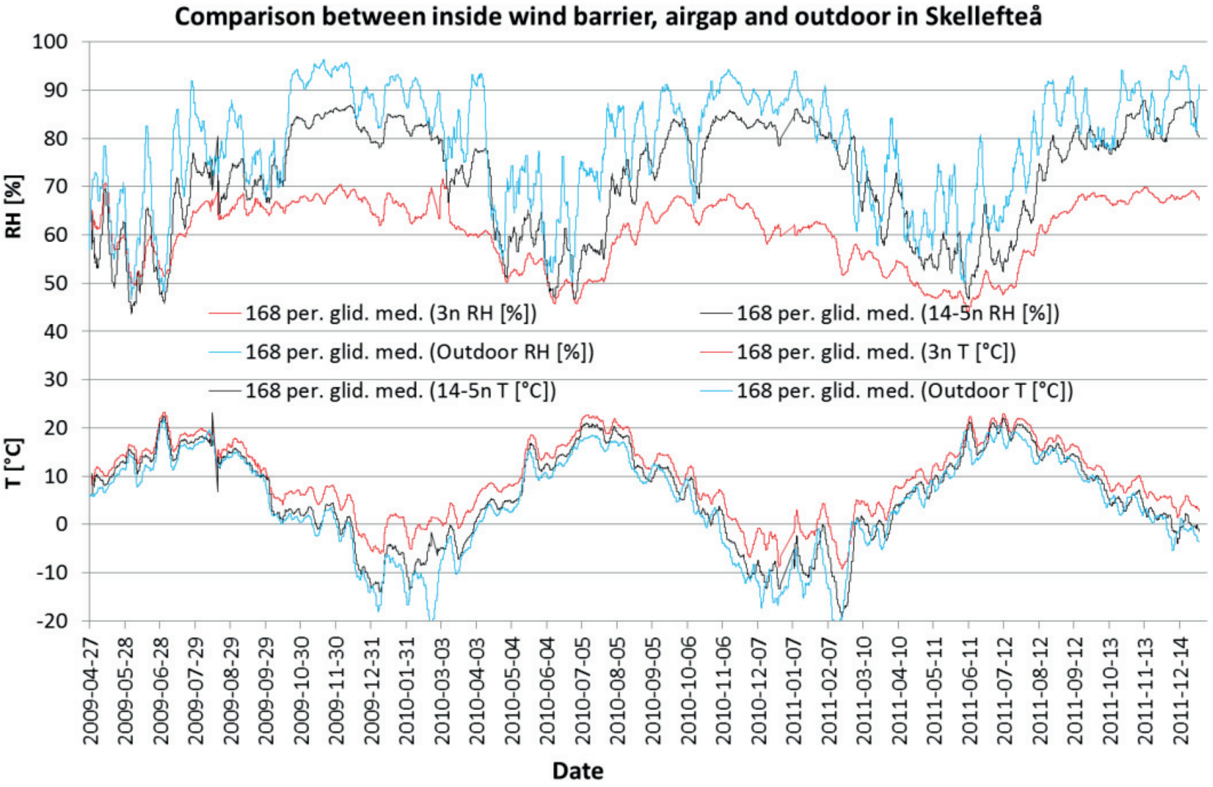


*Figure 45. The curves demonstrate sliding weekly average values (168 hours a week) of measured RH and temperatures near the wall stud (3n), in the ventilation gap behind the façade (14-5n), both placed in the façade facing north and outside (by SMHI), during the period between 27 April 2009 and 31 December 2011, for multi-storey buildings in Skellefteå.*

The measurements show a RH around 65-70% at most on the outside of wooden studs. The comparison demonstrates a surprisingly large difference in temperature, approximately 2°C between the inside of the wind barrier and the ventilation gap (see Figure 45). One explanation could be that the RH and temperature sensor have been installed further into the wall and, depending on how the insulation has been installed around the sensor, this means that it could have ended up warmer and thereby drier. A likely temperature difference would probably be around 0.5-1.0°C as at the detached house in Växjö. The MRD index carried out for measurement point 3n is therefore likely to produce a value lower than it should (see Table 10).

### 4.4.2 Calculation results for microbial growth in structures

The MRD index is calculated on measured RH, temperatures and their duration at each measurement point. Calculations have also been made for roofs, partly as a lot more measurement points have been accessible for material sampling than walls, partly to verify the calculation model. This has been done for the measurement points that are considered to have the least favourable climate. An account of the climate at all measurement points is presented in (Mundt-Petersen 2013a-d). The calculation has been carried out by Jonas Niklewski and Professor Sven Thelandersson at LTH. At some measurement points, measurement data has been missing occasionally or for long periods, however, our assessment was that it was not of any particular significance for the conclusions.

*Table 7. The MRD index for external wall stud, in the ventilation gap behind the façade, near the underside of the roof underlay and roof beam. The building is a single-storey detached house in Falkenberg.*

| **Single-storey detached house in Falkenberg** | | | | |
|---|---|---|---|---|
| **Measurement point** | **MRD index in the external surface of the stud** | **MRD index in the ventilation gap (wall)** | **MRD index at roof underlays** | **MRD index in the roof beams** |
| 6 | 0 | - | - | - |
| 8 | - | 2.7 | - | - |
| 9 | 0.5 | - | - | - |
| 11 | 0 | - | - | - |
| 12 | - | 1.8 | - | - |
| 13 | 0.2 | - | - | - |
| 23 | 0 | - | - | - |
| 18 | - | - | - | 0.2 |
| 24 | - | - | 0.3 | - |

*Table 8. The MRD index for external surface of the stud, in the ventilation gap behind the façade, near the underside of the roof underlay and roof beam. The building is a single-storey detached house in Växjö.*

| **Single-storey detached house in Växjö** | | | | |
|---|---|---|---|---|
| **Measurement point** | **MRD index in the external surface of the stud** | **MRD index in the ventilation gap (wall)** | **MRD index at roof underlays** | **MRD index in the roof beams** |
| 2 | 0 | - | - | - |
| 4 | 0.3 | - | - | - |
| 6 | - | 0.9 | - | - |
| 10 | - | 0.3 | - | - |
| 13 | - | - | 0.3 | - |
| 14 | - | - | - | 0 |
| 16 | - | - | 0.5 | - |
| 17 | - | - | - | 0.3 |

*Table 9. The MRD index for external wall studs, in the ventilation gap behind the façade, near the underside of the roof underlay and roof beam. The building is a multi-storey building in Växjö.*

| **Multi-storey building in Växjö** | | | | |
|---|---|---|---|---|
| **Measurement point** | **MRD index in the external surface of the stud** | **MRD index in the ventilation gap (wall)** | **MRD index at roof underlays** | **MRD index in the roof beams** |
| 6B | 0.1 | - | - | - |
| 16 | 0.7 | - | - | - |
| 22 | - | 1.0 | - | - |
| 42 | - | - | - | 0.1 |
| 43 | - | - | 0.2 | - |
| 46 | - | - | - | 0.1 |
| 47 | - | - | 0.2 | - |
| 50 | - | - | - | 0.2 |
| 51 | - | - | 0.2 | - |
| 54 | - | - | - | 0.4 |

*Table 10. The MRD index for external wall studs, in the ventilation gap behind the façade, near the underside of the roof underlay and roof beam. The building is a multi-storey building in Skellefteå.*

| **Multi-storey building in Skellefteå** | | | | |
|---|---|---|---|---|
| **Measurement point** | **MRD index in the external surface of the stud MRD index in the wall** | **MRD index in the ventilation gap (wall)** | **MRD index at roof underlays** | **MRD index in the roof beams** |
| 3n | 0 | - | - | - |
| 14-5n | - | 0.1 | - | - |
| 6ö | 0 | - | - | - |
| 15ö | 0 | | - | - |
| 15-5ö | - | 0.1 | - | - |
| D | - | - | - | 0 |
| E | - | - | 0 | - |
| M | - | - | 0 | - |
| I | - | - | - | 0 |
| J | - | - | 0.1 | - |
| S | - | - | 0.1 | - |

There is no risk of microbial growth in any of the building's wooden studs and roofs (see tables from Table 7 to Table 10). In three of four buildings, established growth may have occurred in ventilation gaps behind façades. Note that growth in ventilation gaps behind façades is deemed permissible according to the Swedish National Board of Building, Planning and Housing regulations (2006, 2011). This means that a sufficient temperature difference between the ventilation gap and the outside of the wooden studs is important in order to prevent growth on the wooden stud, particularly in southern Sweden.

Calculations have also been made for the outdoor climate, in order to see whether there are any factors at all which are likely to promote growth with regard to outdoor climate (see Figure 12). Calculations demonstrate that there is an obvious risk of growth on material in structures that are in contact with an outdoor climate in Falkenberg and barely any risk at all in Skellefteå. This fact that there is a difference between different areas of the country is something that Vinha (2007) has also demonstrated in mould risk calculations for Finland.

### 4.4.3 Results of microbiological analysis

Sampling of material at measurement points and microbiological analysis has been carried out for two houses, which should provide answers about whether microbial growth has occurred in those structures. The microbiological analyses have been carried out by Gunilla Bok and Pernilla Johansson, both of SP, and Robert Daun at Botaniska Analysgruppen. In addition, the results can be used to verify whether the MRD index calculations correspond with reality.

*Table 11. Results of microbiological analysis for each measurement point both 'before' (6 March 2009) and after the measurement period (30 August 2012) for a single-storey detached house in Falkenberg.*

| **Single-storey detached house in Falkenberg** | | | | |
|---|---|---|---|---|
| **Measurement point** | **Material** | **Growth [Frequency]** | | **Comments** |
| | | **2009**** | **2012** | |
| 17* in the vicinity | Impregnated plywood | None | Slight | |
| 18 | Roof truss | - | Slight | Actinomycetes |
| 19 | Roof truss | - | None | |
| 24 | Impregnated plywood | - | None | |
| 24 | Roof truss | - | Slight | |
| 21 near the attic hatch | Roof truss | - | None | |

* Material samples were taken during the construction phase and this sample has been taken from exactly the same surface.
** (Olsson et. al 2010)

*Table 12. Results of microbiological analysis for each measurement point both 'before' (29 August 2009) and after the measurement period (30 August 2012) for a multi-storey building in Växjö.*

| **Multi-storey building in Växjö** | | | | |
|---|---|---|---|---|
| **Measurement point** | **Material** | **Growth [Frequency]** | | **Comments** |
| | | **2009**** | **2012** | |
| 6 | Stud | - | None | |
| 6B | Outside stud | - | None | |
| 6B* | Outside stud | - | None | |
| 6B | Felt on the rear of the wind barrier | - | Slight | |

| **Multi-storey building in Växjö** | | | | |
|---|---|---|---|---|
| **Measurement point** | **Material** | **Growth [Frequency]** | | **Comments** |
| 7 | Timber battens | - | None | |
| 8 | Timber batten in ventilation gap | - | None | |
| 9 | Outside stud | - | None | |
| 16 | Outside stud | - | Moderate | |
| 16* | Outside stud | - | None | |
| 16 | 2 cm into the stud | - | None | |
| 16 | Felt on the rear of the wind barrier | - | Slight | |
| 17 | Stud | - | None | |
| 42-52 in the vicinity | Roof truss | - | None | |
| 42-52 in the vicinity | Planed tongue and groove board | None | None | |
| 47 | Planed tongue and groove board | None | None | |
| 47 | Roof truss | None | Slight | Actinomycetes |
| 50 | Roof truss | None | None | |
| 51 | Planed tongue and groove board | None | None | |
| 50-51 in the vicinity | Plasterboard | - | Slight | Hyphae + Actinomycetes |
| 51-55* in the vicinity | Roof truss | None | None | |
| 52 | | - | None | |
| 54-55 in the vicinity | Gypsum board | - | Slight | |
| 54-55 in the vicinity | Cellulose insulation | - | Extensive | Extensive pollen |
| At the door | Gypsum board | None | Moderate | Actinomycetes |
| 54 | Stud | Extensive | Extensive | Hyphae + blue stain, growth probably existed prior to assembly. |
| 55 | Roof truss | None | None | |

* Material samples were taken during the construction phase and this sample has been taken from exactly the same surface again.

** (Olsson et. al 2010)

Material samples were taken after the measurement period at 32 measurement points, of which 10 had slight growth and 2 had moderate or extensive growth (see Table 11 and Table 12) according to the microbiological analysis. At 10 measurement points, samples were also taken in 2009, i.e. at the beginning of the survey follow-up (Olsson et al 2010). No growth had occurred at these measurement points during the measurement period, except at measurement point 47 and at a door (on a piece of gypsum board) in the attic of a multi-storey house in Växjö, as well as at measurement point 17 (impregnated plywood) in the roof underlay in Falkenberg. Actinomycetes were discovered in the attic in Växjö, which probably requires approximately 95-100% RH, this type of climate has not occurred during the measurement period. Therefore, the growth has probably occurred prior to assembly. The underlay roof is designed to deflect condensation and any possible penetrating precipitation, but does not appear to be able to prevent free water transportation entirely in lap splices, which is why this could explain the slight growth at measurement point 17 in Falkenberg.

A third of all samples did, however, have growth. The fact that there could be slight growth on material prior to assembly has been established in two earlier studies (Olsson et. al 2011a), (Olsson and Mjörnell 2012b).

At three measurement points, it can be assumed that the material was free from growth prior to the 2009 measurement period, as the material sample was taken during the construction phase and new samples have been taken from the exact same surface since the measurement period. At measurement point 16, multi-storey building in Växjö, material samples were taken during the construction phase, which is why the underlying surface can therefore be considered clean. Samples taken after the measurement period of the exact same surface as before showed no growth, which corresponds with the MRD index of 0.7, i.e. no growth according to calculations (see Table 9). There was growth adjacent to this surface. The growth may have occurred during the construction phase, or the new surface is not as likely to be infested as intact material surfaces. In addition, the measurement point has been exposed to inward leakage, which could also have created differences depending on where the water flowed.

All in all, it can be said that there is nothing to suggest that there has been growth on the analysed measurement points during the usage phase, except due to inward leakage of rain. Calculation of the MRD index in earlier chapters demonstrates the same.

### 4.4.4 Measurement results – Indication of rain penetration

Despite the measurement points representing a very small proportion of the house's wall structure surface areas, inward leakage adjacent to the timber frame has been detected in three of the four houses examined. Below is an example of measured RH, temperature, MC and calculation of the MRD index for a measurement point in the multi-storey building in Växjö. The measurement point was placed at the outer section of the wooden stud on the inside of the insulated wind barrier.

*Figure 46. The image shows placement of sensor 16 (RH and temperature) and extension cables for MC bolted onto the outside of the stud.*

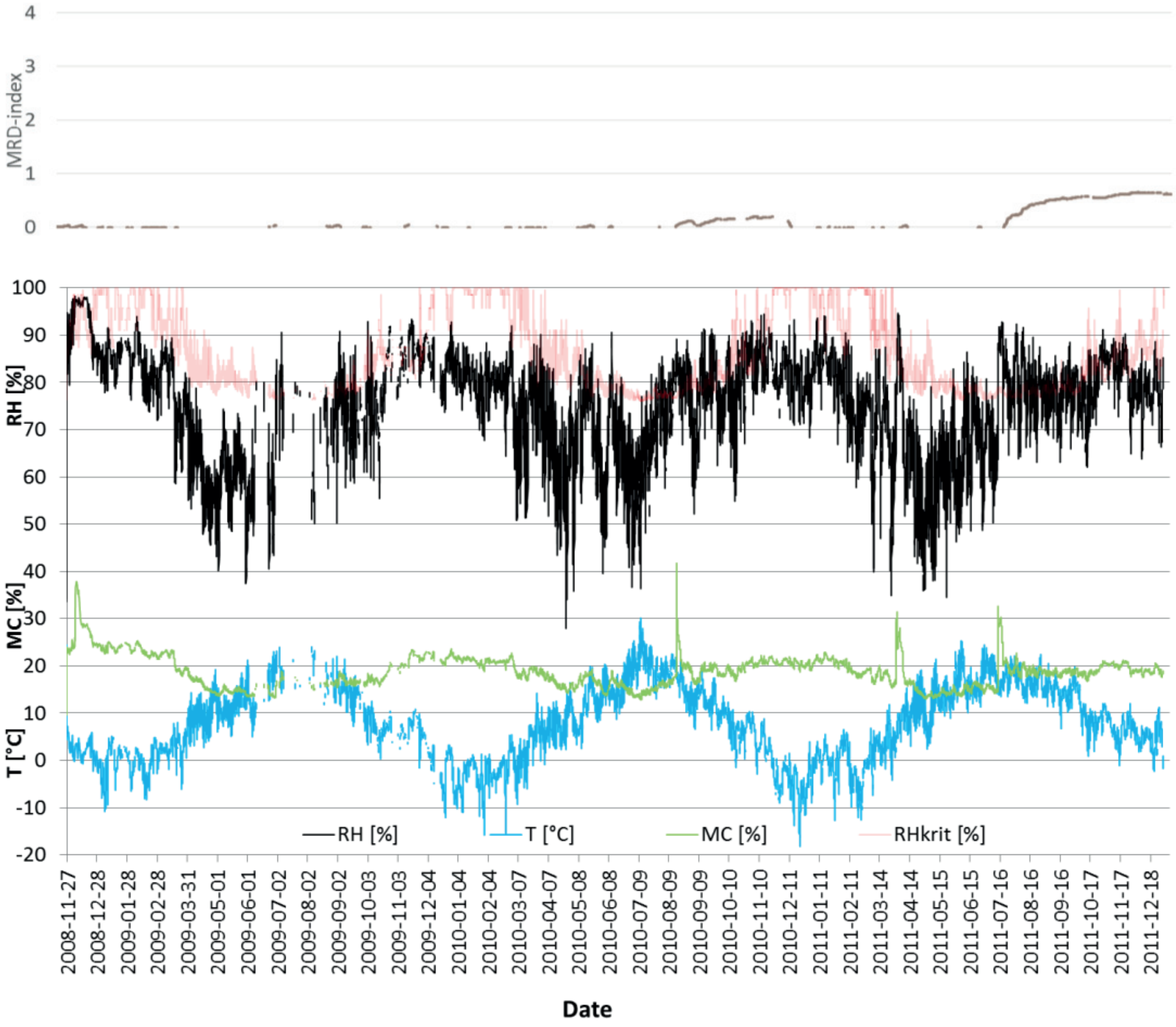


*Figure 47. Measurement point 16. The curves in the lower diagram demonstrate measured RH and temperatures near the external surface of studs and ** MC in the external surface of studs as well as **$RH_{crit}$ *during the period between 1 February 2009 and 31 December 2011. The upper diagram shows the MRD index.*

*$RH_{crit}$ is a critical RH curve for LIM 1 according to (Sedlbauer 2001). The values in the $RH_{crit}$ curve are based on measured temperatures and when growth can occur on biodegradable material for each temperature. This demonstrates whether at all it has been sufficiently favourable for microbial growth to begin. However, duration is not shown, which must also be taken into account in order to determine the risk of established mould growth, to which the above MRD index provides the answer.

