Relating relative humidity fluctuations to damage in oak panel paintings by a simple experiment

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Relating relative humidity fluctuations to damage in oak panel paintings by a simple experiment

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ABSTRACT
Panel paintings are essentially wooden boards painted on one side. Due to the vapor resistance of the paint layer, changing ambient conditions lead to exchange of moisture on only one surface. Subsequently, a non-uniform moisture content profile is formed across the thickness of the board. As a result, differential expansion causes the board to bend in case of no mechanical restriction, or it leads to a build-up of stresses inside the material if restrained. Experiments with oak boards sealed on one side and exposed to a change in the ambient relative humidity (RH) were performed. By scaling, the response of any board with different thickness can be predicted. Since the bending of the board can be described as a linear system behavior, the frequency response can be predicted based on the step response. In combination with critical strains for wood and gesso from the literature, this gives insight into allowable RH fluctuations in terms of frequency and amplitude for different board thicknesses.

Introduction

The most extensively used supports for portable paintings until the early seventeenth century were wooden boards, joined together by glue, dowels, and cross-pieces. Typically, some layers of gesso and/or fabric were added to serve as a carrier for the paint layer. Well-known masterpieces have been constructed accordingly, e.g. by da Vinci, Rubens, or Rembrandt. Panel paintings are therefore often an important part of a collection. Owing to the hygroscopic nature of wood, a panel will exchange moisture with the ambient air upon changes in the relative humidity (RH). These changes in local moisture content result in strain, which, if locally restrained, results in stresses in the material. This can give rise to permanent deformation or even failure, manifested e.g. as cracks. A vast amount of money and energy is therefore spent on a stable indoor climate in museums to conserve these collections. Nevertheless, changes in the ambient RH, as small as they may be, are inevitable. These fluctuations are most often cyclic, e.g. daily or seasonal. Knowledge of the response of materials used in panel paintings to these changes is therefore of great importance for risk management and indoor climatic strategy (Michalski 2007).

A panel painting with a pictorial layer which is much less permeable than wood can conceptually be approached as a board with an impermeable layer on one surface (Allegretti and Raffaelli 2008). Although some panel paintings were originally painted on both sides, many of them have been cut within the thickness of the board, resulting in a single-sided panel painting (New 2014). Let us consider an unrestricted board in equilibrium with air having an RH of 50% as schematically shown in Figure 1(a). In case the RH of the ambient air changes to e.g. 90%, moisture exchange between the board and the air will only occur at the unpainted surface, since the other surface is impermeable. Consequently, the moisture content will be unevenly distributed throughout the thickness of the board (see Figure 1(b)). Since wood expands upon an increase in moisture content, this will result in differential expansion across the thickness, causing the wooden board to bend. Meanwhile, moisture transport takes place, equilibrating the moisture distribution in the board. As a result, the bending will decrease in time. In the final configuration, the board is straight again, but elongated (see Figure 1c). In case the ambient RH changes continuously, the constantly changing moisture content distribution results in transient bending. Stresses, caused by a mismatch between the actual strain and the free strain, will be present in the material in the unrestrained case. Stresses will generally be much larger in case a

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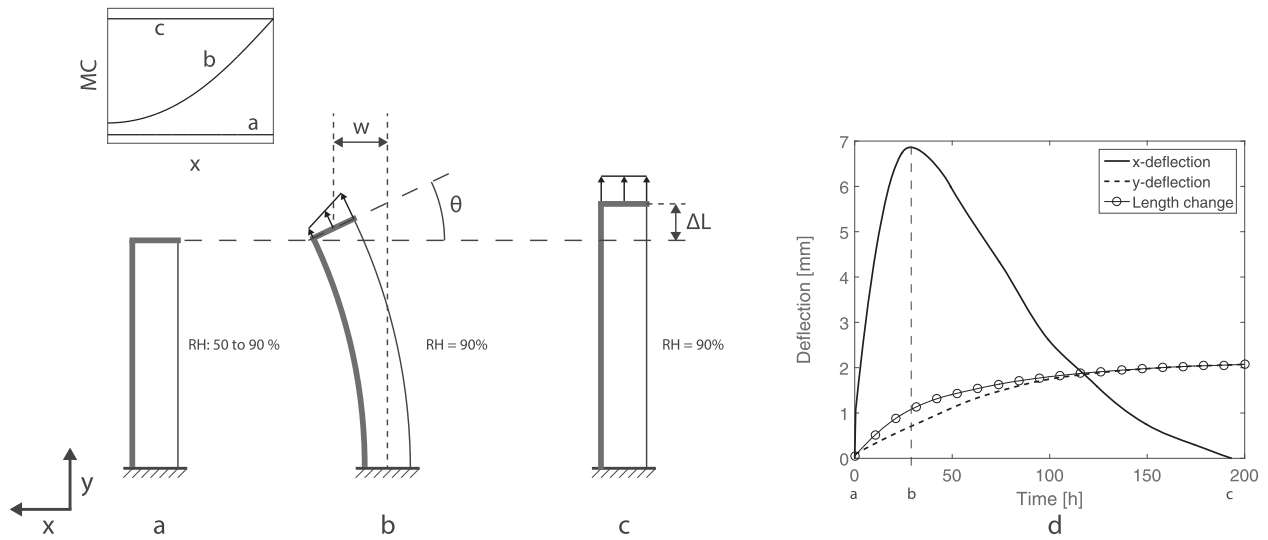
Figure 1. Conceptual visualization of the bending response of a painted oak board and the corresponding moisture content profiles. The board is sealed on all surfaces except one, resulting in one-dimensional moisture transport upon a change in the ambient RH. (a) The material is initially in equilibrium with air with an RH of 50%, resulting in a constant moisture content throughout its thickness. (b) A step change in the RH results in a moisture content gradient in the material. Differential expansion induces a bending moment, reflected in the deflection of the free end w and the angle of the cross-section θ. (c) Eventually, the moisture has equilibrated and the board is straight again, but elongated (ΔL) due to higher moisture content. (d) Typical deflection and length change of a board exposed to a step change in the ambient RH. The board has a thickness of 7 mm, a length of 100 mm, and a width of 30 mm.

