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Wooden objects in historic buildings

Effects of dynamic relative humidity and temperature

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Cover: The pulpit in Hörsne church on the island of Gotland, Sweden, dated 1688.
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Abstract

Cultural heritage objects and interiors are not only housed in museums but are also found in historic buildings, which are often less climate-controlled compared to museums. In such buildings the indoor environment may be colder and more humid. The overall aim of the research presented in this thesis was to contribute to the understanding of the actual cause-effect relationship between dynamic indoor environments as found in poorly-heated historic buildings and wooden objects housed in them.

This compilation thesis consists of five papers which cover three complementary parts of the same research project:

1) Paper I aimed to investigate how existing recommended climate ranges are interpreted and used by the cultural heritage sector. As a tool for this study two risk assessment websites were used. Relative humidity and temperature data from four buildings with different degrees of climate control were uploaded on, and the risk for wooden objects was interpreted by, the two websites. The results from the two websites showed low agreement for the risk of mechanical damage in environments from historic buildings. This suggests that the knowledge of dynamic environments and the influence of low temperatures are not sufficiently studied.

2) Papers II and III aimed to relate damage of painted wooden objects to the past and present indoor environments in historic buildings. The study examined to what extent it was possible to relate damage of painted pulpits in churches to past and present energy consumption (heat output) of each church. The total heat output during 1900-1990 was revealed from archives in the form of fuel costs and types of heating systems used by the

churches and was used as a proxy for energy consumption. A damage assessment was performed of the painted wooden pulpits in each of the churches. In this way both the indoor environment as well as the damage could be quantified and the two parameters could hence be correlated. The results suggested that more damage, in terms of craquelure in the paint layers, was present in churches with a higher heat output and there was increased damage in churches which used background heating compared to churches which did not.

3) Papers IV and V both developed a method and studied moisture transport in wood. The aim was to be able to record moisture diffusion and hence the impact of dynamic environmental conditions. In climate chamber studies various possible indoor environments were simulated and the method chosen in Paper IV was used to estimate the rate and distribution of moisture in wood over time. It showed that low temperatures reduced the moisture transport and increased the response delay, resulting in moisture content fluctuations of smaller amplitudes and hence a smaller mechanical impact on wood.

The overall result of the thesis is that low temperatures are beneficial for the preservation of the wooden objects. These findings are important because, from an energy saving perspective, they can contribute to how heating and climate control are used in historic buildings. However, these results also need to be validated. Further systematic, transdisciplinary research projects are needed where field studies, laboratory experiments as well as analysis and modelling are closely linked. These would reveal further insights into the influence of low temperatures on relative humidity and the subsequent impact on cultural heritage objects of various materials.

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List of Papers

I. **Bylund Melin, C.** Comparison of two risk assessment websites for evaluating the impact of indoor environments on objects. *[Manuscript]*

II. **Bylund Melin, C. & Legnér, M.,** 2013. Quantification, the link to relate climate-induced damage to indoor environments in historic buildings. In J. Ashley-Smith, A. Burmester and M. Eibl, eds. *Climate for Collections Standards and Uncertainties, Post Prints of the Munich Climate Conference, 7-9 November 2012*. London: Archetype Publisher Ltd.; 2013:311-323. Available at: http://www.doernerinstitut.de/downloads/Climate_for_Collections.pdf.

III. **Bylund Melin, C. & Legnér, M.,** 2014. The relationship between heating energy and cumulative damage to painted wood in historic churches. *Journal of the Institute of Conservation 37(2):94-109,* doi:10.1080/19455224.2014.939096

IV. **Bylund Melin, C., Gebäck, T., Heintz, A. & Bjurman, J.,** 2016. Monitoring dynamic moisture gradients in wood using inserted relative humidity and temperature sensors. *E-Preservation Science, 13:7-14.* Available at: http://www.morana-rtd.com/e-preservationscience/2016/ePS_2016_a2_Bylund_Melin.pdf

V. **Bylund Melin, C. & Bjurman, J.,** 2017. Moisture gradients in wood subjected to RH and temperatures simulating indoor climate variations as found in museums and historic buildings. *Journal of Cultural Heritage, 2017, 25:157-162,* doi: 10.1016/j.culher.2016.12.006

The author's contribution to each paper

Paper I

Jonathan Ashley-Smith introduced the idea of comparing the two websites. However, the planning, implementation and writing of the paper were carried out by Bylund Melin alone.

Paper II

The original idea of this study was developed in cooperation between the two authors. Legnér carried out the archival research on church heating and provided those results. Bylund Melin made the damage assessments of the pulpits. Discussions on the results were by mutual agreement; however, compiling the two data sets and writing the majority of the paper was done by Bylund Melin, with the exception of the section *Historic data collection: method and results*.

Paper III

The same allocation of responsibilities and work as for Paper II. Legnér wrote the section on *Heating.*

Paper IV

The original idea of monitoring moisture in wood was by Bjurman. Development of the experimental method was mainly done by Bylund Melin although Bjurman was consulted. The empirical work was done by Bylund Melin. Bylund Melin wrote the majority of the text with contributions from Bjurman. Gebäck and Heintz modelled the data received from the experiments and wrote the parts concerning the modelling.

Paper V

The planning was done by Bjurman and Bylund Melin in collaboration. Execution of the experiments and writing the article were mainly done by Bylund Melin with input from Bjurman. The modelling was performed by Gebäck from the data received from the experiments, see Paper IV.

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Foreword and acknowledgements

Being a conservator, the discussions since the 1990s and onwards on the recommended climate ranges for museum objects are well known to me. Due to continuous research these recommendations have gradually been widened. However, while working in a museum it is still not always straight-forward to give clear environmental recommendations for individual works of art on loan or for objects in showcases and exhibitions at the museum. I must admit that this uncertainty sometimes leads to stipulations which at times are probably unnecessarily strict. But still, I would rather recommend a too narrow climate range than put the museum objects at risk; this is after all my task as a conservator. On the other side of the coin is the frustration, knowing that strict climate control is not consistent with energy efficiency, which is becoming increasingly more important due to climate change. Are these two sides at all compatible?

I started my career as a stone conservator, mainly working with outdoor objects. One large threat was air pollution and the deterioration of limestone and sandstone ornaments on facades in cities was fast and frightening. Although conservation efforts could reduce the disintegration, it was obvious that to save this cultural heritage, the air pollution had to be minimised. Later I turned to conservation of sculptures and objects during my employment at The Nationalmuseum in Stockholm. The museum is located in a historic building, erected in 1866. Climate control was challenging and stable relative humidity and temperature levels could, at that time, only be kept in parts of the building. Therefore one of my tasks was to maintain a stable relative humidity in display cases during exhibitions by using silica gel as a humidity buffer.

The performance, advantages and disadvantages of using silica gel later became the subject of my master's thesis (Bylund Melin 2005). This work led to additional questions on the actual impact of relative humidity and temperature on objects made of hygroscopic materials. One of those was the direct and indirect influence of temperature on mechanical deformation.

In 2008 I was happy to become a PhD candidate in the *Spara and Bevara* research project and got the opportunity to study the impact of the indoor environment in historic buildings and its impact on wooden objects. Now, after this long journey, I would say that this area is still one of great challenges in the field of preventive conservation because of the many factors which need to be considered in order to fully understand how hygroscopic materials respond to indoor environments. The indoor environments found in non-heated or partly-heated historic buildings can be considered the true *worst case scenarios.* Understanding how they affect hygroscopic materials will also influence the environmental recommendations in museums so that they can be more safely adjusted for energy efficiency purposes. It has been a privilege to have had the chance to study these questions in depth. It has been a long and challenging journey, but one I'm grateful to have made.

The approach to this work is through the eyes of a conservator. Besides the empirical work behind the five papers of this thesis was a wish to compile and to better understand the research which has been performed in the field of conservation science as well as the adjacent research which has been achieved in wood science and building physics. Hopefully this combination will give new perspectives to continue research in our field.

The PhD project was carried out at the Department of Conservation, University of Gothenburg and funded by The Swedish Energy Agency (Energimyndigheten) as part of their support for the entire research programme. The research programme was initiated and managed by University of Uppsala, Campus Gotland (formerly Gotland University). Further generous financial support for this PhD project was provided by the Department of Conservation, University of Gothenburg, *Berit Wallenbergs stiftelse*, *Märta, Gunnar och Arvid Bothéns stiftelse*, and *Svea Orden (Logen Ingeborg)*, which all are gratefully acknowledged.

A number of people have supported me in my work and been of invaluable help to me in order to complete this thesis, which I need to acknowledge:

First and foremost I would like to thank my three supervisors; my main supervisor Professor Jonny Bjurman, PhD (University of Gothenburg) who believed in me and this project, I thank you for inspiring discussions and for giving me free hands to develop this PhD project within the framework; Assistant Professor Maria Brunskog, PhD (Uppsala University, Campus Gotland) for the genuine support, indepth knowledge of the material wood and thoughtful comments and interest in this subject; Professor Elizabeth E. Peacock, PhD (University of Gothenburg), I thank you for encouraging discussions and sharing your thorough academic knowledge. I'm truly grateful for the time and knowledge that all three of you have shared with me over the years.

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Stockholm, October 2017

This thesis is dedicated to my parents
Anita Torsdotter (1935-1988) and Per Bylund (1936-1989)

1
Introduction

The aim of this thesis, *Wooden objects in historic buildings: Effects of dynamic relative humidity and temperature,* was to contribute to the understanding of how indoor environments (relative humidity (RH) and temperature (T) influence wooden objects, in order to avoid climate-induced permanent damage. The papers of the thesis comprise three parts or perspectives on this field: 1) To evaluate the present understanding and interpretation of climate criteria as known in the conservation field by comparing two risk assessment websites, 2) To relate damage and deterioration of wooden objects to the past and present indoor environments of historic buildings, and finally, 3) To study moisture transport in wood during climate chamber experiments simulating different indoor environments found in historic buildings and museums. These parts were identified as being less studied during a literature review survey at the beginning of this PhD project, the focus being on existing cultural heritage research literature on the impact of indoor environments on objects and buildings (Leijonhufvud & Bylund Melin 2009).

The PhD project is a part of the *Spara och Bevara research project*[1], Part 1 (2007-2010) and Part 2 (2011-2014), which was the Swedish Energy Agency's research program for energy efficiency in cultural heritage buildings (Spara och Bevara n.d.). While the Spara och Bevara project's overall purpose was to increase the expertise in energy efficiency in cultural heritage buildings, the main focus of this thesis is the indoor environment in

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[1] *Spara och bevara* is Swedish for *Save and Preserve* as in save energy and preserve objects and buildings

historic buildings and its impact on cultural heritage objects housed in these buildings. Saving energy is of importance also in historic buildings; However, such measures must not put cultural heritage objects at risk. The recommended climate variation is important to identify so that energy efficiency measures can be taken without harming the objects and also, if possible, improve the preservation conditions for both buildings and objects.

Objects made of hygroscopic, organic materials are in particular influenced by the indoor environment. Wood, for instance, responds to changes in the ambient air. With an increase in RH the material will gain moisture from the ambient air and swell; with a decrease in RH the material will release moisture and shrink. If objects are restrained and changes in RH and temperature are large enough, mechanical deformation may become permanent and cause damage such as warp, cupping or cracks. High RH and temperatures also promote chemical and biological degradation. One key question which has been prevailing in this area of research is: *which RH and temperature set points are the safest for objects and collections and which fluctuation amplitude and duration can be allowed from this set point?* This question has been studied in the museum context since at least the 1930s (McCabe 1931/2013). It became heavily debated in the 1990s after the scientists at the Smithsonian Institution announced that the RH ranges could be widened from the previously accepted narrow specifications (class 1: 50 or 55 +/- 5 % RH and 19 +/- 1 °C (winter) up to 24 +/- 1 °C (summer)) suggested by Gerry Thomson (Thomson 1978; Thomson 1986; Schultz 1995). On one side were, generally speaking, engineers and researchers who advocated that wider recommended environmental climate ranges could be tolerated by most museum objects and were necessary because museum climate control systems are energy demanding and therefore a heavy financial burden. On the other side were predominantly conservators who argued that the issue had not been fully examined and that museum collections, which were known to be in good condition in the stable indoor environment, should therefore not be put at risk in more unstable environments (Real 1994; Erhardt *et al.* 1995; Lull & Junction 1995; Appelbaum 1996; Weintraub 1996). Interest in the topic has not dimished over time; on the contrary, the growing need to save energy due to climate change has put further pressure on museums and collection managers to reduce energy consumption and thus also costs (Burmester & Eibl 2013). However, it should also be pointed out, as was done at the IIC Hong Kong Congress panel discussion *Preventive conservation and the environment* in 2014, that conservators are aware of their social responsibility, when it comes to environmental issues, to address alternative ways of reducing energy consumption in museums. Moreover, conservators in general have shifted from having a more idealistic attitude in preservation matters to becoming more relativistic, more focussed on *managing change*. Conservation scientists were encouraged to find research solutions on the issues raised. Conservators should on the other hand give time to understanding the historic conditions of collections in buildings with no climate control (Atkinson 2016).

The growing threat of climate change and temperature increase to cultural heritage has resulted in research projects which predict future climate change and its impact on cultural heritage buildings and the indoor environment in those buildings. *The Global*

Climate Change Impact on Built Heritage and Cultural Landscapes; Noah's Ark Project (2004 – 2007) brought forward the fact that little attention had been paid to the impact of global change on cultural heritage and that this needed to be better recognised and perceived as relevant. Due to climate change, a range of direct and indirect effects were expected to be observed on built heritage. The results of the Noah's Ark Project were presented as maps that linked climate change to potential damage to material heritage, from the near future to the far future. Moreover, guidelines for various materials were produced. For wooden objects in historic buildings, mechanical damage due to large RH changes (+/- 30 %) would be expected throughout Europe, with northern Europe as an exception (Sabbioni *et al.* 2012; Sabbioni n.d.).

Cassar and Pender used a climate model to study a range of climate scenarios. They predicted an increase in warmer and wetter winters as well as greater contrasts between summer and winter seasons. Moreover, a questionnaire was sent to heritage managers of 17 different cultural heritage sites in the UK to answer questions as to whether they could observe changes to their sites related to climate change. Almost all heritage managers had noticed progressive changes in the climate patterns at their sites, mostly in terms of increased wind-driven rains and rivers flooding. Predicted changes in RH and temperature were considered to be small and gradual. However, concern was expressed over the indirect future effect of an increased demand for mechanical cooling in the summer periods (Cassar & Pender 2011).

The EU research project *Climate for Culture* (2009 - 2014) studied the impact and mitigation strategies for preservation of cultural heritage in times of climate change. The project developed simulation models to estimate the impact of future global change on the indoor environments in different types of buildings in different regions of Europe. For instance, the models can be used to estimate the future energy demand for climate control in historic buildings. According to the project the indoor temperature in non-heated buildings in parts of northern Europe will at first (2021 to 2050) increase but in the far future (2071 to 2100) decrease. For mould growth there is a predicted increase both in the near and far future (Leissner *et al.* 2015).

Transfer functions have also been used to predict the future indoor environments in non-heated historic buildings. The results by Lankester and Brimblecombe suggest that both the outdoor temperature and indoor temperature will increase. On an annual average, indoor RH generally will not change much, or might even decrease, because the temperature is becoming higher. However, there are individual differences at different European locations. Moreover, a seasonal level RH indoors results in slightly higher values in winter and lower in summer in non-heated buildings (Lankester & Brimblecombe 2012a; Lankester & Brimblecombe 2012b).

In the field of conservation, the impact of climate change has been internationally debated with a focus on objects and museum collections, noticeable in the round table discussions arranged by the International Institute for Conservation of Historic and Artistic Works (IIC) and the Getty Conservation Institute (GCI); *Experts' Roundtable on Sustainable Climate Management Strategies* (The Getty Conservation Institute 2007), *Climate Change and Museum Collections* (IIC 2008) and *The Plus/Minus Dilemma: The Way Forward in Environmental Guidelines* (IIC 2010). The participants agreed that climate change is a threat to museum buildings and collections and that museums need to take measures to contribute to saving energy and reducing their carbon footprints. Agreements reached at those meetings on what are acceptable climate ranges are still not generally accepted and implemented, although the conferences and meetings have generated more scientific research.

Organised by the Netherlands Organisation for Scientific Research (NWO) and Rijksmuseum Amsterdam, about 30 international conservators and scientists met in 2011 to discuss a number of research topics which would advance the field of panel painting conservation. Their report, *The conservation of panel paintings and related objects: Research agenda 2014-2020,* emphasised that a balance between preservation of art, energy cost and effects on buildings in the widest sense, should be encouraged. They agreed on the need for research which should include: modelling behaviour patterns including validation studies, experimental population studies, analysis of hygro-mechanical properties of ageing wood in panels and inter-laminar stress and fracture mechanics, which also affect paint layers (Kos & van Duin 2014).

In 2013 a public *Summit on the museum preservation environment* was held at the Smithsonian Institution, Washington DC. Two themes of importance for future studies were identified during the discussions; firstly the importance of collaboration in establishing and maintaining preservation environments and secondly the need to separate standards based on urban myths or traditions from evidence-based decision making (Stauderman & Tompkins 2016).

It is clear that the cultural heritage sector is aware of the need for additional research, which should include both preservation of museum collections and energy efficiency measures. In fact several libraries, archives and museums have implemented new climatic strategies on a number of different levels (Boersma *et al.* 2014). The research on environmental impact on objects has also resulted in new guidelines and standards as a result of existing knowledge. This is presented in more detail in Section 3.11.

However, the area of research is complex and does not always give clear and direct research results. Common to objects found in both historic buildings and museums is that they are often of a substantial age and may have been subjected to a variety of different indoor environments, either because of transfers between different locations or due to changes of indoor environment in the one building. To link the damage and deterioration visible today to indoor environment is not a straight-forward task (Strlič *et al.* 2013). The environmental impact can result in chemical and biological deterioration or mechanical damage either as an individual response to deteriorating agents or as complex synergetic or antagonistic responses (Koestler *et al.* 1994). One way to tackle this problem is to reduce the number of variables in scientific experiments. However, the more the experiments are designed in order to be reproducible the less they resemble observations in reality (Ashley-Smith 2011).

The recommended climate ranges as they are known today are thus mainly derived from the results of laboratory experiments (Atkinson 2014). Moreover, because of the diversity of cultural heritage collections and objects as well as the indoor environments in which such objects are housed, it is important to find methods to validate experimental results through the actual impact on objects in the *real* world. This is acknowledged by the Getty Conservation Institute (n.d.) in their current research project *Managing Collection Environments Initiative* which uses laboratory research in combination with field studies to reach a better understanding of the response of hygroscopic materials to climatic fluctuations. In the same research project an epidemiological approach was proposed for quantifying mechanical damage due to indoor environment (Druzik & Boersma 2017). Another promising ongoing research program is the Climate4Wood project, a collaboration study between Rijksmuseum, the Universities of Technology of Eindhoven and Delft and the Netherlands Cultural Heritage Agency. In this project a combination of a large-scale, systematic analysis of the condition of wooden cabinet doors and panel paintings with a modelling study is used to determine safe environmental ranges (Ekelund *et al.* 2013; Ekelund *et al.* 2017).

The early research focus on the impact of indoor environment on objects was primarily on the museum environment in buildings which could be climate controlled to desired levels of RH and temperature. Although it was clear that cultural heritage objects were also located in historic buildings, it is only recently that these buildings have gained more focus. There are knowledge gaps in this area particularly for collections and objects housed in historic buildings that are not climate controlled, or only partly climate controlled. An area understood to need further research is the indirect effects of low temperatures. Moreover there are no systematic damage assessment studies of objects in historic buildings which could support experimental results from laboratory studies (Leijonhufvud & Bylund Melin 2009). After World War II many churches became permanently heated with their indoor climate changing from generally cold and humid to warmer and dryer. The consequence was alarming as noticed by many conservators. Medieval altarpieces and polychrome sculptures of high cultural heritage value became desiccated and seriously damaged in a short period of time (Tångeberg 1979; Olstad 1994; Brunskog 2012). Similar effects were observed for hygroscopic objects in other types of historic houses which became heated (Michalski 1993b; Staniforth *et al.* 1994) or moved from damp conditions to museum environments of 55 % RH (Padfield 1994). In recent years it has been observed that painted wooden objects in non-heated historic buildings with an indoor environment far from the climate controlled museums are often in a surprisingly good state of preservation (Brunskog 2003; Schulze 2013; Atkinson 2014).

The need for energy efficiency measures in historic buildings and museums is acknowledged. In large parts of the world it is generally accepted that societies need to preserve selected, objects and historic buildings for the benefit of their people. The fact that the professionals involved in research and conservation of cultural heritage objects are not in agreement with the present recommended environmental ranges should encourage more studies. A focus on indoor environments in historic buildings with insufficient climate control will not only show the impact on objects during assumed adverse climate conditions, but will ultimately contribute to research on the recommended indoor environment in museums. This in turn will have an impact on energy consumption.

1.1 Research aim and objectives

The overall aim of the research presented in this thesis is to contribute to the understanding of the cause-effect relationship between dynamic indoor environment and wooden objects, particularly in the combination of high RH at low temperatures as found in poorly-heated historic buildings during winter periods.

The research focusses are on the following objectives:

- To evaluate how risk assessment websites are using existing research on climate-induced damage to interpret the risk for mechanical damage, chemical and biological deterioration to wooden objects (Paper I)
- To explore a cause-relation method to quantify past and present indoor environments and cumulative damage to objects in order be able to relate environment to damage (Paper II and paper III)
- To design a method which can monitor gradient changes of moisture content in wood during longer periods of time, to be used in laboratory settings as well as in field studies (Paper IV)
- To study moisture transport in wood exposed to well defined and controlled environments in a climate chamber, using the method developed in Paper IV in order to broaden the understanding of the underlying mechanisms of mechanical deformation in wooden objects (Paper IV and paper V)
- To study the influence of low temperatures on relative humidity fluctuations and the subsequent moisture sorption rates and deformation in wood (Papers I – V)

1.2 Thesis methodology and disposition

To regulate RH and temperatures for the benefit of the objects is one of the corner stones in preventive conservation or *environmental preservation*. Such measures will influence the largest number of objects or collections and is a continued, theoretically endless process (Muños Viñas 2005). To widen the research to fully understand the impact of RH and temperature, various natural indoor environments need to be studied in relation to damage of objects. Through carrying out studies of what is considered to be adverse indoor environments and their impact on objects it is possible to take steps towards a more approved environment. The lack of knowledge identified in the review paper written at the beginning of this PhD project set the direction for areas to be looked into more deeply through the empirical work. One such area was the influence of low temperatures in non-heated buildings (Leijonhufvud & Bylund Melin 2009). Observations by conservators on the often good state of preservation of fragile objects in non-heated environments (Brunskog 2003; Schulze 2013; Atkinson 2014), far from those presently used in museums, had not been analysed in a systematic manner before. To describe the thesis briefly, it can be seen as consisting of three parts.

The aim of the first part was to investigate how existing recommended climate ranges are interpreted and used by the cultural heritage sector. For this purpose, two different risk assessment websites, *eClimateNotebook* and *Physics of Monuments*, were used. RH and temperature data was uploaded on the two websites and in return an assessment of the risk for chemical and biological deterioration as well as mechanical damage for different materials was received. In this part four different sets of environmental data were used, recorded from different indoor environments: 1) from a museum with a typically stable indoor environment; 2) from a church with temperature control but no RH control; 3) from a dehumidified room in a castle and 4) from a second room in the same castle with neither RH nor temperature control. These data sets were uploaded on both the two websites and the results were compared and interpreted.

The second part was an *in situ* study which aimed to relate damage of painted wooden objects to past and present indoor environments. It emphasised that damage and deterioration are often cumulative and methods are needed in order to quantify both damage and indoor environments. The study examined to what extent it was possible to relate damage of painted pulpits in 16 churches on the island of Gotland to the historic and present energy consumption of each church. For this purpose the total heat output during 1900-1990, as revealed from archives as fuel costs and heating systems of the churches, was used as a proxy for energy consumption. In addition, damage assessment of the painted wooden pulpits in each of the churches was performed. In this way both the indoor environment as well as the damage could be quantified and the two parameters could hence be related.

The third part consisted of laboratory studies on moisture transport in wood. The aim was to develop and use an improved method for monitoring moisture gradients in wood in order to be able to study the effect of dynamic environmental conditions. The method consisted of data loggers with miniature sensors which were inserted into samples of fresh, seasoned wood at different depths. The tests were performed in a climate chamber where RH and temperatures were programmed to simulate different indoor environments. In this way the indirect effect of low temperatures on the rate of moisture transport could be traced.

The need to point out which areas of research were incomplete and needed further research inspired the first part. The second and third parts were designed to link a field study with a laboratory study, since such coupling was missing in many other earlier studies, with the obvious difficulty of results validation. This coupling was considered crucial because it was assumed that the results of the field study alone would not generate significant scientific evidence. They needed to be verified by the laboratory experiments. Methods for field studies (relating actual damage of objects to indoor environments) are of importance because these might reveal the actual cumulative, synergetic effect of chemical and biological degradation as well as mechanical damage. Methods which can accurately monitor moisture movement in wood due to a variety of RH and temperature combinations over time may predict the deformation of wood and thereby also the damage, or lack of damage, seen on objects in various environments. As far as known, such methods have only been constructed and used in a few experimental studies (Brischke *et al.* 2008; Fredriksson *et al.* 2013).

