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Original article

Moisture gradients in wood subjected to relative humidity and temperatures simulating indoor climate variations as found in museums and historic buildings

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ABSTRACT

Climate-induced mechanical damage to cultural heritage objects of hygroscopic materials is not yet fully understood. This is particularly true of objects in historic buildings with less climate-controlled indoor environments. Research aiming at clarifying the response of hygroscopic materials to changes of the ambient relative humidity *and* temperature is scarce. The objective of this study was to use a method to monitor relative humidity and temperature at three different depths inside samples of Scots pine (*Pinus sylvestris L.*), subjected to relative humidity and temperature fluctuations in a climate chamber. This approach is important because mechanical stress is related to the moisture content of the material. However, the knowledge on how moisture gradients in wood progress before reaching equilibrium has not been studied in depth in cultural heritage science. The monitored relative humidity and temperature data in the wooden samples were converted to moisture content using a method that took both temperature and the hysteresis effect into account. The samples were subjected to step changes and daily relative humidity fluctuations at different temperatures. Moreover, museum climate, a non-heated historic building climate, and intermittent heating of a typical church were simulated in the experiments. Low temperatures reduced the moisture diffusion rate, resulting in moisture content fluctuations of smaller amplitudes. A response delay was noted which gradually increased with depth in the wood and with low temperatures. A combination of a step-change and daily fluctuations increased the time to reach equilibrium due to the slower desorption process compared to adsorption process. Occasionally, the moisture content could also exceed equilibrium at some depths. The moisture content levels in wood during intermittent heating stayed stable overall. The conclusion is that moisture transport in wood is complex and is influenced by the moisture history of wood, as well as duration and amplitude of the combined fluctuations in relative humidity and temperature.

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1. Introduction

Research on indoor climate, namely the effects of relative humidity (RH) and temperature (T) on museum collections of hygroscopic materials has been intense during the last decades, in order to establish safe climate ranges. Narrow climate ranges are energy-consuming and there is a general agreement in the cultural heritage sector that energy consumption should be reduced to mitigate global climate impact. As a result, the *International Institute for the Conservation of Historic and Artistic Works* (IIC) together with the *International Council of Museums, Committee for Conservation* (ICOM-CC) presented a joint *Declaration on Environmental Guidelines* in 2014 [1]. Although the RH and T range recommendations are now widened, recent review articles on this issue state that there is still extensive work to be carried out. There is not enough evidence to convince the conservation community that further relaxing climate ranges will not cause damage to hygroscopic objects [2,3]. Moreover, it has also been pointed out that there is a lack of experimental data for wide climate ranges outside the ranges considered safe [4].

In the cultural heritage sector the most intensive research has focussed on deformation in relation to RH of the ambient air or equilibrium moisture content (EMC) of the material. The *worst case scenarios* have used maximum yield strain to determine

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the allowable climate ranges in museum environments [5]. This approach has limitations since important parameters involved in the processes are not included. Most important is that it does not reflect the actual response of the objects in different environments, from stable museum environments to fluctuating indoor climates in historic buildings with limited or no climate control. Additional knowledge of the influence of temperature is crucial to understand the actual dimensional response of wood.

Moisture transport studies are frequently performed in wood science, particularly in relation to drying of fresh wood. RH and temperatures influencing cultural objects are less studied. One step towards a greater comprehension is to study in detail how moisture moves in wood under various indoor climate conditions. The work presented here is the result of moisture transport studies in wood, simulating conditions with and without climate control.

Upon an increase in ambient RH, wood adsorbs moisture from the ambient air and upon a decrease in RH the wood desorbs moisture. These processes lead to mechanical deformation and if the deformation exceeds the yield strain, it may become permanent. The actual deformation is related to the moisture content (MC), defined as the ratio of mass of moisture to mass of dry wood, and only indirectly to RH. Moisture moves from areas of high concentration to areas of low concentration. Reaching EMC, the state when the material is not gaining or losing in weight at a constant RH, may take a very long time and in fact it is uncertain if EMC is ever reached under real-life conditions [6].

The relationship between RH of the ambient air and EMC of wood is often plotted as S-shaped sorption isotherms. EMC is dependent on the sorption history in that, at a given RH of the ambient air, EMC reached through adsorption will not be the same as that reached through desorption. Desorption is a slower process due to the tightly-bound water molecules which are not easily released, the so-called hysteresis. The final EMC value after a change in RH has also been shown to be higher if the final RH is reached through one large single step compared to several multi-steps [7].