board is mechanically restrained by e.g. a rigid frame, as often is the case in paintings.

The mechanical and dimensional response of wood to changes in RH have been studied extensively, both experimentally (Chomcharn and Skaar 1983; Schellen 2002; Bratasz et al. 2010; Senni et al. 2010; Caré et al. 2012; Derome et al. 2012; Gauvin et al. 2014; Lanvermann, Wittel, and Niemz 2014) and numerically (Gloimüller et al. 2012; Rafsanjani et al. 2012; Saft and Kaliske 2013). Also, the consequences of unilateral exposure of a wooden board to a step change in RH have been studied for kiln-drying (Brandao and Perré 1996; Allegretti, Rémond, and Perré 2003; Allegretti and Ferrari 2007; Uetimane Junior et al. 2010; Rémond et al. 2013) and in a panel painting (Dionisi Vici, Mazzanti, and Uzielli 2006). Whereas the implications for panel paintings exposed to a sinusoidally fluctuating environment have been studied numerically (Rachwal et al. 2012a, 2012b), experimental studies are scarce. The response of a panel painting to cyclic RH changes has been imitated by mechanical stretching and compression (Kozlowski et al. 2011), but not measured directly with sinusoidal RH changes.

Determining the response of panel paintings to sinusoidal RH changes with different frequencies directly is time-consuming, even more for a thick panel. We will first show that a short and simple experiment with a board, exposed to moisture on one surface, contains a major amount of information. The results can be scaled to predict the bending behavior of the boards with different thicknesses. Furthermore, the short experiment provides information on the frequency behavior of the bending. Combining these two findings with the criteria for plastic deformation and damage, we can assign combinations of board thickness, fluctuation frequency, and amplitude in RH which are safe or potentially harmful.

Simplified model of bending due to RH changes

The bending of wooden boards mimicking panel paintings was studied in detail in a recent publication by the authors (Arends, Pel, and Huinink 2017). By describing moisture transport with the diffusion equation, and assuming the material to be linear elastic, the bending could be described analytically. Here, we will only discuss the scaling parameters with which responses of different board thicknesses can be compared. The time t can be scaled with the typical diffusion time (d^2/D) according to

$$t^* = \frac{Dt}{d^2},\tag{1}$$

where t^* is the dimensionless time, D is the moisture diffusion coefficient of the material, and d is the thickness of the board. Hence the scaled time reflects the moisture transport process. A second scaling concerns the total strain ε at some point in the board. This expansion can be scaled according to:

$$\varepsilon^* = \frac{\varepsilon}{\alpha \Delta c},\tag{2}$$

with ε^* being the scaled expansion, α the hygroscopic expansion coefficient, and Δc the change in moisture content associated with the change in RH of the ambient air.

Bending of a board can be reflected in the x-deflection of its free end w (see Figure 1), which, for small deflections, is linearly proportional to the angle θ of the cross section. For the same exposure condition, a thin board will bend more heavily than a thick board: the angle of its cross section will be larger. The angle can be scaled as:

$$\theta^* = \frac{\theta d}{L_0 \alpha \Delta c}, \tag{3}$$

where θ^* is the dimensionless tangent of the angle and L_0 is the initial length of the board.

Finally, similarly to the time-scaling in Equation (1), the frequency f of RH fluctuations can be scaled as

$$f^* = \frac{d^2 f}{D}. \tag{4}$$

The scaled frequency f^* thus represents the ratio of two timescales: the internal moisture transport timescale (d^2/D) over the external RH fluctuation timescale (f^{-1}). For small values of f^*, the fluctuations are much slower than moisture transport and the board will always be in equilibrium with the surrounding air, with a more or less flat moisture content profile. In the range around $f^* = 1$, both timescales are balanced, and the moisture content profile exhibits asymmetries with large moisture content gradients. At large f^*, the external fluctuations are too fast to be transferred into the material, consequently the moisture content changes only in a thin layer near the exposed surface.