The disposition of the thesis is as follows: The Background chapter (Chapter 2) presents the basics on indoor environment in historic buildings and the brief characteristics of wood as a material. Chapter 3, the Research Overview, includes state-of-the art knowledge on moisture transport in wood and deformation of wood. The aims of these two chapters are several. One was to understand how different research fields approached the same subject. Another was to gain more in-depth knowledge on the subjects which had been studied during the research for this thesis and presented in the five papers. This included both laboratory studies on wood as well as field studies of actual wooden objects in their own environments. A quite large portion of the theoretical framework was concentrated on the results of laboratory experiments studying deformation of wood subjected to changes is RH. Although this subject was not covered by the research carried out in this thesis, Chapter 3 aimed to provide the necessary background knowledge for understanding how moisture transport can result in various types of deformation.

It was clear from the beginning that research performed on these subjects in wood science, building physics and engineering science had a different approach and focus from conservation science. To emphasise this difference these parts were mainly presented separately (Sections 3.1 to 3.4 and Section 3.5). The direct and indirect influence of temperature, in particular low temperatures, is presented in a separate section. Since the research on low temperatures is rare in all disciplines mentioned above, Section 3.6 uses the collective references found.

One way to evaluate the state of preservation of wooden objects which have been subjected to assumed adverse indoor environments is to study the mechanical properties of aged wood in comparison with fresh wood. This is presented in Section 3.7. Only a few research projects have studied the actual dimensional change in indoor environments of historic buildings and museums. In Section 3.8 these studies are compared and also related to the yield strain, recommended as being a climate criterion in the field of conservation. The information on moisture transport, deformation and the impact of low temperatures is also summarised in Section 3.9. Damage assessment, a common method used in risk assessment in conservation and addressed in Paper II and Paper III of this thesis, has been questioned as a tool to relate damage to indoor environment and this is discussed in Section 3.10. The following Section 3.11 describes the environmental guidelines and standards which are the result of current state-of-the-art research.

The three research parts covered by the five papers are presented in summary in Chapter 4. It is followed by Discussion and conclusion (Chapter 5) and Suggested future research (Chapter 6). Relevant terms which will assist the reading are listed in Glossary of terms, Chapter 7. Finally the five individual papers are presented at the end of the thesis.

1.3 Definitions and delimitations

Research on the impact of relative humidity and temperature on hygroscopic materials is not new. In recent years several researchers have summarised the early knowledge from a historical perspective (Michalski 1993a; Brown & Rose 1997; Erhardt *et al.* 2007; Caple 2011; Staniforth 2013; Atkinson 2014; Boersma *et al.* 2014; Michalski 2016). This thesis takes its start in the environmental specifications published by Gerry Thomson and *The Museum Environment* (Thomson 1978) because these specifications were the benchmark for the continued research, on the impact of RH and temperature on various hygroscopic materials.

In this thesis *the indoor environment* is defined as RH (the non-dimensional ratio between the actual pressure of the vapour and its saturation vapour at the same temperature), most often expressed in percent (%), and temperature (the condition that determines the direction of the net flow of heat from a warmer to a colder body), here expressed as °Celsius (°C) (Camuffo 2014). There is a strong dependence of temperature on RH and hence the temperature is of importance in non-heated buildings which experience large temperature variations on a daily and seasonal basis. Monitoring RH and temperature is often related to considerations and obstacles. Local variations in RH and temperature will create micro-climates as found in various areas in historic buildings. These issues are of importance when studying the indoor environment and the impact on the building itself or objects housed. However, they are out of the scope of this thesis and will not be further discussed here.

Wood was chosen to be the representative organic material of this study. The reason for this choice was that objects made of wood are extensively found in historic buildings, as free-standing objects or as immovable parts of the interior. Painted wooden objects are considered to be highly vulnerable to adverse indoor climates as discussed in the preventive conservation literature regarding recommended climate criteria for museum objects (Mecklenburg *et al.* 1998; Bratasz 2013b). Therefore, research on mechanical damage of painted wooden objects has been published extensively.

The *paint layers* on wooden supports are not the focus of this thesis as such, except as potential indicators for movements in wood substrates such as craquelure or delamination due to adverse indoor environments, as described in Papers II and III. Moreover they can act as a physical barrier and hence reduce the moisture exchange rate between the ambient air and the underlying wood substrate, which may give peculiar types of deformation of the wood.

2
Background

Although museum environments are not the primary focus of this thesis, museum environments cannot be entirely ignored and need to be discussed in relation to the environment of historic buildings. It is acknowledged that there are many museums located in historic buildings and there are examples of both indoor environmentally-controlled and less environmentally-controlled museums irrespective of the age of the building. However, the definition of a museum in this thesis is a building which is strictly RH and temperature controlled for the benefit of the objects, with a room temperature level suitable for visitors and staff. This is opposite to a historic building which is here presumed to be a building of some age, ranging from poor shelters built of low-cost material and simple construction such as rural vernacular houses, to elaborate and massive buildings such as manor houses, churches, cathedrals, castles and palaces. It is noticed that in cultural heritage literature found for the purpose of this study, the historic buildings studied were predominantly churches, manor houses and palaces. The type of building as such is of little importance for this study; however all such historic buildings are clearly less climate-controlled than museums.

2.1 Indoor environments in historic buildings and museums

A museum's main task is to use its collection, that is, to exhibit it to visitors and make it accessible to researchers, at the same time safeguarding it for coming generations. Cultural heritage objects in historic buildings are likewise often on display or in use for instance as a part of the liturgy in churches. Adverse levels or fluctuations of ambient

RH and temperature are considered one major threat to objects of hygroscopic materials and substances. Thomson's (1986) specifications for a Class 1 museum environments are 19 to 24 °C and 50 to 55 % RH (set points) with recommended daily fluctuation from the set points of ± 1 °C and ± 5 % RH respectively. Energy costs are influenced by controlling the indoor climate ranges. As seen in Fig. 1, the more stable and narrow the desired climate fluctuations, the larger the energy consumption. This exponential relationship between energy cost and consumption and the variance (short term fluctuations) in indoor temperature and RH has also been confirmed in the research by Artigas (2007).

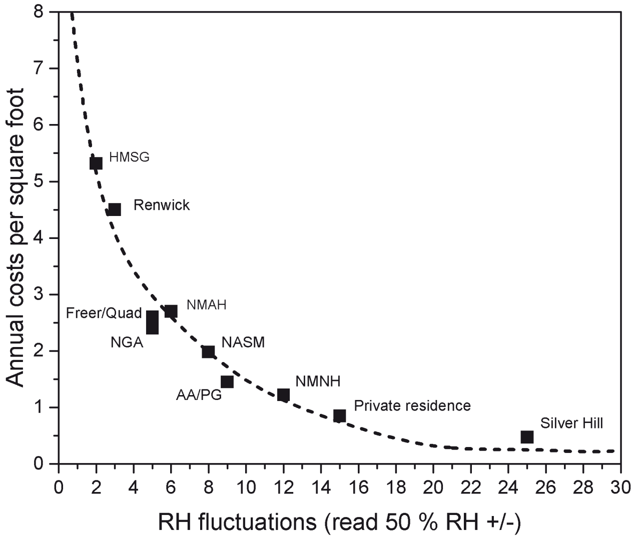

Fig. 1. The energy cost for the fiscal year 1993 in relation to the annual RH fluctuations of different buildings belonging to the Smithsonian Institution. (Provided courtesy of Marion Mecklenburg, unpublished data).

The indoor environment in historic buildings is difficult to control to the same standards as in museums. These buildings often have large interior volumes with a high air infiltration rate, which obstructs efforts to regulate indoor RH and temperature (Oreszczyn *et al.* 1994). Historic buildings themselves are often of a high cultural heritage value and therefore interventions, such as installation of air conditioning plants or alterations to the building envelope to decrease the air infiltration, may be restricted. There is also an increased risk of installing air conditioning to increase RH to levels suitable for objects and at the same time keep temperature to levels suitable for humans, due to condensation risk and hence freezing in the walls (Padfield 1987; Mecklenburg 2007c).

There are several different heating or climate-control strategies which are known in historic buildings; *background heating* is often used to keep a low general temperature above the freezing point in buildings, for instance to prevent water pipes installed in the walls from bursting at freezing temperatures; *intermittent heating* is used by many churches and results in cold and humid climates during the weeks and higher temperature and reduced RH during Sunday services (Klenz Larsen & Broström 2015). *Conservation heating or hygrostatic heating* uses the temperature to regulate RH. The method was developed by the Canadian Conservation Institute (CCI) and is extensively used by for instance in the National Trust's (UK) properties (Lafontaine & Michalski 1984; Blades & Staniforth 2011). There are also several examples of buildings which are *dehumidified* with no temperature control, for instance Läckö Castle in southern Sweden (Bylund Melin *et al.* 2010). There are combinations and variations of these strategies, for instance background heating and intermittent heating in rural churches, as common in Swedish churches. Padfield *et al.* (2007) and Rhyl-Svendsen *et al.* (2010) have explored variations of conservation heating and passive climate control in museums and archives housing large amounts of moisture-buffering materials which successfully stabilise the indoor environment. There are also buildings which have no active climate control and still keep cultural heritage collections which are only protected by the building envelope. Probably the most well-known example in Sweden is Skokloster Castle where the majority of the exhibition rooms are non-heated (Broström & Leijonhufvud 2010). Finally, there are buildings which are heated to human comfort year round without controlling RH, resulting in a very low RH in the winter periods.

The diversity of indoor climates in many historic buildings that are far from the ideal preservation climate in museums make these buildings suitable places to study impact on hygroscopic objects. Indoor environments which could be found in historic buildings and are selected for study in this thesis are several. Fig. 2 shows annual RH and temperature data from a non-heated, a dehumidified and a strict temperature-controlled building in comparison with a climate-controlled museum environment. The indoor environments in such buildings range from cold (occasionally sub-zero temperatures) and humid, via warm and dry, to a stable environment in both RH and temperature.

Only quite recently have focused comparisons of different climate-controlled methods for historic buildings been performed. Klenz Larsen and Broström compared conservation heating and dehumidification (absorption dehumidifier for low temperature environments) in two different types of buildings. The method which performs the best does so due to several factors; the air exchange rate, the volume of the room or building and the U-value (the rate of heat through a structure). For small buildings, dehumidification is more efficient, unless the building is very leaky. For large buildings conservation heating with heat pumps appears to be more energy-efficient, unless the thermal insulation is very poor (Klenz Larsen & Broström 2011). In a study by Wessberg *et al.* (2016) three different methods were compared (conservation heating, dehumidification and adaptive ventilation) with the purpose to reduce RH and hence the mould risk in the non-heated Skokloster Castle. Both active climate-control methods were considered very energy-efficient. However between the three methods, dehumidi-

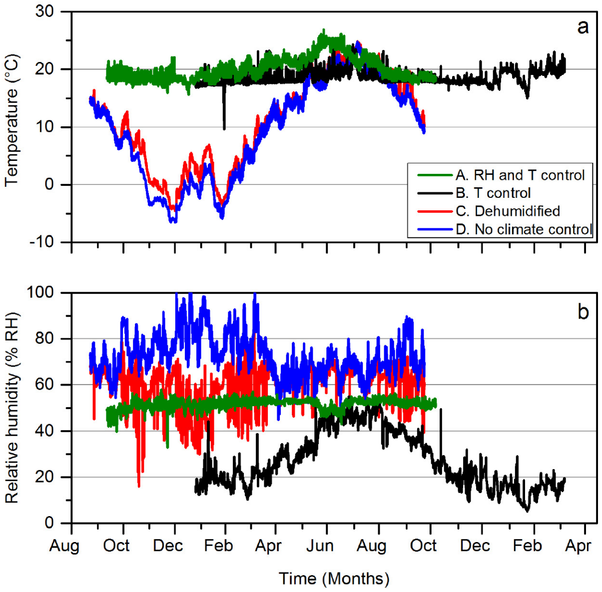

Fig. 2. RH and temperature during one year in different buildings with different types of climate control. A) Illustrates a museum building environment with both RH and temperature control aiming to keep RH at 50 % and temperature at 20 °C. B) is a church environment with temperature control, programmed not to drop below 18 °C. RH is not controlled, resulting in very low RH during winter periods. C) is a historic building with dehumidification which turns on if RH exceeds 70 %. Temperature is not controlled and drops below 0 °C. D) is the same building as C but from a part of the building with neither RH nor temperature control.

fication was the least energy-consuming and also the most effective in reducing mould growth. It is clear according to Fig. 2 that dehumidification creates an indoor environment which is stable on a seasonal RH basis, although the short term fluctuation amplitudes are similar compared to the uncontrolled environment.

2.2 Characteristics of wood

Wood has been used since ancient times and is one of the most common materials in building construction, interior decoration and thus also objects found in cultural heritage contexts. Wood as found in cultural heritage objects in historic buildings and museums has, since the growing tree was cut, been seasoned and most of the liquid water present in the living tree has disappeared. Below follows a brief description of wood in general. It is focussed on softwoods and Scots pine (*Pinus sylvestris*) in particular, as this wood species was used for the laboratory studies in this work and predominated in the *in situ* studies, of the Gotland churches. If no references are cited, the sources used in Section 2.2 are from Kollman and Côté (1968), Esping (1992), Hoadly (1998a; 1998b), Glass & Zelinka (2010).

Wood is a heterogeneous, hygroscopic, anisotropic (the properties are directionally dependant), organic material. It consists mainly of woody cells which chemically are mainly composed of fibrils of cellulose (40-50 %), hemicellulose (20-30 %) and lignin (25-30%). Cellulose gives wood its structure as the skeleton and is resistant to tension forces. Hemicellulose is the matrix and lignin is the encrusting substance, providing resistance to compression. Each woody cell consists of an outer cell wall and an inner cell cavity (lumen). In the cell walls one type of pores (pits) are seen as recesses of the cell walls, through which moisture and liquid water can be transported. A membrane in the opening, sensitive to pressure, regulates the moisture flow. The cellulose cells have mostly a long shape (traceids), giving wood its grain direction, parallel to the stem. Perpendicular to the longitudinal cells are ray cells, grouped together in flat rays. The pits mostly serve the tangential moisture movements and the rays the radial moisture transport.

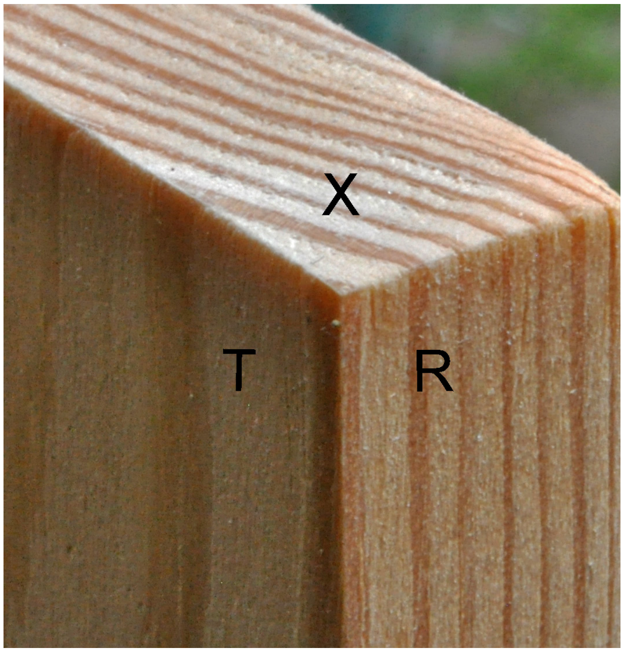

Fig. 3. A sample of pine showing typical growth ring patterns (the light coloured part of the annual rings is early wood and the darker part of the rings is late wood). The symbols indicate the three anatomical planes; tangential surface (T), radial surface (R) and cross-sectional surface (X). Adapted from Hoadley (2000).

Cross sections of many wood trunks, such as pine, reveal an inner core of dark-coloured wood (heartwood) and an outer, lighter-coloured shell (sapwood). Moreover, wood from temperate regions is divided into darker (late wood) and lighter (early wood) growth rings indicating the growing pattern over the annual seasons. The density of wood varies between species and as a consequence the moisture content (MC) also varies due to the ability of the cell walls to swell and shrink. Time (1998) showed that the dry density of the same species can vary dramatically. Her tests showed differences of as much as 300 to 640 kg/m^3 between different samples of the same species. The density parameter can therefore be a factor of miscalculation in modelling.

Wood is normally described according to its three structural planes, transverse (cross-sectional), tangential and radial directions (Fig. 3). Lumber is often sawn as boards or planks in the tree's lengthwise (longitudinal) direction as seen in Fig. 4. Radial cut (quarter sawn) pieces are those cut through the pith (centre) of the stem and the others are the tangential cut (flat sawn). Quarter, or radial boards are the most dimensionally-stable and are therefore considered as being the best quality.

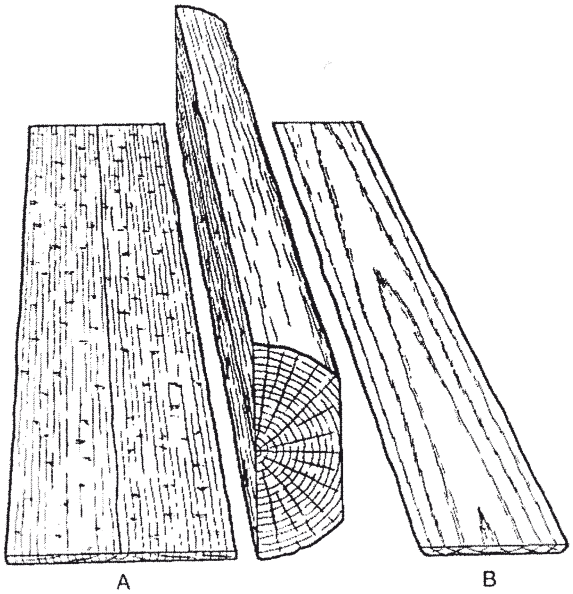

Fig. 4. Two boards sawn from a log. Board A is cut through the pith of the stem and has a radial (quarter sawn) cut. Board B is flat sawn (tangential) in cut (Laboratory Forest Products 2010).

3

Research overview

3.1 Moisture movement in wood

If no references are cited the sources used in Section 3.1 are from Kollman and Côté (1968), Esping (1992), Hoadly (1998a), Hoadly (1998b), Glass & Zelinka (2010).

In the growing tree the root, stem and branches are saturated with sap, as liquid water in the pores, and bound water, held by intermolecular attractions (hydrogen bonding), within the cell walls. After felling, when the tree is cut and exposed to the atmosphere, it will begin to dry, initially losing the free water in the lumen. When no more liquid water remains in the wood it has reached the *fibre saturation point* (FSP) and the remaining water is found as bound water in the cell walls and as moisture vapour in cell lumens and pit openings. At this point the MC is approximately 30 % by weight. Below FSP, wood enters the hygroscopic range, and will adsorb[2] (gain) and desorb (release) moisture from the ambient air depending on the actual RH and temperature. Theoretically, FSP coincides with 100 % RH of the ambient air. In the hygroscopic range most of the physical and mechanical properties of wood, as well as reaction to biological agents such as decay fungi and insects, are affected by MC. Changes in RH and temperature can make wood shrink, swell and cause change in strength.

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[2] In the context of wood in contact with ambient air, a<u>d</u>sorption is the adhesion of water molecules to the sorption sites on the surface of the cell walls of the wood. A<u>b</u>sorption is a process where water molecules (fluids) assimilate throughout the bulk of the wood.

The MC in wood is defined as the mass of water in relation to the oven-dried wood, expressed as a percentage. In the hygroscopic range, it includes only the bound water in the cell walls. *Equilibrium moisture content* (EMC) is defined as the MC at which the wood is neither adsorbing nor desorbing moisture from the ambient air. This will only occur if RH and temperature is constant for a long-enough period of time for the wood to be fully acclimatised to the ambient air throughout. This may take a very long time and during real-life conditions it is uncertain if EMC is ever reached (Engelund *et al.* 2013).

A large amount of research has been performed on moisture movement in wood, both in wood science in general and in particular in the area of wood drying. The results and conclusions are often ambiguous and inconsistent (Avramidis 2007). Moisture in wood below FSP is transported via a combination of water vapour diffusion in the lumen voids and through pit openings, as well as bound water diffusion in the cell walls (Fig. 5). The driving forces (potentials) for the diffusion are governed by differences in moisture concentrations (moisture vapour and bound water) in the wood. Also, sorption processes, including adsorption and desorption between cell walls and lumens in order to attain equilibrium, are present (Fig. 5).

Table 1 presents the percentile distribution of moisture transport in cross grain direction at different MC and temperatures, compiled by Esping (1992). It shows that the dominant transfer is the sorption processes. However sorption and diffusion vary both with MC range and temperature. Sorption and bound water diffusion increase with higher MC but are fairly resistant to temperature differences. Moisture vapour diffusion in lumens and pit openings, on the other hand, decrease with higher MC but increase with temperature.

The *diffusion coefficient* (diffusivity) is a quantitative measure of the diffusion rate (Avramidis 2007). The higher the diffusion coefficient, the faster is the diffusion. It is approximatley 2000 times higher for water vapour diffusion in the lumens (longitudinal direction) compared to the resistance created by the cell wall in the tangential and radial directions. This is the reason why the total moisture transfer is determined by the cell wall sorption (Esping 1992; Avramidis 2007). Although moisture transfer is slower across the grain (tangential and radial directions) compared to in the grain direction, the bound water diffusion is often the most important in wood drying because of the often-shorter distance to the wood surface of, for instance, a plank (Zítek *et al.* 2015). Moreover, the diffusion coefficient is 20 to 50 % higher in the tangential direction compared to the radial direction (Avramidis 2007).

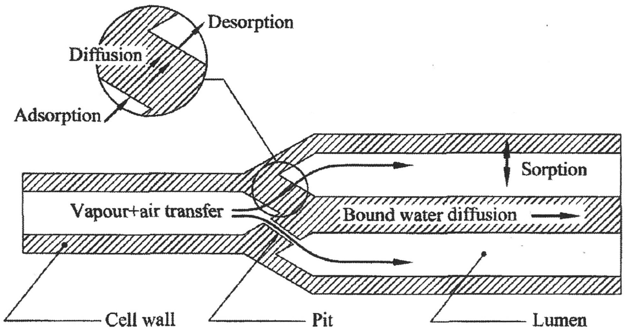


Fig. 5. Moisture transport model in wood (Krabbenhoft & Damkilde 2004). Longitudinal transport (horizontal direction in the picture) consists of vapour and air movement in the lumens and through pits in the cell walls or as bound water diffusion in the cell walls. Tangential and radial movements (vertical direction in the picture) of moisture are mainly a sorption/diffusion process through the cell walls.

Table 1. Distribution of moisture transfer cross the grain in Western pine (Transcriped from Esping (1992)

Temperature (°C)	**40**		**80**	
Moisture content (% MC)	**5**	**25**	**5**	**25**
Bound water diffusion (%)	2.9	6.0	2.7	5.7
Sorption through cell walls (%)	80.0	86.3	73.2	86.1
Moisture vapour diffusion in lumens and sorption through pit membranes (%)	7.5	7.6	7.1	8.0
Moisture vapour diffusion in lumens and pit openings (%)	9.6	0.1	17.0	0.2

3.2 Sorption isotherms and hysteresis

In the hygroscopic range the relationship between EMC in the wood and RH of the ambient air at constant temperatures is represented by a *sorption isotherm* (Avramidis 1997). Sorption in wood can be explained as a displacement of the equilibrium between water vapour, sorption sites and bound water:

$$H_2O_{\text{(vapour)}} + \text{Sorption sites} \rightleftarrows H_2O_{\text{(bound)}}$$

Therefore, the reaction rate depends on concentration differences and the number of available sorption sites (Lund Frandsen 2005).

Moisture is attached by hydrogen bondings to the hydroxyl groups of the cellulose and hemicellulose. In wood the bonding is characterised by sorption where the moisture develops single layers and multilayers on the sorption sites (available hydroxyl groups), and these are firmly attached to the cell walls (Simpson 1980; Lund Frandsen 2005). The sigmoidal curve as seen in Fig. 6 represents three regions along the X-axis. The first steep section, at low RH up to about 6 % EMC, corresponds to random attraction of water molecules by the sorption sites. The dominant mechanism for sorption is here chemical attraction between water and hydroxyl groups. It is mainly governed by water-vapour diffusion and is strongly bound to the sorption sites in a mono-layer. The attraction forces can only be released by increasing the temperature. In the second, mid-region, the intermediate MC range up to approximately 15 % EMC, the water molecules reorganise, more sorption sites are created and therefore more water molecules can

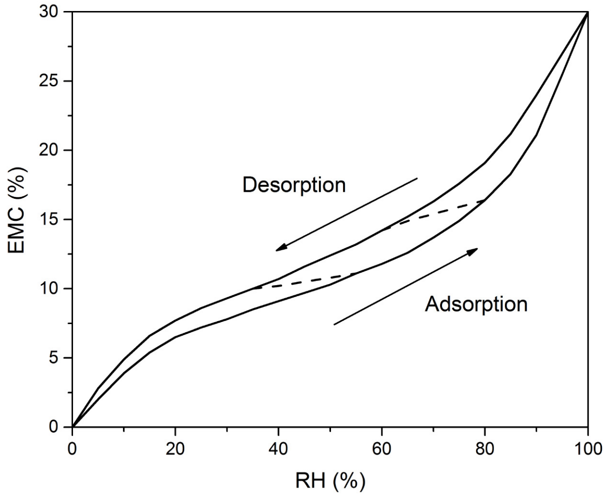


Fig. 6. Graph showing adsorption and desorption isotherms of a non-specific species of wood in the full RH range. The dashed lines are the scanning curves running between the border isotherms.

be adsorbed. Multilayers of water molecules are built up as the RH increases and are held together by electrostatic forces. During this phase, which is governed by a combined bound water and water-vapour process, the driving forces are weaker and therefore the sorption proceeds at a slower rate. In the third region at high RH levels the sorption is mainly influenced by bound-water diffusion. Due to swelling of the wood constituents and breaking of hydrogen bonds between the cellulose chains, additional hydroxyl becomes available (Lund Frandsen 2005). It is important to note that the time-dependant sorption plays a significant role in the process. At low RH ranges, bound-water diffusion is a relatively slow process, and the moisture transport is governed by moisture diffusion. In the mid-RH range a relatively fast sorption of bound water occurs. At high RH levels the bound-water diffusion becomes more predominant although the kinetic sorption rate decreases (Lund Frandsen 2007).