**The MC is measured using extended electrodes with a large contact surface, which is why the values are somewhat higher than in reality.

Measurements show RH around 80-90% at most, briefly over 90% during the construction phase and thereafter for occasional hours over 90% RH (see Figure 47). The higher humidity level appears to have occurred in connection with inward leakage (see MC peaks) or during the colder months when outdoor RH is at its highest. The MRD index shows 0.7, which is why microbial growth should not have occurred at the RH sensor, based on calculations. However, the MRD index was worryingly high, particularly considering the fact that the wall has thermal insulated frame protection and is exposed to direct sunlight. The probable cause of this is inward leakage. The MC appears to have dropped over time, despite recurring inward leakage, which means that the humidification that has occurred at the measurement point seems to have been able to dry out within the following weeks. However, we do not know if the inward leakage has worked its way further down or somewhere else in the wall. Microbial growth has however been discovered on the outside of studs and the possibility that this occurred during the construction period cannot be ruled out (see Table 12).

There were sudden increases in MC of over 30% on 17 August 2010, 31 March 2011 and 17 July 2011, which were probably caused by inward leakage. Climate observations show rain at these times and with wind direction from the southeast and east and the façade is also east-facing. In 2012, the wall was opened up from the outside to investigate the cause. Above the measurement point, there is a horizontal joint in the façade board, where water could have penetrated between the board and the joint profile. This could explain the problem, together with the fact that there was a visible gap in the weather barrier, which consists of stiff mineral wool slab, where water could have penetrated into the wall (see Figure 48).

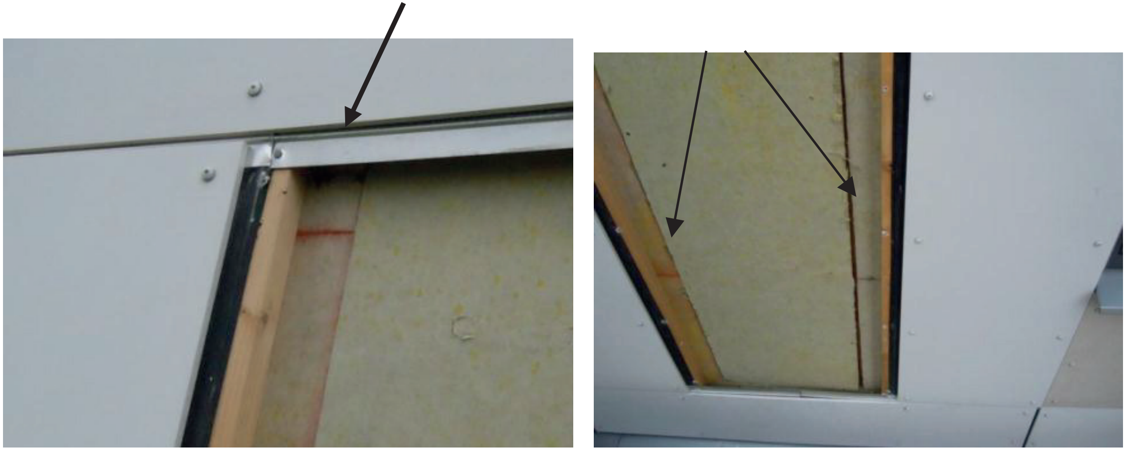


*Figure 48. Exposed façade board. Added arrows show probable inward leakage route for rain water.*

# 5 Discussions

Mould growth and mould odour from material and structures can give rise to indoor air problems. As extensive growth is usually invisible to the naked eye, the infestation could be hidden from a layman looking for the mould source or mould problems. Mould odour can be experienced differently by different people. This means that expertise is usually required to investigate this type of problem. Usually when people complain, there tends to be evident damage if the source of the problem is located. However, it is difficult to define when damage becomes damage. Most of today's buildings are probably impaired somewhere with slight growth here and there, as construction practices and timber handling have permitted elevated moisture levels or the humidification of material and structures during the construction period. This may have caused an infestation of mould growth, particularly on the material surfaces that have not been able to dry within a day or so. However, moisture has usually been able to dry out eventually. It seems as though ongoing damage generation or such which has gone on for a long period of time is worse than old dry damage that occurred briefly. As long as there is damage, it is difficult to give a house a completely clean bill of health. However, it is reasonable to believe that slight growth, barely detectable under a microscope, to a limited extent, in dry conditions, separated from an indoor climate, does not generate direct indoor air problems. As there is nevertheless uncertainty about this, caution should surely be exercised until it is proven otherwise. It should also be added that material that has not been exposed to critical moisture levels is often free from mould growth.

A measurement study of moisture redistribution has been carried out on timber that has previously been scattered and exposed to an outdoor climate under cover for a period of 7-8 days after being removed from the chamber drier. MC was measured during sampling at the sawmill. However, it took a further five days before RH measurements began on the samples in the laboratory. In moisture redistribution calculations, this exposure and time period has not been taken into consideration. This explains why the MC of the timber surface differs between the start of the survey and the start of calculations. The calculations demonstrate that the greatest moisture redistribution occurs during the first two weeks, which has probably also occurred in the specimens, as the measurements do not show any major changes in measurement values during the measurement period. The final MC differences in the cross-section of the timber item correspond well between calculation and measurement.

There seems to be little chance of using the timber surface (because it is drier than the centre of the timber after drying) to extend storage time of timber stacks with elevated MC – a few weeks at best – as time is often needed between drying and final processing at the sawmill. In reality, there is probably a large variation in the time lapse between the timber being removed from the chamber drier and it being planed and stacked.

In the study in which timber was tested at 80% RH and 15ºC, a limited amount of the timber became mouldy within 6 weeks, but there was also timber that did not become at all mouldy within 16 weeks. In other words, there is a large variation in mould susceptibility in various timber grades. This study covers timber from three different timber yards. Whether or not this particular study is representative for timber in general has not been established. However, other studies and results for mould models suggest similar results, which is why it should nevertheless be seen as a reasonable result. In other words, mould susceptibility can differ between different timber stacks and timber batches. Therefore, specific timber should be tested in order to determine its actual mould resistance, particularly if a better than average resistance is to be invoked.

A MC of 16% in timber items is not considered a risk with regard to microbial growth in a timber stack. However, individual timber items could have an elevated MC of up to 20.8% according to current MC standards with a target MC of 16%. There is a risk of microbial growth in these types of timber item, particularly if the timber item end up adjacent to each other. In addition, 6.5% of all timber items are permitted to be outside a MC of 11.2% - 20.8%, which means that there may be timber with significantly higher or lower MC in a timber stack. This means that there is probably always timber at risk of becoming mouldy in a timber stack, as long as the MC cannot be kept below 17% in all timber items in a timber stack. If the timber sorting process could reject timber with an elevated MC, this would reduce the risk of mould growth. It would also be possible to reduce the risk if the timber were to undergo conditioning during the drying process, in other words if the drying process is carried out in an air-conditioned location, which means that the timber stack would have a lower MC distribution value.

Measurement of MC during goods reception inspections appears to be necessary, despite the standards being met, as long as timber suppliers are not reporting the actual average MC and avoiding critical storage conditions, for example, humidification or direct sunlight. However, according to a newly published study

(Kjellander and Scheepers 2013), it does seem that the sawmills keep the average MC well below the target MC of 16%, which is why there should not therefore be any general risk of mould growth for a large proportion of a timber stack with a target MC of 16%.

Calculation of the MRD index is based on critical doses for planed spruce timber studs and critical doses for commercial tongue and groove board when it comes to underlay roofing. However, the critical dose is a qualified estimation (Thelandersson and Isaksson 2013) that is based on several studies and the most sensitive timber within the studies.

The site visits that were carried out during the construction process have included a few hours of observations on one or more occasions per building. This means that it has not been possible to observe other situations during the construction process. As the visits were nevertheless carried out randomly, all visits should represent an overall picture.

It has not been possible to measure the exact RH in the interface layer between different materials in the external walls on site with the instruments used. Deviations from actual values increase exponentially the higher the temperature rises above the volume in which the sensor is located. The greatest uncertainty occurs in places where the sensor is located between wind barrier fabric and wooden studs compared to thermal insulated wind barriers and wooden studs. However, there are other uncertainties, such as an insulating effect with spacer battens of wood outside the wind barrier, and whether the wind barrier is firmly against a stud or not. There are also other factors, for example, material variations and differences in the installation of materials, that could be of significance. In addition, there should be a difference between the centre of the external surface of a stud and the corner of a stud. Bearing all this in mind, it is my assessment that the laboratory measurements are representative enough to be able to draw conclusions. When it comes to site measurements near the outside of wooden studs, the RH and temperature sensors have been placed 30 mm away from the studs and 15 mm away from the wind barrier. It is difficult to assess how much the casing plastic and possible air pockets around the casing produce a temperature difference that should be compared to the temperature of the stud and whether it forms a thermal bridge to a certain degree.  There may be fixtures that could contribute locally to a worse climate, thermal bridges for the outside of the wooden stud. The assessment is that the measured values represent some part of the outside of studs assuming that the yellow casing was located just next to the inside of the wind barrier. In addition, the values measured in the ventilation gap have been compared with calculation of the MRD index, which might really represent the worst climate for the wooden stud if the wind barrier is thin and very vapour-open.

It is likely that the temperature on the underside of tongue and groove roofing board might be somewhat lower than the temperature sensor shows, particularly in attic structures. At the same time, the average temperature in attic spaces is generally higher than the outdoor temperature. However, in roofs with well-ventilated ventilation gaps, the surfaces around the gap and the temperature sensor should have a relatively similar temperature. However, small temperature differences could be of significance to the relative humidity. It is likely that the MRD index presented are underestimated, which is why it is reasonable to speculate that the MRD index would have been slightly higher if the sensors had been able to measure the surface of the tongue and groove board. As the MRD calculations are nowhere near any risk of mould growth on the tongue and groove board, based on RH and temperatures measured at the sensors, and the microbiological analysis of tongue and groove board in the multi-storey building in Växjö showed no signs of growth, it is nevertheless likely that the risk of growth is low on the tongue and groove board in these studied cases. The MRD index for roofs and the results of microbial analysis of material samples from roofs have been presented in order to verify the MRD model. In this study, the MRD model has been harmonised with the microbial analyses of sample material from the measurement points.

In the site measurements that were carried out, it has not been possible to detect inward leakage over entire wall surfaces, instead it has been carried out on a very limited scale. Sensors have been placed beneath façade details, and have covered an approximate area of 5x40 mm. When it comes to laboratory tests, sufficiently long indicator strips have been used, based on absorbent paper with long metal threads as electrodes, which made it possible to intercept any possible inward leakage. The reason these are not used on site is due to fact that the paper is susceptible to mould.

Inward leakage of driving rain into the wind barrier can be expected. However, the wind barrier does not generally seem to resist running water particularly well, as penetrations and joints are not sealed. Nor does it appear to be covered by the "General material and workmanship specifications 11" (Svensk Byggtjänst 2012).

It is not unusual for openings into the ventilation gap behind façades to be almost entirely clogged with horizontal nailing battens, which limits ventilation. Whether or not this limits ventilation has however not been studied. In addition, drainage in the gap is obstructed by horizontal nailing battens, as water can become stagnant on horizontal surfaces, which has however been studied.

Careless end grain treatment of wooden panelling façade appears to be common, particularly end grain behind windows and corner external trim. As driving rain penetrates via small gaps in the panelling, absorption can occur in panel ends according to the laboratory test. This is likely to impair the durability of the façade.

# 6 Conclusions and recommendations

In southern Sweden, there is a significant risk for mould growth on wooden studs in well-insulated north-facing external walls that lack external thermal insulation outside the wooden studs. In northern Sweden this risk is significant much lower or it is no risk at all. It is common for wooden structures to become wet during the construction phase, during rainfall, and there is a high risk of mould growth. Better construction solutions, rainproof assembly methods or complete weatherproofing are required. There appears to be a constant risk of wetting sills, including interior wall sills, both during the construction and the usage phase, which should be prevented. This can be tackled, for example, by building up a plateau, level difference with a moisture resistant material onto which the sill or the lower edge of the wall are placed, whereby water absorption and thereby mould growth is prevented.

A small amount of rain that does not create running or dripping water on timber materials and which can dry out the same day should not lead to a risk of mould growth. In general, however, precipitation and material exposed to rain pose a high risk of mould growth.

External thermal insulation of the timber frame with vapour-open and mould-resistant insulation protects against a humid outdoor climate and increases the drying potential for the frame. This also provides a reduction in thermal bridges and lower energy consumption as a result.

Nor do wind barrier products provide complete rain-proofing protection in places like material joints, penetrations, windows and other connections, which creates a risk of inward water leakage. This has been established both in the laboratory and on site. One reason is that most products are not manufactured to provide an overall or system function.

Results from both laboratory and site measurements suggest that leakage at windows and other connections in façades or external walls is fairly common. It is also clear that the solutions being used are not verified with regard to driving rain leakage.

Outdoor humidity is generally not a problem in prefabricated timber frame house-building during construction phase, i.e. short-term exposure, for example, for one month during the summer. During the winter there is no risk of mould growth, due to the low temperatures.

There is a risk of mould growth on timber surfaces that are exposed to an outdoor humidity in southern Sweden for more than a month, but not at all in the mountain areas or northernmost Sweden. The lower the temperature and humidity, the lower the risk of mould growth. This means that timber storage ought to be limited if it is exposed to an outdoor climate in southern Sweden. Exposure times can be established from a compiled table (see Table 4).

Mould growth has been detected relatively often on delivered timber, albeit usually to a slight extent. Probable causes are, for example, that the timber has not been sufficiently dried, ≤16% MC, individual timber items have shown elevated MC and discoloured timber has not been rejected.

Timber items that are, for example, dried to a MC of 18% achieve MC differences in the cross-section of approximately 4% at moisture equilibrium (equivalent to approximately 80% RH). Redistribution is relatively fast, a few weeks. MC reach 15% in timber surfaces and 19% in the centre at moisture equilibrium. The reason for the MC differences in the cross-section is the hysteresis effect. The fact that in reality there are significant differences in timber items at moisture equilibrium is not well known. This applies to timber that has not previously been in a drier state internally.

When it comes to MC measurement on the surface, approximately 15% is a critical level, as it is equivalent to approximately 80% RH, during a humidification phase, which poses a risk for mould growth over about a month of exposure at 15ºC, for example when stored during the summer.

If timber is dried to a MC of ≤16%, it should be possible to store the timber stack during the summer or in a heated storage area without any direct risk of mould growth, though there is probably still a risk of growth on individual timber items with deviating MC.

In cases of structures and conditions other than those presented above, moisture calculations that are based on expected climates should be applied and they can be evaluated using the MRD model. Walls that are exposed to driving rain, are poorly ventilated or that face north, as well as shaded walls should be given special consideration. Monitor structures with moisture surveys; this provides a verification of functionality as well as generating knowledge and documented experience. The preferred approach is also to use a method to control and document the moisture resistance work in the construction process, for example ByggaF.