Since most fluctuations in ambient RH are cyclic of nature, we are interested in the frequency behavior of the bending. The frequency bending behavior of a 2-mm-thick board (the amplitude in ε_m and θ as a function of frequency) has been determined directly by experiments with a sinusoidal fluctuation in RH (50 ± 40% and different frequencies), and is shown in Figure 2. Alternatively, we can predict this frequency behavior from the response to a step change in RH (Arends, Pel, and Huinink 2017). First, the step response is fitted by a single exponential function (expansion at half-thickness ε_m) or a double exponential function (angle θ). The Laplace transform of the fit then provides the transfer function of the system (Franklin, Powell, and Emami-Naeini 1987), from which the amplitude as a function of frequency can be derived. The frequency behavior of the same board derived from its step response to a change in the ambient RH from 50% to 90% is also shown in Figure 2. It can be seen that the frequency response of the system is well predicted by its step response for a wide range of frequencies. Measuring the step response is a short experiment; we therefore save time predicting the
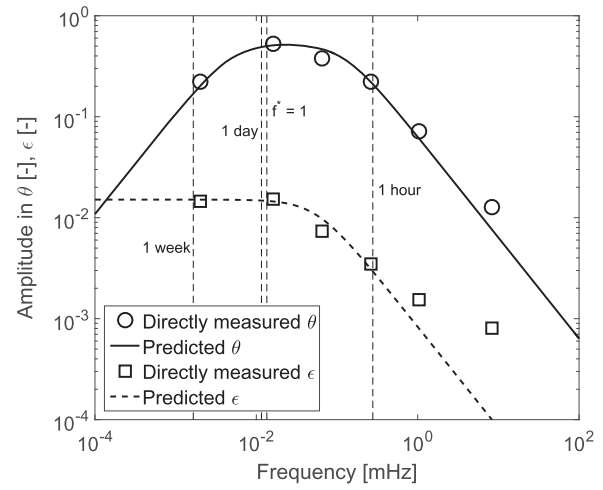
Figure 2. Amplitude in the angle θ (see Figure 1) and expansion at the middle of the board ε_m as a function of the frequency of the RH fluctuations for a 2-mm-thick board. Predictions from its step response are verified by experiments with a sinusoidal RH fluctuation. For the experimental values, the period of the slowest variation is 134 hours, the fastest 2 minutes. Vertical dashed lines are added corresponding to different fluctuation periods (1 hour, 1 day, 1 week), and the fluctuation period corresponding to $f^* = 1$.

frequency response rather than measuring the behavior directly.

If we know the scaled bending behavior, we can determine how a panel with a certain thickness, exposed to an RH fluctuation with a certain frequency and amplitude, would bend. Using Equation (2), the expansion at the unexposed surface, i.e. in the finishing layer of the panel painting, can be determined. To this end, the amplitude in moisture content should be known. If we assume the amplitude in moisture content to be linearly proportional to the amplitude in RH, we overestimate it for small fluctuations around an RH of 50%. In this region, the sorption curve relating equilibrium moisture content to RH is flatter than at higher and lower RH. Accordingly, the relation between amplitude in moisture content and RH amplitude is nonlinear. An estimation of this relationship will be provided in the following section.

Materials and methods

Material

Due to its widespread use in panel paintings (New 2014), oak is used for the experiments. Boards with a length of 100 mm, a width of 30 mm, and different thicknesses (2–9 mm) were prepared with the grain direction along the width of the board, the tangential direction along the length of the board, and the radial direction along the thickness. Transport will hence occur in the radial direction of the wood, whereas tangential expansion causes the boards to bend. All boards were prepared from the same large

board, which was stored at an RH of 30%. The experiments start at an RH of 50%. The boards are allowed to equilibrate in a desiccator containing a saturated Mg(NO$_3$)$_2$·6H$_2$O solution, ensuring an RH of 53%. Bison silicone kit$^©$ is applied on five sides of the board before the experiment, leaving one of the two main surfaces open.

Experimental setup

A schematic representation of the experimental setup designed to measure the deflection of a wood board due to a change in RH is shown in Figure 3. One end of the wood board is clamped between two PVC strips. On the other, free end of the sample, a pointer is mounted. This set-up is placed in a plastic container in which the RH can be controlled by the help of a humidifier, mixing a wet and a dry air stream, which operates in the RH range 0–95%. A Dino-Lite$^©$ digital microscope records time-lapsed images to measure the deflection. A Matlab optical recognition program is used to determine the position of the pointer automatically.

To determine the relation between the RH amplitude and amplitude in moisture content of oak, a modified thermogravimetric analysis set-up was used. An oak cube with sides of 6 mm was placed on the balance of a Mettler Toledo TG50; the mass of the sample is measured while exposed to an air stream with changing RH. The RH is fluctuated sinusoidally around 50% with a period of 10 hours, with a linearly increasing amplitude in RH from 0% to 40% over 10 cycles. The moisture content of the sample changes sinusoidally too, with a nonlinearly increasing amplitude. Data fitting then provide the relation between RH amplitude and moisture content amplitude.