Desorption is the reverse process, although desorption is slower compared to adsorption due to the tightly-bound water molecules which are not easily released from the sorption sites (Skaar 1988). Sorption of wood is dependent on the moisture history in that, at a given RH of the ambient air, EMC will not reach the same value if it is attained through adsorption or desorption, the so-called *hysteresis phenomenon* (Lund Frandsen 2005). The final EMC value after a change in RH will therefore also be higher if the final RH is reached through one large single-step compared to several multi-steps in the same RH range (Skaar 1988). The EMC values are attained by equilibrating a wooden sample to each humidity step although the time required to reach EMC can take weeks or months (Skaar 1988). This creates the two typical pathways of the adsorption and desorption isotherms as seen in Fig. 6. The adsorption and desorption isotherms indicate the maximum EMC values between 0 and 100 % RH can be considered the *boundary isotherms*. Any smaller EMC changes, so-called *scanning curves,* will stay within the area between the boundary curves as seen in Fig. 6 (Lund Frandsen *et al.* 2007). Previously it has been assumed that liquid water could also exist due to capillary condensation below FSP in contact with ambient moisture (Engelund *et al.* 2013). However, nuclear magnetic resonance (NMR) analysis has shown that no significant amount of liquid water is present below 99.5 % RH, if wood is only in contact with moisture of the ambient air (Thygesen *et al.* 2010).

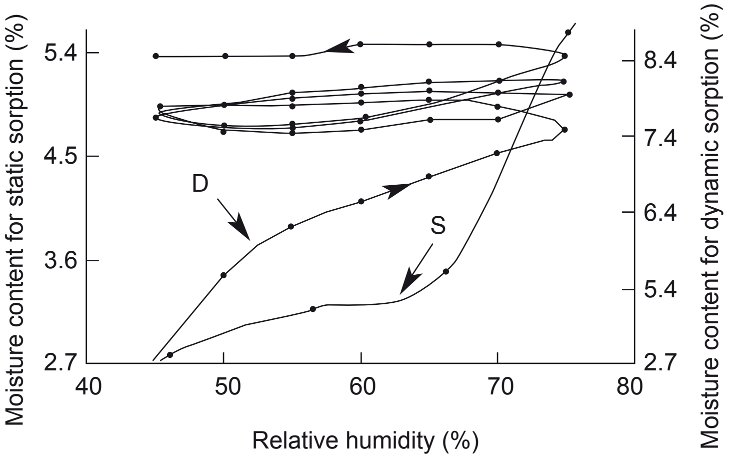


Fig. 7. Graph showing MC in relation to RH for Chinese fir cycled at 3.5 h, together with a part of the static adsorption isotherm (D: dynamic sorption; S: static (equilibrium) sorption). The experiment was executed at 25 °C and the starting point for both curves was at 45 % RH (Ma *et al.* 2005).

For dynamic situations, when EMC is not reached, the isotherm concept is more complicated. Ma *et al.* (2005) studied equilibrium and non-equilibrium conditions of the sorption process of 4 mm thick Chinese fir samples. Instead of waiting for EMC to be reached after each change in RH they let RH change at decided time intervals (1, 2 and 3.5 h) to simulate dynamic situations. As can be seen in Fig. 7 the dynamic loops (D) are less steep (in this example almost horizontal) compared to the equilibrium loop (S) and lie above the area which would be expected to be between the boundary isotherms. Similar results presenting the loops not within boundary isotherms are also presented by Skaar (1988), Svennberg & Wadsö (2008) and Yang & Ma (2013). These results support the hypothesis that the impact of dynamic RH fluctuation doesn't reach EMC and therefore the impact on deformation will not completely follow the isotherms.

On an annual basis Skaar (1988) has illustrated the same phenomenon comparing EMC with the actual MC of wood in relation to RH and temperature, as seen in Fig. 8. It can be seen that the MC curve is less fluctuating and also appears with some delay, resulting in MC values at times both higher and lower compared to the calculated EMC.

Hysteresis is not only dependant on RH but also temperature (Fig. 9). At the full RH-range (0-100 % RH) EMC is higher at colder temperatures and lower at higher temperatures at the same RH and is more pronounced in the lower temperature range. Above 75 °C it ceases to exist (Skaar 1988). However, it seems unclear to what extent temperature affects the adsorption and desorption isotherms respectively. The influence on both isotherms appears to be similar in the study by Krupińska *et al.* (2007), while the investigations by Kelsey (1957) showed that the adsorption isotherm was less influenced by temperature than was the desorption isotherm. Hill *et al.* (2010) showed that it is only the desorption isotherm that is affected by temperature, while the adsorption isotherm remains unaffected.

The diffusion coefficients can be determined by two main experimental methods. In the *steady-state method* (cup measuring method) a wooden disc is put as a lid in a cup subjected to two different RH on each side, allowing moisture diffusion through the disc. By weighing the cup until equilibrium at regular intervals, the slope of the curve (weight change versus time) the diffusion coefficient can be calculated. For transient or unsteady-state conditions however,

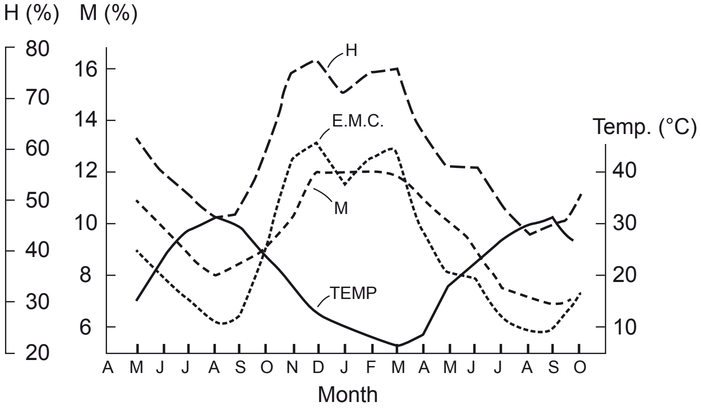


Fig. 8. The measured MC (M) and calculated EMC (E.M.C.) during one year of wood samples from an outdoor but sheltered location in Greece in comparison with RH (H) and temperature (TEMP) of the ambient air (Skaar 1988).

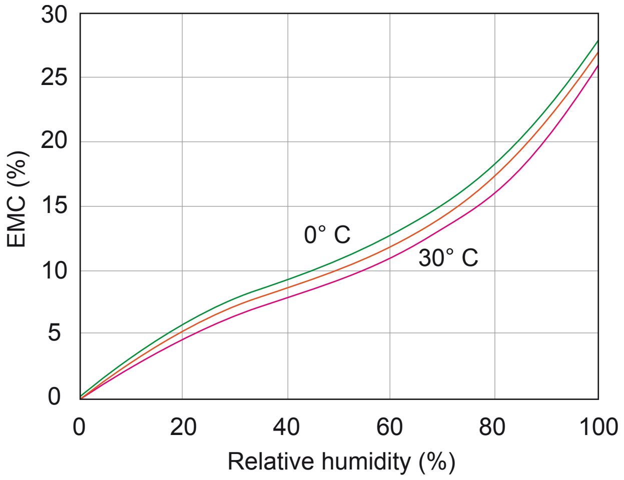


Fig. 9. Sorption isotherms at different temperatures (Padfield n.d.(b)). The lower the temperature, the higher the EMC at each RH.

the *sorption-measuring method* is used; an equilibrated wooden sample at certain RH is put in a stable climate chamber of another RH and the weight change of a wooden sample is measured until EMC at the new RH is reached. Similar to the cup measuring method, the diffusion coefficient can be calculated from the initial slope of the curve (weight change versus time) (Wadsö 1993b; Avramidis 2007). Diffusion can be described by one of Fick's two laws. *Fick's first law* describes the steady-state conditions where the moisture concentration gradient is constant and independent of time during the moisture diffusion. *Fick's second law* describes unsteady state (transient) conditions. It anticipates that moisture concentration gradients change over time and the diffusion flux is hence time dependant. Wadsö (1993a; 1993b) observed that Fick's second law is essentially valid only in the 54-75 % RH range. Moreover, he also showed that the rate of sorption is lower at higher RH range (75-84 % RH), which is opposite to the general belief that transversal diffusivities are constant or increase in the higher RH range (upward-bending part of the isotherm seen in Fig. 6. The reduced diffusion coefficient at the higher range has later been confirmed by others (Håkansson 1998; Ma *et al.* 2005; Avramidis 2007; Rachwał, Bratasz; Łukomski, *et al.* 2012). The moisture transport processes in the higher RH range are also much more complex compared to the central RH range. The reason is that water vapour and bound water are not always in equilibrium because diffusion of vapour is almost instant compared to bound water diffusion. This slow process is responsible for the so called *non-Fickian behaviour* at high MC levels (Lund Frandsen 2005). It is probably related to softening of amorphous polymers and might increase the capacity to accommodate more water molecules in the cell walls (Engelund *et al.* 2013). Because of the different rate of bound water diffusion and vapour diffusion, it is accepted that it cannot be described by a single model (Wadsö 1993b). The complex combination of both diffusion and sorption processes, the use of mixed numerical-experimental methods and models consisting of coupled sub models, one for each process, are emphasized (Krabbenhoft & Damkilde 2004; Gamstedt *et al.* 2012).

3.3 Mechanical properties and deformation in wood

Wooden cultural heritage objects may have adjusted, sometimes for hundreds of years, to the hygroscopic range (that is below FSP) and are still showing hygroscopic behaviour in relation to the indoor environment. Deformation, dimensional change or displacement, such as swelling or shrinkage of wood is complex because it depends on several factors such as wood species, quality of the wood (for instance fast grown or slow grown, ratio between late wood and early wood, knots, density), volume, thickness and age of the sample or object. Due to the anisotropic behaviour of wood, the free shrinkage coefficient in the tangential direction is, for instance in the case of Scots pine, approximately twice that in the radial direction. The dimensional change in the longitudinal direction is considerably smaller than the change in the two cross sectional directions (Sandland 1996). Examples of deformation which are found in flat, square and round pieces of wood are shown in Fig. 10.

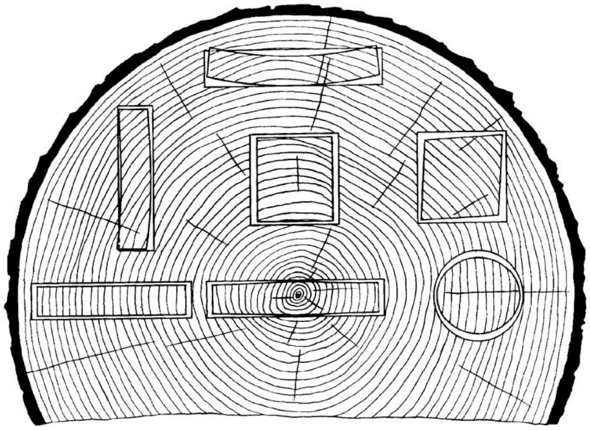


Fig. 10. Characteristic shrinkage and deformation of different cut pieces as affected by the direction of the growth rings in the wood. The cupping behaviour is larger for the tangential cut board compared to the radial cut boards. Moreover, the shrinkage is twice as great for the tangential board compared to the radial board (Laboratory Forest Products 2010).

3.3.1 Dimensional change of wood due to changes in MC

During drying green wood above FSP, at first only liquid water is removed. Since the cell walls above this point are saturated with bound water, no dimensional change of the wood will occur. Below FSP the cell walls will reach unsaturated states. Moisture gradients develop because the drying only occurs from the surface of the wood. At this stage *internal stresses* develops. They exist along the thickness of the wood but internal stress cannot be directly observed or measured (Perré & Passard 2007). In practice it is impossible to eliminate internal stresses completely during moisture changes in wood (Skaar 1988).

External mechanical stress progresses when the piece of wood is restrained to deform, or is subjected to compressive or tensile forces. In laboratory tensile and compressive testing, stress is calculated as the load or force (MPa) applied to the sample, divided by its sectional area (Bratasz 2013a). The response to stress is deformation. It is calculated as the change in length divided by the specimen's original length, usually the dry length (strain). Deformation of wooden samples which are not restrained but allowed to freely expand or contract due to changes in RH are referred to as *free swelling strains* (Mecklenburg 2017a).

When a load or a force is applied to wood, a subsequent dimensional change occurs. This relationship can be plotted as a stress versus strain curve. Initially the relationship between stress and strain is linear. That is, the deformation in this region of the stress-strain curve is reversible (elastic), meaning that once the load is removed, the sample will return to its original dimensions. The slope in this linear region is called the *Modulus of elasticity* (E-modulus or MOE) which is a measure for a material's stiffness or resistance to deform when a force is applied to it. A stiffer material will have a higher E-modulus and one which is more flexible has a lower E-modulus (Mecklenburg 2007a). At a certain point the relationship gradually becomes less linear, and this transition point is called *the yield point* or *strain-to-yield*. Beyond this point, plastic or permanent deformation remains even when the applied load is removed. Continuing to increase the load will lead to *ultimate strength,* which is the maximum load the material can resist prior

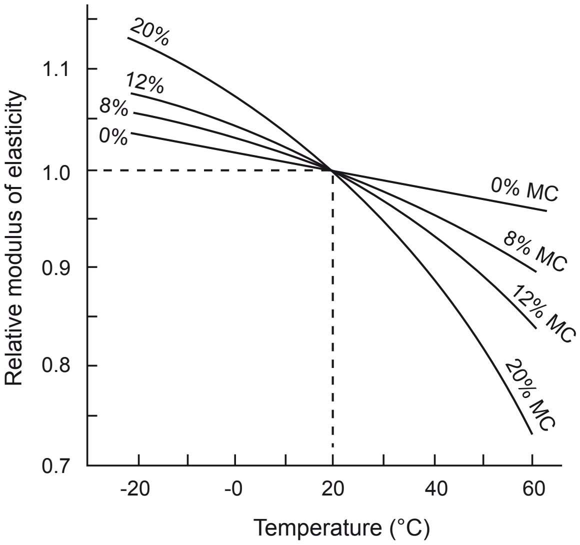


Fig. 11. The relative modulus of elasticity (E-modulus) at different levels of MC and temperatures relative to 20 °C, ranging from -20 to 60 °C (Bodig & Jayne 1982). The higher MC in combination with low temperatures makes the wood stiffer.

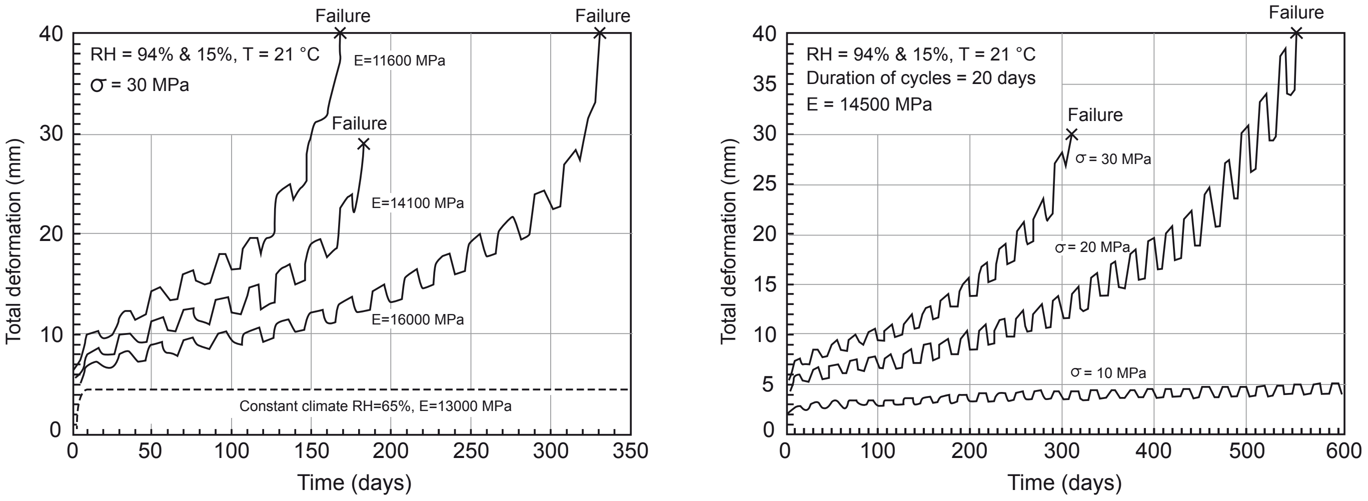
to failure. Stress corresponding to the ultimate load is known as *ultimate stress*. Eventually the increased loading will cause the wood to fail, reaching the *strain to failure* (breaking strain*).* Experiments on cottonwood showed that while the yield strain is rather constant in the entire RH range, the breaking strain is constant in the low and mid-RH ranges. Above 80 % RH the breaking strain dramatically increases (Erhardt *et al.* 1997).

For wood, all types of deformation are influenced by RH and temperature of the ambient air and hence MC of the material. In general, the magnitudes of E-modulus and compressive and tensile strength increase with decreasing MC (Green & Kretschmann 1994). With increasing temperature the slope of stress-strain curves decreases. This increasing temperature results in a lower E-Modulus in both tension and compression, as well as a lower ultimate stress. It also accelerates creep (for explanation see below in Section 3.3.1) (Bodig & Jayne 1982; Sandland 1996; Kretschmann 2010;). Based on this one might assume that in an non-heated building, a decrease in E-Modulus due to higher MC would be balanced by the higher E-Modulus due to lower temperature. However, the combined effect of temperature and MC changes are difficult to predict and complex to interpret. According to Bodig & Jayne (1982), high constant MC levels in combination with low and sub-zero temperatures increase the relative E-modulus as seen in Fig. 11, thereby making the material stiffer.

The relationship between EMC and the corresponding *anisotropy* (the dimensional changes in tangential direction divided by the dimensional changes in the radial direction) in wood has not been studied in conservation science but is expected to be of importance to three-dimensional wooden objects; the damage patterns of panel paintings may be different from those of polychrome sculptures. The stability of the shape of the piece of wood is dependent on the absolute difference between swelling in tangential and radial directions and the smaller the difference the more stable the object (Noack *et al.* 1973). Moreover, this relationship is not uniform during the entire humidity range and increases sharply at high EMC (Chauhan & Aggarwal 2004).

Creep and stress-relaxation

Wood also exhibits time-dependent behaviour when subjected to a load. This behaviour is an important aspect of deformation, referred to as *creep* and *stress relaxation*. Creep is defined as the time-dependent deformation exhibited by a material under constant load (Sandland 1996). Initially the wood deforms reversibly (elastic creep) but if the load is maintained, permanent deformation occurs. Upon unloading there will be a partly im-



Figs. 12a-b. Mechano-sorptive behaviour of clear Scots pine samples (dimension 10 x 10 x 300 mm) subjected to bending loads and 20 days fluctuating RH (15 to 94 %) at constant 21 °C . Fig. 12a shows the effect of different E-modulus (E) at a constant load (σ) of 30 MPa. The dotted line shows the behaviour of a similar wooden sample subjected to constant RH of 65 % as a reference. Fig. 12b shows the effect of different bending loads (σ) and a constant E-modulus (E) of 14500 MPa. Transcribed and adapted from Mohager (1987).

mediate and complete recovery but some permanent deformation will remain (Toratti & Svensson 2000; Kretschmann 2010). Thus, creep can be divided in two parts; v*iscoelastic creep* (delayed elastic) and *viscous creep* (permanent) (Mohager 1987). Creep is greater at higher stresses but will also occur even at very low stresses and can continue over many years. At sufficiently high stresses the wood will eventually fail (Kretschmann 2010). Creep is higher at higher temperature levels and is accelerated by a temperture increase. However the creep acceleration is diffucult to study as the MC of the wood will also change with temperature (Mohager 1987).

Mechano-sorptive creep (also referred to as mechano-sorption or mechano-sorptive effect) is induced by changes in MC due to changing RH, when an external, constant load is applied (Fig. 12a-b). If, for instance, the sample is subjected to a load and is allowed to dry, the final deformation will be greater compared to the sum of a pure creep deformation and an unconstrained drying sample (Mårtensson 1994; Dahlblom *et al.* 1996; (Jordow & Enockson 1996). When the applied force is removed but RH continues to fluctuate, creep-recovery is larger for mechano-sorptive creep compared to creep under stable MC (Nordström & Sandberg 1994; Kretschmann 2010).

Mohager (1987) showed that, besides RH fluctuations, E-modulus and magnitude of applied load are of importance for mechano-sorption (Figs. 12a-b). Fig. 12a shows that a higher E-modulus (stiffer material) results in lower deflection and increased time to failure. Fig. 12b shows the impact of bending loads. Obviously, the higher the applied load the larger the total deformation. Additionally, the general shape of the plot also changes with load. At 10 MPa, the plot had an asymptotic shape. As the load increased the plots became more exponential, leading to increased deformation and to faster breaking strain at a lower strain. This means that, depending on the load, the deformation can either increase with time or become more or less constant. However, it must be taken into consideration that the conditions for building physics experiments are not similar to the impact of experiments in conservation science or in historic buildings. Mohager (1987) used stress loads of 10 to 30 MPa in his experiments. The loads used in the cultural heritage experiments are predominantly below 5 MPa as seen for instance in work by Erhardt *et al.* (1995). Moreover the fluctuations are only rarely as large or last as long as in the experiments presented by Mohager (1987). Therefore it is likely that the deformations of wooden objects are overall smaller in historic buildings than in the experiments see for instance Mohager (1987). Still, the actual stress of assembled or painted wooden objects (internal and external), is difficult to predict.

Viscoelastic creep is often considered insignificant compared to mechano-sorption, since it occurs partly in the elastic range and is therefore often excluded (Nordström & Sandberg 1994; Häglund 2008). However, this opinion is not consistent because the viscoelastic and mechano-sorptive creep effects interact and should not be viewed as separate phenomena. This is also important as viscoelastic creep is mainly time-dependent whereas mechano-sorptive creep is primarily dependent on magnitude of the MC changes (Hanhijärvi & Hunt 1998). For thick panels the MC gradients are steeper compared to those in thin panels, and would hence be associated with higher stress levels. However, the time required to dry thicker boards is longer and hence allows more time for the viscoelastic creep to reduce the stress levels (Rémond *et al.* 2007).

If a strain is applied instantaneously and held constant, stress will decrease with time. This is known as stress relaxation or just relaxation. It is governed by the same time-dependent, temperature and MC characteristics of the material as creep (Bodig & Jayne 1982). As with creep, relaxation is affected by fluctuations in RH and temperature (Kretschmann 2010).

Compression set

Compression set occurs when the material is constrained and subjected to RH variations. This may result in loss of dimension and permanent deformation. One example of the occurrence of compression set takes place when drying green wood. At FSP a moisture gradient from the surface to the core of the wood will develop when the hygroscopic range is reached. The surface tries to shrink but is restrained by the still-wet inner part, resulting in severe tensile stresses at the surface and milder compression stresses in the core. As the drying proceeds the compressive stresses in the core increase as intermediate layers dry and start to shrink. After additional time, the reverse process occurs where compression stresses in the outer layer and tension in the core develop (Skaar 1988; Sandland 1996). Drying green wood will of course create large variations in compression and tension in the wood. However, compression set is also noted in seasoned wood, as found in heritage objects. An example is cupping of painted panels attributed to compression set (Padfield n.d.(a)) Compression set may also occur if a relatively dry wooden object is subjected to extremely high RH or if the surface becomes directly wetted, which can result in, for instance, loose tool handles or wobbly furniture (Hoadly 1998b).

Fatigue

Fatigue is defined as the progressive damage that occurs in a material subjected to cyclic loading. In engineering, this loading may be repeated (same type of stresses; that is, always compression or always tension) or reversed (alternating compression and tension stresses). When sufficiently high and repetitious, cyclic loading stresses can result in fatigue failure.