# 7 Future research needs

More knowledge is needed about the proportion of timber items with elevated or high MC that end up adjacent to each other in timber stack, and what that means with regard to risk of mould growth.

How structures perform over a long period of time, for example 10-20 years, has not been studied. Long-term measurements of newly built walls should therefore be performed in order to create documented experience and knowledge, partly about structures and partly about assembly.

More knowledge is needed about the leakage quantities that can be expected through façades. In addition, we need to know more about the pressure differences and their durations that occur above the façade layer. Drainage capabilities behind façades is another area where we are lacking detailed knowledge. We need to know more about this in order to open up the opportunities to be able to make reliable calculations.

What significance with regard to mould growth on material do organic particles in the outdoor air have when they enter ventilated structures?

It is difficult to always guarantee negative interior pressure in buildings when doors and windows are opened. This means that humid indoor air can escape into the structure and could cause moisture damage. What are the conditions for preventing moisture damage?

We should develop and evaluate wall elements that can be assembled during precipitation without becoming moisture-damaged.

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# Paper I

# Omfördelning av fukt och risk för mögel på virkesstycken i virkespaket

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Ströat virkespaket efter kammartork men före hyvling och emballering

Energiteknik

SP Rapport 2012:60

# Abstract

## Redistribution of moisture and the risk of mould on timber in timber packages

The background to this project is the discussion on the risk of the growth of mould in timber packages that has been in progress within the WoodBuild research project for a long time. A report from 2009 (Nilsson 2009) assessed the risk of mould growth as relatively high, but there is no proof of whether this is the case in practice. There has also been discussion of what the moisture conditions are to which timber in packages of timber is exposed, and this is another area of which there is a lack of knowledge. Some workers claim that mould does not grow in packages of timber. Against this claim is the fact that it is not possible to determine with the naked eye whether an apparently clean and unstained piece of timber has been attacked by mould: this can be done only by microbiological analysis. This means that invisible mould growth is hardly likely to be seen in practice. In addition, other investigations (Olsson et al 2010), (Olsson 2011) have reported finding mould growth in timber packages.

The purpose of this investigation is to improve our knowledge of the time taken by, or needed for, redistribution of moisture and stabilisation of moisture content in pieces of timber in timber packages, and to investigate the importance of moisture content in combination with storage temperature and storage time as far as their effect of mould growth is concerned.

**Results:**

- Redistribution of moisture in the cross section of timber pieces takes about two weeks.
- Measurements and calculations both indicate a difference of about 4 percentage points in the moisture content between the surface and the centre of timber pieces after redistribution of the moisture, with the entire piece having a value of 80 % relative humidity.
- Some pieces of timber that were tested at 80 % RH (equivalent to 18 % average moisture content) and 15 °C developed mould within six weeks, but there were also other pieces that had developed no mould at all after 16 weeks.
- In 2009, calculations of the tendency of three timber stores to develop mould growth (based on the temperatures in the stores) indicated that timber in packages with an average moisture ratio of 18 % suffered from mould growth when stored in summer temperature.

**Conclusions:**

- The possibility of utilising the surface of a timber piece because it is drier than the centre of the piece after drying in order to extend the storage time of the packages seems quite slight (a few weeks at best, as there is often sometime between drying and final machining of the timber at the sawmill).
- Moisture content differ at different depths in the timber when complete moisture equilibrium conditions have been established. This phenomenon, known as hysteresis, is in good agreement with earlier knowledge described in the literature.
- Timber packages with an average moisture content of 17 % or above can be regarded as vulnerable materials, i.e. there is a risk of mould growth if the temperature is favourable and they are stored for a sufficiently long time.

- An average moisture content of 16 % in the pieces of timber is not regarded as presenting any direct risk of mould growth in a packages of timber. Individual pieces with an average moisture content over 16 % are equivalent to a relative humidity of over 75 %, which means that there is a risk of mould growth, particularly if the pieces are next to each other. The fact that timber with a higher moisture content can tend to be grouped together has been noted in an earlier investigation (Malmgren et al. 2005).
- There seems to be a considerable variation in the propensity of timber to develop mould.

**Recommendations**:

- The average moisture content in a package of timber should not exceed 16 % if it is to be stored in a heated area or outdoors in the summer.
- A surface moisture content above 14 % presents a risk of mould growth. Steps should be taken to reduce the timber's moisture content, particularly in heated storage areas or outdoors during the summer.
- There is no direct risk of mould growth on timber with average moisture content of 17-18 %, if it is stored cold (e.g. under 10 °C), but there is a risk if it is stored outdoors during the summer or indoors for about a month. A maximum storage time can be determined by calculating the risk of mould growth in the particular climatic conditions of the storage.
- A more statistically supported quantitative investigation should be performed, in order to be able to state the proportion of pieces of timber with elevated moisture content that end up adjacent to each other. This would provide material for assessing the risk of mould growth on individual pieces of timber in the package.

Key words: moisture content, moisture redistribution, timber, wood, hysteresis, mould

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# Paper II

# Moisture and mould in prefabricated timber frame constructions during production until enclosure of the house

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***KEYWORDS:*** *prefabricated timber house, damp, moisture, microbial growth, mould, wood, timber*

***SUMMARY:***
*Moisture and temperature conditions in wood were investigated in 24 prefabricated detached houses, three timber house factories and two apartment buildings. The results from this investigation consist of data on exposure climates during the construction process, moisture ratios in wood and microbiological analyses of wood at all stages from storage at the factory until assembly at site. Climatic conditions to which wood is normally exposed during the construction stage do not seem to contribute to the growth of mould provided that the wood has not been exposed to free water or has been kept under damp conditions for longer periods of time at favourable temperatures. Microbial growth was found on almost one-third of all the samples that were taken. Elevated or high moisture ratios were found in one-third of all the samples.The exposure conditions depend to a very large extent on the weather conditions while the building is being erected and before it is weatherproof. The results also seem to indicate that wood can have collected microbial growths before it has reached the manufacturer's stores or production in factory. The work shows that, regardless of the particular manufacturer, the most moisture-exposed and, at the same time, probably the most critical, part of the structure is generally the bottom edge of the outer wall and the sill. The risk of materials being damp, and of microbial growth, can be reduced by appropriate changes to the method of erection and modifications of the design, or by better weather protection or coverage of the site.*

## 1. Introduction

### 1.1 Definition of problems

This study is one of several parts in the major project. The major project 'Timber-framed House of the Future' is intended to support the timber-framed house industry in development of future houses, ensuring that they are energy-efficient, moisture-safe, with good indoor environmental conditions and low environmental impact. The Swedish Building Regulations (Boverket, 2008) specify requirements in respect of reduced energy demand and greater security against moisture during the construction process and in new buildings. It is important that any measures or improvements intended to reduce energy use should not result in greater risks of moisture problems. During the construction stage, there is always a risk of the wood becoming damp, thus enabling micro-organisms to start to grow. Today, it is not known with certainty for how long wood can be exposed to damp climatic conditions before microbial growth starts, and nor is it known to what extent it is possible to dry out wood that has become damp without microbial growth starting. The question is, in other words, how well wood materials survive the climate conditions and production process used, or whether there is a need for changes to designs and production methods.

### 1.2 Swedish regulations and recommendations

According to the HUS AMA 98 (Svensk Byggtjänst, 1999), the moisture ratio in timber in stud frames or sills/ground plates must not exceed 18% after the timber has been covered or enclosed. In addition, the risk of growth of mould after the wood has been covered or enclosed must decline. According to (Esping, Salin, & Brander, 2005), a moisture ratio over 18%, or a relative humidity over 84%, are critical levels for the growth of mildew on spruce at 15°C with an exposure duration of two months. The critical level is based on interpretations of laboratory experiments carried out by (Viitanen, 1996).

The Swedish Building Regulations (Boverket, 2008) include mandatory requirements:

- "Properly understood and documented critical moisture conditions shall not be exceeded for materials or material surfaces on which mould or bacteria can grow. When determining the critical moisture conditions for a material, allowance must be made for possible dirt. If the critical moisture condition of a material has not been thoroughly investigated and documented, a relative moisture ratio of 75 % shall be employed as the critical moisture conditions."

### 1.3 Hypothesis and limitations

The work has started from a 'zero-hypothesis', as follows: 'not exposing wood to such conditions, in terms of dirt, moisture, temperature or duration, during the building stage (from initial storage of the timber until completed building) that could cause the growth of mould'. This does not include the cladding of the building.

Three prefabricated timber house manufacturers, producing elements in factories, together with a housing company running a construction project for a multi-storey apartment building in timber, made their construction processes and construction objects available for the investigation. It is difficult to say anything about general conditions, as there are an almost infinite number of variations of climate conditions, which makes it impossible for these measurements and results to reflect reality on a statistically acceptable basis. However, the measurements that were made, and the samples that were taken, provide snapshots of the respective times and buildings, and can be regarded as giving some idea of the climate conditions normally encountered at building site.

### 1.4 Study objects and methods

#### *1.4.1 Descriptions of objects*

The detached houses were factory-prefabricated in the form of wall elements and roof trusses. From the factory, the parts are delivered to the construction site by goods vehicle. Walls, ceilings and floor structures consist of timber stud frames, while all the buildings had slab-on-ground foundations, as shown in

FIG 1. The main structural frame of one of the apartment buildings consisted of massive solid wood sheets. Wall elements are one storey high, and several meters long. The exterior walls are finished as far as possible in the factory, including the facade cladding, fitting of windows and preparations for running of services. If the facade is to be, for example, plaster or brick, then this is applied or built at the site.

Assembling the frame of a detached house generally takes one to two days, and requires the use of a crane. After the walls and roof trusses have been lifted into position and secured, the underlay of the roof can usually be applied within three days of starting to erect the structure. The concrete foundation slab will usually have been prepared by applying insulation for the sill and fitting sill location day or two before the elements or house are delivered. It is quite common for the materials to be used inside the house to be lifted in by the crane before the roof is erected.

**FIG 1.** *Erection of a detached house in progress.*

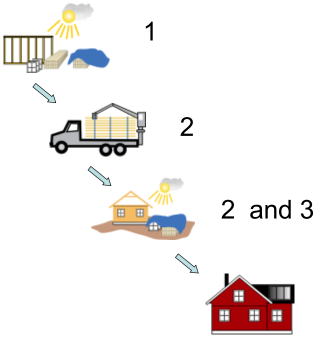

**FIG 2.** *Schematic diagram of the investigated phases in the building process.*

### *1.4.2 Description of the study methods*

The survey covered 24 detached houses, three timber house factories and two apartment buildings. Of them, eight detached houses and one of the apartment buildings were not actually visited: instead, climate conditions were logged by means of a logger fitted in the factory and then removed at a later stage of the construction process. Measurements and visits were made during all four seasons. The buildings were selected by SP Technical Research Institute of Sweden in a random manner, taken from the manufacturers' lists.
The following studies were performed (as even shown in FIG 2):

1. Relative humidity and temperature of the air in the factory timber store were logged/continuously measured at all times of the year. In addition, each company's timber store and factory production has been visited at least once. At least three stacks of timber, several roof trusses and from completed elements, were inspected visually, looking for dirt and staining. 5-15 scattered moisture ratio measurements were made, and material samples taken

for microbiological analysis, in most cases. A limited assessment was also made of the extent of any non-compliances.

2. The relative humidity and temperature of the ambient air around the building elements/wall elements were logged/continuously measured from the factory, during transport and until completion of the building. After erection of the main structure, and erection/fitting of enclosing surfaces, these measurements represent the ambient climate inside the building. For each building, the logger was attached to a window stud on one of the wall elements. Apart from purely practical aspects, the choice of this position is interesting as the inside surface of exterior walls is not intended to be exposed to outdoor conditions for any substantial length of time. Material samples for microbiological analysis were taken twice from interior studs (as visible in the window reveal), at the factory and at the construction site in order to provide information on how the wood withstands the climate during the construction process.
3. Sixteen of the buildings were visited at the construction sites. The various parts of the buildings and/or surfaces were given a general visual inspection for dirt, staining or defects. Material samples were taken for microbiological analysis and measurement of moisture ratios. The sampling strategy was that each part of the structure should provide at least five distributed test points. Any stacks of timber, or storage areas, were inspected in essentially the same way as during the corresponding visits to the factories.

### *1.4.3 Description of measurement methods:*

- Moisture ratios in wood were measured in real time by resistance measurement. Uncertainty of measurement is estimated as being better than ±1.5 percentage points over a moisture ratio range of 8-25%. Uncertainty is assumed to be greater for moisture ratios over 25 %, and so any measured values above that limit are shown as 25%.
- Relative humidity and temperature was continuously measured. Uncertainty of measurement is estimated as better than ±3.5 percentage points for relative humidity, and ±0.7°C for temperature.
- Samples of wood materials were taken by using a chisel and hammer to take a thin piece of surface material (2-5 mm thick). The size of these samples varies from one to another, but was normally in the range 5-10 cm².
- The samples taken in the field were examined under a microscope by the method described in (Hallenberg & Gilert, 1988), using a stereo-microscope at 10-40 times magnification. Micro-organisms were classified as hyphae or actinomycetes. Any occurrence of blue-stain fungus was noted separately (require high moisture levels, or free water, for growth).

# 2. Summary of results

A summary of the results is given in this chapter. The climate measurements are shown in the form of isopleths in order to be able to show the combination of moisture, temperature and time for two objects that exhibited high moisture values.

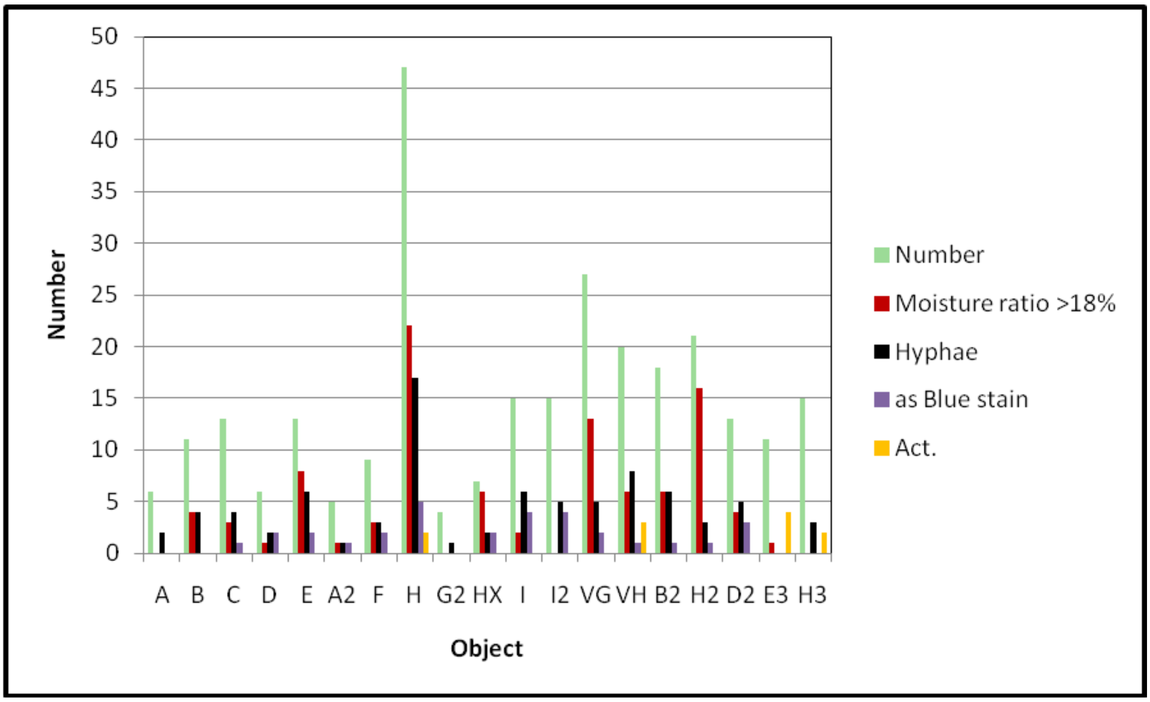

**FIG 3.** *Shows fifteen detached houses, three factory timber stores (A2, I2 and G2-HX (same factory)) and one apartment building (VH). Number of samples taken of each object (A, B, C…) and number of samples with hyphae (including blue stain), blue stain only or actinomycetes (Act.) The diagram also shows the number of samples having moisture ratios over 18%.*