Results

Experiments

In total, eight experiments were performed with boards with thicknesses between 2 and 9 mm. The boards were exposed to a step change in RH between 50% and 90%. The typical deflective and expansive response was already shown in Figure 1 for a 7-mm-thick board. The angle θ of the board can be calculated with the x- and y-deflection of the free end and scaled according to Equation (3). The expansion of the board at half-thickness ε_m, retrieved from the x- and y-deflection, is scaled with Equation (2). The results for all board thicknesses used in the experiments are scaled accordingly and averaged over all board thicknesses. An average diffusion coefficient D of 4.7×10^{-11} m^2 s^{-1} is found, which corresponds well with the values in the literature (Simpson 1993; Saft and Kaliske 2013). The average scaled expansion at half-thickness ε_m^* and

scaled angle θ^* as a function of dimensionless time t^* are shown in Figure 4(a). The result is fitted with a single exponential (for the expansion ε_m^*) and a double exponential (for the angle θ^*). The scaled expansion ε^* at a certain dimensionless distance $x^* = x/d$ from the unexposed surface of the board can be described in terms of the scaled expansion at half-thickness ε_m^* and the scaled angle θ^*:

$$\varepsilon^*(x^*) = \varepsilon_m^* + \left(x^* - \frac{1}{2}\right)\theta^*. \qquad (5)$$

Equation (5) can be made dimensional again for different board thicknesses. The time evolution of the expansion at the painted surface, middle of the board, and unpainted surface (configuration schematically shown in Figure 4(b)) can accordingly be determined for different board thicknesses. This is done for boards with thicknesses of 2 and 20 mm, shown in Figure 4(c and d), respectively, as a function of time after a step change in the RH of 40%. As can be seen, the unpainted surface expands faster than the rest of the board and the finishing layer is initially slightly compressed due to the bending, but expands later on. Furthermore, the process is much faster for a thin board than for a thick board.

The amplitude in ε_m^* and θ^* as a function of the scaled frequency f^* is shown in Figure 5(a). Note that this figure is similar to Figure 2, but scaled such that information on all board thicknesses can be retrieved from this frequency behavior. Employing Equation (5) and Equations (3) and (4), we can determine the amplitude in expansion at the painted surface, middle of the board, and unpainted surface of a board (configuration schematically shown in Figure 5(b). The result is shown for board thicknesses of 2 and 20 mm in Figure 5(c and d), respectively. As can be seen, a daily fluctuation, indicated by a vertical dotted line in Figure 5(c and d), results in large amplitudes in expansion in a thin board (Figure 5(c)), but in much smaller amplitudes in a thick board (Figure 5(d)). As can be expected, the figures are qualitatively the same; the lines are shifted along the frequency axis. For low frequencies, the amplitude in expansion is the same for all positions; the external fluctuations are much slower than the internal moisture transport and the moisture content profile is more or less flat. The absence of considerable differential expansion causes the board to be straight with negligible bending. With increasing frequency, the amplitude in expansion declines at all positions with a constant negative slope on the logarithmic scale. The amplitude in expansion is the highest at the exposed surface; the amplitude is similar at the middle of the board and at the painted surface.

The moisture content of the oak cube as a function of the RH during a sinusoidal RH fluctuation with linearly increasing amplitude is shown in Figure 6(a). As
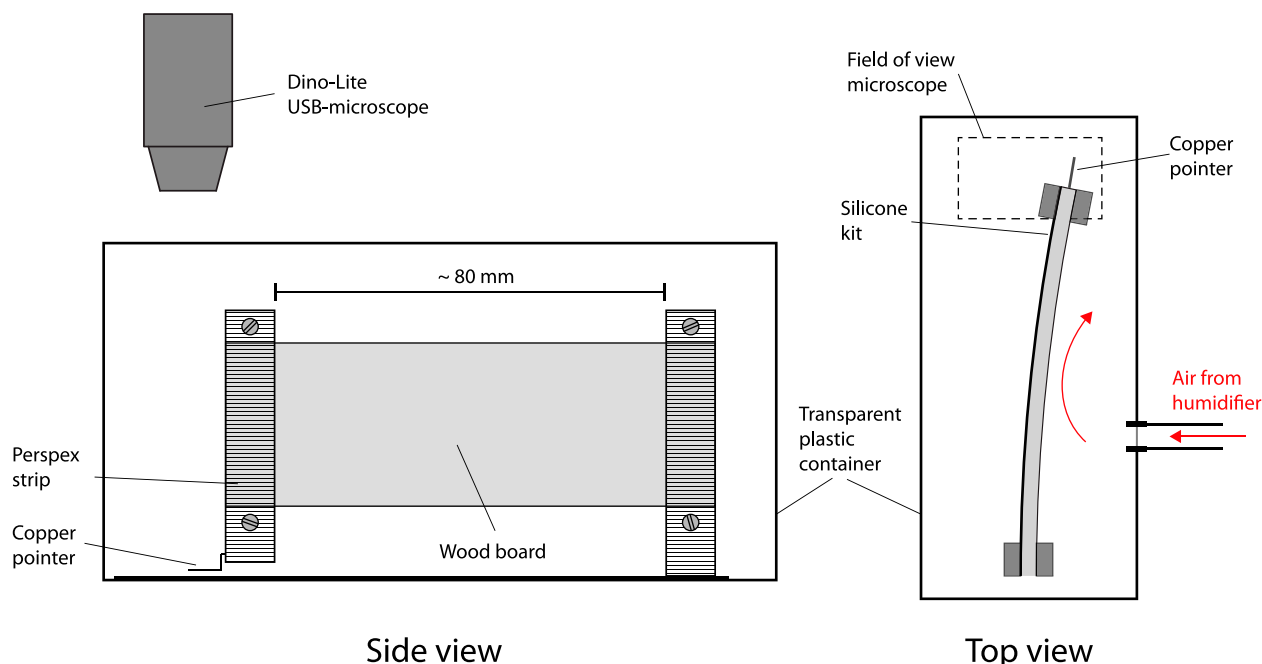
Figure 3. The experimental setup for measuring the bending of an oak wood board under dynamic humidity conditions. On the left, the side view of the experimental setup is shown, and the top view is shown on the right.