Luxford *et al.* has pointed out that there is very little information on how cycling RH may affect the fatigue failure of wood and whether there are maximum allowable numbers of cycles within the safe RH fluctuation range (Luxford *et al.* 2012). In general wood is resilient against repeated loading. Moreover, it is difficult to differentiate between creep and fatigue in timber members. In timber structures, fatigue is usually found in metal connectors (joints) (Robert Kliger, personal communication). However, fatigue has in conservation science been studied for gesso[3] layers applied to wood surfaces. The reason for using gesso to study is that this material is less responsive compared to wood and paint on changes in RH. The yield strain for gesso is found to be only 0.2 % (Kozłowski *et al.* 2011; Rachwał, Bratasz, Krzemień, *et al.* 2012; Krzemień *et al.* 2016). See also Section 3.5.3.

3.4 Relation between dynamic MC and deformation of wood

The same types of stress and resulting deformation (or damage) occur in wooden objects in historic buildings as in laboratory experiments of drying green wood or for engineering purposes. However, in laboratory conditions the loads, magnitudes of RH fluctuations applied to the wooden samples are often larger and occur over shorter periods of time compared to the cultural heritage environment where the impact is assumed to vary over time and last over longer periods of time, sometimes centuries.

The different types of deformation introduced in the previous sections may also affect the wood coincidentally, to smaller or larger degrees. Therefore one important question is, to what extent MC changes in wood can be related to stress and strain in wood. The results of research by Bratasz have shown that the relationship between the dimensional change and EMC was close to linear between approximately 3 to 12 % EMC, which corresponds to about 10 to 70 % RH (Bratasz 2013a). In dynamic environmental conditions, mechano-sorptive deformation could be expected to be one of the major contributors to deformation of wooden objects. Below are a few examples which show that the responses of wood to fluctuating environmental conditions are different from those in response to step-changes in RH.

In a study by Toratti and Svensson, pine wood samples were subjected to step-changes and fluctuating RH from 60 to 90 % RH and from 60 to 45 % RH under tensile and compressive loads of 0.5 MPa. The results showed that the swelling and mechano-sorptive strains were significant compared to normal creep (i.e. under constant RH) during

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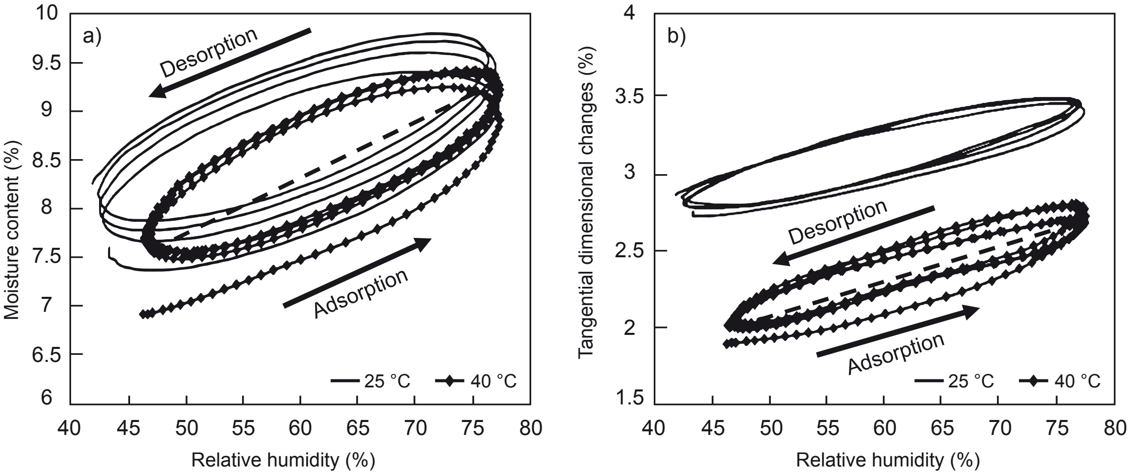
[3] Gesso is a mixture of hide glue and gypsum or ground chalk (inert fillers). It is used to obtain a smooth and paintable surface on wood. The ratio between the hide glue and fillers has a large influence on the mechanical and dimensional properties of gesso (Mecklenburg *et al.* 1998).

the experiments. Moreover, the deformation was generally higher in compressive tests compared to tensile tests. The moisture range under which RH was cycled (low or high RH) did not have a large influence on the deformation, which was instead dependent on the magnitude of the RH change. After finishing the tests, the total recovery showed similar results from samples in tension and compression. However, samples which had been subjected to the higher RH range (60 to 90 % RH) had a higher recovery rate than those which had been exposed to fluctuations in the lower RH range (45 to 60 % RH) (Toratti & Svensson 2000). In a following paper, long-term experiments on wood samples in cyclic environments subjected to both tensile and compression loads were performed. Released deformations at different depths were measured from cross-sections after cutting the samples into slices, after which the stress distribution through the sample could be calculated. They concluded that the mechano-sorptive strain produced during fluctuating RH was higher compared to a single cycle. However, the impact of fluctuating RH on the deformation decreased over time. Finally, the strain rate accelerated when the RH entered ranges not previously experienced. Stress remained in the wood also after EMC was reached (Svensson & Toratti 2002).

Ma *et al.* have investigated MC response and delay as well as swelling deformation of wooden samples upon RH fluctuations of different durations and amplitudes at different temperature levels (Ma, Nakao & Zhao 2010; Ma, Nakao, Zhao, *et al.* 2010; Yang *et al.* 2015; Yang & Ma 2015; Yang & Ma 2016). They found that MC of the wood sample showed fluctuation patterns due to fluctuating RH, although with a response delay. Further, the MC amplitudes increased at higher temperatures (40 °C compared to 25 °C) and the response delay decreased with higher temperature. The thicker samples showed increased response delay compared to the thinner ones. Sorption hysteresis and subsequent swelling hysteresis were present at different levels at the two different temperature levels (Figs. 13a-b). According to the authors, the cycles are seen as overlapping



Figs. 13 a-b. Dynamic sorption isotherms for MC (a) and the subsequent swelling (b) in the tangential direction for a 10 mm thick poplar wood sample cycled 6 hours, at two temperatures, 25 and 40 °C (Yang & Ma 2015).

ellipses, as in Fig. 13a. However, while the ellipses at 40 °C quickly converge, the ellipses at 25 °C continue to shift. This is due to the fact that higher temperatures increase moisture diffusion as well as the structural relaxation rate (Yang & Ma 2015). The same pattern cannot be seen for dimensional change (Fig. 13b). However, their most interesting results were that, upon RH fluctuations, the maximum swelling deformation occurred earlier than the maximum change in MC, suggesting that dimensional changes are faster than MC changes. No satisfactory explanation could be given to explain these data (Ma, Nakao & Zhao 2010; Ma, Nakao, Zhao, *et al.* 2010).

In cultural heritage multi-material objects are restrained to various degrees as each material and/or member of an assembled object, such as a piece of furniture, responds differently to changes in RH, and thus they will restrain each other. How large the typical stresses or loads carried by cultural heritage objects are, is in most cases not known. Moreover, it is likely that stresses are not equally distributed throughout the entire object but may rather be concentrated around certain areas, for instance the hinges of an open door, or cracks or open joints allowing some dimensional response (Bratasz *et al.* 2008). Another factor which also needs to be taken into account is that the restriction within individual parts of an object will vary over time due to their volumetric changes in a fluctuating environment.

The complex task to actually relate deformation and damage in objects and collections to the indoor environment has led to the development of the worst case condition concept. Here the materials are tested while being fully restrained in the most responsive (tangential) direction, using the yield strain as the limit for acceptable climate ranges (Mecklenburg *et al.* 1998). In order to sidestep the impossible mechanical response calculations, Michalski (2007) introduced the *proofed fluctuations* model. It is based on the assumption that objects which have been exposed to a certain environment in the past have already developed possible damage in that particular environment. The risk of further damage from fluctuations, in the same RH and temperature range, is therefore small. This conclusion is supported by the experiments made by Svensson & Toratti (2002). Mohager (1987), on the other hand, showed that this is to a large extent dependent on the magnitude of the E-modulus or applied load. If sufficiently high, it can cause deformation to increase exponentially with time.

3.5 The environmental impact on wood as studied in the field of conservation

The amount of research on wood and its response to the environment, both concerning moisture transport and deformation, are vast in areas such as wood science, engineering and physical science. In the cultural heritage sector however, research on the preventive conservation of wooden objects is small in comparison. The focus of conservation science and the questions raised here are partly different and therefore wood science research cannot always be extrapolated to conservation science. For instance there is only limited research on the impact of low temperatures whereas on high temperatures used in the field of wood drying there is an immense amount of research results available. The objects or museum collections are also complex, both concerning the objects' construction, and the fact that many objects consist of a combination of various materials. The objects' age and history (environmental as well as use, deterioration/damage and previous restoration measures) are also important. Each object is in that sense truly unique and is often associated with a high cultural heritage value. Research has therefore to be made on substitute materials or the use of non-destructive monitoring methods of single objects or collections. The main focus of this section is to highlight methods and results from monitoring deformation in uncontrolled indoor environments and to put these results in relation to the present environmental recommendations. Hence the background for the present environmental recommendations is also given.

3.5.1 Yield strain as the safety limit for avoiding mechanical damage to organic materials

As a response to Thomson's strict climate recommendation for museums (class 1: 50 or 55 +/- 5 % RH and 19 +/- 1 °C (winter) up to 24 +/- 1 °C (summer)) (Thomson 1986), research on the indoor effect on hygroscopic materials shifted from laboratory studies on the response of various different materials to RH changes to studies on the worst conditions objects and materials could withstand. Systematically-performed laboratory experiments were initiated for instance in collaboration between CCI, National Gallery of Art (NGA) and Conservation Analytical Laboratory (CAL) at the Smithsonian Institution (Mecklenburg 1991). The reason was to develop rational guidelines for the control of the air-conditioning systems in museums. Research which was simultaneously performed at CCI resulted in early environmental guidelines (Lafontaine 1981; Michalski 1993b). The scientists at the Smithsonian Institution made comprehensive and systematic studies during a period of approximately 40 years on the impact of RH and temperature on the individual materials found in the majority of museum objects (Schultz 1995). Their approach was to identify the worst case scenarios for mechanical deformation of wood, paint and other materials which were fully restrained and exposed to long-term climate extremes resulting in full response of the materials. In this way the safe recommended climate ranges were able to be established. The research was performed as laboratory studies, mainly at room temperature but occasionally also at other temperatures. The starting point was to determine the damage mechanisms caused by RH fluctuations and the properties of the materials involved. The aim was to determine the maximum deformation for each material in the elastic range, meaning the maximum stress a material can undergo without exceeding the yield point, in order not to risk plastic deformation. In these tests the rate of RH change was not critical as long as the maximum allowable strains were not exceeded, but the maximum strains were assumed to be achieved at full EMC due to a step-change in RH (Mecklenburg *et al.* 1994; Erhardt *et al.* 1995; Erhardt *et al.* 1996; Erhardt *et al.* 2007; Mecklenburg 2007a). Finite element analysis (FEA) was also used to study complex layered structures of paintings and predictive modelling was used to match observed damage (Mecklenburg *et al.* 1994; Erhardt *et al.* 2007).

It was further discovered that the stress wood, and other materials, would be subjected to at a certain change in RH or temperature, should be equivalent to the situation where the piece of material would be allowed to shrink or swell freely and then stretched or pushed back to its original dimension. Two types of experiments were performed and then connected; stress strain curves under rapid and equilibrium conditions and stress development under restrained conditions with variations in temperature or RH. From

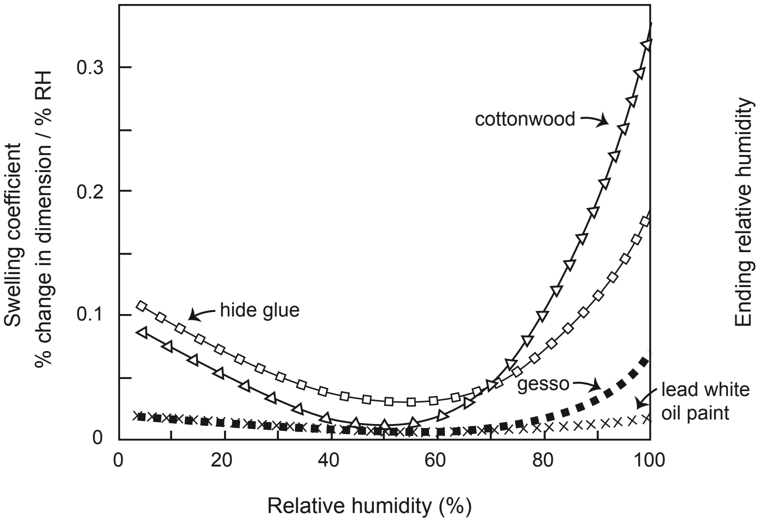


Fig. 14. Swelling coefficients of various materials common in panel paintings at different RH. The largest differences are found in the high and low RH ranges, indicating increased strain development between the individual constituents of the panel painting (Erhardt *et al.* 1995).

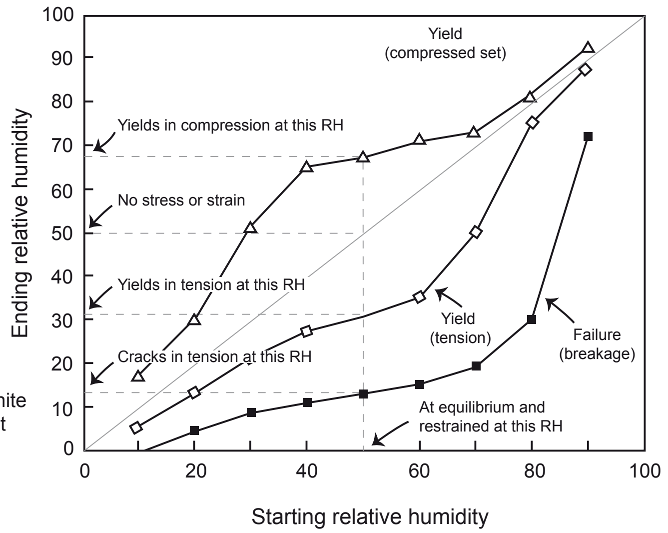


Fig 15. Diagram showing allowable RH fluctuations as well as the yield and failure points for restrained cottonwood in tangential direction (Erhardt *et al.* 1995).

these experiments a general equation for the behaviour of materials under RH and temperature changes was developed (Mecklenburg & Albrecht 1985). The tests showed that mid RH-ranges (40 to 60 % RH) were the safest because here the change in dimension (swelling coefficient) was the smallest and most equal for different materials due to the least steep moisture adsorption isotherm. This means, larger fluctuations in this range can be tolerated compared to low and particularly high RH-regions as seen in Figs. 14 and 15 (Mecklenburg *et al.* 1995).

The conclusion of their work was that the initial yield point is approximately 0.4 to 0.5 % for most polymers at all RH levels (Mecklenburg *et al.* 1998; Erhardt *et al.* 2007). The breaking strain is usually around 2% in the mid-range RH (Mecklenburg *et al.* 1998). However, using pine as an example, the breaking strain is 1.7 % at 48 % RH but this value increases with increasing RH level and reaches 3.5 % at 81 % RH (Mecklenburg *et al.* 1995). Using the yield point as the limit, variations within the range 30 to 60 % RH are mechanically safe for general collections (Erhardt *et al.* 2007). At higher or lower RH the yield strength is dramatically reduced (Fig. 15).

Mecklenburg also pointed out that many cultural heritage objects may have already passed the yield point on one or several occasions, for instance because of exposure to a new environmental range. The material has then undergone so called *strain hardening* (strengthening of a material by plastic deformation) which results in the materials being able to stretch further and be set permanently to a different and higher yield point. In an example for cottonwood, the initial yield point had increased from 0.4 % to 0.55 % after strain hardening (Mecklenburg *et al.* 1998; Mecklenburg 2007a). Although the term strain hardening is well known for metals, information on strain hardening for wood has not been found in literature elsewhere. It is of particular interest for determining strain limits for cultural heritage objects.

The yield strain of 0.4 to 0.5 % for many materials, including wood, has since been considered to be the threshold yield strain to what these materials can withstand. Although the broadened environmental ranges have been criticised for being too wide (Erhardt *et al.* 2007) the yield strain value has been regarded by others as very conservative considering that the wood can be stretched considerably more before it breaks (Bratasz 2013a). Research in the laboratory and on single objects in churches and museum environments was carried out by the scientists at Jerzy Haber Institute of Catalysis and Surface Chemistry at the Polish Academy of Science. They have continued the work of the scientists from Smithsonian Institution. Based on the conservative criteria on the more fragile gesso's yield and fatigue fracture their conclusion was that moderate variations within the range 50 +/- 15 % RH are safe (Bratasz 2013a). See also Section 3.3.1 and Section 3.5.3.

3.5.2 RH changes and moisture transport in wood

In the conservation literature changes, in particular in RH, are often discussed as *fluctuations* or *step-changes*. A fluctuation is here defined as an increase (or decrease) in RH and a return to the initial RH level or another level after a certain period of time. Fluctuations are often repetitive. A step-change, on the other hand, is an instant change from one stable RH level to another stable RH level. The recommended environmental ranges are not only determined by a set point or a set range but also recommended fluctuations from that set point. The reduction of damage is at least partially due to stabilisation of RH, rather than to a specific value of RH (Erhardt & Mecklenburg 1994). However, the response of wooden objects to RH fluctuations of different magnitude and duration has only more recently been studied. Laboratory experiments studying the combination of seasonal and daily RH fluctuations have not been found, although Michalski has shown this effect using risk modelling (Michalski 2013).

The duration of a RH or a temperature fluctuation are usually discussed as *short-term* and *long-term* fluctuations. In the conservation research literature however, the definition of these two terms is vague. Short-terms fluctuations are often labelled as daily fluctuations (Glass & Zelinka 2010). They have also been defined as the difference between the measured data and the monthly moving average (CEN EN 15757 2010). Long-term fluctuations usually refer to seasonal changes (Baronas *et al.* 2001), emphasizing the difference between summer and winter periods. There are of course fluctuations of additional durations. Pretzel used daily, weekly and monthly fluctuations in order to quantify RH data and compare data from different locations (Pretzel 2011). Michalski rather defines the fluctuations from the material's individual response time based on type of material and thickness. Fluctuations shorter than one hour do not affect most museum objects. The most stressful fluctuations are longer than the response time, but shorter than the stress relaxation time (Michalski 1993a).

In historic buildings with low climate control the indoor environment consists of a combination of gradual long-term and short-term *fluctuations* of both RH and temperature. Occasionally, noticeable changes over one or several weeks may occur due to changes of the weather conditions (Fig. 2). However, most laboratory research in both wood science and the cultural heritage sector is performed while testing different materials during a *step-change* in RH at a constant temperature, approximately 20 °C (room temperature). Such climate conditions can be useful for determining the EMC of wood samples or comparing various materials at different RH (Brewer 1991; Allegretti & Raffaelli 2008). Objects transferred from one indoor environment range to another may experience conditions related to a step-change. However, step- changes have not been found, either in museums or in historic buildings and such results from laboratory experiments can therefore not fully be applied to dynamic environmental situations.

Studies which relate moisture transport in wood to deformation over time are rare in the field of conservation science. Dionisi-Vici *et al.* (2006) related moisture transport as a weight change to deformation of a wooden panel. There was a clear linear behaviour between moisture exchange and deformation on a step-change in RH until EMC was reached. However, this was not found in a fluctuating RH environment. Senni *et al.* (2009) used a portable NMR device and monitored a panel painting. They noticed that MC varied not only in depth but also in different areas of the surface of the panel. In this study it depended on irregular irradiation. Jakieła *et al.* (2008b) aimed to model moisture transport in wood and therefore needed to determine the EMC of wood samples and moisture diffusion coefficient parameters. Bratasz (2013a) suggested that deformation of wood should be related to EMC and not RH. Moreover, the EMC parameter on adsorption and desorption is essential for modelling wood deformation (Bratasz *et al.* 2008; Bratasz *et al.* 2012; Rachwał, Bratasz, Łukomski, *et al.* 2012). It is clear that using the moisture condition of wood is closer to reality than moisture condition of the air because the hysteresis effect on EMC can be included. However, the time factor and the moisture distribution of the wood prior to EMC are not taken into account when using EMC in the models.

3.5.3 Wood's response to RH changes

Response is in most cultural heritage research related to deformation of the material upon a change in RH. Maximum response is often considered to occur when the wood has reached EMC and therefore maximum deformation. These values are used for determining worst case scenarios and for mathematical modelling of deformation. However, often the time to reach EMC is not considered (Lull & Junction 1995; Jakieła *et al.* 2008b). Michalski prefers to express temperature and RH response times as half times (half of a full response). It has two advantages: it emphasises the rapid first part of the response and avoids the second part of the response which is difficult to determine because of the asymptotic and abnormal approach to equilibrium (Michalski 1991). Dionisi Vici *et al.* (2006) introduced two terms: *time-to-equilibrium* (response rate) which includes the time needed to reach EMC or a determined fluctuation in RH; likewise, *time-to-response* (response lag) was introduced as a measure for the delay in deformation which will occur upon a change in RH. These two factors are important because they include the changes in deformation which will occur before EMC and full response is reached. According to Michalski, most museum objects are not affected by fluctuations shorter than one or two hours and the most stressful fluctuations are those which are longer than the response rate, but shorter than the stress relaxation time. This accounts for *thin, fast* objects. For *thick, slow* objects, for instance those with impermeable coatings, the response times are longer than the relaxation times. Therefore the relaxation processes counterbalance the slowly-developed dimensional response to a long RH cycle (Michalski 1993; Michalski 2010). Pretzel came to the same conclusion, that the change in RH needs to be both large enough and persist long enough for the material to respond, and hence to be harmful (Pretzel 2014). While studying the propagation of cracks in a wardrobe made of wood, Łukomski *et al.* concluded that the cracks would only propagate when two conditions are simultaneously met. Firstly, a fall in RH must go beyond a certain critical level, and secondly, the variation must last longer than the response time of the wooden panels to bring about their dimensional change (Łukomski *et al.* 2013). In other words, the logical conclusion is that short-term changes will affect thin materials such as single sheets of paper, veneer on furniture, and the surface or the painting layer of a wooden object, whereas long-term fluctuation will gradually influence the bulk of thicker pieces of materials (Jakieła et al. 2008b; Olstad & Haugen 2007). However this is not straightforward. In a study by Jakieła *et al.* (2007) the acoustic emission method (AE) was used to trace stress due to micro-fracturing in wood. By simulating a heating episode and subsequent RH drop, *two* consecutive AE episodes occurred. There are other studies which show different and contradictory results as will be seen in the following section.

Environmental standards and guidelines were initially presented only as a band width and not until 1979 did CCI began to express the environment as a set point and accompanying recommended daily fluctuations. This approach thereafter became the internationally generally-accepted norm (Michalski 2016). Considering the various response rates for different types of objects it can be questioned if using a set point and allowable *daily* fluctuations is the most suitable way of expressing indoor environments. Pretzel (2011) stresses the importance of including the impact of fluctuations of different intervals for specifying allowable environments. In order to predict the rate of occurrence of unsafe changes, a statistical approach is needed. This is important because evidence has shown that RH fluctuations of 90 days are also damaging for furniture. Bratasz (2013a) showed that durations of fluctuations of approximately two weeks were the most harmful to painted wooden panels. It is clear that not only the amplitude but also the duration of RH and temperature fluctuations need to be paid attention to in environmental recommendations.

Response rate

The response rate of a material to a change in RH and temperature is important in order to understand the impact of the indoor environment in terms of seasonal and shorter fluctuations. Repetitive or cyclic RH variations have also been tested. A number of different investigations have been performed in laboratories involving climate chamber experiments and numerical modelling, studying the response of wooden panels of different thickness to various RH conditions. These will be presented here.

The acoustic emission technique (AE) and numerical modelling was used to trace fracture intensity in a wooden cylinder, 10 cm in diameter. The largest response that occurred, on reaching the vicinity of the yield point, was in relation to a drop in RH from 70 to 30 % RH in 0.25 hours. As the duration of the same fluctuation increased, the response decreased and a drop of 48 h duration was hardly detectible (Jakieła *et al.* 2007; Jakieła *et al.* 2008a). In another study, Jakieła *et al.* (2008b) simulated environmental impacts on a wooden cylinder using numerical modelling. From a starting set point of between 30 to 75 % RH an immediate step-change of +/- 10 % RH would not cause permanent damage. By increasing the duration of the RH fluctuations of the same magnitude to 24 hours, the range for the starting set point could be increased to between 10 to 90 % RH. Moreover, on a set point of 50 % RH, tolerable fluctuations had also increased to +/- 20 % RH. These two studies indicate that the faster the RH-change the larger is the response, including for massive wood samples. Instant step-changes are the most detrimental. Experiments based on moisture diffusion in wood and correlated modelled deformation in laboratory settings as well as in non-heated historic buildings support the conclusion that fast environmental fluctuations and instant RH changes should be avoided so as not to put wooden objects at risk (Zítek *et al*. 2015).