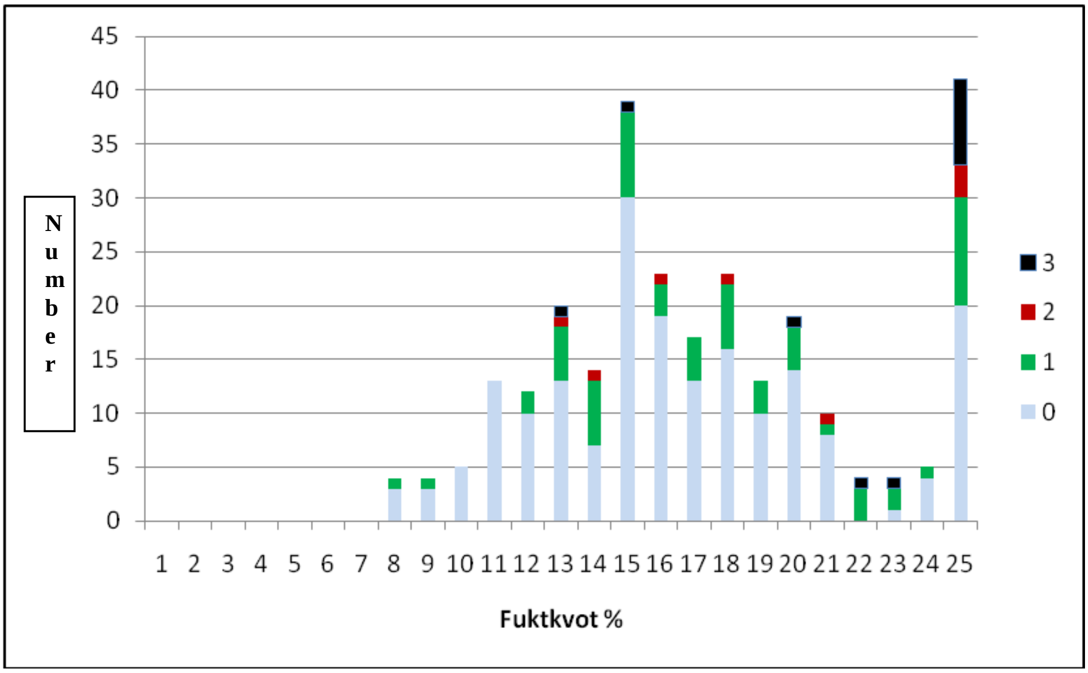

**FIG 4.** *The bars are grouped to show measured moisture ratios. Those showing moisture ratios of 25% represent all samples with actual moisture ratios above 24%. Each bar indicates the number*

*of samples and the proportion of samples with the respective growth levels: 0 = no growth,1 = slight growth, 2 = modest growth, 3 = extensive growth 3.*

## 2.1 Objects with highest moisture level

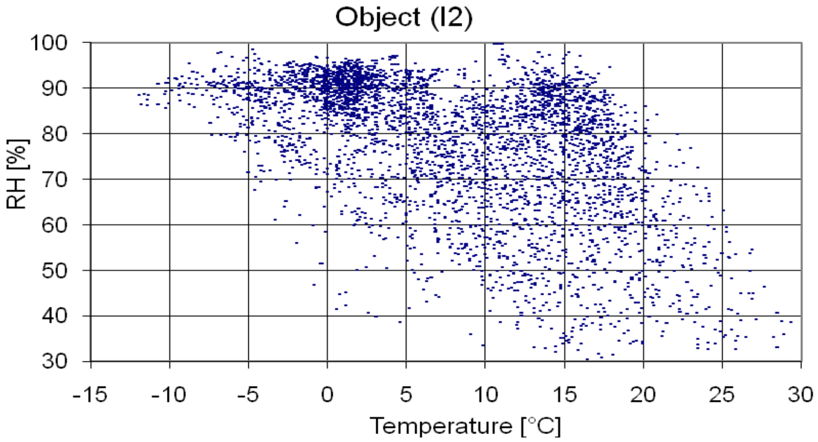

***FIG 5.*** *Climate conditions were logged every second hour (each point represents two hours) over almost a year from December 2008 until November 2009 in an outdoor timber store under cover.*

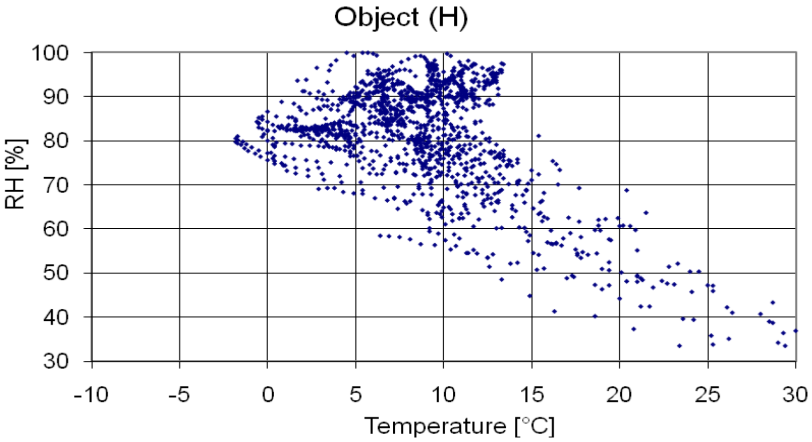

***FIG 6.*** *Climate conditions were logged each hour (i.e. each point represents one hour) from 24th September 2008 to 21st November 2009 on wall element/building object (H).*

### 2.2 Observations at building sites and factories


FIG 7.


FIG 8.


FIG 9.

FIG 7, 8 and 9 show observations from outdoor storage of wall elements wrapped in plastic. One of the house manufacturers stored completed wall elements outdoors in the factory area for several weeks. They were wrapped in plastic, although parts were found that were not wrapped. In some cases, the plastic was torn in several places. As a result, some parts of the elements were extremely wet, while others had microbial growth on them.


FIG 10.


FIG 11.

FIG 12.

Wet sills were found in six objects in interior and exterior walls, as shown in FIG 10 and 11. These sills had also microbiological growth. FIG 12 shows the exterior of an outer wall, with poor joints in wind barrier/protection board and gaps around windows. If it was raining while buildings were being erected at site, the sills were unavoidably wet. In several cases (from all manufacturers) the sills were found still wet for several weeks after the building had been erected. Exterior wall designs from all three manufacturers were found in which the sill was visible diagonally from below or from the outside. One of the manufacturers supplied a roof underlay consisting only of impregnated plywood , which was assessed as not being resistant to direct rain. Microbial growth was also found on the underside of this roof. The wind barrier was exposed to rain in six of the objects over longer periods of time, despite having leaking joints and connections. See, for example, FIG 12. Dirt was found on timber and parts of the structure in five objects, while roof leaks in store buildings were found at two manufacturers' premises.

## 3. Conclusion

Climate conditions (air humidity and temperature) to which the building elements were exposed during transport or the erection stage were not sufficiently favourable to permit growth. In four of the

24 buildings, the local relative humidity remained essentially over 80% RH for a month, while the temperature remained below 13°C, see FIG 6. In other buildings, the RH never (or only briefly) exceeded 80% RH. In general, temperatures were low, at about 0-10 °C, during those times when the local RH exceeded 80%. Material samples for microbiological analysis were taken twice from studs, these studs were exposed to ambient air but never free water, on elements/walls at the factory and at the construction site in order to provide information on how the wood withstands the climate during the construction process. No microbiological growth was found on these studs. However, it is clear that in many cases growth has occurred on materials and elements that were exposed to free water in the factory or at the building site. The main structures of houses, for example, are generally erected regardless of the weather conditions, apart from strong winds.

Microbial growth was found on almost one-third of all the samples that were taken. Elevated or high moisture ratios were found in one-third of all the samples, see FIG 4. The results show that growth was just as likely to be found on dry wood or materials as on damp wood or materials. Blue stain growth was found on two-fifths of the samples having some form of growth, and particularly on dry samples. As blue stain requires free water for growth, this indicates that it probably occurred before the wood reached the factory. All the objects that we visited departed in one way or another from the hypothesis. This also means that, in general, the Swedish Building Regulations have not been met in these buildings.

Measurements of climate conditions in two factories, having unheated areas for timber, show that the only period during which the relative humidity remains continuously above 84% is during the winter (November – March), when temperatures were below 10-15°C. In the third factory, climate measurements were made in a outdoor timber store under cover, but exposed to outdoor air. Conditions during the winter were measured as much the same as those in the other factories, while conditions in the summer saw relative humidity over 84% for long periods of time, together with temperatures over 15°C, see FIG 5. There is a risk for microbiological growth during those condition and depends on duration.

The work shows that, regardless of the particular manufacturer, the most moisture-exposed and, at the same time, probably the most critical, part of the structure is generally the bottom edge of the outer wall and the sill. The risk of materials being damp, and of microbial growth, can be reduced by appropriate changes to the method of erection and modifications of the design, or by better weather protection or coverage of the site. Also need for sealed joints for wind barrier, see FIG 12.

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# Paper III

# Laboratory investigation of sills and studs exposed to rain

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Keywords: construction methods, mould, sill, stud, rain, wood, timber frame

## ABSTRACT

Wooden sills frequently become wet due to rain during construction. This study sought to examine whether wooden sills and wooden studs can withstand short-term exposure to free water, before or after the wall design is closed up, and whether there is any risk of mould growth. The results show that all sill designs tested in the study were damaged by extensive mould growth if they were subjected to water for as short a time as one or three days. Mould growth occurred mainly on the material surfaces facing the direction in which drying-out was impeded by the moisture barrier, steel plates or other materials that were damp or impermeable to water vapour. The drying time for sills was at least three to six weeks, depending on the design. Many surfaces had no visible mould growth, but when examined under a microscope, the mould growth was extensive. This strengthens the view that microbial analyses are necessary in order safely to determine whether the wood is contaminated by mould. The results from the study will be used to formulate guidelines for the construction industry on how to design, use, and handle wood in exterior wall designs.

## 1. Introduction

This study is part of WoodBuild, a research programme within the Sectoral R&D Programme 2006–2012 for the Swedish forest-based industry. WoodBuild's objectives include improving knowledge of durability aspects of wood when used as part of the envelope of buildings. Experience from site visits, as described by Olsson et al. (2010), is that wooden sills are exposed to rain if it rains while the building is being put up. However, opinions in the building industry have been divided as to whether this represents a problem in terms of the risk of growth of mould.

Swedish Building Regulations (Boverket 2008) require critical moisture values for materials used in the design to be stated. If the value is not known, a critical value of 75% RH must be applied.

Swedish HUS AMA 98 General Materials and Work Methods Descriptions (Svensk Byggtjänst 1999) prescribe that the moisture content of timber that is intended to be enclosed in the form of structural frames or sills must not exceed 18% MC, in order to minimise the risk of mould in the design.

The purpose of this study was to investigate whether wooden sills or studs can withstand being briefly exposed to water before or in connection with being built into the designs, and whether there is a risk of mould growth. This was done by investigating the drying process, moisture conditions, and microbial activity in sills and studs that were briefly exposed to water. The work was carried out in the laboratory, with appropriate conditions being created through conditioning of materials and simulation of exposure in climate chambers. The presented constructions in this study represent common use sill designs and were selected by Swedish forest-based industry and SP. All wood material was Swedish spruce.

## 2. Test wall and sill designs

The test wall used in the study was divided into five sections, as shown in Figure 1 and 2, with different sill designs as shown in Figures 3, 4, and 6. Each section was, insulated with mineral wool (MW), 600 mm wide and was separated from the next by plastic film in order to ensure that moisture could not pass between the sections. Height of the test part of the wall was 1.0 m, terminated at the top with plastic film. The wall section continued up for a further 1.5 m above the top of the lower part and was insulated. 100 mm of EPS insulation was applied between the climate chamber floor and the test wall in order to eliminate edge effects due to temperature.

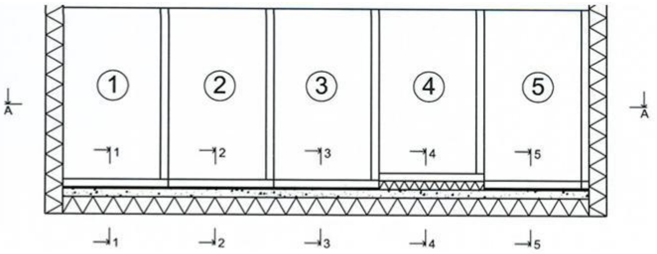


Fig. 1. The five sections and different sill designs.

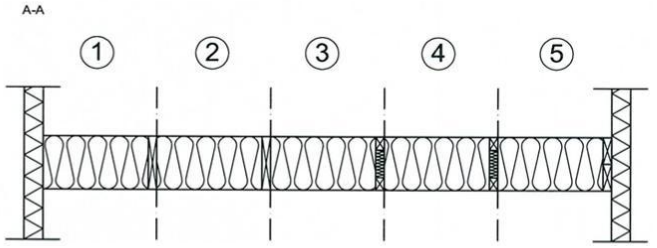
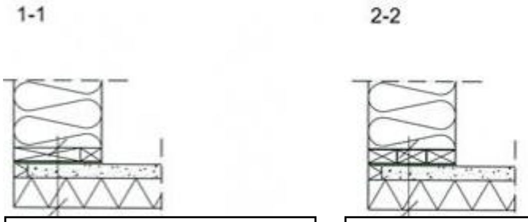


Fig. 2. Horizontal section through the wall above the sills.

The wall was built on a 5 cm thick 'concrete slab', consisting of four 12 mm cement slabs, resting on 100 mm of EPS insulation, in turn resting on the floor of the climate chamber. The slab extended 750 mm into the warm part of the chamber in order to represent the floor. The slab was divided by a 290 mm long and about 50 mm wide strip of EPS, as shown in Figure 5. The insulation was positioned directly beneath the sealed end of the sill, with the intention of separating the sections in terms of temperature effects.

### 2.1 Sill designs and cross sections



45 mm Wooden sill (220 + 70 mm)
8 mm Polyethylene foam
0.2 mm Polyethylene film
48 mm Slab of cement boards
100 mm EPS

3 mm Hardboard
45 mm Wooden sill (95 + 95 + 95 mm)
8 mm Polyethylene foam
0.2 mm Polyethylene film
48 mm Slab of cement boards
100 mm EPS

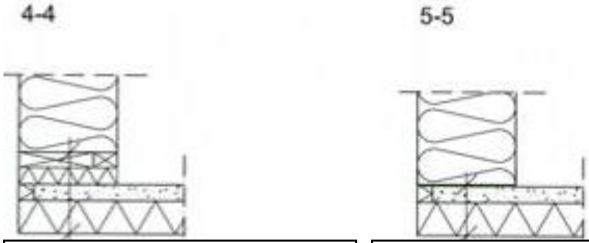
Fig. 3. Vertical sections through Sections 1 and 2. Section 1 has no fitting sill, while Section 2 has a fitting sill in the middle.

3 mm Hardboard
45 mm Wooden sill (70 + MW+70 +70)
8 mm Polyethylene foam
0.2 mm Polyethylene film
48 mm Slab of cement boards
100 mm EPS

Fig. 4.

Fig. 5.

Figure 4 is a section through Section 3. A fitting sill and mineral wool insulation are incorporated in the middle of the design. Figure 5 shows the position of EPS in the concrete slab.



45 mm Horizontal wooden stud (220 + 70)
0.2 mm Polyethylene film
50 mm XPS Extruded polystyrene
48 mm Slab of cement boards
100 mm EPS

Steel sill and vertical wooden stud
0.2 mm Polyethylene film
48 mm Slab of cement boards
100 mm EPS

Fig. 6. Vertical sections through Sections 4 and 5, neither of which has a fitting sill. Section 4 has 50 mm of XPS beneath the horizontal stud in order to make the wall less accessible to water.

Fig. 7.

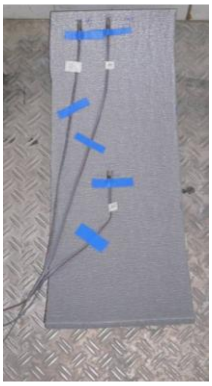


Fig. 8.

Figure 7 shows the sill design 6 (45 x 220 mm wooden sill) and sill design 7 (45 x 220 mm wooden stud) in the outdoor part of the climate chamber. Figure 8 shows the position of the relative humidity sensors in the moisture barrier before installing the sill (Section 6).

All the timber (sills and studs) were ordered with a maximum moisture content of 17–18% from a builders' merchant in Borås, Sweden. Sample measurements of the moisture content of the timber were made by resistance measurements. The sill pieces were then stored for about a month under steady-state conditions of 50% RH (equivalent to a moisture content of 10%) and 23°C. In order to be able to get five different wall sections into the climate chamber, the sills were sawn into 600 mm sample lengths. In addition, one end of each sill was sealed with adhesive (see Figure 5), in order to simulate the conditions in the centre of long sills.

## 3. Method

Samples of the material surfaces were taken for analysis of microbial activity before the sills and studs were exposed to simulated rain. The sections were exposed for one or three days, depending on the design of the test section. The test pieces were weighed before and after simulated rain. Those test pieces that were to be built into the test wall were built in within 25 minutes of the end of simulated rain. Each sill design had been prepared so that it could be closed up as soon as possible. It took about eight hours from fitting the first sill until the internal plastic film/moisture barrier and external wind barrier were fitted. The other two sill designs were located in the outdoor climate area of the climate chamber. Climate simulation continued for about three months, with continuous measurement of relative humidity, moisture content, and temperature. At the end of this period, samples were again taken from the same positions as before for analysis of microbial activity.