From a mathematical point of view, Fick's second law has been used to model moisture diffusion in wood and to predict sorption in wood during transient, dynamic situations. Wadsö, and later Håkansson, showed that the rate of sorption is lower at a higher RH range (above 75% RH), which is opposite to the general belief that transversal diffusivities are constant or increase in the higher RH range [8,9]. The understanding of hysteresis is disputed, but one recent explanation is the accessibility of available sorption sites in relation to the number of water molecules at different RH [10].

It is common to measure moisture content in wood by resistance meters. However, several measuring errors in relation to resistance monitoring have been identified, due to reduced contact between wood and electrodes during swelling and shrinkage for instance [11]. Two methods for studying MC profiles in wood were compared by Bylund Melin et al. [12]. One was a commercial resistance method, the other a new method monitoring RH and temperature with miniature data sensors at different depths from the surface. The two methods were validated by using Fick's second law as described by Krabbenhoft and Damkilde [13]. The RH and *T* measuring method showed consistent and reliable results for the purpose of this investigation, while the resistance method did not. In the study presented here, the RH and *T* measuring method is used to monitor formation of moisture gradients in wood as a result of changes in ambient RH and *T*. The impact of the recommended museum climate, as well as intermittent heating which would be expected during a Sunday service of a typical church, are also presented. The focus is on RH ranges predominating in non-heated buildings in temperate climate zones.

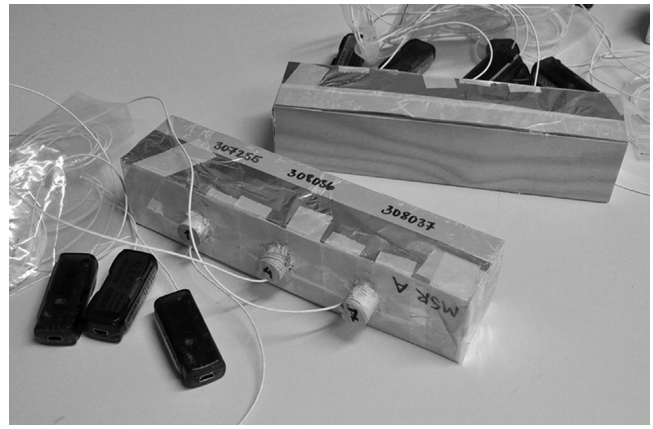

Fig. 1. The RH and *T* measurement sensors inserted in the wood samples. The sample in the foreground shows the reverse side with the wood plugs sealing the sensors in the bottom of the drilled holes. The sample in the background shows the front side that is exposed to changing RH and *T*.

2. Research aim

The aim of this study was to extend the understanding of how wooden cultural heritage objects respond to indoor environments. Internal moisture levels at three different depths were monitored, giving a picture of moisture gradients which can occur in regular museum conditions as well as in historic buildings with less-regulated climate control. The knowledge is important in order to improve understanding of the underlying factors which cause swelling and shrinkage and eventually permanent mechanical damage to this type of artefacts.

3. Materials and methods

Below follows a brief summary of the RH and *T* measuring method using MSR data loggers. A full description of this method is presented in Bylund Melin et al. [12]. The experiments were carried out in a *CTS Climatic Test Chamber* where RH and *T* could be programmed in combination. The wood species used for the experiment was Scots pine (*Pinus sylvestris L.*). The monitored front surface was planed and had a tangential cut with the bark side facing out. The specimens had a dimension of 200 × 45 × 45 mm and three 15 mm diameter holes were drilled from the reverse side in to each of the specimens at 1, 4 and 7 mm depth from the front surface. Each sensor was placed in an acrylic tube and sealed by silicon discs and a wood plug made from the same Scots pine as the wood sample, in order to avoid RH and *T* interference from behind (Fig. 1). For each depth, three recordings were performed and hence the presented data is based on value triplicates. The remaining five surfaces were covered with aluminium foil to prevent moisture transport through those sides. On rare occasions the battery of some of the RH and *T* loggers became discharged and then no results were present for certain depths, as seen in Fig. 3a and b.

Since the RH and *T* measuring method only measured RH and *T* in the air pocket inside the wood, the data was converted to MC. This was carried out according to Frandsen et al. [14] taking into account both hysteresis effects and *T* dependence of the sorption isotherms, as described in [12].

4. Results

The results of the climate chamber studies are presented in Figs. 2–7. All figures show the calculated MC values at 1, 4 and 7 mm inside the wooden samples as well as the ambient RH and *T* in the climate chamber. Fig. 2 also presents the original monitored

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