In a later experiment, Rachwal, Bratasz, Łukomski *et al.* (2012) studied the response rates (moisture diffusion in relation to strain) of unrestrained lime wood samples (*Tilia sp.)* of different thicknesses subjected to variations in RH. In these experiments 0.2 % strain in the tangential direction was used as the critical yield strain because the tests took into account an imagined applied gesso layer. Moreover, in order to simulate non-symmetric moisture exchange and gradients in the wood in the modelling, wooden panels open to moisture diffusion from both faces were compared to panels with one face covered to prevent moisture diffusion from one side. The results showed that the thinner panels (10 mm) open to diffusion on both sides were the most responsive. Both increased thickness of the panels and panels which were prevented from exchanging moisture on one face showed slower response to RH changes. The most reactive panel did not respond to fluctuations shorter than one day although the amplitude of the RH change was 20 % or larger. The longer the duration of the fluctuating RH, the lower was the tolerable critical RH amplitude. An increase of the RH change duration to full response was obtained after 14 days for the 10 mm thick wooden board and 90 days for the 40 mm thick board. In those cases the allowable RH fluctuations were only approximately 6 % RH.

A follow-up article described how the wooden panels, coated with gesso on one side, were tested. The results were presented in terms of strain and corresponding critical amplitude of RH variations in relation to the number of RH cycles as well as allowable amplitudes of RH in relation to duration (Rachwał, Bratasz, Krzemień, *et al.* 2012). These results showed that the relation between strain and number of cycles had a sigmoidal appearance. A panel covered with gesso could tolerate approximately 20 000 cycles as long as the changes in RH did not exceed 50 +/- 6 %, which corresponded to 0.2 % strain (Rachwał, Bratasz, Krzemień, *et al.* 2012, Fig. 7). This would correspond to daily fluctuations during a period of sligthly less than 55 years. However, reading the same graph in this same paper, an allowable yield strain of 0.4 % would correspond to fluctuations of 50 +/- approximately 12 % RH allowing only 50 to 60 cycles before fractures in the gesso layer would occur. These values assume that the gesso has reached EMC and full dimensional response and therefore also the duration of the fluctuations are important.

The result for identifying the worst case duration of a single RH cycle were 15 days for a 10 mm thick panel open for diffusion on both faces and an RH change of 15 %. For a 40 mm thick panel open for diffusion on both faces, the worst fluctuation was estimated to be of +/- 14 % and a duration of 90 days. In this study the allowable RH fluctuations had clearly increased compared to Rachwał, Bratasz, Łukomski, *et al.* (2012) presented in the previous paragraph. In a later review article, it was concluded from the above investigations that moderate fluctuations within approximately 50 +/- 15 % RH were safe, based on the conservative criteria of the gesso's yield and fatigue fracture, and assumptions of the worst case of the wooden substrate's response (Bratasz 2013a).

Moreover, there are additional results presented which further increase the complexity. Due to stress relaxation, a given strain applied to wood (or another material) would cause 50 % less stress if applied over four months compared to one day at moderate temperature. Thus, a four-month seasonal change of +/- 20 % RH should cause less stress in most artefacts than a one-week fluctuation of +/- 10 % RH (ASHRAE 2011). Michalski used a risk-modelling tool to show the combined effect of daily and seasonal RH fluctuation impact on a heavy, painted one-centimetre thick wood sample. An average seasonal drop of 20 % RH with daily fluctuations of 20 % RH was more detrimental compared to an average seasonal drop of 10 % RH with daily fluctuations of 40 % RH (Michalski 2013).

So far the number of experiments which have been conducted are few and the results presented would need to be verified. Moreover they are not always easy to compare because the changes in RH amplitude vary as do the durations of the RH change. Also, a change in RH can be instant (step-change) or be a gradual change from one RH level to another until full response of the material. Further, such experiments are normally based on EMC and maximum strain. Repetitive cyclic fluctuations do not necessarily reach EMC and it is unclear if the modelled values used in the papers cited above (Rachwał, Bratasz, Łukomski, *et al.* 2012; Rachwał, Bratasz, Krzemień, *et al.* 2012) are based on full strain response experiments in relation to EMC or MC or modelling.

It is sometimes unclear to what extent the laboratory studies presented above are based on actual experiments or numeric modelling established on equilibrium values in MC and deformation. The studies above (in the Section *Response rate*) do not imply that MC and deformation are at times not correlated. It is clear that a panel which can exchange moisture to and from both faces would experience faster and larger dimensional change on a change in RH. It would allow larger RH fluctuations in the elastic range, because such a situation is assumed to be internally and externally unrestrained. On the other hand, panels that are non-permeable on one face experience slower moisture exchange but are known to be influenced by interior restraints. Panel paintings and polychrome sculptures are considered to be among the objects most vulnerable to adverse environments. This is because of anisotropic behaviour as well as the different response to ambient RH and temperature of objects with one painted or gilded surface. Due to asymmetrical moisture gradients, temporary warping (out-of-plane deformation) occurs fast after a step-change in RH followed by a longer relaxation period until equilibrium. The deformation will occur regardless of the cut of the wood. When viewed from the painted side, it appears convex in response to a drop in RH (as a result of contraction and warp) but concave in response to increasing RH (as a result of expansion and warp) (Buck 1963; Buck 1972; Brewer & Forno 1997; Brewer 2000; Dionisi-Vici *et al.* 2006; Padfield n.d.(a)). Dionisi-Vici *et al.* compared 40 mm thick wooden boards with one and two faces open to moisture exchange as well as letting the panels be either free to deform or restrained. Here, both the free swelling strain and the force of the constrained panels were monitored. In one test the moisture exchange was monitored as weight change of the panel. The panels were subjected to either step-changes or fluctuating RH. During step-changes, the panel with both faces open to moisture exchange showed a typical asymptotic behaviour and deformation, reaching its final state in 2-3 months. For the constrained panels, the acting forces followed the same asymptotic trend. For the panels water-proofed on one face and subjected to step-changes in RH, the cupping pattern was much more complex. It showed a strong transient reaction after two weeks but this faded out during an additional three months. The deformation started prior to any change in MC and this led to the conclusion that, especially when mechano-sorptive behaviour is involved, non-linear relationships do occur as shown with the rapid warping of panels upon a step-change in RH. In tests where a panel was subjected to short-term fluctuations of uneven amplitude and duration, the deformation of the board typically followed the RH fluctuations. On the other hand, the moisture exchange, monitored as a weight change of the board, was much slower in its response to the fast RH fluctuations and did not follow the deformation path (Dionisi-Vici *et al.* 2006).

Other studies have also monitored weight change of the wooden sample or object and simultaneously deformation until equilibrium. The results of such studies confirm that when one face of the panel is subjected to a step-change in RH the deformation increased rapidly and peaked, followed by a gradual relaxation of the panel (Brewer & Forno 1997; Brewer 2000). Two early studies observed that the dimensional change in coated and uncoated wood samples continued after EMC was reached (Buck 1961; Stevens 1961). In a study by Holmberg (2001), an 18th century cupboard door panel (dimensions not reported) painted on one side was moved from an environment of 30 % RH and 20 °C and placed in the non-heated environment of Skokloster Castle. In response to the seasonal change in RH and temperature at the castle (fluctuating RH of 60-75 % RH and fluctuating temperature of -2 to 5 °C), the door panel showed maximum cupping between 10 and 13 days and maximum weight increase in 27 to 30 days.

Response delay

Response delay is of importance in dynamic environments because it will reflect on how responsive an object or a sample of certain dimensions is to the ambient environment. For instance, Knight and Thickett (2007) noticed a response delay of 41 hours when they monitored a gilded wooden table in a historic building and also proved that the table did not respond to shorter fluctuations than 41 h and therefore was not influenced by daily fluctuations.

Apart from this work only a few studies have noted the response delay in their published results: immediate response for wooden painted panels (Stevens 1961; Klein & Bröker 1990; Brewer 2000; Bernikola *et al.* 2009), five minutes delay for a painted wooden panel (Brewer & Forno 1997), one hour response delay of a polychrome sculpture in a church (Jakieła *et al.* 2007), 12 hours response delay for a painted panel (Senni *et al.* 2009) and no response to daily RH fluctuations or shorter for wooden panels with gesso on one side (Rachwał, Bratasz, Łukomski, *et al.* 2012). Numerical modelling of a cylindrical wooden sample showed immediate response 10 µm below the surface and three hours response delay one centimetre below the surface (Jakieła *et al.* 2008b).

The difference in response delay may reflect the difference of the wood (species, thickness, dimensions, cutting etc.) as well as the climate variations during each of the studies. The resolution of the various methods used for monitoring deformation is probably also one reason. Transducers screwed to the wood for monitoring at depth and optical fibre sensors glued to the wooden surface will respond to a thicker layer of the wood compared to other methods. For instance *Digital Holographic Speckle Interferometry* (DHSPI), which is very sensitive to small variations in movements and will only monitor the outermost surface of a painting layer, obviously will respond faster to RH changes.

3.6 The influence of low temperature on moisture transport and deformation in wood

Low temperature, as may be found in non-heated historic buildings, has been reported to have a positive impact on wood in that it decreases the rate of chemical reactions as well as biological activity and therefore reduces the chemical and biological degradation of organic materials (Bordass 1994; Michalski 2002; Michalski 2009; Klenz Larsen & Broström 2015). It is also known that moisture diffusion is retarded by low temperatures due to lower vapour pressure at lower temperatures, which in turn reduces and delays deformation in wood (Buck 1961; Håkansson 1998). Unger *et al.* (2011) pointed out that lower temperatures allow for larger RH amplitudes because the strength of wood increases with reduced temperatures. Below 100 °C, changes in strength due to temperature are reversible (Bowyer *et al.* 2007).

Despite this knowledge, limited research has focussed on low temperatures and the mechanical impact on wood and other organic hygroscopic materials. In laboratory deformation experiments, the temperature has normally been kept constant between 20 and 30 °C and the temperature factor is therefore seldom taken into account, for instance in modelling. Investigations on fluctuating temperature and subsequent fluctuating RH have not been found, although this is the common situation in poorly climate-controlled or leaky buildings. However, research in the field of conservation has on the other hand been performed on low-temperature preservation of photographic materials. Likewise, even sub-zero temperatures have been a focus of research while freezing objects for pest and insect-eradication purposes.

3.6.1 Interaction between temperature and MC

Wood has a low *thermal conductivity* (a measure of the rate of heat flow through the thickness of the material) and a low *thermal diffusivity* (a measure of how quickly a material can absorb heat from its surroundings) (Glass & Zelinka 2010). One approach to the temperature influence has been its potential to cause stress and dimensional change to materials in the same way as RH. When subjecting wood to changing temperatures while keeping RH stable, wood responds dimensionally to temperature in that it will expand on heating and contract on cooling because the thermal expansion is due to an increase in distance between molecules as they increase in oscillation (New 2014). However, the coefficient of thermal expansion is much smaller compared to moisture-related deformation and is therefore, in the context of climate-induced mechanical damage, often ignored (Mecklenburg 1991; Hoadly 1998; Jakieła *et al.* 2008b; Richard 2011). At low temperatures Michalski concluded that in the case of wood the effect of a slightly higher EMC due to a lower temperature overrides the thermal shrinkage completely (Michalski 1991). The temperature as a single parameter is also regarded as being of minor importance because temperature in the material changes rapidly on a temperature change of the ambient air (Bratasz *et al.* 2005). The dimension of the wooden object is of course of importance. Because wood is a natural insulator, in the case of larger, massive pieces of wood much longer time is needed to equilibrate the core temperature with the ambient air, and further this does not change evenly (Strang 1997).

However, the interaction between temperature and MC in wood on a macroscopic as well as and microscopic level is complex and not fully known. According to thermodynamics, adsorption of moisture on the wood surface is accompanied by an evolution of heat (exothermic reaction) (Avramidis 1997) and the opposite endothermic reaction is expected during desorption of moisture. Moreover, of importance is the effect of temperature on MC and thereby the changes in dimensions. This is clearly exemplified by wooden objects in a confined, sealed space, such as microclimate packaging. The dimensional response of panel paintings is almost exclusively due to temperature changes because of their influence on MC (Richard 2011). New points out that an increase in temperature drives out moisture and therefore the net result of assumed expansion due to temperature increase is shrinkage (New 2014).

Moisture transport which creates temperature and MC gradients in the material results in additional phenomena. One example is when the temperature on the surface of the wood is higher in comparison to the core simultaneously as MC is higher in the core compared to the surface; the moisture potentials will have opposite directions and in some situations may level each other out (Esping 1992). On a microscopic level, MC gradients are also found through the cell walls and during the phase change of water from vapour in the lumen to bound water in the cell walls, and the reverse. In the case of adsorption, the released energy results in a local temperature increase. For desorption the situation is reversed (Eitelberger *et al.* 2011).

Avramidis *et al.* (1994) observed in desorption experiments of wood that in the beginning of the experiments, just below the surface at which evaporation takes place, an increased moisture front developed which seemed to move towards the core of the specimen as desorption progressed. Traditionally, MC gradients have been used as the driving forces for diffusion but the authors stresses the importance, when modelling moisture transport and gradients in wood under unsteady-state, non-isothermal conditions, to consider heat and moisture transport as coupled processes and thermally-induced mass transfer (the *Soret effect* or *thermophoresis*).

3.6.2 Temperature's influence on deformation

Only a few studies on the influence of temperature on deformation have been found in conservation science. However Michalski (n.d.) has compiled information on incorrect temperatures for cultural heritage objects resulting in chemical and biological degradation as well as mechanical damage. From the perspective of indoor environments in historic buildings, low temperatures and fluctuating temperatures are most relevant. For low temperatures he concludes that some materials, such as wood, benefit from low temperatures while for instance acrylic paints and oil paints, often associated with wood, are more sensitive to low temperatures. According to the author, two situations which can lead to damage due to fluctuating temperatures are when the components of a complex assembly have different coefficients of expansion, and when an object is subjected to a fluctuation more rapid than its ability to respond to it. However, single fluctuations of 30 to 40 °C are not considered harmful. Sensitive materials will not suffer from fatigue stresses when subjected to daily fluctuations of 10 °C in thousands of years. Less sensitive materials can even tolerate fluctuations of 20 to 40 °C. However care must be taken not to risk condensation on the objects' surfaces due to fast temperature changes. In a closed and empty room or display case at 20 °C and 50 % RH, a 10 °C drop in temperature will reach the dew point and may cause condensation. The recommended temperature levels are above 5 °C in winter and below 25 °C in summer in terms of total risks, taking both chemical deterioration and mechanical damage into account (Michalski n.d.).

Below are the few studies found which take the effect of low temperatures of wooden objects into account.

In a study investigating micro-displacements in the surface of a model painting, Bernikola *et al.* (2009) observed that the deformation was larger upon desorption compared to adsorption. Monitoring deformation of a 19th century icon, a linear relationship was found on a step-change from 23 to 58 % RH at a constant temperature of 26 °C, but an exponential relationship when the temperature decreased from 34 to 22 °C and RH simultaneously rose from 22 to 47 % RH. No explanation for this behaviour was given.

Bratasz, Koslowski *et al.* (2007) monitored the response of different parts of a polychrome sculpture in a church. On a sudden heating episode where the temperature was raised from 4 to 21 °C and RH subsequently dropped from 54 to 27 %, the wood expanded during a time frame of approximately two hours. It was explained as an initial response to temperature rise followed by shrinkage due to a RH reduction (Bratasz, Kozłowski, *et al.* 2007, Fig. 9b). It is possible that this phenomenon is the *Sorets effect* described in Section 3.6.1.

A more recent study by Rachwał, Bratasz, Łukomski *et al.* (2012) showed that the critical RH amplitude influencing wooden panels increased significantly at lower temperatures and the effect of lower temperature was more pronounced for short-term fluctuations and gradually less important for long-term fluctuations. This demonstrates that moisture diffusion is retarded at low temperatures. However, it should also be mentioned that there are results on temperature dependence which are opposite to the general belief that lower temperatures reduce deformation. A study by Yang *et al.* (2015) investigating MC changes and dimensional responses of wood at constant RH (60 % RH) with repeated step-changes in temperatures (25 to 40 °C) gave surprising and opposite results from other studies. The shrinkage coefficient showed that wood suffers 1.5 times as many dimensional changes per unit degree Celsius compared to unit % RH for samples of the same size. Furthermore the static, step-change in temperature was more serious compared to dynamic conditions (Yang *et al.* 2015). According to this study it appears as if temperature has some effect on wood at constant RH, while the results' varying with thickness and cut indicate that response to changes in temperature are not immediate. In another study by the same authors, their experiments showed that MC exchange due to fluctuating RH between 45 and 75 % RH was lower at 40 °C compared to 25 °C, which was explained as the hygroscopicity of wood decreasing with increasing temperature as a result of losing sorption sites (Yang & Ma 2016).

During natural conditions a temperature fluctuation without a subsequent RH change is not likely to happen in any other environments than in a tightly-sealed and buffered show case or transport crate (Padfield *et al.* 1984). Therefore, in any natural environment there will always be a direct or indirect influence of temperature on RH and MC, both on a daily as well seasonal basis. Because the RH and temperature levels in non-heated buildings vary with the seasons and in relation to each other it is not straightforward to separate the two parameters during dynamic conditions so as to be able to evaluate the impact of RH and temperature separately.

3.6.3 Sub-zero temperatures

RH at sub-zero temperatures is defined as the actual moisture pressure in the ambient air divided by the saturation *vapour pressure over ice*. However, moisture adsorbed by hygroscopic materials tends to maintain equilibrium with *vapour pressure over super-cooled water* below zero, which means that it is higher than *vapour pressure over ice.* Not until the vapour pressure over ice becomes lower than water pressure over super-cooled water will ice formation occur in the wood or any other hygroscopic material (Padfield n.d.(c)). It is however uncertain if damage due to freezing of water occurs in wood. One of the few studies of the influence of low and sub-zero temperatures is by Hedlin (1966). He showed that, for 12 different types of wood species, EMC was substantially lower at 99 % RH (over ice) at -12 °C in comparison to the same RH and 21 °C. It means that wood stored under such cold conditions will tend to have a MC below that of FSP during the winter season. Moreover, the hysteresis was clearly lower compared to above the freezing point.

It has also been shown by Bodig & Jayne (1982) that the E-modulus continues to increase below the freezing point and that the larger effect of low temperatures is more predominant at higher MC ranges (Fig. 11).

3.6.4 The influence of low temperature on painted wooden objects

In the cultural heritage sector, wooden objects frequently have a painted, varnished or gilded surface. Research has been performed to study the impact of low temperatures on hide glue and paints with different binders and pigments. Varnishes, lacquers, oil, alkyd and acrylic paints are at risk when exposed to low temperatures. These materials show much lower dimensional response to temperature compared to RH and therefore low temperatures could be considered not to be harmful. However paints such as acrylics, alkyds and oil, undergo a glass transition or phase transition (T_g) from *rubbery* via the *leathery* region to the *glassy* state at low temperatures, where these materials become very brittle. In this leathery region the materials are still able to partly deform elastically (Michalski 1991; Mecklenburg 2007b). The leathery transition can occur during a temperature interval from 0 to -30 °C for different types of oils, with and without pigments, aged and not aged. Not until -30 °C does full glassy response occur (Michalski 1991).

Different studies give different information on the T_g for paints, which might be due to the large variety and constituents of paints that exist, in addition to age and history, which may also have influenced the paint. Traditional oil paints have a T_g of around – 15 °C and for alkyd paints T_g is about – 5 °C according to Mecklenburg and Tumosa (1999). Young and Hagan (2008) tested a range of modern alkyd and acrylic primers and showed that, despite there being a variation among the tested paints, the E-modulus and ultimate tensile strength increased and the strain to failure decreased with temperatures ranging from 20 to -10 °C. T_g, was shown in this test to be 10 °C for alkyds and 0 °C for acrylics.

Damage to painted or varnished wooden objects subjected to low temperatures are according to Mecklenburg seen as craqelure in the surface layer, running predominantly perpendicular to the wooden grain (Fig. 16). The explanation for this behaviour is that the dimensional response of most materials to changes in temperature is low and remarkably consistent from one material to another.

Fig. 16. Detail of a gilded picture frame. The grain of the wood is vertical in the picture and the craquelure run mostly horizontally in the gilded surface, which is perpendicular to the grain. This damage is therefore assumed to be a result of low temperatures.

However, because wood has an anisotropic behaviour it will only deform to a minor degree in the direction of the grain upon a fall in temperature. In the cross-grain direction it will instead contract and thereby release stresses and strains in the surface layers in the cross grain directions. Temperature-induced cracking in the varnished or painted layer can occur as soon as the object has reached the new temperature equilibrium (Mecklenburg 2007b).

Experiments which fluctuate both temperature and RH simultaneously are few. In a study by Erlebacher *et al.* the correlation between low temperatures and brittleness of acrylic paint was tested. It suggested that there is a difference in T_g which is due both to RH and temperature. They noted that T_g was passed near 5 °C at 50 % RH and 10 °C at 5 % RH. The ambient moisture in the air would then act like a plasticizer, resulting in a lower T_g (Erlebacher *et al.* 1992). This may even give a lower T_g in the higher RH range, common in the winter periods in non-heated historic buildings.

Low temperatures and sub-zero temperatures are commonly used for museum objects for eradication of insect infestations or mould. During these circumstances the freezing process is of course thoroughly controlled in a way not occurring in historic buildings. In these situations, Strang (1997) agrees that oil paint and polymers become brittle when cooled down to low temperatures. However, painted wooden objects down to -20 °C are considered safe. Below this point there is a small but real possibility of increased craquelure in painted and varnished objects. As mentioned earlier, wood which is only in contact with moist air does not contain liquid water (Thygesen *et al.* 2010) and therefore theoretical freeze/thaw cycles should not cause damage. Carrlee (2003), who has thoroughly reviewed the risks from low temperatures and freezing of museum objects concluded that there should not be any significant structural damage to wooden objects which are repeatedly frozen for pest control.

3.7 The influence of age on wood's mechanical properties

Comparing the mechanical properties of aged and fresh wood is expected to give additional information on climate-induced damage to wooden objects which have been subjected to unfavourable environmental conditions for long periods of time. Although it is often impossible to know exactly the environmental history to which aged wood has been exposed, a large-enough number of individual studies could give a general indication on the impact of low temperatures and high RH. The results of such studies as were found are presented in this section.

Buck tested the adsorption and desorption ability of various wood species and various ages, dating from one to approximately 3700 years old. He concluded that, over time, wood would not be less prone to respond to changes in RH, on the contrary the sorption properties did not change significantly with age (Buck 1952). Experiments comparing the mechanical and physical properties of wood (strength, stiffness, elasticity and strain-to-break) showed no significant difference between 17th century and fresh Scots pine (Erhardt et al. 1996). However, Unger *et al.* (2001) compiled the results of several researchers on the impact of age and noted some results also showed that the EMC could be reduced by age. Moreover, aged wood may be more deteriorated due to exposure to pest or insect attacks which have changed their properties. This would result in increased hygroscopicity but not necessarily to changes in dimension. Such objects may also have been exposed to maintenance or conservation treatments which will alter the mechanical properties. Fracture intensity using acoustic emission (AE) was used by Jakieła *et al.* (2008a) to predict the evolution of damage to materials. They compared an aged, approximately 500 years old polychrome lime wood sculpture from a church and a fresh lime wood sample. The result showed that the response pattern between the two were similar.

In Table 2, Section 3.8, the results of two studies testing strain of wood of different ages (Klein & Bröker 1990; Dionisi-Vici *et al.* 2013) are illustrated. There was no detected difference in strain comparing a fresh wooden panel and a wooden panel from the 16th century monitored by Klein and Bröker (1990). However, there was a difference in two wooden samples monitored by Dionisi-Vici *et al.* There was less strain in the 1200-year-old oak sample compared to the sound wood. This could possibly be explained by the conservation treatment of the archaeological wood (Dionisi-Vici *et al.* 2013).

One comprehensive study was found comparing aged and fresh wood. This was by Mohager (1987). He examined various mechanical properties of newly-felled as well as aged wood. The latter had been used as construction timber in buildings which were heated (170-, 190- and 360-years-old wood) and non-heated (120- and 250-years-old wood). The wood from the non-heated buildings had been used as roof trusses just below an uninsulated metal roof exposed to extremes in RH and temperatures including condensation. The results showed that the samples' E-modulus decreased with age. The sorption isotherm was considerably higher for the fresh wood compared to the aged wood. Moreover the sorption isotherm for wood from the non-heated buildings was lower compared to the wood from the heated buildings. During cycling RH tests (20 days fluctuations, 15 to 94 % RH for approximately 600 days), MC magnitudes were larger in the fresh wood compared to aged wood. The moisture movement across the grain was also much slower in the aged wood indicating a reduced hygroscopicity by age. This may be explained by an increased number of pit openings in the wood become permanently closed with age. Creep tests show that the age of wood clearly had an influence on creep. At a constant RH and temperature, the older the wood the less creep was recorded. Moreover, all the samples which had previously been subjected to the more harsh environmental and mechanical impact (non-heated buildings) showed less creep compared to those which originated from heated buildings. Cyclic RH experiments at a load of 10 MPa showed that there was less creep in the aged wood compared to the fresh wood and moreover that the aged wood had a higher viscoelastic deformation (recovery) in relation to deformation compared to the fresh wood. However, the total deformation was generally higher for the aged wood since it had a lower E-modulus compared to the fresh wood. During bending experiments at a constant RH the fresh wood had a higher breaking strain compared to the aged wood (Mohager 1987).