can be seen, the changes in moisture content are small with small amplitudes in RH. Additionally, the slope of the curve increases for increasing RH amplitude. This is an indication for the nonlinear relation between RH amplitude and moisture content amplitude, which is shown in Figure 6(b), normalized by the amplitude in moisture content corresponding to an RH amplitude of 40%. The linear approximation is also shown; the difference between the two curves is high especially at low RH amplitudes. In the following, the nonlinear curve is used to determine the amplitude in moisture content Δc in Equation (2) when different RH amplitudes are considered.

Coupling with failure criteria for an unrestrained board

With the scaled frequency behavior known, case studies can be explored. We will consider the case of an unrestrained board first. The unrestrained board is allowed to deform; as a consequence, the stresses in the wood are small compared to a mechanically restrained board. The finishing pictorial layer on the unexposed surface, however, experiences strain when the panel bends. Above certain strain levels, this may result in plastic deformation or even failure, e.g. cracking or separation from the wooden support. Michalski (1991) recognized the ground layer as the most mechanically vulnerable material in paintings due to overpigmentation, and Mecklenburg, Tumosa, and Erhardt (1998) mention gesso to be the limiting material in the finishing layer because of the low yield and breaking strain (0.0025 and 0.01, respectively). It has been recognized before that, in the

fifteenth-century panel paintings, there is little cracking in the paint layers independent of the gesso layers; cracks in the pictorial layer originated in the gesso layers (Mecklenburg 2007). The amplitude in expansion at the unexposed surface should therefore not exceed the critical yield and breaking strain levels of gesso, which will be used in the following to determine allowable fluctuations in RH.

Three different situations can thus be distinguished, in which the gesso deforms elastically, plastically, or suffers from damage. The occurrence of either of the situations will depend on fluctuation frequency, fluctuation amplitude, and board thickness. These three different regions are shown in a frequency versus thickness plot for amplitudes in RH of 30% and 10% in Figure 7(a and b), respectively. The plots should be read as follows: a certain combination of fluctuation frequency and board thickness corresponds to a point in the figure. Depending on the amplitude in RH, the point is located in either one of the three regions (elastic deformation, plastic deformation, damage). The thick, dotted line in Figure 7 separates the elastic deformation region from the plastic deformation region, whereas the thick, solid line separates the plastic deformation region from the damage region.