### 3.1 Pre-conditioning with rain and water simulation

The sill designs were placed in a shallow water bath, containing a water depth of 1–2 mm of distilled water, and exposed outdoors under a roof for one or three days, starting on 2 August 2010 (see Figure 9). Twice a day (morning and evening) for two days, the fitting sills in designs 2, 3 and 6 were exposed to rain for about one minute (simulated by water spraying) for an equivalent of 0.3 mm of rain per application. The ends of the vertical studs (Sections 5 and 7) were also placed in water baths, but not exposed to rain. The horizontal stud in Section 4 was exposed to only about two minutes of water bath, followed by air drying for one day.

Section 4 was intended to represent a structure in which the timber frame does not come into contact with water. The water bath was positioned outdoors under a roof, and without being directly in the sun, so that it was accessible to airborne spores as naturally encountered in outdoor air. The sills designs were weighed before or after exposure to the rain and water bath, as shown in Table 3.

Fig. 9. Sills and vertical stud in the water bath (1–2 mm depth), outdoors under a roof.

### 3.2 Climate simulation

The outside of the wall was exposed to 10°C and about 70% RH for one week; then about 90% RH for the next week. The inside face of the wall was exposed to 20°C and naturally varying indoor humidity (see Figure 10 for more details).

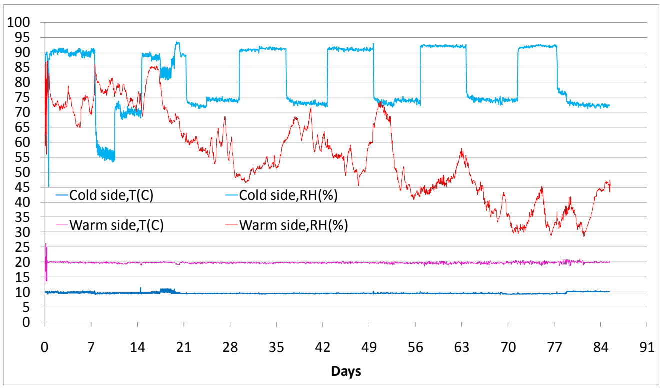


Fig. 10. Measured values of relative humidity and temperature for the cold (outdoor) and warm (indoor) parts of the climate chamber.

### 3.3 Measurement of moisture content

The moisture content in the wood was measured as an instantaneous value, by resistance measurement. Two electrodes, about 13 mm apart, were applied to the surface or inserted to some depth into the wood. The measurements were compensated for temperature effects. Uncertainty of measurement was estimated as less than ±1.5% points over the 8–25% moisture content range. Uncertainty of measurement can be expected to be higher for moisture content values over 25%. The instrument cannot measure below 9%, and so any indicated values below this have not been shown.

The ends of the electrodes were bonded, using electrically conducting adhesive, to the surface of the wood or inserted into it to a certain depth by drilling a hole in the wood and inserting a liner tube almost to the bottom of the hole (1 mm from the bottom). Adhesive was then applied to the bottom of the hole via a hypodermic needle, after which the electrode was pushed down into the adhesive. This method of measurement was developed by (Fredriksson 2010)

### 3.4 Relative humidity

The relative humidities and temperatures at the specified test points in each section were measured hourly throughout the test period. The sensor lengths were 25 mm and diameter 6 mm. Uncertainty of measurement was estimated as lower than ±3.5% for relative humidity and ±0.5°C for temperature.

### 3.5 Microbiological analysis

Samples of wood materials were taken by using a chisel and hammer to get a thin piece of surface material (2–3 mm thick). The size of these samples varied in the range of 2–5 $cm^2$. The samples were examined under a microscope by the method described in (Hallenberg & Gilert 1998), using a stereo-microscope at 10–40 times magnification. Micro-organisms were classified as hyphae. Any occurrence of blue-stain fungus was noted separately. Blue-stain fungus requires high moisture levels, or free water, for growth.

### 3.6 Positions of the measurement points

Figures 11 to 15 show the positions of the measurement points (test points) in the wall sections to which they apply. However, in some cases the actual positions are not as shown in the figures, in which cases it is the position of the test point in a postulated coordinate system that applies.

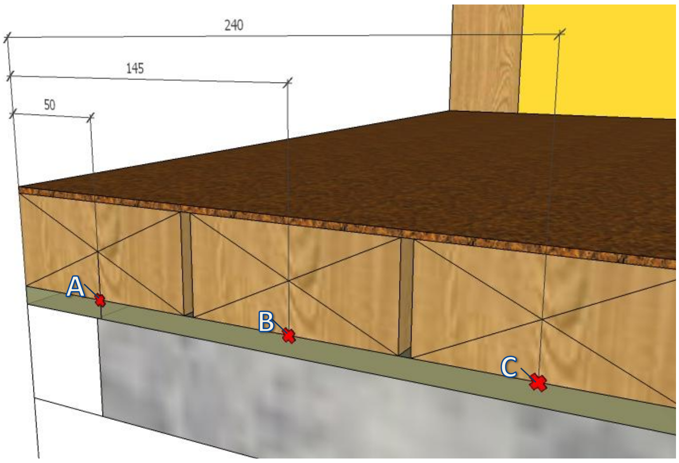


Fig. 11. Positions of test points in the sill ends.

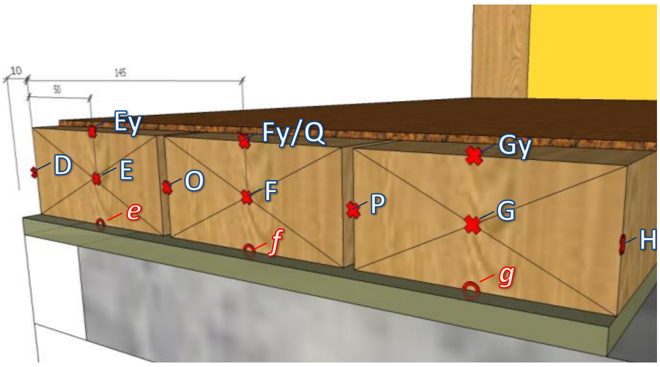


Fig. 12. Positions of the test points 10 mm from the end of the sill.

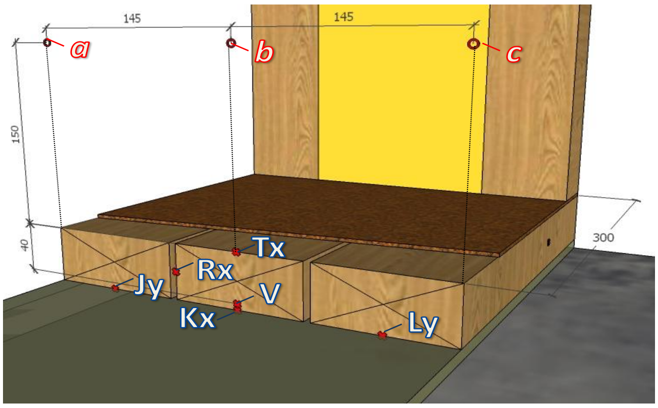


Fig. 13. Test point positions in the sill, 300 mm from the ends of the sill, and in the wall insulation.

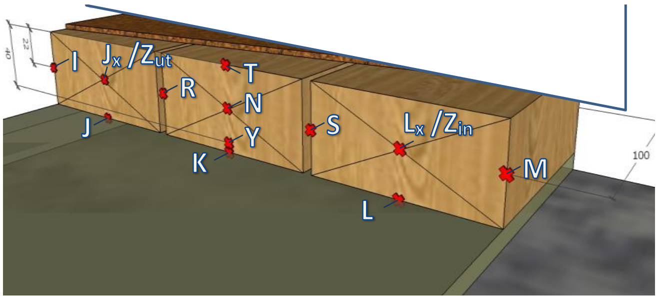


Fig. 14. Test points 100 mm from the sealed end of the sill.

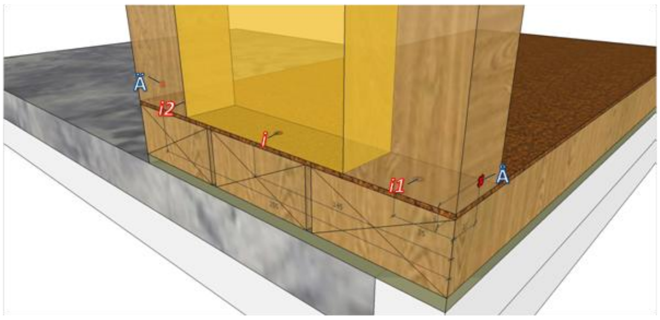


Fig. 15. Test points in the connecting wall stud. The stud is 555 mm from the sealed end of the sill.

## 4. Results

This chapter presents the measured results in detail for only two of the wall sections: Sections 3 and 6. The complete results are published in a Swedish report (Olsson 2011).

### 4.1 Results for Section 3

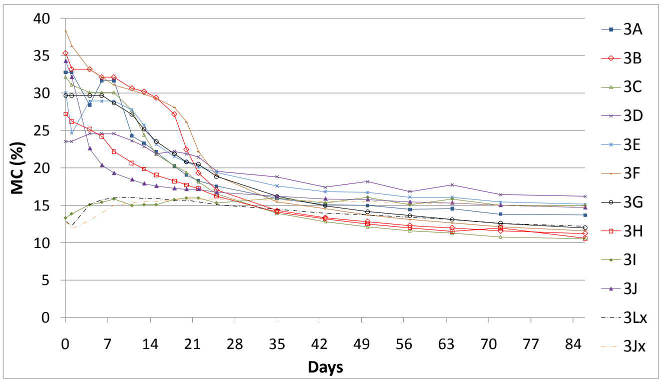


Fig. 16. Measured values of moisture content over 86 days.

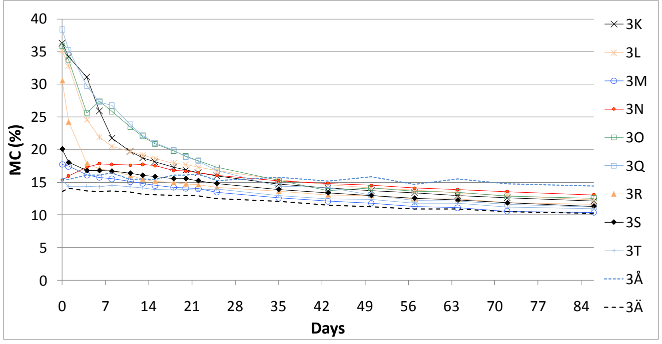


Fig. 17. Measured values of moisture content over 86 days.

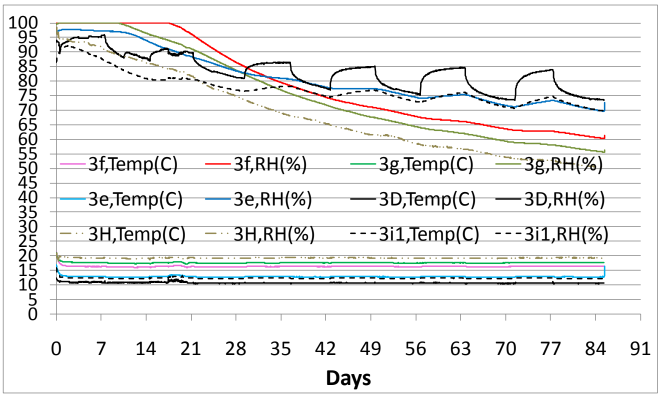


Fig. 18. Measured values of relative humidity and temperature over 86 days.

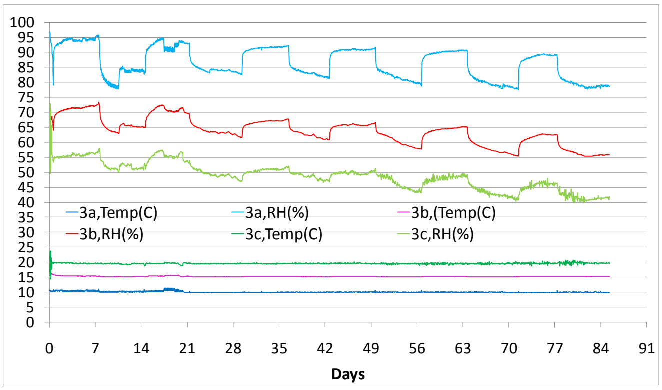


Fig. 19. Measured values of relative humidity and temperature over 86 days.

Table 1. The table shows whether there was mould growth before pre-conditioning or after climate simulation, whether it was visible to the naked eye, measured/estimated temperature, number of days with RH value over 84% or moisture content over 18%.

| Position | T (°C) | Number of days >84%RH or >18% MC | Mould growth | | Visible growth |
|---|---|---|---|---|---|
| | | | Before | After | |
| 3A | 13 | 23 | 0* | 3 | No |
| 3B | 16 | 24 | 0* | 3 | Yes |
| 3C | 18 | 22 | 0* | 3 | Yes |
| 3D | 11 | 38 | 0 | 3 | No |
| 3H | 19 | 18 | 0 | 0 | No |
| 3I | 11 | 0 | 0 | 0 | No |
| 3i1 | 11 | 10 | 0 | 0 | No |
| 3i2 | 19 | 0 | 0 | 0 | No |
| 3J | 13 | 17 | 0 | 0 | No |
| 3K | 16 | 15 | 0 | 0 | No |
| 3Kx | 16 | - | - | 3 | Yes |
| 3L | 18 | 15 | 0 | 1 | No |
| 3M | 19 | 0 | 0 | 1 | No |
| 3O | 14 | 22 | 1 | 2 | No |
| 3P | 16 | - | 1 | 3 | No |
| 3Q | 15 | 22 | 1 | 3 | No |
| 3R | 14 | 3 | 0 | 0 | No |
| 3Rx | 14 | - | 0 | 0 | No |
| 3S | 16 | 1 | 0 | 0 | No |
| 3Å | 11 | 0 | 0 | 0 | No |
| 3Ä | 19 | 0 | 0 | 0 | No |
| 3e | 13 | 28 | 0 | 3BB | No |
| 3f | 16 | 30 | 1 | 3B | Yes |
| 3g | 18 | 28 | 1 | 3BB | No |

0 = No mould growth; 1 = Slight mould growth; 2 = Modest mould growth; 3 = Extensive mould growth. $^{B}$ = Blue-stain fungus; $^{BB}$ = Blue-stain fungus starting; $^{*}$ - Sawn surface from cutting to size; (-) = No information.

Fig. 20. Visible mould growth on the underside and end of the sill.

### *4.1.1 Comments, Section 3*

The dampest test points needed about four weeks to dry out to less than 85% RH or 18% moisture content, as shown in Figures 16-18. Microbial analysis showed extensive growth of mould at many test positions especially on the end faces or close to the end faces, as shown in Table 1. Blue-stain fungus was found at test positions e, f, and g, where the relative humidity had exceeded 95% for at least two weeks. Visible mould growth could be seen at a few test positions, as shown in Figure 20, but in most cases with substantial growth there was nothing to be seen by the naked eye. No musty smell could be detected from any of the material samples.

General comments for Sections 1, 2, and 3:

- The measurements indicated higher moisture contents over a longer time at test positions E, F, G, A, B, and C, close to the end faces, where substantial quantities of water could be absorbed, than at test positions J, K, L, M, and N, which could not absorb as much water.
- Test positions I, D, and Å, close to the outside, showed moisture contents close to those of the outdoor ambient conditions (70–90% RH). Test positions H, M and Ä, well inside the design, but outside the vapour barrier, showed lower moisture contents as the temperature at these positions was almost 10 °C higher.
- Test positions i, Å, and Ä, at the bottom of standing studs, and connecting to the sill end under investigation, do not seem to have been exposed to such migration or effect of moisture that mould growth has occurred.
- Some of the measured values at a few test positions may differ from what would be expected, due to such factors as variations in the materials, or small air passages between uneven contact surfaces that could have affected drying-out. Nor can we rule out possible poor contact between the moisture content electrodes and the materials.

## 4.2 Results for Section 6

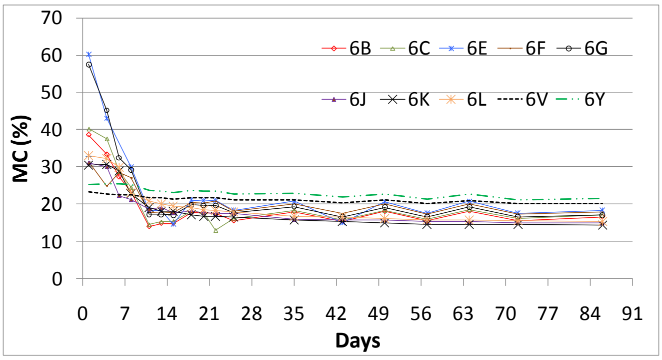


Fig. 21. Measured values of moisture content over 86 days.