In a recent review paper by Cavelli (2016) the investigated mechanical properties of aged wood from 30 different studies were compared. In general the results showed a low concurrence between the different studies for bending, compressive, tensile and shear strength. However, the results on the E-modulus (bending stiffness) remained unchanged, or were not significantly affected over time, which is opposite to the results by Mohager (1987). The varied results from the 30 studies were presumed to be due to the fact that the woods tested varied in terms of their physical properties and resistance to ageing. These variations include differences between wood species, exposure to different, often unknown environmental conditions, and the effect of load history. Moreover, the testing procedures were not standardised and the tested wood samples ranged from small clear wood specimens to large construction elements. (Cavalli *et al.* 2016).

The results of the investigations presented in this section show low agreement and therefore it is not possible to make reliable conclusions. Additional studies on aged and fresh wood are of importance because they will add to the knowledge on strain hardening in wood as proposed by Mecklenburg *et al.* (1998) as well as to the proofed fluctuation concept suggested by Michalski (2007).

3.8 Monitored deformation of wooden objects and samples in uncontrolled indoor environments

In conservation literature remarkably few investigations have monitored deformation of wooden samples or objects in relation to RH and temperature in natural environments. However, since the yield strain (approximately 0.4 %) and the breaking strain (approximately 1.7 %) according to Mecklenburg *et al.* (1995) and Mecklenburg *et al.* (1998) are determined during RH step-changes in laboratory conditions, it is interesting to relate the actual deformation of wooden samples or objects in their own environments to these threshold values. The question is, during what climate conditions does the yield strain or the breaking strain in historic buildings occur and can they relate to the recommended climate range of 50 +/- 15 % RH as suggested by Bratasz (2013a). In Table 2 are listed the papers found which have studied deformation of wooden objects or samples in poorly- or non-climate-controlled indoor environments, museums as well as historic buildings. In some cases the authors have expressed the strain in relation to a RH range during a certain time period, such as Dioni-Vici *et al.* (2013). In other cases these values have been extracted from the graphs of the publications showing maximum and minimum strain during certain RH ranges and time durations. These are marked (*) in Table 2 and are estimated as the largest change in deformation during the full monitored period of time in each study.

As seen in Table 2, the most common method used to monitor deformation is different types of transducers. The periods monitored were between one week and 16 months. The temperature was only presented in the more recent studies. It is assumed however, that the temperature in museum and laboratories are approximately 20 °C. Information such as wood species, cut of wood, type of coating and observed damage to paint and wood, are important but not always reported.

Among the studies in Table 2, it is difficult to find clear tendencies between RH change and strain but it is clear that measured RH changes are generally larger in historic buildings with no climate control than the recommended RH changes, centred between 35 and 60 % RH (Mecklenburg *et al.* 1998) or 50 +/- 15 % RH (Bratasz 2013a). The

Table 2. Deformation of wood in uncontrolled indoor environments

Source	**Wood species and object characteristics**	**Cut: Radial (R), tangential (T), Cross grain (C)**	**Observed largest RH change and recorded temperature in a monitored period**	**Duration of monitored period**	**Monitoring method**	**Experiment location and type of climate control**	**Reported dimensional change**	**Reported strain or calculated strain from graphs available in published paper. The latter is marked (*)**
Klein and Bröker 1990	Oak panel (new from 1987)	R	RH: 60-43% (17 % RH drop) T: ?	7 days	Inductive displacement transducers	Museum exhibition	-	**0.09 %***
	Painted oak panel from 15th-16th cent.	R	RH: 47-60 % (13 % RH increase) T: ?	1 month	Inductive displacement transducers	Museum exhibition	-	**0.08 %***
Olstad 1994	Decorated wall. Painted (?) wood	?	RH: 13-75 % (62 % RH max difference in fluctuating cond.) T: ?	8 months	Transducers (?)	Stave church (heated during winter)	-	**0.4 %***
	Wall memorial. Distemper on wood	?	RH: 5-55 % (50 % RH max difference in fluctuating cond.) T: ?				-	**1.0 %***
	Crucifix (1). Painted (?) wood	?	RH: 30-95 % (55 % RH increase) T: ?			Stave church (non-heated)	-	**0.12 %***
	Crucifix (2) Painted (?) wood						-	**0.26 %***
	Decorated wall. Distemper on wood	?	RH: 30-99 % (59 % increase) T: ?				-	**0.6 %***
Falciai *et al.* 2003	Dummy of panel treated with a gesso layer on one side and constrained with dove-tailed cross beams on the other. Made of poplar (Populus alba), total 670x920x12 mm	C	RH: 38-63 % (25 % RH increase) T: ?	8 days	Fiber Bragg grating sensors	Uncontrolled climate conditions in laboratory	-	**0.1 % ***
Bratasz and Kozłowski 2005	Polychrome wooden sculpture. Three parts were monitored: Head, drapery and finger of different dimensions	?	RH: 30-70 % (40 % RH increase) T: 10-17 °C	2 months	Triangulation laser displacement sensor	Historic church, intermittently heated	-	Head: **0.3 %*** Drapery: **0.6 %*** Finger: **2.3 %***
Knight and Thickett 2007	Gilded wooden table	C	RH: 74 -34 % (30 % RH drop) T: 11-20 °C	3 months	Linear variable differential transformer (LVDT) monitoring the width change of approximately 2 mm wide crack	Uncontrolled climate conditions in a historic house	0.1 mm	-
Dionisi-Vici *et al.* 2013	Uncoated sound oak board	R	RH: 22-83 % (61 % RH increase) T: 17-27 °C	5.5 months	Transducers (Deformometric Kit, DK)	Museum exhibition with uncontrolled environment	-	**0.843 %**
	Oak board ca 1200 years old (archaeological and impregnated with linseed oil and creosote in 1904)							**0.599 %**
Allegretti *et al.* 2017	Painted wooden panel made of pear wood. Dated 1534	R and sub-R	RH: 55-35 % (20 % RH drop) T: 25-30 °C	1.5 months (2 periods during 2 years)	Transducers (Deformometric Kit, DK	Storage with no climate control	-	**0.55 %***
			RH: 57- 25 % (32 % RH drop) T: 17 °C					**1.2 %***

majority of the studies show set points between 45 and 55 % RH. In the studies which show strains above 0.4 %, the majority of objects have been subjected to RH changes of above +/- 20 % RH during the monitored period, irrespectively of the set point. In the studies presenting results below the yield strain, the objects have mainly experienced RH differences of less than +/- 16 % RH, which is in accordance with the recommendations. However, there are exceptions; the study by Olstad (1994) does not follow this trend. Here the RH mean is below 44 % RH in the heated church and 60-65 % RH in the non-heated church. For the crucifix and decorated wall in the non-heated church the fluctuations are +/- 30-35 % RH. In the same environment, the crucifix showed strains clearly below the yield point and the decorated wall above the yield point. Olstad pointed out that the monitored wooden objects in the non-heated church were in good state of preservation compared to the objects in the heated church. It is possible that this is a result of the expected cold winter in Norway. In the study by Allegretti *et al.* (2017) the RH was relatively stable (48 +/- 16 % RH) but the subsequent strain was large (1.1 %). No explanation for this was found.

None of the studies in Table 2, except the strain of the sculpture's finger in the work by Brataz and Koslowski (2005), showed results which approached the breaking strain. The environment in this church was 50 +/- 20 % RH and non-heated except for services in the church resulting in occasionally short periods of low humidity. The article pointed out that old, large cracks were visible in the massive head of the sculpture. Such cracks would be able to serve as expansion joints, allowing larger movements of the wood and hence recorded deformation. In this study however, the head exhibited the lowest strain of the monitored sites. The remarkably high strain for the finger, which did not show signs of visible damage, might be a result of monitoring errors. Knight and Thickett (2007) suggested that the method used, *triangulation laser displacement,* monitors only the outermost surface of the sculpture which is also the reason why this method only shows minor response delays.

There are additional papers measuring or monitoring damage to wood, using other methods to monitor damage. For instance, *acoustic emission* (AE) was used to monitor crack propagation during two years, examining a wooden cupboard from 1785 on display at the National Museum in Krakow (Strojecki *et al.* 2014). The cupboard was on display in an exhibition were the temperature was kept at room temperature but RH was not controlled, resulting in large RH decrease during winter periods. The results showed a crack propagation of 0.6 mm per year. According to the authors the climatic conditions in the galleries were considered to be a relatively low risk for the collection. However, this may be a matter of disagreement because objects like this cupboard are to be expected to be exhibited for centuries to come. With the rate of propagation measured it would correspond to 60 mm in 100 years in the present environment. Whether this type of damage is considered to be serious or not also influences the proofed fluctuation concept (Michalski 2007), as well as the apprehension that objects will acclimatise to a particular environment in a year's time or longer (CEN EN 15757 2010). The same slow, hence continuing deformation in dynamic environments due to mechano-sorption was also noted by Mohager (1987) as seen in Figs. 12a-b.

To be able to make sustainable conclusions from *in situ* deformation monitoring, more studies need to be carried out. However, it is important to improve the procedures and methods used. Here a standardised methodology could be useful in order to make different studies comparable. For instance, how to define *original length* of a sample during dynamic environmental conditions as strain is defined as the *change in length divided by the sample's original length* (Mecklenburg 2007a). Until now it appears that a random length has been chosen as the reference. The minimum information needed is found in the headings in Table 2. Other variables which need to be taken into account are the distance between the measuring points, which is required to calculate the strain as well as the location of the measuring points. Klein and Bröker (1990) showed that the distance between the measuring points is of negligible importance. However, the monitoring location on the panel can give significantly different results. The authors noted a difference of up to 0.1 % for different locations of the same panel monitored at the same occasion. Knight and Thickett (2007) monitored the width change of a crack opening. This is interesting since open cracks are considered to work as expansion joints and are able to relieve stresses in wood (Camuffo et al. 2014). If the distance between the transducers' attachment points to the wood had been reported and not only the width of the crack (Table 2), the accurate strain value could have been calculated and would have included the deformation of the wood as well as the opening and closing of the crack. However, the authors further notice that some unexpected phenomena occurred. At times the wood did not at all respond to RH changes or at other times deformed without a change in RH. This was explained as possible release of accumulated stress and that large deformation could also occur on small changes in RH (Knight & Thickett 2007). These observed phenomena could possibly also be influenced by temperatures or be explained by studies on moisture gradients in wood during dynamic climate conditions.

Among those studies listed in Table 2, which reported the cut of the wood used in their research, all were radial. This is known to be much more dimensionally-stable compared to the tangential cut. This may be one reason why the divergent results cannot really be compared. Another problem to overcome when monitoring deformation of objects or samples is the influences of stresses in materials. To what extent the wood is constrained and therefore totally, partly or occasionally limited in its movement will of course influence the results and restrict different studies from being related. In Table 2 it is not known to what extent all of the monitored objects or samples are restrained or not and this will of course also influence the results. One would expect constrained wood to show less strain compared to wood which is free to swell and shrink. However, there are also published results which show the opposite. Brewer and Forno (1997) made tests on radial-cut oak panel samples. One was free to swell and shrink and the other cradled on the reverse side. Both panels were sized and coated with linseed oil paint containing lead white on the front side. For an unrestrained panel subjected to a step-change in RH from 29 to 80 % RH the recorded in-plane strain was 0.47 %. For the cradled oak panel subjected to a step-change from 33 to 72 % RH, the cross-grain average strain was recorded to be 0.52 %. There was also a clear asymmetry in distribution of the measured strains; close to the edges, the strain was 0.61 % which can be attributed to greater moisture permeability towards the end grain of the panel. The battens are also influential. In front of a fixed batten the strain was typically 0.35 % but as much as 0.69 % between the battens. Other reasons which may influence the results are the relation between in-plane and out-of-plane deformation; some battens restrict bending but not in-plane movements (Brewer & Forno 1997).

Under a fixed load the materials will creep and stress relax under fixed displacement constraints. Deformation or damage due to mechano-sorption, which is significant in fluctuating RH and temperature environments, not only show larger deformation but also a larger recovery degree, compared to step-changes. How this influences the total strain and permanent damage should be investigated in future studies.

3.9 Summary and conclusions of Sections 3.1 to 3.8

Wood responds to changes in RH and temperature of the ambient air by adsorbing or desorbing moisture. This in turn leads to deformation of the wood if the samples are free to swell and shrink, or to internal stresses if the wood is restrained from moving. In conservation science the majority of research has been performed on mechanical deformation of the material. As in engineering and wood sciences, the research has gradually been more focused on developing numerical models to validate the empirical experiments and to be able to use the models as a complement to the experiments. The developed models are often based on the wood reaching full EMC at different RH levels on adsorption and desorption (isotherms) and simultaneously maximum deformation at each EMC step. Such experiments have been performed in laboratory settings on step-changes in RH and constant temperature. These worst case scenarios are the foundation for the recommended environmental ranges for hygroscopic cultural heritage objects. From this research the yield strain has been proposed to be the precautious limit not to cause plastic, permanent deformation. The materials tested are mainly associated with paintings on wood and canvas. Besides museums, there are a very large number of cultural heritage objects housed in buildings which are not environmentally-controlled to museum standards. Observations of objects in such buildings have shown that permanently-heated buildings with no RH control have caused much damage to hygroscopic objects while those hygroscopic objects in less-heated buildings are in a rather good state of preservation. In non-heated or intermittently-heated buildings the highest RH levels are normally found during the winter seasons and therefore coincide with low, and in periods, sub-zero temperatures. Moreover, such environments are characterised by large daily and seasonal RH and temperature fluctuations.

The overall factors which will determine how much a wooden object or sample will deform or lead to increased internal stress, is the RH and temperature amplitude in combination with the duration at which it is subjected to these conditions. Materials′ E-modulus and external load (restraint) are also important factors. Studying several parameters simultaneously is complicated and hence it is understandable that investigating more than solitary parameters at the same time is the preferred method. However, knowledge of the combined influence of daily, seasonal and sometimes weekly or monthly fluctuations of RH and temperature is crucial, because it has not been proven that they can be covered in the worst case scenario concept. It is more likely that these parameters, from time to time, either reduce or enhance the actual deformation and stresses. It is clear that the area of research is very complex and the results of the studies are often unclear and inconsistent. There are assumed to be additional areas which need to be studied further in order to confirm or adjust the present climate criteria in museums and in historic buildings (see Chapter 6).

It is reasonable and could be anticipated that seasonal changes in RH would influence MC and deformation at depth in more massive objects while the daily fluctuations only influence MC and deformation in thin objects or the surface of thicker objects. The research results so far show contradictory results and therefore conclusions cannot yet be drawn. In dynamic environments EMC is probably seldom or never reached and therefore the actual deformation can be assumed to be smaller compared to deformation at full EMC. However, before EMC is reached, moisture gradients through the material are present, which creates transient internal stresses in the material. Knowledge on how these stresses develop and during which circumstances they increase or decrease is scarce. Theoretically, moisture gradients could possibly also function as a buffer and reduce the rate of MC changes in wood and thereby release stresses.

Moisture transport processes are complex, especially in the higher RH range. The isotherm in the higher RH range is steeper compared to the mid-RH range and therefore a small change in RH is assumed to cause a relatively large change in EMC and subsequent deformation. However, in the higher RH range the diffusion coefficient (rate of sorption) is reduced, which indirectly also influences the rate of deformation. The practical consequence is that, although a small change in RH will cause a large change in EMC, in natural environments the wood will take longer time to respond to a change in RH in the higher RH-range compared to the mid-RH range and hence the impact will not become as large as theoretically calculated. Low temperatures retard the response delay and response time even further. Using actual MC data instead of EMC might come closer to reality but is still only a mean value of the moisture present in the entire wood sample. It will not show the progress of the moisture gradients inside the wood. To predict moisture transport and deformation in wood by means of mathematical modelling used to predict the environmental impact on cultural heritage objects is not completely consistent with reality, especially not in the higher RH range. Complex combined models are needed to reflect the actual deformation process.

On a step-change in RH the MC and deformation of an uncoated wooden sample and resulting deformation is normally asymptotic, showing initially a fast increased change, which gradually decreases and results in maximum deformation or stress. This occurs when EMC is reached. In cultural heritage objects assembled of parts of various materials and thicknesses, the response rate needs to be considered because the pieces of the objects have individual response rates. While some materials may have reached EMC and the assumed maximum deformation in a given period of time, others may not have started to respond to the RH change yet. Objects of combined materials, such as painted panels, respond quickly to their maximum deformation and have fully or partly relaxed in the same time period. Parts of the object may be subjected to restraints or loads while other parts are free to swell or shrink. Objects are therefore subjected to both external stress, due to restraint or applied load, and internal stress due to changes in RH or temperature. The combined effect should be able to increase or even at times decrease the impact allowing the object to stress relax.

In non-climate-controlled environments this is of course even more complex. Based on the worst case scenario, wooden objects are assumed to be fully restrained, not allowed to swell and shrink. In such conditions, it is likely that objects in historic buildings are subjected to a large extent to creep deformation. However, not much research has so far been performed on mechano-sorptive creep in the cultural heritage sector although such circumstances are likely of outmost importance for objects in historic buildings. Repetitive RH cycles under load are shown to create larger deformation in wood compared to an applied load on a single step-change in RH under the same load. However, depending on the load magnitude, the stress will increase or decrease over time. Low temperatures reduce the MC fluctuations in wood. In the cases where RH fluctuations are larger so is the recovery on released load. The magnitude of mechano-sorption depends on RH amplitude not the RH range (mid compared to high RH range). Recovery is larger in the higher RH range compared to the mid-RH range. Viscoelastic creep may also be involved and it is possible that it reduces stress levels over time in thicker wooden objects. Also the type of load or restraint is important. Compression load results in larger deformation compared to tensile load.

Experiments have shown that, while the yield strain is rather constant in the entire RH range, the breaking strain is only constant in the low and mid-RH range. At high RH the breaking strain is dramatically increased, allowing larger deformations before failure. It has been proposed that most cultural objects have been subjected to harsh environments for longer or shorter periods of their existence and that they likely have undergone various degrees of plastic deformation, the so called strain hardening.

Comparing the difference in moisture transport and mechanical properties of aged wood in comparison to fresh wood from several studies showed that there is no clear distinction between fresh and aged wood. However, in a thorough study, fresh wood was compared with aged wood which had been located in different environments, heated buildings as well as in non-heated buildings. It showed that the fresh wood had the highest sorption isotherm and moisture transport rate compared to the aged wood, indicating a reduced hygroscopicity with age. Of the aged wood the timber which had been housed in a cold environment showed least response to RH changes. The same pattern was seen in the creep experiments, the least creep deformation was recorded in the aged wood from the non-heated building. Moreover, the experiments showed the aged wood had a higher viscoelastic deformation (relaxation) in relation to deformation compared to the fresh wood. The difference from this pattern was the total deformation which was greater for the aged wood.

Low temperature retards moisture transport in wood and therefore the MC amplitudes will be reduced and the response delay will increase. However, creep and the structural relaxation time will also be prolonged. As far as has been found, limited research has been performed in wood science and engineering on low temperatures. The levels of temperatures' influence on mechanical deformation has mostly been ignored and seen mainly as a factor to control RH. There are research results which favour the use of low temperatures and others which raise concerns on the painted or gilded layers on wood. Sub-zero temperatures are considered to cause damage to paint and varnish layers due to the passing of T_g. On the other hand sub-zero temperatures are used for pest eradication and are considered safe also for painted wooden objects.

The relationship between stress and strain has a linear behaviour in the elastic range. The E-modulus is influenced by MC as higher MC results in a lower E-modulus, which in turn results in a more flexible material, whereas low T increases E-modulus. In a non-heated historic building during winter the combination of high RH and low temperatures could be assumed to balance the high and low E-modulus. However, according to Fig. 11 higher MC in combination with colder temperatures results in a stiffer material. In a fluctuating environment creep is strongly dependant on the E-modulus, in that a higher E-modulus makes wood more resistant to deformation and the wood will last longer before failure (Fig. 12a). This combination may be a contributing factor to why wood can tolerate cold and humid environments. Moreover, it is also suggested that high RH may act as a plasticiser for acrylic paints decreasing *Tg* which would then make the paint less fragile in non-heated buildings. Published studies on the combined effect of fluctuating temperature and RH on wooden objects in the cultural heritage sector have not been found.

Based on the research which has been performed in the cultural heritage sector alone it is difficult to make conclusions on what should be considered to be recommended environmental criteria for wooden objects in historic buildings. One important reason is likely the experimental setups. The methods and the materials, or combination of materials tested are too diverse to be compared.

The question is, whether deformation during stable and fluctuating RH and temperatures can be compared at all and hence whether climate criteria based on worst case scenarios are suitable for objects in historic building environments? From literature it cannot be evaluated if those conditions are better or worse. In several articles the strain has been monitored in relation to the fluctuating RH (Table 2). The results showed that in those cases the yield strain (0.4 %) was not reached, RH monitored was not exceeding +/- 16 % RH. When, on the other hand, the yield strain was exceeded the RH changes were above +/- 20 % RH. In a non-heated church the change was +/- 32-35 % RH and still the monitored yield strain was not reached. Hence, it is possible that the cool temperature was contributing to the reported good state of preservation of the painted crucifix in this church. At present, studies are too few to make a reliable conclusion. However it should be noted that RH fluctuations and the yield strain of the wooden objects partly fit with the suggested climate criteria. Low temperature may increase the safe RH changes.

At present the results of different experiments are difficult to compare directly, since different loads, samples size, RH and temperature ranges, types of monitoring or analysing equipment might give different results. For instance, the different methods of monitoring deformation need to be evaluated and compared. When comparing engineering or wood research and cultural heritage research, both the aims of the research and the methods used are different. However, it is necessary to map any discrepancies or conflicts in understanding areas which need to be further investigated. In the end it would be useful to develop standardized methods for laboratory as well as in-situ applications to achieve a larger number of results which are both comparable and aim to study the impact of climate on objects in historic buildings.

3.10 Damage assessment, cause-effect and damage functions

As can be stated from the above in Chapter 3, there is an extensive amount of research on moisture transport and deformation of wood available in wood science and engineering science. However, the results cannot be used uncritically and unprocessed in conservation science to evaluate the impact of indoor environments on objects or whole collections. The task conservation science is facing is much more complex in many ways. The results presented in cultural heritage research on environmentally-induced damage and suggested recommended climate ranges are still unclear. Monitoring of mechanical deformation of individual objects in their own indoor environments has been employed, as presented in Table 2. However it is not always possible to observe on a macroscopic level when an object has passed the yield strain and is suffering from permanent deformation. Studies of climate- induced damage to objects are rare and the individual cultural heritage objects are too unique to give statistical foundations for types or groups of objects. Therefore additional methods should be engaged by comparing the results from laboratory studies of specific materials to ascertain what type of, and to what extent, damage to objects are present or absent in particular indoor environments (Luxford *et al.* 2012).

Damage assessments or condition surveys aim to determine the state of the objects or collections and causes of deterioration (Taylor & Watkinson 2003). However, to specifically evaluate the cause-effect relationship between damage and indoor environment is extremely complex, which has been pointed out by several authors (Ashley-Smith 1999; Ashley-Smith 2013; Leijonhufvud *et al.* 2013; Strlič *et al.* 2013). Referring to the research project *Collection Demography: On Dynamic Evolution of Populations of Objects,* Ashley-Smith disagrees with the claim that demographic studies of objects exposed to different environments are possible to be performed, unless the population studied is both large and fairly homogenous, as for instance books or paper in archives and libraries. (Ashley-Smith 2013; UCL Institute for Sustainable Heritage n.d.). This is so because both *damage* as well as *indoor environment* need to be defined and quantified in order to be able to be correlated. The cause-effect relationship should therefore be based on a sufficient number of observations of the factors which affect the rate of deterioration so that it is possible to combine the most important of these into mathematical equations or algorithms.

Mecklenburg explains *damage* to be either permanent deformation or actual cracking (Mecklenburg 2007a). Within the Climate for Collection project, Ashley-Smith at first defined damage as *unwanted irreversible change*. However he also questions this definition since not all damage would be regarded as unwanted. Historic objects are valued because they not only are old, but look old, and this change would not normally be called damage, but being venerable, timeworn or having a patina (Ashley-Smith 2013). *Damage function* is a quantitative expression of cause and effect relationships between environmental factors and material change. In the cultural heritage sector a damage function can be defined as an equation or an algorithm that relates quantifiable factors in the object's environment to quantifiable changes within the object. *Dose-response relationship* is a subgroup of damage functions. A dose-response function shows the relationship between the total accumulated dose of a hazard such as light or a pollutant gas to measureable change in a material after a certain time of exposure. The function is linked to the rate of change and to the concentration of the active agents of deterioration (Ashley-Smith 2013).

Leijonhufvud *et al.* (2013) explained a number of uncertainties in damage functions; one example is the damage functions being based on single materials and thus not being representative of the variety of forms in which materials are found in cultural heritage objects. Deterioration processes nor synergetic effects are included in the damage functions which may also make them incomplete. Another factor influencing the damage functions is the interpretation of the output, that is, the predicted material change. Most damage functions will only predict a relative change and the interpretation of damage is subjective. Michalski (2013) generally describes damage functions as having low precision because they assume a universal object and have a poor applicability to a varied collection; they generalise average behavior of materials and assume a single, simple geometry. Another important aspect of damage assessments is the often low reliability in the results of such surveys. Taylor has in a number of papers studied the subjectivity, bias, reliability, causes and extent of varying results; subjectivity or bias was for instance present among surveyors with a different range of levels of conservation background when performing condition surveys (Taylor & Stevenson 1999). Even interventive and preventive conservators may give different scores in condition surveys (Taylor 2013). The agreement of the same surveyor executing condition surveys of the same object but ten weeks apart also showed a large variation, from almost identical response to near-chance agreement. One surveyor will not show more consistency in assessment than two different persons will (Taylor 2011).