As an example, let us consider a daily fluctuation, indicated by a narrow, vertical dotted line in Figure 7 (a). For boards with a thickness exceeding 12 mm, a daily fluctuation with an amplitude of 30% is in the elastic deformation region, i.e. it is a safe fluctuation. The same fluctuation results in plastic deformation for a board with a thickness between 5 and 12 mm, and in damage for a thickness smaller than ∼5 mm. For a daily fluctuation with an amplitude of 10%, boards
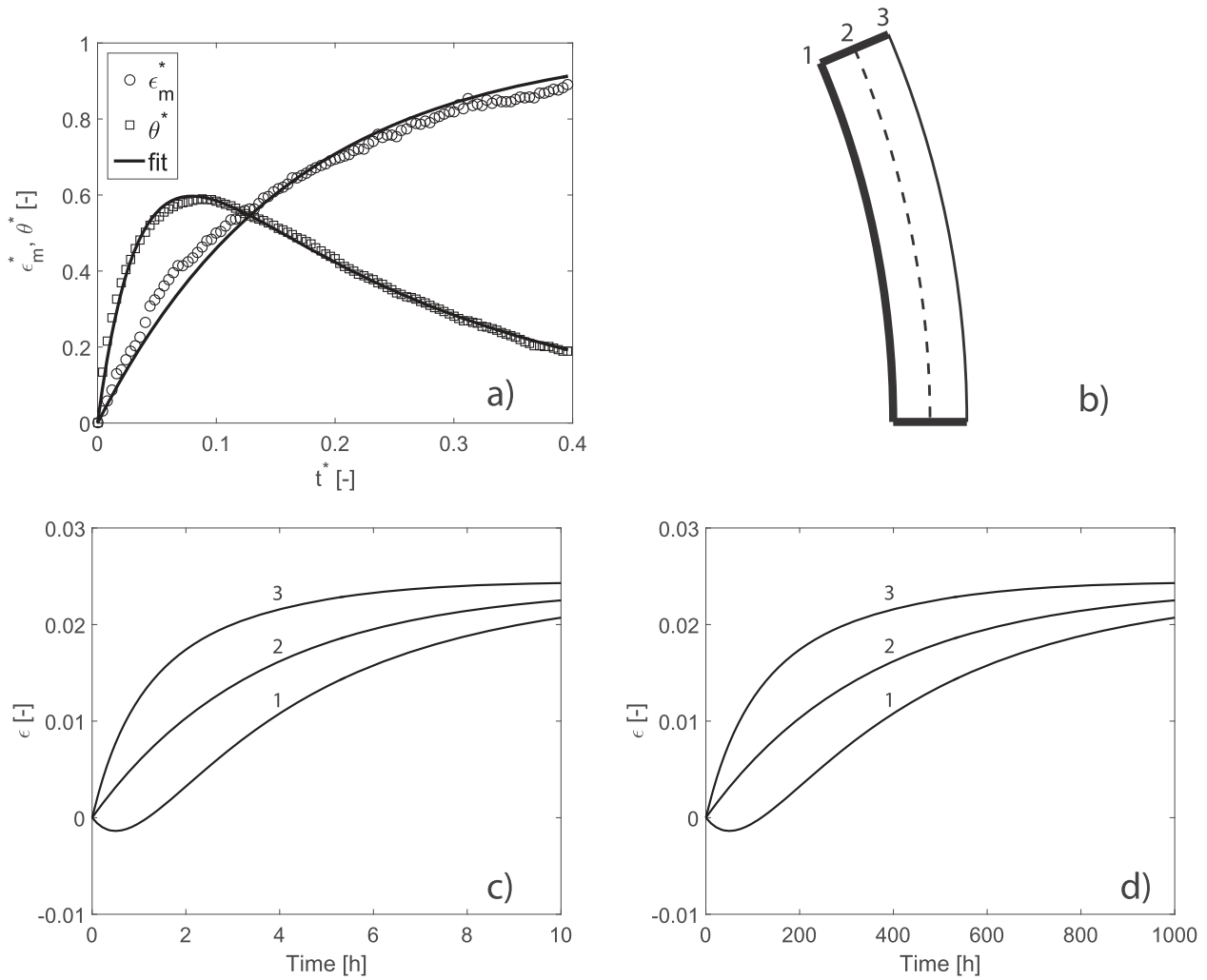
Figure 4. (a) Scaled expansion at the middle of the board ε_m^* and scaled angle θ^* as a function of dimensionless time t^*. Results shown are averages of experiments with boards with thicknesses varying between 2 and 9 mm, complemented with fits with a single exponential (for ε_m^*) and a double exponential (θ^*). (b) Schematic representation of the board with the different positions along the thickness indicated. Derived expansion as a function of time at the painted surface (1), middle of the board (2), and unpainted surface (3) of boards with a thickness of (c) 2 mm and (d) 20 mm.

thicker than 5 mm are in the safe elastic region. Boards with a thickness smaller than 5 mm are subjected to plastic deformation, whereas damage does not occur at this amplitude in RH.

For a slower fluctuation, the situation is different. As can be seen in Figure 7, the boundaries of the regions shift for different frequencies. If we consider a yearly fluctuation with an amplitude of 30%, panels with all thicknesses considered here (up to 40 mm thickness) are in the damage region. On the other hand, all panel thicknesses considered here result in plastic deformation for a fluctuation of 10%.

A different representation of the same results is shown in Figure 8, where the three different regions are visualized on a frequency versus amplitude plot, for two different panel thicknesses (5 and 20 mm). A point in the plot corresponds to a combination of fluctuation frequency and RH amplitude. Contrary to Figure 7, the boundaries of the different regions are now determined by the panel thickness. In other words, a certain fluctuation (combination of frequency and amplitude) may be damaging for a thin board, but not penetrate far enough to cause damage in a thick board.