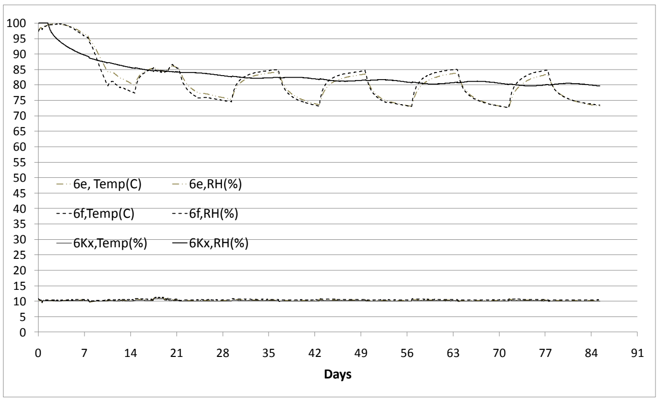


Fig. 22. Measured values of relative humidity and temperature over 86 days.

Table 2. The table shows whether there was mould growth before pre-conditioning or after climate simulation, whether it was visible to the naked eye, measured/estimated temperature, number of days with RH value over 84% or moisture content over 18%.

| Position | T (°C) | Number of days >84%RH or >18% MC | Mould growth | | Visible growth |
|---|---|---|---|---|---|
| | | | Before | After | |
| 6C | 10 | 9 | - | 3 | No |
| 6H | 10 | - | 1 | 3 | No |
| 6J | 10 | 14 | 0 | 1 | No |
| 6K | 10 | 14 | 1 | 1 | No |
| 6L | 10 | 20 | 0 | 0 | No |
| 6T | 10 | - | 0 | 0 | No |
| 6e | 10 | 11 | 0 | 3 | No |
| 6f | 10 | 10 | 0 | 3 | No |
| 6Kx | 10 | 15 | 0 | 2 | No |
| 6Ly | 10 | - | 0 | 0 | No |
| 6Jy | 10 | - | - | 3B | Yes |

0 = No mould growth; 1 = Slight mould growth; 2 = Modest mould growth; 3 = Extensive mould growth. $^{B}$ = Blue-stain fungus; $^{BB}$ = Blue-stain fungus starting; $^{*}$ - Sawn surface from cutting to size; (-) = No information.

Fig. 23. No visible mould growth on the underside of the sill at the end of the sill. Microbial analysis showed extensive growth.

### *4.2.1 Comments, Section 6*

The dampest test positions needed about 1.5 to 3 weeks to dry out to about 85% RH or 18% moisture content, as shown in Figures 21 and 22. However, drying-out could not continue down to low moisture values as the entire sill design was exposed to the outdoor part of the climate chamber. The microbial analysis indicated extensive mould at many test positions, as shown in Table 2, but no musty smell was noted from any of the material samples.

### 4.3 Results for water absorption

Table 3. Weight and weight gain for sill designs before or after exposure to rain and water bath. Sill designs 2, 3, and 6 were also exposed to rain.

| | Sill designs | Aug 2 (g) | Aug 4 (g) | Aug 5 (g) | Weight gain (g) |
|---|---|---|---|---|---|
| 1 | (45 x 220+70) | - | 3433 | 3623 | 190 |
| 2 | (2 pieces 45 x 95) | - | 3321 | 3423 | 102 |
| 2 | Styrsyll (45 x 95) | 1417 | - | 1497 | 80 |
| 3 | (2 pieces 45 x 70) | - | 2116 | 2223 | 107 |
| 3 | Styrsyll (45 x 70) | 795 | - | 878 | 83 |
| 4 | (45 x 220+70) | - | 3524 | 3557 | 33* |
| 5 | Vertical studs (2 pieces 45 x 145) | - | 4944 | 5035 | 91 |
| 6 | (45 x 220) | 2586 | - | 2837 | 251 |
| 7 | Vertical studs (45 x 220) | 3880 | - | 4008 | 128 |

*Sill design 4 was exposed to two minutes water bath.

## 5. Summary of results

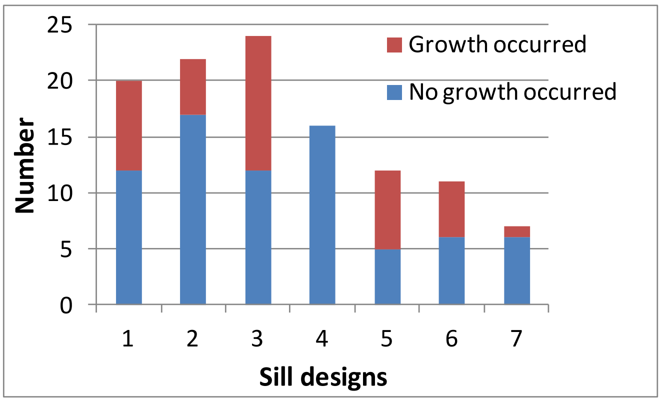


Fig. 24. The columns represent the total number of samples with and without microbial growth. The growth column includes values for all test points for which we clearly know that growth has occurred.

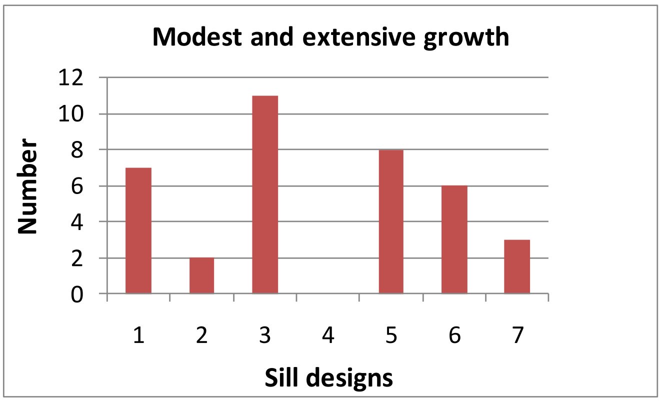


Fig. 25. The column heights represent the number of samples attacked by moderate or extensive mould growth.

Figure 24 is a summary of occurred growth of mould. Sill designs 1, 5, 6 and 7 include additional test points at which we assume that growth has occurred, but which are not shown in Figure 24. At the test positions having moderate or extensive growth, actinomycetes bacteria or single-cell fungi were found afterwards. As we did not find any signs of such attack at any of the test points before the start of the tests, it is probable that they occurred during the progress of the tests.

## 6. Conclusions

All the sill designs (whether built-in or non-built-in) that were exposed to water for one or three days were attacked by extensive mould growth, with the growth occurring mainly on those surfaces facing the direction in which drying-out was restricted, such as against moisture barriers, steel parts or items, or materials that were damp or vapour-proof. In addition, it seems as if water absorption by end faces of the wood is very critical in terms of the risk of mould growth. Moisture levels were lower at measurement points well away from end faces, with lower values being reached more quickly. At many of these positions, no mould growth occurred at all, although there were some test points in all of the sections that were well away from end faces but which were attacked by mould growth.

Our assessment is that there is a high risk of mould growth on installed sills and studs that have been exposed to rain and water under field conditions. However, based on the results of this study, brief exposure to rain splashing that does not involve dripping or running water, and which dries off during the same day, ought not to present any direct risk of growth of mould on wooden surfaces.

In principle, the drying-out time from enclosure until relative humidity had fallen to 80–85% ranged from three to six weeks for all the wall sections that had been exposed to water. Specific drying-out times varied from design to design.

The study has not shown any tendency for materials at lower temperatures (11–13°C) in the outer part of the wall to have less growth than materials in the inner parts of the walls at higher temperatures (16–19°C). Moisture levels have been high and relatively long-lasting in both cases.

At many of the test points where growth was high, the growth was not actually visible to the naked eye. This confirms that microbial analysis is necessary in order to be able safely to decide whether the timber has been attacked by mould.

Several of the test positions showed slight growth before exposure to water or climate simulation, with the material having presumably become infected with the growth before it was delivered at the laboratory.

## 7. Recommendations

The results of the study show that the wooden sills and stud ends that were briefly exposed to water were attacked by mould during their drying-out process. Ways in which this could be prevented in practice include:

- The use of full weather protection.
- Avoiding erection of the design during bad weather, and at the same time providing economic compensation for waiting time. (This could be difficult if the bad weather persists for long periods.)
- Designing the building elements or modules in such a way that inward leakage of water or uptake of moisture cannot occur.

  The connection between the wall and the concrete slab should be designed in such a way that the lower edge of the wall is not exposed to the water that often collects on the slab. Examples of appropriate designs include replacement of timber sills by sills made from non-absorbent and moisture-resistant materials, or by providing a raised ridge around the edge of slab, made from a non-absorbent and moisture-resistant material, and on which the walls are positioned. The possibility of thermal bridges and maintenance of air-tightness must not be overlooked when pursuing this arrangement. This can also reduce the risk of water absorption in the walls from leaks from building services systems during the life of the property. The bottom edges of studs should not be exposed to water absorption, which can be avoided if they are part of a weather-protected prefabricated element or module. However, it is important that potential new designs should be tested and evaluated before they are used, with erection and care instructions being prepared for them.

Proposals for future solutions under development:

- Sill design 4 (in this report).
- Sill design 5 (in this report), with sealing of the end faces of the vertical stud elements.

## Acknowledgements

This project is part of WoodBuild, a research programme within the Sectoral R&D Programme 2006–2012 for the Swedish forest-based industry. This programme is jointly funded by the government, industry and other stakeholders with interests related to the Swedish forest-based industry.

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# Paper IV

# Laboratoriestudie av träfasaders täthet mot slagregn

Lars Olsson

SP Sveriges Tekniska Forskningsinstitut

Pågående slagregnsprovning av träfasad med detaljanslutningar

Energiteknik

SP Rapport 2012:45

# Abstract

## Laboratory investigation of the resistance of wooden façade to driving rain

This investigation is a sub-project within the larger WoodBuild programme, initiated within the framework of the 2006-2012 Forestry and Timber Industry Sector Research Programme. One of the aims of the WoodBuild programme is to improve knowledge of durability problems associated with the use of wood in the building envelope.

Increasing the protection of  a wooden façade against inward leakage, reduces the risk of moisture and durability problems arising from rain. Earlier studies have found that one of the areas in which there is a risk of inward leakage due to rain is that between walls and exterior windows. This may be due to poor workmanship in fitting details, poor designs or leaks in the wooden façade itself. How well present-day prefabricated exterior wall elements mirror the findings of earlier studies is unclear, and needs to be investigated.

The objective of this study has been to obtain better knowledge of the protection against driving rain provided by present-day wooden façades, whether prefabricated or constructed in situ, by investigating how well the exterior of the façade, penetrations and connections withstand rain. This has been done with the assistance of two prefabricated house manufacturers, who have each supplied two exterior wall elements; one with vertical façade panels, and one with horizontal façade panels. The panels also included common façade details such as windows, fastenings and penetrations.

Summary of the results and conclusions:

- Significant leakage into the air gap occurred in three of the four test objects. Connection hardware in wood façades may increase the risk of leakage, at least into the air gap, despite the fact that, in principle, the air gap acts to equalise pressures on each side.
- Much of the inwardly leaking water was absorbed by the rear panel, laths etc.
- On the whole, and regardless of manufacturer, the study shows several defects or shortcomings in both workmanship and design features, such as:
  - Substantial leaks between horizontal panels and inner reveals of windows, where water found its way in.
  - In one case, water penetrated all the way in to the structural frame.
  - Inward leakage occurred, despite the use of sealing mastic.
  - Some panel ends were found to be unpainted, where water could be absorbed, with risk of rot.
  - One manufacturer incorporated a layer of thermal insulation outside the wind barrier fabric, which is beneficial for the stud and structure inside it, as it keeps the framework warmer and drier. On the other hand, it is a drawback as, in principle, the air gap was blocked, preventing drainage and ventilation.

Recommendations:

- Detailed erection instructions of tested and evaluated connection details, verified resistant to driving rain, should be provided. Erection must be performed carefully, and in accordance with instructions. Similar requirements apply to the wind barrier.
- Ensure that the air gap can ventilate and drain properly,  and that horizontal laths do not collect or impede the flow of water.
- Make sure that all parties understand the importance of painted panel ends, and inspect the panels to be sure of this.

- Investigate the effect of different treatments to counter water absorption in inside panels and laths.

Key words: driving rain, wood panel, timber frame, facade

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# Paper V

Paper Passivhus Norden 2012

# Laboratory investigation of timber frame walls with various weather barriers

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## Abstract

The objective of this laboratory study has been to compare various types of weather barriers, and to give an idea of the importance of the weather barrier for the amount of moisture in the wall behind the barrier, on the outside of the timber frame. An experimental wall, incorporating five different structural sections, has been exposed to the climate conditions inside a climate chamber for four months, with continuous monitoring of the moisture and temperature conditions in the wall sections. The measurements have also been compared with the results obtained from two-dimensional calculations based on climate data for a statistically average year.

Four different weather barrier designs (weather barrier fabric, 30 mm and 70 mm stiff mineral wool slabs, and 50 mm EPS-slab, as shown in Figure 1), were built and tested in a climate chamber, maintaining an indoor climate on one side and an outdorr climate on the other. The thickness of the load-bearing part of the wall was 290 mm. The wall consisted of five sections, of which four were insulated with mineral wool and one with loose-fill cellulose insulation. The total wall thickness varied between 290 mm and 360 mm, depending on the type of weather barrier. In addition, one of the sections incorporated two different wooden stud sizes; massive and lightweight.

Comparison of the relative humidity (RH) in the sections, as measured at the measurement position on the inside of the weather barrier, gave the following results:

- The section with 70 mm mineral wool slabs as weather barrier (No. 9) generally showed the lowest RH, with a maximum value of just over 75 %.
- The section with 30 mm mineral wool slabs as weather barrier (No. 8) showed a maximum RH of just over 80 % RH, but generally overall a lower RH value than those of the other wall sections, apart from No. 9.
- The section with wind barrier fabric (No. 6) showed a maximum RH of just over 85 %.
- The section with 50 mm EPS-slab as weather barrier (No. 7) behaved differently to the other wall sections, with the RH at times during the first two months exceeding 90 %, but then falling substantially during the last month.
- The section with wind barrier fabric and loose-fill cellulose insulation (No. 10) showed a maximum value of just under 90 % RH.

Some conclusions are that:

- In general, the greater the amount of thermal insulation and the more permeable the weather barrier material, the less the risk of damp accumulating in the load-bearing part of the wall from airborne moisture from the indoor or outdorr.
- Measurements and calculations both indicate high moisture levels and risk of mould growth in the wall incorporating loose-fill cellulose insulation.

## Introduction

Today, we do not know with certainty for how long wood can be exposed to the outdoor climate before microbial growth occurs on it. Some claim that wood can be used in all parts of the building envelope, while others claim that some limitations should apply, as high humidity can be expected near the exterior part of the envelope, and particularly in structures incorporating high levels of thermal insulation, with resulting risk for microbial growth. The Building Regulations [Swedish National Board of Housing 2008] require the critical moisture values of materials to be stated. If the value is not known, an assumed value of 75 % RH shall be used. Regardless of what is the exact value for microbial growth, the safety margin can be increased or high humidity can be prevented by using a weather barrier having a thermal insulation effect to reduce RH values behind it.

The purpose of this study has been to compare the performance of different types of weather barrier, and to give an idea of the importance of the weather barrier for the amount of moisture in the wall behind the barrier, on the outside of the timber frame. The work has been performed in the laboratory, with appropriate weather conditions being created in a climate chamber. Works has also included a general comparison of measured results and calculated results.

The study has been limited to exclude the façade, rain and solar radiation. The climate exposure on the outside was intended to represent that to be expected in a well-ventilated airgap of a north-facing wall. The specific designs of the test wall sections were selected in conjunction with the Swedish Forest Industries' Federation. All the timber was spruce. Where a massive wooden stud was required, this was arranged by adding a 70 mm stud to a 220 mm stud to give 290 mm wall thickness. The climate conditions were created in a climate chamber, intended to represent an autumn climate in terms of weekly average values of RH and temperature. Exposure of the wall sections to the climate lasted for about four months.

## The test wall, with five sections of different designs

The test wall was divided into five sections, each 600 mm wide and of different design in terms of structure: see Figure 1. Each section was divided by plastic film in order to ensure that there was no exchange of moisture between sections. Section height was 1500 mm, also bounded by plastic film. Neither wooden sills nor horizontal wooden beams were included: the sections incorporated only a vertical wooden stud defining the wall thickness of 290 mm. Section 6, however, incorporated two different types of vertical studs. In addition, 100 mm thermal insulation filled the space between the climate chamber and the test wall in order to eliminate any edge effects on temperatures.