The climate histories of the objects also cause uncertainties since the objects may have moved between various unknown environments, as for instance described by Legrum (1994) and it is not possible to know when certain damage occurred. It is also possible that objects have been subjected to different types of treatment in past times. These could have caused damage to wood and painted layers that today may mistakenly be related to damage due to adverse indoor environments. Damage is cumulative, but does not necessarily develop at the same rate or within the same range over the course of time. Mechanical damage due to RH and temperature does not develop separately from, but is also influenced by, chemical and sometimes biological deterioration. These factors are also in turn influenced by factors such as light and air pollution. Damage assessments will to some extent discover and separate the impact of these factors but it is would remain uncertain to which degree each factor contributes to the overall damage. A condition survey of objects at a certain time will only determine the cumulative damage up to that date. It is not possible to determine the future damage progress rate without knowing about the future environmental impacts and by making regular follow-ups or evaluation in comparison with older photo documentation for example.

In order to link damage to the indoor environment the RH and temperature also have to be monitored and evaluated. However, also here there are some complications which make this factor more uncertain. The microclimate in the vicinity of the objects may not be the same as the RH and temperature data monitored for the general indoor environment of a room or a building and this will affect the understanding of climate-induced damage (Camuffo 2014). Current RH and T data may not be representative for the indoor environment the objects have been housed in during the course of their life and relating damage to those data may also be misleading. Even more important is that RH and temperature is only used as a proxy for MC of the materials; thus the indoor environment is only indirectly being related to damage (Leijonhufvud *et al.* 2013). It is more practical to monitor RH and temperature of the air in comparison to MC of objects or samples to relate to damage. However, a procedure to define and quantify both RH *and* T data as a combination, taking shorter term and longer term fluctuations into consideration, is so far lacking in the cultural heritage sector.

Despite the fact that damage assessment as a tool for evaluating the impact of RH and temperature is both unprecise and coarse, it is a method commonly used by conservators, and it is practised as a part of collection management, preventive conservation and risk assessment. From existing research and knowledge on climate-induced mechanical damage, as well as on chemical and biological deterioration of various materials, risk assessment models have been developed, such as eClimateNotebook (Image Permanence Institute 2015) and Physics of Monuments (Martens 2012). RH and temperature data can be uploaded on their websites and in response an assessment of the risk for various materials is received. As for most research, these tools are based on average material research or single objects and it is questionable if this is a sufficient basis for a risk assessment.

However, there are examples of specialised and systematic studies where an assessment is made of a predetermined type of damage patterns to evaluate a specific research question. These methods could possibly be developed to be used as dose-response functions for climate-induced damage. Here, interpretation of the cause of damage found during the observations is excluded but instead only the damage is recorded and occasionally also quantified. Bucklow used such a method when examining different appearance of crack patterns on canvas paintings and panel paintings in order to determine the country of origin of the paintings (Bucklow 1997; 1998; 1999). Two groups performed the assessment; one professional group, including trained conservators, and a second group consisting of persons with no experience in examining craquelure. The second group was given assistance in how to evaluate the crack patterns while the first group was not assisted. Both groups scored approximately 75 % in determining which paintings where Flemish, Dutch, Italian or French. The results were also statistically confirmed.

Brunskog (2003) used three different models to study the structure, alterations in the material, dating of the objects and answering questions concerning authenticity of the painted surfaces of 61 Swedish japanned objects. One of the models she used was the one suggested by Bucklow (1997; 1998; 1999), presented above. In this assessment she noticed that the interpretation changed with experience of examining many objects and this might have influenced the results. In another study by Brunskog (2012), she compared the impact on painted wooden surfaces in non-heated or intermittently-heated churches to permanently-heated churches. Digital pictures of 394 individual painted surfaces from 53 churches were taken and this procedure was repeated again after approximately three years. During the period between the imaging, the RH and temperature of the churches was monitored. Based on the survey it was not evident that large RH fluctuations could be related to paint loss. However, development of cracks and elongation of existing cracks were more evident in the heated churches compared to the non-heated churches.

Holl (2013) made an assessment of gilded wood ornaments in Linderhof Palace in Bavaria. She compared pictures of gilded surfaces exhibiting damage taken in 1992 and the same surfaces 20 years later. The palace was not heated at the time of the study but had been heated earlier. The results were compared with climate records from two rooms. Delamination of the gilded surfaces and mould growth were related to recorded RH and temperature, analysing the amount of time the climate deviated outside the guidelines of Thomson (1986) and ASHRAE's control class D (ASHRAE 2011). The result showed more damage, in terms of loss of gilded surfaces, close to, or on outer walls. According to Holl, this was attributed to higher and more fluctuating RH which was noted in these locations compared to in the centre of the same room. The observed losses were noted also on the pictures from 1992. It was suggested that the damage was related to the heating which had been in use while the castle was still inhabited. Further, the least damage was notable in the room with the highest RH and lowest temperature. However, this was explained to be due to different gilding techniques used in different rooms of the castle (Holl 2013).

Using damage assessment as a tool to relate damage to indoor environment is extensively questioned. However, the few damage assessments on painted and gilded wood described here show that the methods may be used under certain conditions. Such methods should be developed and used further. Moreover, in a recent report from GCI a group of scientists and conservators have also brought forward the advantage of using epidemiology for future studies in the field of cultural heritage. It can for instance identify how environmentally-driven adverse effects are distributed in museum collections. It can involve both individual studies of comparable groups and, importantly, to develop a governing set of principles for evaluating reliability and accuracy of evidence. Thus it may be used to develop environmental guidelines (Druzik and Boersma 2017).

3.11 Environmental standards, guidelines, specifications and recommendations

As the research on the effects of indoor environments on objects and collections has gradually increased during the last decades, so have the numbers of environmental specifications, guidelines and standards. The RH recommendations in the 1960s were in the RH range 45 to 65 % RH for different organic materials (Michalski 2016) and were followed by the much-narrower climate specifications (class 1: 50 or 55 +/- 5 % RH and 19 +/- 1 °C (winter) up to 24 +/- 1 °C (summer)) as proposed and specified in the 1970s and 1980s by Thomson (1978, 1986). However, as has been cited in conservation literature many times before, Thomson recognised that the tolerance to RH fluctuations was more based on the capacity of the air-conditioning plant than what exhibits can actually stand without being harmed, 'which is not known in any detail' (Thomson 1986 p. 119). It is clear that, although building and exhibition designers need simple climate targets for running climate control in museums, these targets cannot form standards and guidelines for museum collections (Michalski 2011).

As shown in Section 3.5.1, the development of standards based on research was mainly performed in Canada and USA during the 1980s and 1990s and pointed towards less strict environmental standards compared to the specifications by Thomson. CCI had already suggested changed standards in 1979, after recognising that most Canadian buildings could not sustain adjustments of RH levels to 50 % RH during the winter season, and variations in the seasonal RH set point were implemented (Michalski 2011). The scientists at the Smithsonian Institution concluded in 1994, as a result of their studies, that 30 to 60 % RH (45 +/- 15 % RH) was safe for most hygroscopic materials. Ten years later, in 2004, The Smithsonian Institution announced their new environmental standards (45 +/- 8 % RH), well within the recommended ranges (Erhardt et al. 2007). In Europe, the announcement of the Bizot group (National Museum Directors' Conference 2009) on *Proposed interim guidelines for hygroscopic materials* suggested there should be a stable RH of 40 to 60 % range and a stable temperature in the range 16 to 25 °C. Five years later, major conservation associations had accepted the wider environmental standards (IIC and ICOM-CC 2014). In 2016 IIC and ICOM-CC announced that the existing interim guidelines should be guidelines not interim guidelines (Bickersteth 2016).

There are few standards or specifications which are aimed explicitly at historical building environments. Bratasz *et al.* (2007) introduced a new approach, assuming that it is not possible to achieve a perfect environment for mixed collections. Instead they suggested a method to replicate the particular environment objects of organic materials have been located in and hence adapted to. It used a 30 days moving average of the annual RH measurement and removed the 16 % largest, most risky fluctuations, corresponding to one standard deviation, from the moving set point. The method later became CEN EN 15757:2010 and aimed to limit mechanical damage to objects of organic hygroscopic materials in historic buildings. Short term fluctuations of +/-10 % RH or below are considered not to cause any damage to organic materials (CEN EN 15757 2010). The standard can be used for RH or temperature separately but not for both parameters in combination. The EN 15757:2010 standard has later been criticised for not being able usable in all climates, such as the Portuguese temperate climates (Entradas Silva & Henriques 2014).

The United Kingdom's National Trust has long experience in climate control of historic buildings and uses conservation heating for most of their buildings. In their *Specification for Environmental Control* the aim is to keep the humidity between 40 and 65 % RH for 90 % of the time. This specification also accepts a larger temperature range, going as low as 5 °C. The specifications are set to the needs of collections, visitors and staff as well as to reduce the energy consumption as much as possible (Blades & Staniforth 2011).

Environmental guidelines presented in the ASHRAE Handbook, in a new edition every third year since 1999, are the standards that appear to be the most generally useful. They cover the environments in many types of buildings, from strictly climate-controlled museums (class AA or A) to historic buildings with various levels of climate control (class B, C and D). Associated with the classes are also the known related damage and deterioration risks (ASHRAE 2011).

In an overview paper on the development of environmental guidelines Michalski concludes that, after a period of strict environmental guidelines, the environmental ranges are now widened and are back at the 1960s environmental recommendations (Michalski 2016). However there are still criticisms of and scepticism towards the guidelines and standards, arguing that the acceptable climate ranges are not yet fully known and therefore there is an increased and unacceptable risk of damage to collections on allowing wider RH and temperature ranges (Hackney 2009; Cassar 2011; Hatchfield 2011; Roy 2011; Burmester & Eibl 2013; Bickersteth 2014; Staniforth 2014) Conservators have asked if the amount and type of research performed is sufficient for taking further steps towards more relaxed recommended climate ranges. If not, it is centrally important to identify the gaps and specify which type of research is needed, with researchers and conservators being in agreement.

Partly as a response to the *Proposed Interim Guidelines for Hygroscopic Materials* (National Museum Directors' Conference 2009) and the tendencies of widening the environmental guidelines, EGOR (Environmental Guidelines: Opportunities and Risks), a group of mainly British researchers stated that there is not sufficient knowledge on the effect of indoor environment to support existing environmental guidelines (Hackney 2009; Strlič 2009). There had also been serious concerns raised about The British Standard (BS) 5454:2000 *Recommendations for the Storage and Exhibitions of Archival Documents* because it was difficult to meet its narrow environmental specifications without installation of invasive, expensive and energy-consuming HVAC systems. The standard, aimed at archive materials, was also being applied to other types of collections (Ashley-Smith 2016).

In 2009, EGOR presented a report on current knowledge as well as shortcomings in present environmental standards and guidelines at that time (Hackney 2009). One of the outcomes of the EGOR initiative was a recommendation that new environmental standards based on recent scientific evidence should be developed for cultural collections in the UK (Cassar 2011). This standard later emerged as *PAS 198:2012 Specification for managing environmental conditions for cultural collections* (BSI 2012). However, unlike a true British standard, a PAS (publically available specification) is open for comment and may be considered for further development. Its aim is not to tell you what to do, but instead provide a framework to support you in thinking about what you need to do. It emphasises that individual institutions must make their own policies based on their own needs (Ashley-Smith 2016). The important aspect of PAS 198:2012 is that it is only based on actual scientific evidence, taking all materials commonly found in museum collections into account. It acknowledges that there are areas which are not sufficiently known and hence it does not give strict and specific climate ranges. Moreover, it also includes the impact not only of RH and temperature but also light and air pollution. These parameters are presented separately and in combinations with each other to stress the vital impact of synergetic effects. It is aimed at people qualified and experienced in the care and management of cultural collections. It does not take architectural or engineering aspects of environmental control into consideration. However, the reduction of fossil fuels aspect is acknowledged (BSI 2012). PAS 198:2012 was later incorporated in the European Standard, *CEN EN 16893 Conservation of Cultural Heritage - New Sites and Buildings Intended for the Storage and Use of Collections* (CEN prEN 16893 2015).

From the perspective of this thesis, the current research, subsequent environmental standards and critique it is clear that there are areas which need to be studied more thoroughly in order to more firmly establish the appropriate standards among conservators. With few exceptions, standards are not specifically based on dynamic environments. Studies on the effect of temperature on MC and subsequent mechanical impact on wood and other materials will add a more realistic understanding of the influence of indoor environment on cultural heritage objects.

4
Summary of the studied parts

4.1 Background study: Evaluation of how risk assessment websites are using existing research results on climate-induced damage and deterioration (Paper I)

4.1.1 Introduction

In conservation, it is challenging to establish the actual cause-effect relationship and to quantify dynamic degradation as well as mechanical stress and strain within materials. Therefore, the worst case scenario is often used to determine how much change in RH and temperature a material can withstand without permanent deformation. What is examined is the EMC of the materials and thereby what maximum shrinkage and swelling are reached, neglecting the time factor necessary for the material to reach the EMC. Moreover the temperature is seldom taken into account, which will in particular influence the results for historic buildings with limited climate control.

There are methods available for evaluating the risk of the indoor climate to organic and inorganic materials based on current knowledge. Risk assessment websites use present knowledge to determine if collections housed in a specific environment are at risk for chemical, biological deterioration or mechanical damage. Two such websites examined were; eClimateNotebook from Image Permanence Institute (IPI), and Physics of Monuments from the Technical University of Eindhoven (TuE). The latter is no longer in use. IPI based their website on their own research, sometimes in cooperation with other institutes, while TuE used the results of the conservation research community. On both these websites RH and temperature data can be uploaded and the site algorithms respond with quantified estimates on risk impact of the specific combination of RH and T for various materials and objects. The aim of Paper I was to compare and evaluate the performance of these two websites. Of particular interest were whether the two website corresponded and if not, for which type of indoor environments?

4.1.2 Method

Climate data collected during thirteen months, from four different indoor environments, were uploaded onto and analysed by the two risk assessment websites, eClimateNotebook and Physics of Monuments. The environment data originated from a museum with controlled RH and temperature, a church with temperature control, not allowing temperature below 18 °C resulting in very low RH in winter periods, a castle with dehumidification keeping RH below 70 % and finally the same castle but a room with no climate control and consequently large daily and seasonal variations in both RH and temperature (Fig. 2). The result for chemical, biological (mould) and mechanical damage were compared and evaluated.

4.1.3 Results

The results from the two websites showed similar risk patterns for mould. Only in the castle with no climate control there was a clear risk. Also for chemical deterioration the results showed mainly an overall resemblance for the two websites (Paper I, Table 3). Both websites indicate that there is an enhanced risk in the museum environment because of a temperature higher than 20 °C. The least risk was shown in the church with temperature control and subsequent dry environment in the winter periods. However, for mechanical damage risk the results from the two websites were less congruent (Paper 1, Table 4). Both websites are in agreement that the museum climate with a controlled RH and temperature has the most beneficial indoor environment. Besides this, eClimateNotebook considered the temperature-controlled church environment to be a risk while Physics of Monuments considered it to be safe. For the castle with a dehumidified room and a room with no climate control, Physics of Monuments evaluated them to be similarly safe, while eClimateNotebook ranked the dehumidified room to be safe but the uncontrolled environment to be a risk.

Both websites recognise the response delay as an important parameter in assessing damage risk. eClimateNotebook uses a 24-hour running average for temperature and 30-day running average for RH. Physics of Monuments uses set delays for different types of objects (Martens 2012). It is clear that the response delay varies with, for instance, the material, volume and density of the objects. Therefore, to use fixed calculated response delays may give less reliable results than does excluding this factor.

There are many details in this study and there are many possible reasons why the results from the two websites did not coincide for mechanical damage. However the most important conclusion is that the research on which such models are based is up to now not comprehensive. The ways in which the design of the models have interpreted and used existing research results are not clearly revealed. Also, there are knowledge gaps in the literature, such as the influence of temperature, response delay and studies of dynamic climate conditions, which are not taken into account in the models. This is essential, not only to be able to establish safe climate ranges, but also to improve modelling and thereby make risk assessment websites as reliable as they should be.

4.2 Field study: Exploring a cause-relation method to quantify past and present indoor environments and cumulative damage to objects (Papers II and III)

4.2.1 Introduction

It has been observed and reported that mechanical damage to painted wooden objects is more frequent in permanently-heated historic buildings in comparison with non-heated buildings. It is assumed that larger energy consumption will create increased temperatures and reduced RH, which in turn could cause damage. However, the complexity and diversity of the materials and objects studied is large and the indoor climate monitoring which has been performed only reflects a very short time period in which the, often very old, objects have been subjected to the climate studied. The state of preservation of the objects as observed today is the cumulative effect of the indoor environment (and other influences) which the objects have been affected by, constituting the cause. The aims of both Paper II and Paper III were to quantify both the *cause* and the *effect,* by investigating the possibility of evaluating whether damage to painted wooden objects could be related to the total energy consumption and heating regimes over time. In Paper II the focus was on damage assessment and in Paper III the method of using heat output as a proxy for the indoor environment was described.

4.2.2 Method

The method used two measures for studying the relationship under observation: 1) energy used for space heating (heat output) as revealed by archival sources, to extrapolate climate data and 2) relative damage scores from the survey of painted wooden pulpits, which would serve as climate indicators. For this purpose 16 mediaeval churches on the island Gotland in the Baltic Sea were studied. The churches were all erected before ca 1350 and are similar regarding their building location, construction and materials as

Fig. 17. Observation and registration of possible damage to wood and painted layers (Photo: Maria Brunskog).

well as in their furnishing. They have also been subjected to rather similar climate conditions. The time period chosen was 1900 to 1990, a period for which archival data is available on heating and fuel consumption. The pulpits in question used for the damage assessments are all similar in construction and components, and located in a similar position in all the churches.

Energy consumption was used as a substitute for climate records, on the assumption that higher internal temperature and therefore lower relative humidity will occur more frequently in churches with greater expenses for fuel. A number of archives were studied and in some cases the parishes' own records on heating systems and historic fuel consumption. The heating systems used during different periods were revealed, including the systems' efficiency, as well as each type of fuel's specific energy value in order to quantify the output. Sometimes the parish account only specified the cost of the fuel and not the volume. Therefore the local fuel rate during the period was examined to extrapolate the consumption. The values were divided by the square meter area of each church, as a proxy for volume. Every fifth year was explored and therefore the total heat output was multiplied by five to compensate for the years not examined. Finally, the churches which today use back ground heating (11 churches) and those churches not using back-ground heating (5 churches) were also related to damage of the pulpits.

The damage survey, to explore the type and amount of damage, was performed on the pulpits in the 16 churches (Fig. 17). Beforehand, a set of damage patterns for wood and paint was determined as damage indicators (cracks and open joints in the wood, delamination of and craquelure in the painted layers, flight holes from wood boring insects and mould). These could be related to high, low or fluctuating RH. These indicators were strictly used without interpreting the origin of the damage or in any other way evaluating the damage. A subjective ranking from 0 (no damage) to 3 (high amount of damage) was used in order to quantify the damage. For the paint, two separate assessments were made, one for the painted surface as one unit as well as one for the different colours of the polychromy.

4.2.3 Results

The study demonstrated that the energy used to heat a church in the past can be extracted from public archives. It also pointed towards a possible relationship between damage and heat output. The results suggested that more damage is present in churches with a higher heat output and there was increased damage in churches using background heating compared to churches that did not.

The study showed that it is possible to track the heating variations by using archival sources and parish accounts (Paper II, Fig. 6). It is clear that the heat output was low and similar in the 16 churches until the end of World War II and that this was followed by a strong increase which lasted for approximately 25-30 years.

Relating heat output to damage of wood and painted surfaces showed the results that follow. Painted layers appear to serve the purpose of damage indicators the best. There was no relation between damage to wood and flight holes and mould, as described in both Paper II and Paper III, while the paint on the other hand showed weak or intermediate relation with the heat output as well with background heating. Although the tendencies were not strong, which is also indicated by the correlation analysis, the results showed similar tendencies; more craqelure was found in the aggregative paint layers subjected to the higher total heat output (Paper III). Dividing the paint according to colour of the polychromy showed that there was more craqelure in paint from churches with background heating compared to churches without background heating (Paper II). Finally, craquelure in the paint layer and paint delamination was more frequent in churches with background heating compared to churches without. However the correlation analysis only showed a low correlation with craquelure in paint ($r^2 = 0.4$) and none with paint delamination. Furthermore there was no relation between the age of the pulpits (ranging from 1586 to 1778) and damage. The pulpits, in spite of being of different age, are all made of locally available wood (pine) and painted with the same but not identical type of paint. The pulpits also represent a fairly homogeneous population, in that they are immovable, and thus have been exposed in their exact original position, in the same cardinal direction and to the same outdoor climate (Paper II, Table 3). The reason may be several but one is that it appeared as if at least some of the pulpits have been repainted repeatedly. Another reason may be that the indoor environment in the churches has not changed much before the 20th century and therefore the pulpits have adapted to the cool and humid circumstances. However, this method needs to be developed, in particular on improving the damage survey. Larger populations are required to validate the results.

4.3 Laboratory study: Monitoring moisture gradients in wood (Papers IV and V)

4.3.1 Introduction

The aim of most research in the cultural heritage sector on climate-induced damage to wood and other organic materials is to determine recommended climate ranges. Rarer are studies which monitor the actual influence of RH and temperature fluctuations over time. Areas such as the effect of low temperatures and the indirect influence on MC and subsequent deformation of materials are of importance for collections housed in historic, not fully climate-controlled, buildings. In such buildings a dynamic indoor climate prevails, different from that in climate-controlled museums.

The aim of this study was to develop and use a method for monitoring moisture transport in wood. By monitoring MC at different depths in wood it should be possible to study in detail the dynamic impact of RH and temperature. The device should be able to be used for long periods of time *in situ* in historic buildings and museums as well as in controlled laboratory experiments.

The laboratory studies are presented in two papers. The first one (Paper IV) evaluated two methods for monitoring moisture gradients in wooden samples. The second paper (Paper V) used the preferred method emerging from Paper IV to study moisture diffusion in wood subjected to various indoor climate conditions such as can be found in museums and historic buildings.

4.3.2 Method

In Paper IV, MSR data loggers monitoring RH and temperature were used to monitor moisture profiles in Scots pine samples (RH and T monitoring method). The results were compared to the results obtained by using Protimeter HygroTrac equipment which monitors MC in wood by resistance (resistance monitoring method).

For the RH and temperature sensors, holes were drilled from the back (reverse) side of the wooden samples so that they reached different depths as measured from the opposite (front) side. The sensors were inserted in the holes, which were thereafter blocked in order only to monitor RH and temperature changes from the front side (Paper IV, Fig. 2 and 3). For the resistance monitoring method, metal pins were inserted in the wood, again from the reverse side. The monitoring depths for both methods were 1, 4 and 7 mm from the surface. Changes in MC of the wood at different depths were studied in a climate chamber programmed to imitate different fluctuations in RH and temperature (Fig. 18).

For comparing the results of the two methods, the RH and temperature data of the RH and temperature monitoring method had to be converted to MC values. This was done by taking into account both hysteresis effects and T-dependence of the sorption isotherms. According to the modelling of the results this method appeared to be the more reliable of the two and was then further used in Paper V.

In the second paper (Paper V) on the laboratory experiment, the RH and temperature monitoring method was used. The wooden samples were subjected to 10-day step-changes of RH at different temperature levels and daily RH fluctuations at different temperature levels as well as to fluctuating temperature (Paper V, Fig. 2 and 3). Moreover, daily fluctuations of different amplitudes with different set points (50 and 70 % RH) at different temperatures levels were tested, simulating a museum indoor climate and colder historic buildings (Paper V, Fig. 4). Finally, intermittent heating of a church, simulating heating episodes during Sunday services, was examined (Paper V, Fig. 5).

Fig. 18. Wooden samples in the climate chamber and the two different pieces of equipment used for monitoring moisture transport discussed in Paper IV. On the top shelf are MSR data loggers monitoring RH and temperature and on the bottom shelf, Protimeter Hygrotrac loggers monitoring resistance.

4.3.3 Results

The results of the two MC methods did not coincide. The RH and T monitoring method provided reliable and consistent data suitable for calculation of MC from the RH and temperature data monitored at different depths, while the data generated by the electrical resistance method was inconsistent with the model. The results using the RH and temperature method were promising and were used for the monitoring of moisture transport in wood in Paper V.

The results presented in Paper V illustrated that temperature had a clear impact on moisture diffusion in wood. Low temperatures reduced the moisture diffusion rate, resulting in MC fluctuations of smaller amplitudes, both regarding daily fluctuations and for step-changes. Further, the response delay was increased at lower temperatures compared to higher temperatures. Combined fluctuating RH and temperature showed that, for daily fluctuations, the MC amplitude size was between those at constant 7 °C and 25 °C.

For step-changes (10 days), in RH at a constant temperature, or a combined step-change for both RH and temperature, desorption of moisture is a slower process than adsorption. Corresponding MC fluctuations in the wood as a result of RH changes decreased gradually with the depth from the surface. A response delay was also noted which gradually increased with depth.