If we e.g. first consider a 5-mm-thick board in Figure 8(a), we see that the elastic deformation region comprises the lower part of the figure. Slow fluctuations with an amplitude smaller than 8% are found to be safe. For increasing frequency, the region broadens and larger amplitudes become allowable. For slow fluctuations, the plastic deformation region is in a range between amplitudes of 8% and 24%. This range changes towards high frequencies, where the bounds shift vertically. For a daily fluctuation, the plastic deformation extends between 10% and 28%. Finally, the damage region is located in the top left corner in Figure 8(a), above amplitudes of 24% for slow fluctuations, and above amplitudes of 28% for daily fluctuations. For a thickness of 20 mm, shown in Figure 8(b), the boundaries between the regions are simply shifted along the horizontal frequency axis according to Equation (4). Regardless of the RH
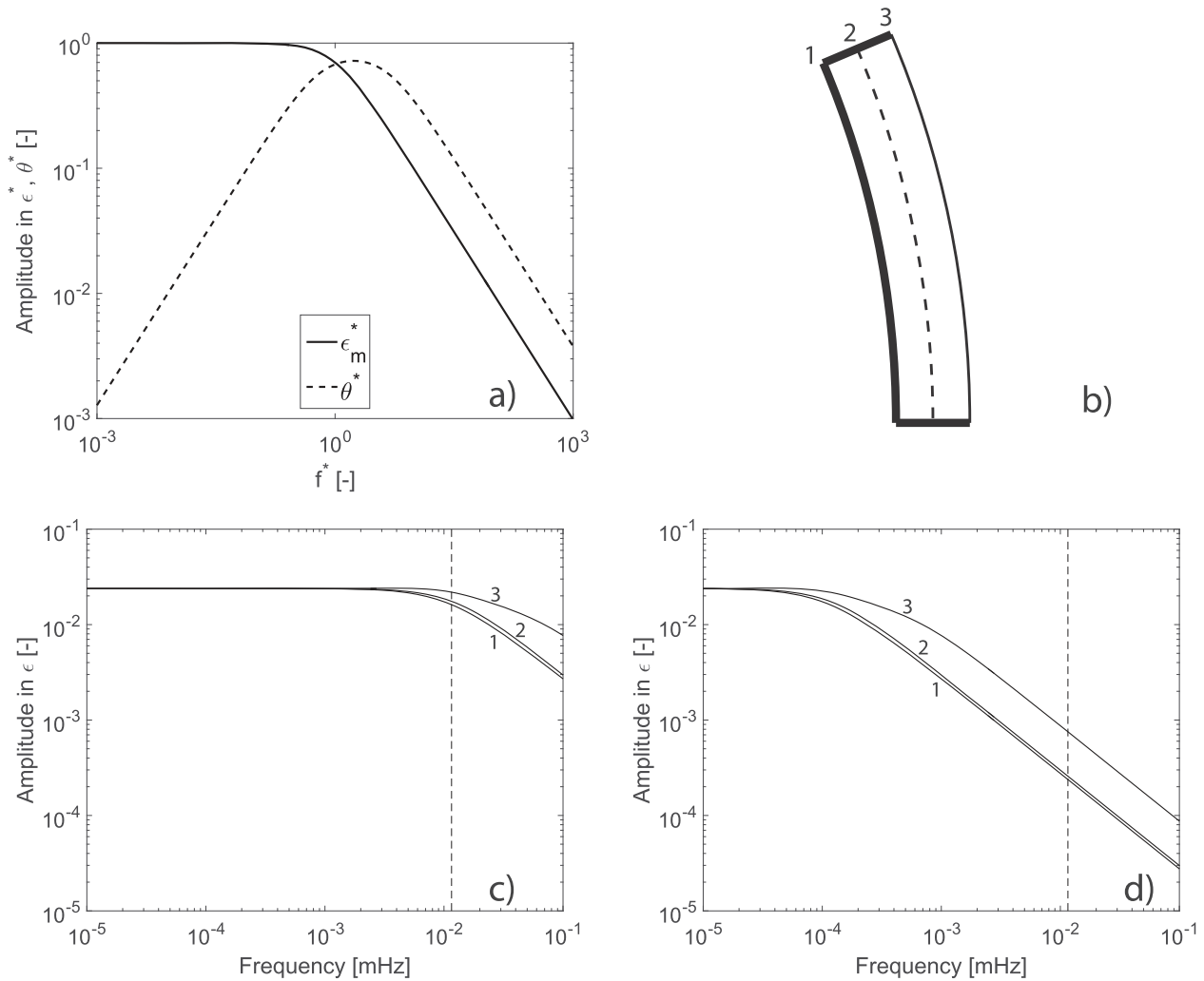
Figure 5. (a) Amplitude in scaled expansion at the middle of the board ε_m^* and scaled tangent of cross-sectional angle θ^* as a function of the dimensionless frequency for different distances from the exposed surface. (b) Schematic representation of the board with the different positions along the thickness indicated. Expansion as a function of fluctuation frequency at the painted surface (1), middle of the board (2), and unpainted surface (3) of boards with a thickness of (c) 2 mm and (d) 20 mm. A daily fluctuation is indicated by the vertical dashed line.

amplitude, all daily fluctuations are in the elastic deformation region for this panel thickness.

Indoor climate data

To link the experimental results to different indoor climates, the extensive empirical database of the Climate for Culture project is used (http://www.monumenten.bwk.tue.nl/CfC). Four distinct indoor climates are selected: Schönbrunn Palace in Vienna (Austria), the Grand Church in Breda and Amerongen Castle (the Netherlands), and a stave church located in Garmo (Norway). The data are acquired as the course of the RH over time, as shown for the Spiegelsaal of Schönbrunn Palace in Figure 9. The sampling frequency is in all cases at least once per half an hour. The time-domain data are discretely Fourier transformed to obtain the frequency spectrum, which is also shown in Figure 9. The dominant yearly, seasonally, and daily fluctuations are obvious in the spectrum. The peak values of these dominant fluctuations are added to

the plots in Figure 8. The amplitude in the RH of the daily fluctuations is small, such that they are located in the elastic deformation region for all board thicknesses. The amplitudes of the slower yearly fluctuations are larger, but are, except for the Garmo stave church, still located in the elastic deformation region.