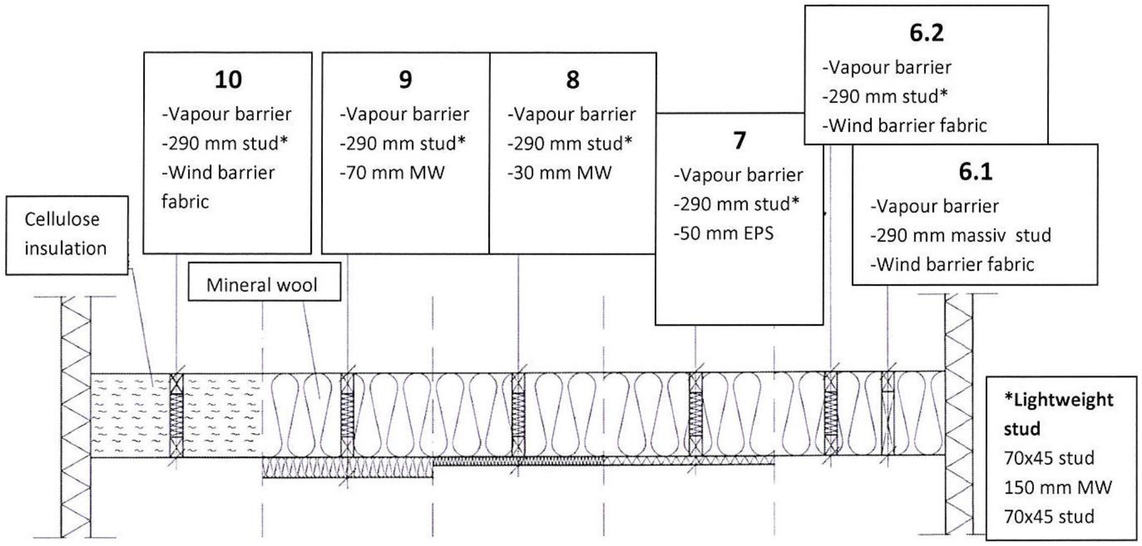

Figure 1. Horizontal section through the test wall, showing the different structural constituents.

| Materials | Vapour resistance (Z) [s/m] | Air permeability (l) [$m^3/m^2$,h, Pa] | Thermal conductivity (λ) [W/m, K] | Moisture content (MC) as delivered [kg/kg] |
|---|---|---|---|---|
| Vapour barrier | 3 000 000 | Impermeable | - | - |
| 290 mm mineral wool (MW) | - | - | 0,037 | - |
| 290 mm cellulose insulation | - | - | 0,039 | 0,18 |
| Wind barrier fabric | 7 000 | 0,01 | - | - |
| Weather barrier, 50 mm expanded polystyrene (EPS) | 36 000 | *2,2–36 | 0,042 | - |
| Weather barrier, 30 mm stiff mineral wool (MW) | 1200 | 3 | 0,033 | - |

| | | | | |
|---|---|---|---|---|
| Weather barrier, 70 mm stiff mineral wool (MW) | 2700 | 1,8 | 0,033 | - |
| * From The Moisture Manual (Nevander, Elmarsson 1994). No value shown on the product itself. | | | | |

Table 1. Material properties of each layer.

The wooden studs were ordered from a builders' merchant, specified to have maximum moisture content (MC) of 17-18 %. Sample measurement of the MC were made by resistance measurement. The test wall, with its studs and vapour barrier, was completed two months before the climate testing started, which meant that the amount of residual building moisture was less than would normally be encountered on a building site. Sections 6-9 were insulated about one week before the climate simulation started: the cellulose insulation of Section 10 was filled about six weeks before simulation started. The weather barriers were applied about one week before simulation started. The entire test wall had been built and stored indoors in the laboratory premises before the test started.

# Method

**Climate simulation:** The outside of the wall was exposed to 10°C and about 90% RH for one week, and then about 70% RH for the next three months. For the last month, RH was about 90%. The inside face of the wall was exposed to 20°C and typical, naturally varying, indoor humidity. (See Results for further details.)

**Relative humidity and temperature:** The RH and temperatures at the specified measuremnet points in each section were measured hourly throughout the test period. The sensor lengths were 25mm, and diameter 6 mm. Uncertainties of measurement for sensors were estimated at less than ±3.5% for RH and ±0.5°C for temperature (for sensors), and ±0.2°C for temperature (for thermo-element).

**Microbiological analysis:** Samples of wood materials were taken by using a chisel and hammer to remove a thin piece of surface material (2–3 mm thick). The size of these samples varied over the range of 2–5 cm$^2$. The samples were examined under a microscope by the method described in [Hallenberg & Gilert 1998], using a stereo-microscope at 10–40 times magnification. Micro-organisms were classified as hyphae.

## Positions of the measurement points

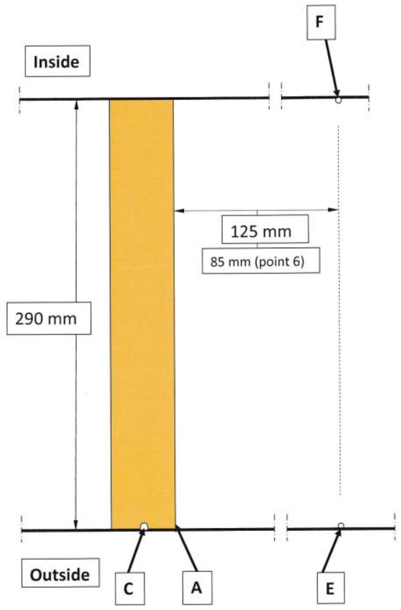

Figure 2. Horizontal section showing the positions of test points on studs. RH and temperature sensors are 6 mm in diameter, which means that the centre of the sensor is about 3 mm inboard of the exterior stud and 3 mm inboard of the weather barrier.

# Results summary – Comparison of RH, temperature and vapour content between the sections

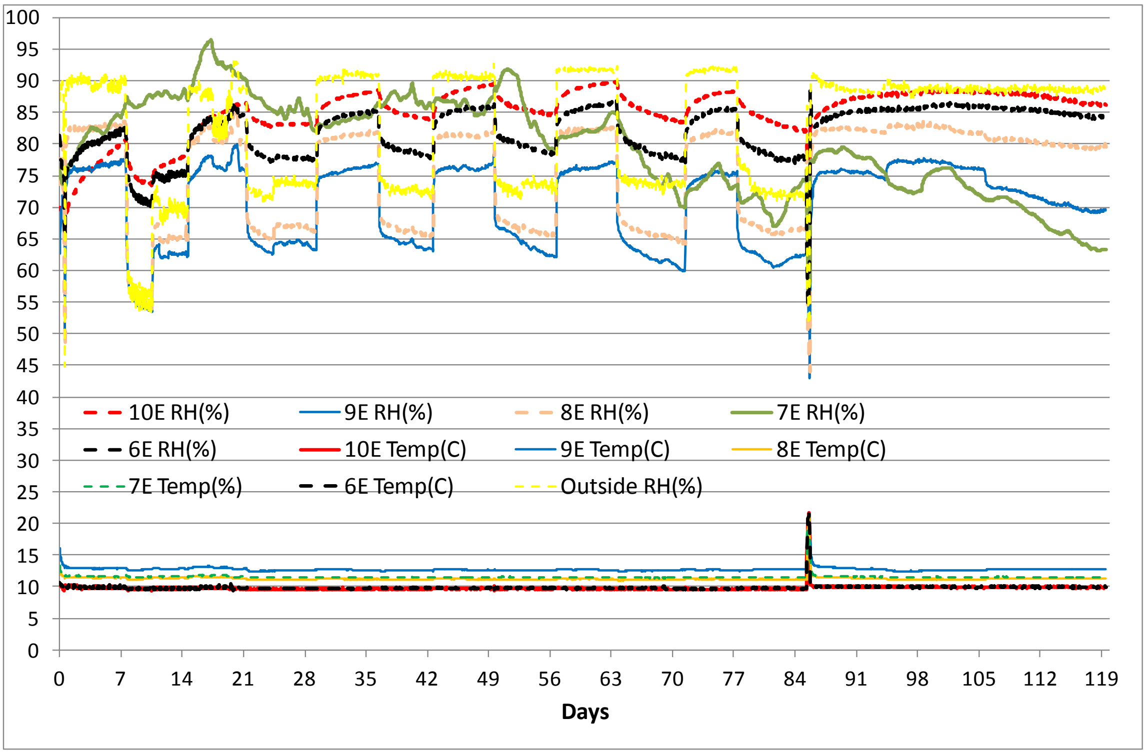

Figure 3. Measured RH and temperatures on outside/cold side and in the wall sections at measurement point E inside the weather barrier, over 119 days.

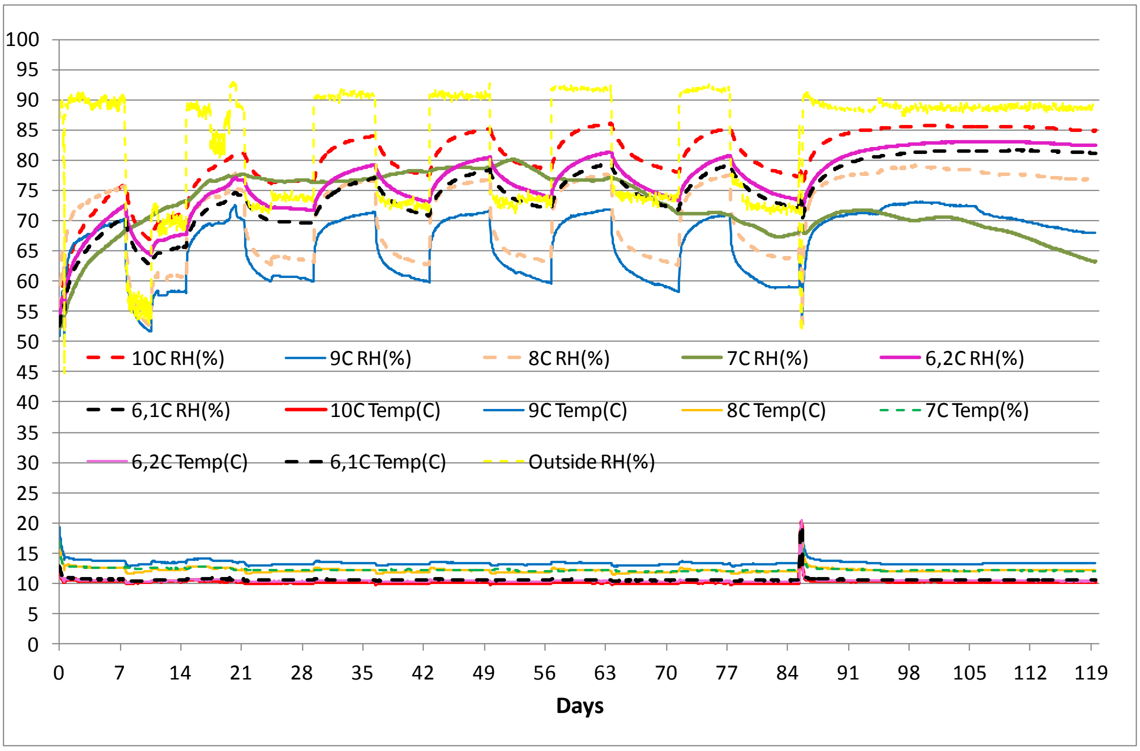

Figure 4. Measured RH and temperatures on outside/cold side and in the wall sections at measurement point C on the exterior studs, over 119 days.

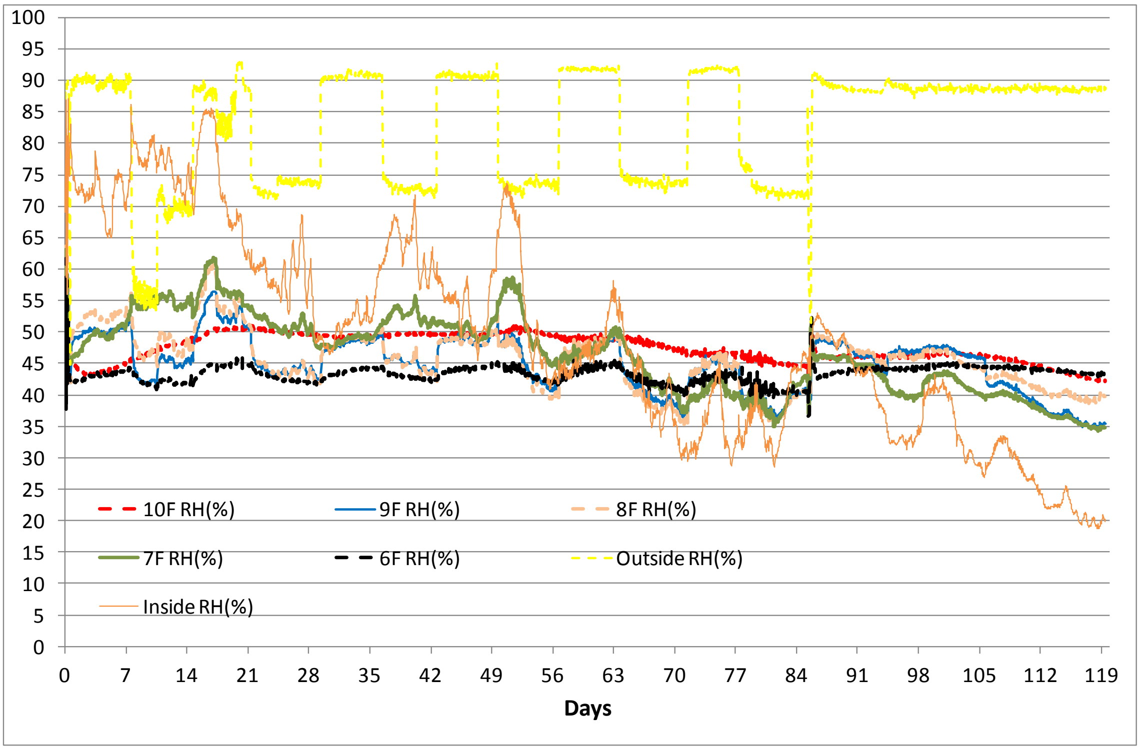

Figure 5. Measured RH on outside/cold side and inside/warm side and in the wall sections at measurement point F outside the vapour barrier, over 119 days.

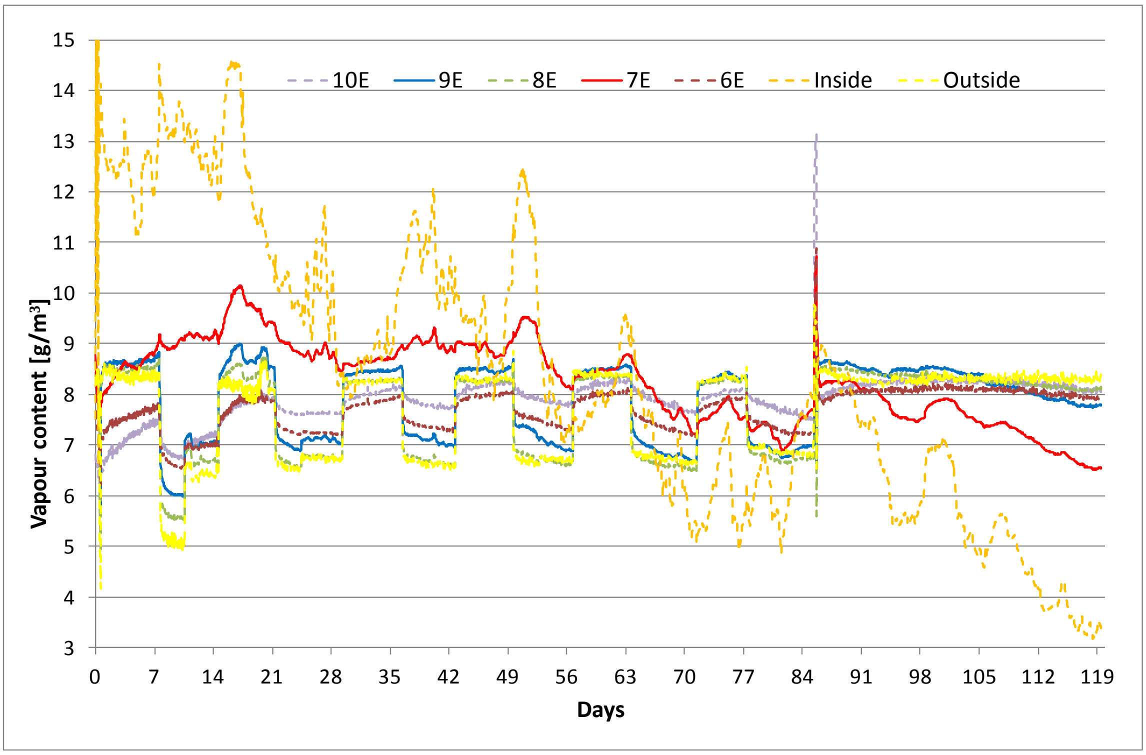

Figure 6. Vapour content over 119 days, as calculated from measured temperature and RH on outside and inside and at measurement point E on inside of the weather barrier.