A combination of a RH step-change and daily fluctuations retarded the time to reach EMC, which in this situation meant in that, in a given time period (12 h), adsorption reached further compared to desorption. Because this phenomenon was more pronounced closer to the surface, compared to deeper in the wood, the result was that MC at the three depths did not coincide but on the contrary spread over time.

On simulated intermittent heating, temperature had very little influence. The short heating episodes did not influence the MC gradients permanently but instead they returned to similar levels between the Sunday services (Paper V, Fig. 7)

The sorption history of the wood is important and will influence the results of moisture transport measurements in dynamic environments. This must carefully be taken into account in laboratory experiments and modelling. Moisture transport is complex and further similar studies are needed also in combination with deformation studies.

5
Discussion and conclusion

The overall goal of the work presented in this thesis has been to contribute to the understanding of the actual cause-effect relationship between dynamic indoor environments and wooden objects. The motivation was to understand the impact on hygroscopic cultural heritage objects subjected to radical changes in the indoor environment such as to climate change or altered heating regimes in historic buildings. The question regarding risks to preservation of museum collections on the one hand, and contribution to energy-efficiency measures, by allowing wider RH ranges in museums on the other hand, has been studied and debated in the conservation community since the 1980s. However, environmental conditions and their influence on objects in historic buildings have not been investigated systematically. The combined effects of RH and temperature need to be incorporated into experiments to give a full picture of how wood responds to the indoor environment.

From the research in the field of preventive conservation on allowable climate ranges for hygroscopic wooden cultural heritage objects, the yield strain developed during laboratory experiments has been proposed to be the safety margin to avoid plastic and thus permanent deformation. However, what needs to be further investigated is the span between the worst case scenario at equilibrium and the point where damage to objects actually occurs in various types of climates. It can be discussed whether the yield strain or the strain to failure should be used as the environmental criterion. Yield strain upon a step-change in RH or temperature can be measured accurately during laboratory experiments but this is much more complicated for actual objects. Mechanical damage visible to a naked eye, such as cracks, craquelure or detachment of paint layers observed in objects must be considered permanent damage as a result of strain to failure. On the other hand, slight warping in wood can indicate either permanent damage or a transient elastic change wherein the material has not reached the yield strain. To identify actual objects which have undergone permanent deformation or yield strains but not yet strain to failure appears thus to be difficult. Such objects may also have been strain-hardened and are therefore more tolerant to changes in RH and temperature. The accumulated knowledge in the conservation field on climate-induced damage to hygroscopic materials is not comprehensive. In some aspects it is ambiguous and in other aspects not fully investigated.

The contribution of this thesis consists of five papers, assembled into three adjacent parts, which investigated: 1) the interpretation of the state of knowledge on the effect of RH and temperature on wooden objects in the field of conservation; 2) a proposed method to relate damage to indoor environment in churches; and, 3) a method to study moisture transport in wood during laboratory experiments as well as in field studies. These objectives were focussed upon through the three parts as follows:

5.1 Evaluation of how risk assessment websites are using existing research results on climate-induced damage and deterioration

The closest agreement between the two websites studied was found for the museum environment (around 50 % RH and 20 °C). For the historic building environments the two websites obtained more diverse results. The credibility of the results from both websites for the museum environment is not proven just because they are similar however. Most research studying the effects of environments have been carried out at room temperature as found in museums, the more distant from such environments in RH *and* temperature, such as the indoor environments found in historic buildings, the fewer studies there are. It is possible that the larger uncertainties in the underlying research regarding environmental impact are reflected in the different results given by the risk assessment websites.

The temperature parameter was included in the models used by the websites regarding chemical and biological deterioration and these results are in fact similar for both websites. For mechanical damage, both websites state that the temperature parameter is excluded in their models. Therefore, they are not adapted to environments with high or low RH and temperature levels and the specific implications those environments may give. Both websites use response delay in their models, but the methods used are dissimilar. Studies on how to use response delay as a parameter to differentiate the response of different materials and different thickness have not been found. As reported in Paper IV and Paper V, the delay in moisture transport varies with depth in the wood and the delay is further increased by lower temperatures. How the delay in moisture transport influences deformation in general and at different depths is not known. Therefore, the relationship between dynamic moisture gradients and the mechanical impact on wood and other materials need to be analysed and these parameters incorporated in the models underlying risk assessment websites. Similarly, understanding of this relationship and the appropriate parameters need to be reflected in guidelines and standards.

According to the two websites, it is noted that the museum environment is not always safer than environments in historic buildings. By changing one of the parameters (RH or temperature), the risk of biological or chemical deterioration according to the websites is almost eliminated. In this study, the environments in the historic building with temperature control and the historic building with dehumidification gave the safer results compared to the museum environment (Paper I, Table 3). Looking at the results from risk for chemical and biological deterioration as well as mechanical damage (Paper I, Table 4), where the results from the two websites agree, it appears dehumidification in historic buildings should be studied further as a method for beneficial overall indoor environment for cultural heritage objects of wood.

5.2 Exploring a cause-relation method to quantify past and present indoor environments and cumulative damage to objects

Population studies are one way to investigate the impact of indoor environment on cultural heritage objects. In order to be able to relate these parameters, the challenge is both to quantify the indoor environment and to assess damage. The method of using archive records to quantify the energy use of the 16 churches is rare. To repeat the method, similarly comprehensive archives are necessary. While such data might be available for the occasional building it is probably rare for larger numbers of similar buildings. The criticism of using damage assessment as a method of relating damage to indoor environment is extensive, as revealed in Section 3.10. These arguments run counter to a large extent to the research on cause-effect relationship studies as used in Paper II and Paper III, and discourage such studies of damage assessment in general because the cultural heritage objects and the environment in historic buildings are by nature heterogeneous. It is true that existing damage-assessment methods are inaccurate and that the uncertainties are many. However, Section 3.10 further reviews adapted methods whereby the value aspect and subjective interpretation of the results are avoided in order to more directly relate mechanical damage to indoor environment. This was the approach was used in Paper II and Paper III.

It is pointed out that the results reported in Paper II and Paper III are not sufficient to give clear outcomes (Druzik & Boersma 2017). The correlation analysis in Paper III gave a weak correlation ($r^2 = 0.4$) for the relationship between craquelure in the paint layers and total heat output in the churches (Paper III, Table 3). This result could be expected from the heterogeneous materials in the objects and indoor environments as well as by the small population of only 16 pulpits and churches. Therefore, the results can only be seen as an indication. However, in Paper II the relationship between craquelure in the paint for each of the various colours on the pulpits and churches with background heating as well as without background heating (Paper II, Fig. 7) was studied and the same tendency was found. Damage was more apparent in churches with background heating compared to churches without any heating. These two results support the observations that painted wooden objects are reported to be damaged in buildings which are heated compared to those which are non-heated. Putting the results from Paper II and Paper III in context with the few other studies reported in the literature where deformation in uncontrolled indoor environments has been monitored (Chapter 3.8 and Table 2), there are indications that RH changes of less than +/- 16 % RH at room temperatures show elastic strains below the yield strain. However, in the non-heated church (Olstad 1994) with larger RH fluctuations (60 to 65 +/- 32 % RH), yield strains were not reached either, and the state of preservation of the wooden sculpture monitored was better compared to the objects in the heated church with an indoor environment of 30 to 44 +/- 25-31 % RH. The weak point in the analysis of the studies listed in Table 2 is the duration of the RH change because it varies between the studies in the range of weeks to months. Daily changes could not be deduced in all the studies and could therefore not be compared. As reviewed in Section 3.8, the duration of short-term and long-term fluctuations in RH and temperature are not defined. As a result it makes comparisons of different studies problematic.

If it is assumed that background heating reduces RH from high levels to mid-ranges and temperatures from low in winter to cool temperatures, it would also be expected to be more beneficial for wooden objects. It is further assumed that background heating is generally used only during the colder part of the year and therefore the indoor environments in non-heated churches and churches with background heating should be similar during the warmer seasons. In Fig. 2, which shows the indoor environments in one museum and four historic buildings, the black curve represents the temperature control not allowing temperature below 18 °C, resulting in very low RH during the winter period. The background heating set points are normally lower (5 to 12 °C according to Paper III). The resulting craquelure in the paint layers is therefore assumed to be due to either too low RH in the winter period or to the difference in RH average in environments between summer and winter periods. It is generally assumed that seasonal drifts in RH set points are harmless to hygroscopic objects. However, studies have shown that fluctuations of three months are harmful to certain types of objects (Pretzel 2011), and there have not been any studies on seasonal changes in combination with large daily fluctuations as shown in Fig. 2.

The additional damage indicators that were chosen for this study (cracks in wood, open joints, mould and flight holes) did not give clear results. It was shown that cracks could not be related to the total heat output or background heating. Instead the crack was confirmed by a photograph from the late 19th century to have existed before more permanent heating was introduced (Paper III, Fig. 5). The Climate4Wood project came to the same conclusion: shrinkage cracks in the objects studied occurred before 1900, that is, before entering the museum collection (van Duin 2014; Ekelund *et al.* 2014). It is therefore concluded that these damage patterns need to be further studied before being generally accepted as climate indicators.

It is hoped that damage assessment methods can be developed to become more reliable since this would be beneficial for comparing the impact of indoor environment and laboratory results. This importance is also emphasised by Druzik & Boersma (2017). In Paper II and Paper III, damage was quantified subjectively and the results have their limitations. There are computer programs monitoring and calculating, for example, dust-particle concentration or estimating the extent of rust on metal surfaces. This type of method could be useful for paint delamination or exit holes from wood-boring beetles. However, it is more challenging for sculptured objects or for mould growth, which often is found hidden inside or behind furniture in more moist areas. For the indoor environment, it is important that both the current indoor environment and the historic indoor environment are related to damage. It is clear that if only the current environment is taken into consideration this may give misleading correlations if the damage developed in past times.

5.3 Designing a method and studying moisture transport in wood exposed to well-defined and controlled environments in a climate chamber using the RH and T monitoring method

Disadvantages with the commonly-used resistance methods for monitoring in wood are that they are dependent on continuous direct contact between the electrodes and the wood, and this may cause monitoring errors when wood shrinks and swells. Moreover, the instrumental accuracy of the resistance method is not consistent over the entire RH range; in particular, measurements in the lower RH regions are inexact. For the purpose of accurately monitoring moisture distribution over time, an alternative method was developed. The RH and T monitoring method has in this respect important advantages. It is independent of mains electric current and is able to be used for long periods of time in laboratory settings as well as in historic buildings.

The RH and T monitoring method was used in a series of experiments where RH and temperature were varied in a climate chamber to study step-changes, short term fluctuations and imitate indoor environments in museums as well as historic buildings. A number of results clearly showed not only the influence of RH, but also the influence of temperature on moisture transport and response delay in wood. The results support the work reported in Paper II and Paper III indicating that low temperatures are beneficial for wooden objects and that the negative impact of short-term fluctuations in the high RH range is reduced if the temperature at the same time is low.

It was shown that large RH step-changes together with daily RH fluctuations will delay or even prevent the wood from reaching EMC. Instead, MC at certain depths can become much higher than EMC during the combination of a step-change and daily fluctuations (Paper V, Fig. 6), despite the fact that MC of wood should not be able to exceed EMC when only in contact with ambient air. This property seems to be linked to the difference in adsorption and desorption rates during a fixed period of time. The common method to determine MC and EMC is by weighing wooden specimens, but this will only reflect the mean amount of moisture in the sample and does not reflect the moisture distribution. It also contradicts the reported results that liquid water cannot be found in wood up to 99.5 % RH (Thygesen *et al.* 2010). The possibility that wood potentially, at times, can show higher levels of moisture than EMC at certain depths does have implications on modelling, but, it is also important due to the increased risk for mould or wood-boring beetles. This possibility needs to be validated since no published data on a similar phenomenon has been found.

Due to the varied delay of moisture transport at different depths in wood a phase shift was noticed. It is not known when the largest stress or strain would occur, whether in in-phase or out-of-phase situations. It may also be possible that this situation results in repeated stress and stress relax situations through the wood. In a study by Jakieła *et al.* (2007), evolution of fractures in wood was traced by using the AE method. In Fig. 4 of their paper, two consecutive energy periods related to fracturing were observed upon a change in RH and temperature. This phenomenon may be related to in-phase and out-of-phase conditions.

The Fickian diffusion model and the conversion of the monitored RH and T data used in Paper IV and Paper V were based on EMC at the monitoring depth and not MC as an average of the wooden specimen. It has been argued in this thesis that using EMC instead of the actual MC does not give the correct data for the models of moisture transport and subsequent deformation. However, the models used were developed using EMC as a parameter and therefore the EMC at each depth was used for our model. MC, on the other hand, indicates that there are moisture gradients present in the wood, although the actual moisture distribution in the wood is still not known. The average weight in relation to dry weight of the wooden sample could be used to determine MC, but other parameters will also influence the models, such as the thickness of the sample or the type of object. To what extent this creates significant errors in the modelling and estimated actual deformation of the wood is uncertain. The model used for the work reported in Paper IV and Paper V was improved upon by including the hysteresis in the model. According to Lund Frandsen *et al.* (2007) EMC is not only dependant on the current ambient RH but also on the RH history. By not including the hysteresis dependence of sorption in wood, it can result in a deviation of 30 to 35 % for the MC at a given RH.

5.4 Studies of the indirect influence of low temperatures and relative humidity fluctuations present in historic buildings on deformation and moisture sorption rates in wood

The results reported in the papers presented in this thesis indicate that low temperature is beneficial for wooden objects, since moisture diffusion is retarded. The implication is that deformation in wood is reduced by low temperature. This may be a contributing factor to why wooden objects are reported to be in a fairly good state of preservation in non-heated buildings. Limited published research results on the influence of low temperatures on wood have been found. The reported opinions on the effects of low temperatures varies from causing severe damage to varnish, paint or gilded layers on wood, to having no or little impact or to be beneficial in combination with high levels of RH. Hence, which temperature levels can be recommended or should be avoided, how other materials than wood are influenced by low temperatures and the risk of damage due to passing of T_g must be studied in more detail before any recommendation can be given. However, referring to the results of this thesis and review of state-of-the-art research, it is uncertain whether dynamic historic building environments are more harmful or less harmful to wooden objects than the environments commonly studied in laboratory experiments. During a full year or more in a non-heated building it is likely that there are periods that are both better and others which are worse compared to the worst case scenario defined in most laboratory-based studies.

Scientists agree that the impact of global climate change will result in an increase in temperatures which will also have a certain impact on the indoor environment, in particular in non-heated historic buildings. The effect on RH in those buildings is less clear due to geographical location, type of building, the building envelope and RH and temperature difference between seasons. It is of utmost importance to closely follow the long-term changes in the indoor environment in cultural heritage buildings as well as the impact on various types of objects in order to validate the predictive models used for climate-induced damage to objects and buildings. A more abrupt change in the indoor environment is the installation or changing of a heating system of a historic building, which can result in a large negative effect on the objects.

Dehumidification as an alternative to conservation heating in non-heated and intermittently-heated historic buildings could be more used in order to benefit from the positive influence of low temperatures. Thereby, a slightly higher RH set-point of maybe 60 % RH could be allowed as long as the temperature remained low, since the lower temperature will reduce the effect of short-term RH fluctuations. Care must however be taken not to increase the RH set-point due to the risk of mould.

For museum storage, the results of the papers in this thesis on low temperatures support research that suggests that temperatures can be allowed to follow the outdoor temperatures. For instance, in air-tight and buffered stores and archives, the temperature can be allowed to drift and stay cooler during winter periods, so-called *buffered conservation heating* (Ryhl-Svendsen *et al.* 2010). This should be a win-win solution for preservation of objects as well as saving energy in museums and historic buildings.

6

Suggested future research

It is clear that each laboratory study cannot simultaneously study all parameters that influence objects in their actual environments. In *in situ* studies, the impact of several parameters sometimes cause synergetic effects and the influence of each may be hidden. Therefore, in order to fully understand how wooden objects respond to the indoor environment, it is suggested that laboratory experiments and modelling be complemented with, and closely related to, observations and monitoring of actual objects and experimental specimens in museums and historic buildings.

To obtain statistically significant results, larger population studies and more comparable studies are required. Additional methods and collaboration between multidisciplinary researchers and institutes is needed. This is not new:

> *'A statistical approach is clearly essential. Hopefully there may be a day when many galleries keep careful records of damage occurring, treatment given and environmental conditions. These records should be as quantitative as possible and exchangeable between museums. It seems to me that this approach is as much a basic duty of museums as a specialised scientific investigation'* (Thomson 1986 pp. 118-119)

There are still challenges to overcome, such as how to quantify indoor environments and damage to make reliable correlation studies. For instance, a new approach for damage assessment has recently been developed within the Climate4Wood research project. It studies decorated wooden panels and takes into account the objects' construction, type of material, their condition and history. Although time consuming, the project has examined almost 300 objects, which will serve as base for experimental and modelling studies (Ekelund *et al.* 2017). Pretzel (2011) suggests additional methods to quantitatively analyse climate data in order to make data from different locations comparable. He stresses the importance of including the impact of fluctuations of different intervals to specify permissible climates, and that, in order to predict the rate of occurrence of unsafe changes, a statistical approach is needed. Hence, it would be useful to develop standardised methods of how to monitor indoor environments, moisture transport and subsequent deformation in experimental specimens and objects in laboratory experiments as well as *in situ.* For instance, Camuffo and Bertolin (2012) have discussed how to define MC and have brought forward the complex task of monitoring MC in cultural heritage materials.

The methods that have been used so far for monitoring mechanical changes and damage to wood should be validated and compared in relation to each other, since the monitoring equipment employed has different resolution and monitors different parts of the material or object. For example, methods such as holography-related interferometry and speckle methods give instant response of the monitored material just below the surface on a RH change, while methods employing linear transducers appear less sensitive and study deformation of thicker parts or the entire thickness of the objects.

Suggested future focussed research projects include:

- Comparison of the effect of step-changes and worst case scenarios in relation to dynamic environments at different temperatures
- The impact of dynamic moisture gradients in relation to stress and deformation. To what extent moisture gradients create temporarily-increased and decreased stress levels inside wood, and how this influences damage, is not fully known
- Moisture transport, response lag as well as response rates are factors that influence the deformation and stress levels in wood. To what extent maximum stress or strain will be reached upon each RH fluctuation or combination of RH and temperature fluctuations of different magnitude and duration is neither completely investigated nor understood
- Laboratory experiments which focus on the impact of mechano-sorptive creep and stress relaxation by imitating RH, temperatures and restraints experienced by cultural heritage objects in historic buildings and in museums environments
- Evaluating whether EMC or MC has the better correlation to damage in wood, and to improve the mathematical models to additionally reflect the impact of dynamic RH and temperature environments.

7
Glossary of terms

Term	**Explanation**
Adsorption and absorption	In the context of wood in contact with the air, adsorption is the adhesion of water molecules to the sorption sites on the surface of the cell walls of the wood. Absorption is a process were water molecules (fluids) assimilate throughout the bulk of the wood
Anisotropic	Wood has the property of being directionally dependent. It means it exhibiting different properties in different directions, that is the tangential, radial and longitudinal directions
Asymptotic	Approaching a given value or condition infinitely close. For instance an exponential curve and a line that get ever closer but do not intersect
Back ground heating	Keeps a low general temperature above the freezing point in building
Coefficient of thermal expansion	A measure of the relative change of dimension caused by temperature change. In completely dry wood it is positive in all directions; that is, wood expands on heating and contracts on cooling

Compression set or compression shrinkage	Permanent deformation remaining when a previously applied force is removed
Conservation heating (hygrostatic heating)	Regulates RH of the indoor environment by varying the temperature
Creep	Time-dependant deformation exhibited by a material under a constant load. The deformation or creep slowly increases with time under constant stress. Creep consists of an elastic part (viscoelastic) and permanent (viscous) and the latter will remain upon unloading
Creep-recovery	The deformative recovery which occurs when the load is removed from the wood
Damage	Unwanted irreversible change
Damage function	A quantitative expression of cause and effect relationships between environmental factors and material change
Deformation	Displacement of the material which can either be elastic (recoverable) or plastic (permanent)
Dehumidification	Reducing the levels of RH of the air without changing the temperature
Desorption	Releasing moisture upon a drop in RH
Diffusion	The movement of molecules from a region of high concentration to an area of low concentration
Diffusion coefficient (diffusivity)	A quantitative measure of the kinetic diffusion rate
Dose-response relationship	A subgroup of damage function. A dose-response function shows the relationship between the accumulated dose of a hazard such as light or a pollutant gas to measureable change in a material
Elastic modulus (modulus, Young modulus or modulus of elasticity. Abbreviated E or MOE)	Ratio between a stress and a strain. Measures a material's resistance to being deformed when a force is applied to it in the elastic region (below the yield strain). It is defined as the slope of its stress-strain curve and measures a material's stiffness or flexibility. A stiffer material will have a higher elastic modulus

Equilibrium moisture content (EMC)	Moisture content at which the wood is neither adsorbing nor desorbing moisture from the ambient air but is in balance with the ambient air
Fatigue	The progressive weakening or localised structural damage of a material, such as wood or metal, which is subjected to cyclic loading. When sufficiently high and repetitious, cyclic loading stresses can result in fatigue failure
Fibre Saturation Point (FSP)	It denotes the point in drying process of wood at which water only remains in the wood as bound water in the cell walls and the free water has been removed from the cell cavities. Below FSP is the hygroscopic range
Historic building environment	Indoor environment in a historic building which is often less climate-controlled compared to a museum
Hygroexpansion	Swelling or shrinkage in wood materials due to changes in moisture content which causes stresses in the cross-section of the wooden structure
Hygroscopicity	A measurement of a material's ability to adsorb or desorb moisture as a function of RH
Hygroscopic range	The moisture content range below FSP. Liquid water does not exist in wood except as bound water in the cell walls or as vapour in the lumen
Hysteresis	EMC attained by wood exposed to a constant RH and temperature level will become higher if reached during desorption compared to adsorption
In-plane deformation	Lateral shrinkage and swelling of the wood
Intermittent heating	Heating strategy used for instance by churches which normally are non-heated or use background heating but are temporarily heated during Sunday services or other events
Longitudinal direction	Wood's lengthwise direction
Lumen (cell lumen)	The voids or cell cavities in wood

Mechano-sorptive creep *(mechano-sorptive deformation mechano-sorption)*	Deformation which occurs when wood is subjected simultaneously to a load and changes in MC
Moisture content (% MC)	The mass of water in relation to the oven-dried wood, expressed as a percentage
Moisture diffusion	Includes water vapour diffusion in the lumen voids, the pit openings as well as bound water diffusion in the cell walls
Moisture transport *(moisture transfer)*	A general expression for the movement of moisture in wood. Consists of diffusion as well as adsorption and desorption
Museum environment	In this thesis defined as an indoor environment strictly RH- and temperature-controlled for the benefit of the objects, with a temperature level suitable for visitors and employees
Out-of-plane deformation	Warp movement such as cup, bow, crook or twist of a wooden plank
Plastic deformation *(permanent set)*	A permanent displacement of a material which will remain after the stress has been removed, creating irreversible change in the structure
Radial direction	Quarter sawn wood
Scanning curves	Intermediate isotherms which 'cross over' between the boundary curves of the sorption isotherms. They are formed when sorption does not follow the full RH range from 0 to 100 % RH but is reversed
Sigmoidal	S-shaped
Sorption	A physical and chemical process by which water molecules become attached to one another. It can be explained as a displacement of the equilibrium between water vapour, sorption sites and bound water (adsorbed moisture). Different use of sorption has been found in literature: 1) Synonymous to adsorption 2) Either the process of adsorption or desorption The second definition is used in this thesis

Sorption isotherms	The relationship between EMC in the wood In the hygroscopic range and RH of the ambient air at constant temperatures
Sorption sites	Available hydroxyl groups in the cellulose
Thermophoresis	Migration of a colloidal particle or large molecule in a solution in response to a macroscopic temperature gradient
Steady-state and unsteady-state diffusion	In a steady-state diffusion process the moisture concentration gradient is constant and independent of time during the moisture diffusion. In unsteady-state diffusion the moisture concentration gradients changes over time and the diffusion flux is hence time-dependant
Strain	Strain is the unit deformation, which is deformation per unit of original length. It is calculated as the change in length divided by the specimen initial length, usually the dry length
Strain hardening	Strengthening of a material by plastic deformation
Strength	The ability to sustain an applied stress without failure. The strength of a material is synonymous with resistance of the material
Stress	External stress is the force or load acting on a unit of area. It is calculated by dividing the force (load) applied to the test specimen by its cross-sectional area. Internal stress may arise from moisture gradients in the wood, mechanical restraints, macroscopic anisotropy as well as microscopic anisotropy of the cell wall itself
Stress relaxation (relaxation)	If a displacement (strain) is applied instantaneously and held constant over time, the stress will subside with time. The internal resistance stress “relaxes” under constant strain
Tangential direction	Flat sawn wood
Thermal conductivity	A measure of the rate of heat flow through the thickness of the material

Ultimate strength and ultimate stress	Upon loading, ultimate strength is the maximum strength the material can resist prior to failure. Stress corresponding to the ultimate strength is known as the ultimate stress
Viscoelastic deformation	Viscoelastic deformation is the elastic part of creep which will recover upon unloading
Warp	Out-of-plane deformation

8
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