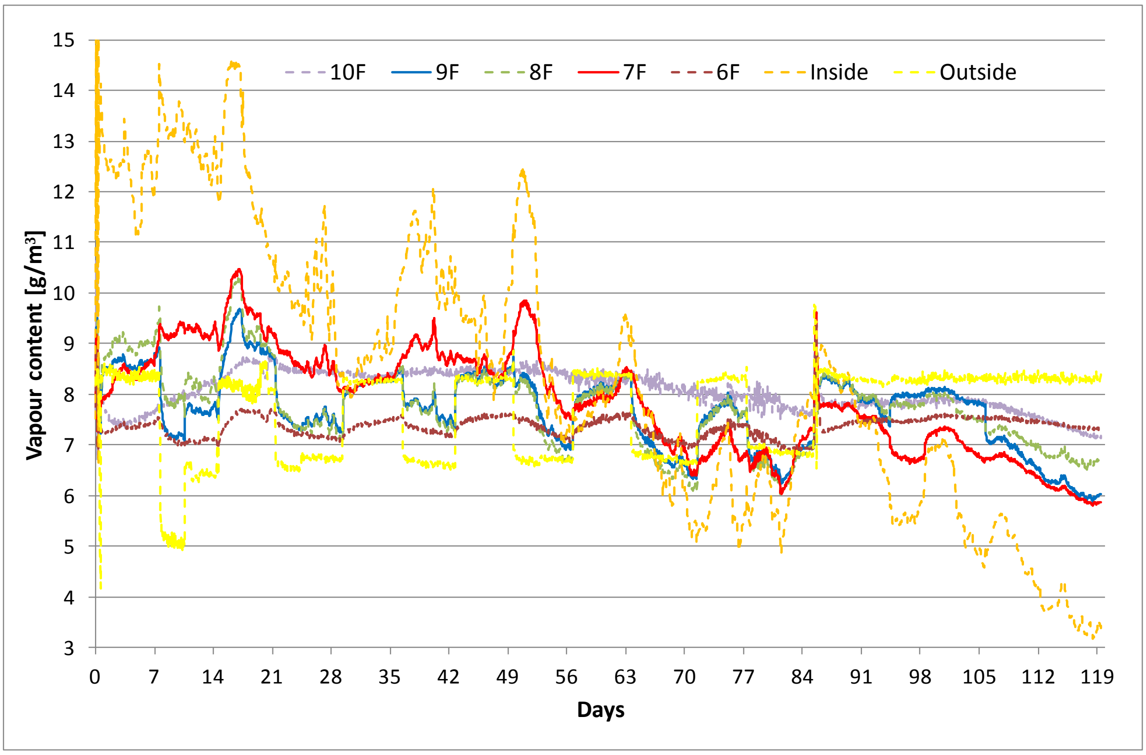

Figure 7. Vapour content over 119 days, as calculated from measured temperature and RH on outside and inside and at measurement point F on outside of the vapour barrier.

## Comments on the results

### Inside the wind barrier, beside the studs

The reason for high RH in Section 7, point 7E (see Figure 3) at first, and then low at the end of the test, was probably because moist air from the inside and later on dry air from the inside penetrated out through small air leak in the vapour barrier, e.g. through cable penetrations that had been sealed with butyl mastic and/or joints that had been sealed with tape. The vapour content in Section 7 (see Figure 7) on the outside of the vapour barrier was the same as that in Section 8, and partly the same as Section 9, during the first month, and so all of them are thought to have suffered from minor air leaks from the interior. However, there was a substantial difference in RH between Sections 7 and 8-9 during the first two months (see Figure 3). One explanation for this difference can be that if moisture gets into Section 7, it seems to have difficulty in drying out.

Section 10 also seems to have suffered from moist air from the interior, but it is more difficult to be certain of this as the cellulose insulation is hygroscopic and tends to smooth out variations. The vapour content at point 10F (see Figures 6 and 7) rose over the first three weeks, which can be an indication of this. At the end of the climate simulation the vapour content falls in Sections 7, 8, 9 and 10, despite the outdoor moisture remaining at about the same value. The reason for this is probably the effect of dryer indoor air causing the moisture level to fall. It is also possible that there is some driving force that powers indoor air to leak out through small gaps, as the temperature difference between the interior and exterior was about 10°C, giving rise to a pressure difference of about 0,4 Pa.

The comparison also shows that Sections 8 and 9 had low values of RH about 65 % during the dry periods, which can be compared with RH values of over 77 % in the other sections: see Figure 3. The sections incorporating weather barrier fabric or weather barrier of EPS-slab thus showed considerably higher RH and vapour content values inside the weather barrier during dry periods than outside it, which shows that drying out takes longer.

### Outside studs

The temperature at point 6.1C (massive stud) was about 0,4°C higher than at point 6.2C ( lightweight stud), which explains why the RH in the outside massive stud was somewhat lower (see Figure 4). The reason for the lower moisture value at point 6.2C (exterior stud) than at point 6E (inside the weather barrier) can be partly explained by the temperature difference and by the fact that the heat flow is greater through a lightweight stud than through insulation. Note that these temperature measurements were made using RH and temperature sensors, which do not indicate exact surface temperatures. For this reason, surface temperatures have also been measured using thermo-elements, which shows somewhat lower temperature differences.

### Microbiological analyses

The microbial analyses found growth only on measurement point 10E, where slight growth was found. As no samples had been taken before the climate simulation started, it is no clear when the growth started. However, that it actually did start at measurement point 10E cannot be ruled out, as measurements found a maximum relative humidity of  just under 90 % at that position.

## Comparison of laboratory measurements and calculations

The purposes of the comparison (see Table 3) are to provide an overview of the approximate moisture levels that can be expected in reality in each of the types of structure, and to check how well the calculation results agree with the measured results and climate exposure in the climate chamber.

[Forsberg 2011] has performed calculations using the Wufi2D program, which provides two-dimensional analysis. Complete calculation results are given in [Olsson 2011], starting from a MC of 15 % in wooden studs and cellulose insulation. The effects of moisture convection have not been included. The facade and the effects of rain were also excluded, with the climate outside the weather barrier intended to represent a well-ventilated wall. The model was simulated as being north-facing, with the climate being that of a statistically average year in Stockholm, with the exception that the RH peaks are clipped at around 95 % during almost the entire year, in accordance with the Swedish climate data in Wufi.

| Point | Laboratory measurement, RH [%] | Calculation RH [%] | Notes |
|---|---|---|---|
| 6.1A | - | 85-90 | - |
| 6.1C | 79-82 | 80-85 | Close |
| 6E | 85 | 90-95 | Partly close (difference of 5-10 percentage points in RH, which can be partly explained by high RH peaks in the outdoor climate parameters used for calculation modelling) |
| 6.2C | 81-83 | - | - |
| 7A | - | 75 (83 Year 1) | - |
| 7C | 70 (77-80 at the start) | 70 (77 Year 1) | Close.  (In both cases, additional moisture at the start gave higher values.) |
| 7E | 75-80 (90 at the start) | 80-89<br>(90-95 in year 1) | Partly close.  (In both cases, additional moisture at the start gave higher values.)  It seems as if moisture level is declining in the calculation case. |
| 8A | - | 70-80 | |
| 8C | 77-79 | 70-80 | Close |
| 8E | 82-83 | 70-83 | Close |
| 9A | - | - | - |
| 9C | 72-73 | - | - |
| 9E | 75-77 | - | - |
| 10A | - | 85-90 | - |
| 10C | 85 | 80-87 | Close |
| 10E | 87-90 | 95 | Partly close (difference of 5-10 percentage points in RH, which can be partly explained by high RH peaks in the outdoor climate parameters used for calculation modelling) |

Table 3. The calculated results are very similar to the measured results, particularly in respect of the RH values on the outside of the studs. The calculated values also mirror the differences between sections seen in the measured values. The measured values agree quite well with the calculated values in terms of showing to what extent the different designs react to ‘outdoor’ and additional moisture (residual and convection moisture).

## Conclusions

- Wall section no. 9, with 70 mm MW as weather barrier, showed an RH value in the exterior stud of less than 75 %. In the other sections, RH values on the outside of the timber frame exceeded 75 %. According to [Swedish National Board of Housing 2008], the critical moisture condition for wood needs to be investigated for these cases.
- In general, the better the thermal insulation and the more vapour-permeable the wind barrier, the less the risk of moisture accumulation in the wall structure from airborne moisture from inside and/or outside.
- The choice of weather barrier, and any lack in the quality of workmanship, can have a significant effect on the moisture conditions in the wall.
- High moisture levels can build up in the timber structure if it is externally insulated with a more vapour-proof weather barrier as EPS-slab in combination with moisture permeating into the wall from the inside or with residual building moisture.
- During dry periods, the moisture level was higher inside the wind barrier fabric than outside, which shows that drying-out is impeded by the wind barrier fabric.
- The moisture level was somewhat lower in massive studs than in lightweight studs, which can be explained by the fact that heat-conductive material get higher temperature and lower moisture level in the outer parts of the wall.
- Measurements and calculations both show high humidity levels and a risk of mould growth in the wall section incorporating cellulose insulation.

## Recommendations

- Applying external thermal insulation to the main timber structure reduces the risk of high moisture levels. The greater the amount of external insulation, the less the amount of moisture in the timber structure.
- When designing to ensure moisture control, the effects of residual building moisture and moisture convection must not be overlooked.
- This investigation has not included the effects of wind and rain, which could affect the local climate conditions inside the wall. If a weather barrier also provides protection against rain and condensation, detailing and workmanship must be such that such protection is provided unbroken at joints and penetrations.

## Acknowledgements

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# Paper VI

# Fuktmätningar under två år efter byte av putsfasad

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En putsad regelvägg med ett fönster


En avklädd regelyttervägg och placering av en
fukt- och temperaturgivare alldeles under ett fönster.

Energiteknik

SP Rapport 2011:67

# Abstract

## Moisture measurements in two years after replacing the ETICS

Moisture damage has been found in houses having, well-insulated, rendered (ETICS - External Thermal Insulation Composite System), unventilated and undrained stud walls. A national survey has been carried out in order to determine the extent of the problem. It became clear during the survey that it would be important to monitor the moisture conditions in walls that were built or rebuilt, in order to check that the results were as intended. However, there is no documented experience from subsequent monitoring of moisture conditions in such wall structures. Representatives of contractors and materials manufacturers were asked during the survey to make available buildings that were renovated or new builds, for monitoring of moisture conditions behind the rendering of exterior walls. Buildings in two areas of Helsingborg, where the facades were in need of rebuilding, were offered.

The resulting field study has continuously monitored moisture and temperature conditions over a two-year period in houses that were rebuilt, but which retained the ETICS design and stud walls, although with improved detailing. It has also monitored these parameters in one house that was rebuilt to incorporate a ventilated stud wall design. Measurements were made in the outer part of the stud structure, at 12-13 points per house, and particularly in the vicinity of facade details exposed to weather conditions.

Results:

- In general, the measurements behind the ETICS in the stud walls show normal values: at most, about 75 % RH, i.e. not elevated moisture values that could result in moisture damage. However, there were some exceptions, with the measurements indicating elevated or high values of 90-95 % RH, or a moisture content of 25 % MC. However, bearing in mind their relatively short durations, these measured moisture conditions ought not to result directly in moisture damage.

- In general, measurements behind the ventilated facades show normal values, at most of about 75-80 % RH. One exception showed brief high moisture values of over 90 % RH. Again, and with the relatively short duration, these measured moisture conditions ought not to result directly in moisture damage.

- We recognize that all penetrations and connections were specifically designed and particularly carefully constructed using mastic. Even so, inward leakage has occurred. The actual reason for these exceptions has not been identified, which should be done.

It can be recommended that facade rendering systems using present facade details should be tested and evaluated, and that facade systems and designs should be constructed to incorporate additional moisture safety design aimed at tackling commonly encountered weaknesses. One way of demonstrating the long-term performance and function of facades is to quality-assure them, e.g. through P-marking of building systems for exterior walls and facades in accordance with SP Certification Rule 021. See www.sp.se for further information.

Key words: ETICS, EIFS, render systems, stud wall, moisture measurement

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# Paper VII

# Fuktmätningar i fyra trähus

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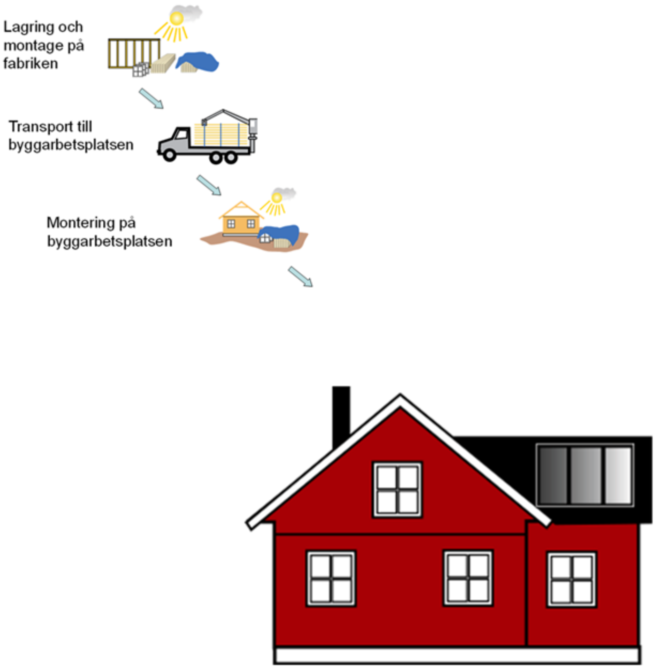

Utvärdering av färdiga hus

Placering av en fukt- och temperatursensor i ytterdelen av en träregelvägg

Energiteknik

SP Rapport :2013:33

# Abstract

## Moisture measurements in four timber frame houses

More stringent requirements in respect of resistance to moisture, and of the durability and service life of construction products, have created the need for starting the research projects, WoodBuild and Future Wooden Houses, as part of the work of the forest products and wood industry's 2006-2012 sector research programme. The evaluation of the results is based on documentation, measured data and site visits from both projects. The overarching research projects complement each other, thus producing synergy effects.

The aim of the work is to improve knowledge of the moisture and temperature conditions and their duration encountered in the exterior envelope of well-insulated wooden buildings, such as in roofs and walls, and to study the effects of these parameters and values on microbial growth.

Conclusions

- From the extensive measurements made on four wooden houses over the period of 2009 to 2011, there is nothing to indicate that any generally critical conditions have arisen in the exterior envelope, roof or walls that give rise to microbial growth. Such well-insulated timber frame houses should therefore perform without any general risk of microbial growth resulting from effects of the outdoor humidity, particularly in northern and central Sweden. However, it does seem as if materials that became attacked by mould before incorporation in the houses have been used. Rain on materials during the construction of the houses, and inward leakage due to unsealed gaps in the façades, are thus causes of microbial growths that have been found. It should be noted that growths that have been found have generally been limited in their extent, often invisible to the naked eye, and with no noticeable smell, and so have been regarded as marginal problems in comparison with what is usually regarded as moisture damage in a building.
- In humid areas of southern Sweden, there seem to be a risk of microbial growth in exterior walls not having external insulation. However, roof structures have performed well, despite being in the south of the country. The following factors have presumably played a part: exposure to the sun, good roof space ventilation, heat sources or passive heating from building services systems, and thermal bridges. This evaluation cannot therefore completely relieve ordinary well-insulated roofs of the risk of microbial growth in southern Sweden, if they are mostly shaded.
- Sills or sole plates in walls of detached houses seem to be relatively dry, due to the concrete foundation slabs conducting heat to them. However, there is a large risk of them becoming damp during the building work, especially due to water puddles on the concrete slab, or of water splashing on to them from the outside, as they are often left unprotected.
- Sudden unexpected inward leakage to the stud wall structure of exterior walls has occurred in three of four houses, but does not seem to have resulted in microbial growth at the actual test points as indicated by the calculated MRD index, Mould Resistance Design. However, we do not know whether the water has found its way further into some other part of the structure. There are façade details such as windows, joints or connections between the wall and the foundation in the vicinity of the

inward leakage positions. Many of the leaks are the result of rain and a wind direction directly on to the façade.

Recommendations

- Apply mould resistant and vapour permeable external insulation outside the wooden frame walls. This is particularly recommended for sites in southern Sweden.
- Protect joints, connections and penetrations by means of wind barriers, applied in accordance with verified designs, to prevent water from finding its way into the wooden frame of the wall.
- If a traditional roof is likely to receive little or no sun, or heating from some source or strong ventilation, an improved design should be chosen. This could include, for example, controlled ventilation in the roof space, restricted ventilation, some form of heat input or insulation outside the structural. Subsequent performance must be followed up by measurements.
- Use only timber with a mean moisture content of 16 % or less. Create a 1-2 centimetre level difference between the concrete foundation slab and walls, e.g. by using high-strength insulation, to separate the sill from water puddles on the concrete slab. Protect materials from the weather while work is in progress, and ensure that they are not splashed or exposed to precipitation or dirt at any time.
- Perform moisture calculations that allow for the expected outdoor climate, and evaluate the results using the MRD model. Particular attention should be paid to walls exposed to driving rain, north-facing walls, roofs with a steep slope to the north, and shadowed structures, and their performance must be followed up by measurements.

Key words: moisture, outdoor climate, driving rain, mould growth, wood, timber frame, walls, façade, roofs, attics, wind barrier, weather barrier, MRD-index, field tests

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