Coupling with failure criteria for a restrained board

We have used the derived frequency bending behavior to determine maximum allowable fluctuations in RH for failure in the finishing layer of an unrestrained panel. It was assumed that the stresses in the wood itself were small due to the absence of mechanical restrictions. In case the board is not free to deform, stresses build up inside the wood when exposed to a change in RH. Here, we make a first estimation of the consequences for damage in the wood in case the panel is mechanically retrained.
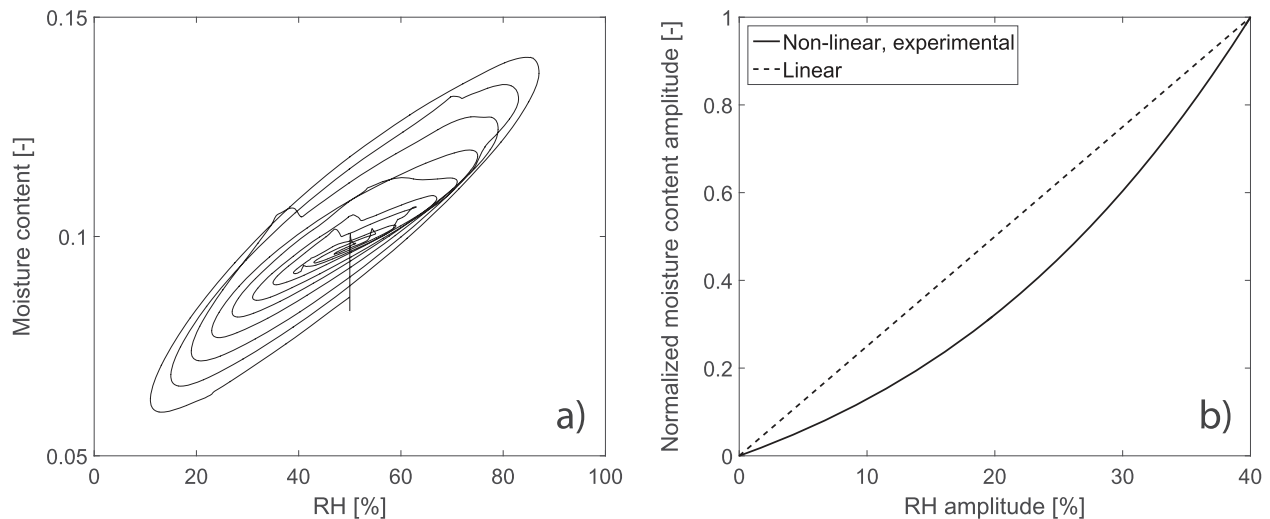
Figure 6. (a) The moisture content of an oak cube as a function of the RH during a sinusoidal fluctuation in RH around 50% (period of 10 hours), with a linearly increasing RH amplitude from 0% to 40% over a period of 100 hours. (b) The amplitude in moisture content, normalized by the amplitude corresponding to an RH amplitude of 40%, as a function of the RH amplitude. A linear relation between the moisture content amplitude and RH amplitude is added to show the discrepancy with the experimentally determined curve.

Since the frequency behavior of the expansion, i.e. the amplitude in expansion as a function of frequency, is dependent on the position along the thickness of the board, a position needs to be chosen. The assessment here will be made for the middle of the board, i.e. along the dotted line in Figure 4(d). The frequency behavior of the expansion in the middle of the board was already shown in Figure 5(c and d). If we assume that the wood is locally stress-free when macroscopically unrestrained, the free strain in Figure 5 results in a buildup of stresses in case of mechanical restriction. Although stresses are present in case of an unrestrained board, these stresses are small compared to a mechanically restrained board, especially at half-thickness. The amplitude in free strain should not exceed critical values, which are adopted from the literature

(Mecklenburg, Tumosa, and Erhardt 1998). The yield strain for white oak in the tangential direction was determined as 0.004, and the breaking strain as ~0.012.

Figure 10 shows a frequency versus thickness plot, indicating three different regions for two different amplitudes in RH (30% and 15%), similar to Figure 7. For boards thicker than 12 mm, a daily fluctuation with an amplitude of 30% (Figure 10(a)) is in the elastic deformation region. The same fluctuation results in plastic deformation for a board with a thickness between 5 and 12 mm, and in damage for a thickness smaller than 5 mm. For a daily fluctuation with an amplitude of 15% (Figure 10(b)), boards thicker than 5 mm are in the safe elastic region. Boards with a thickness smaller than 5 mm are subjected to plastic deformation, whereas damage does not occur at this
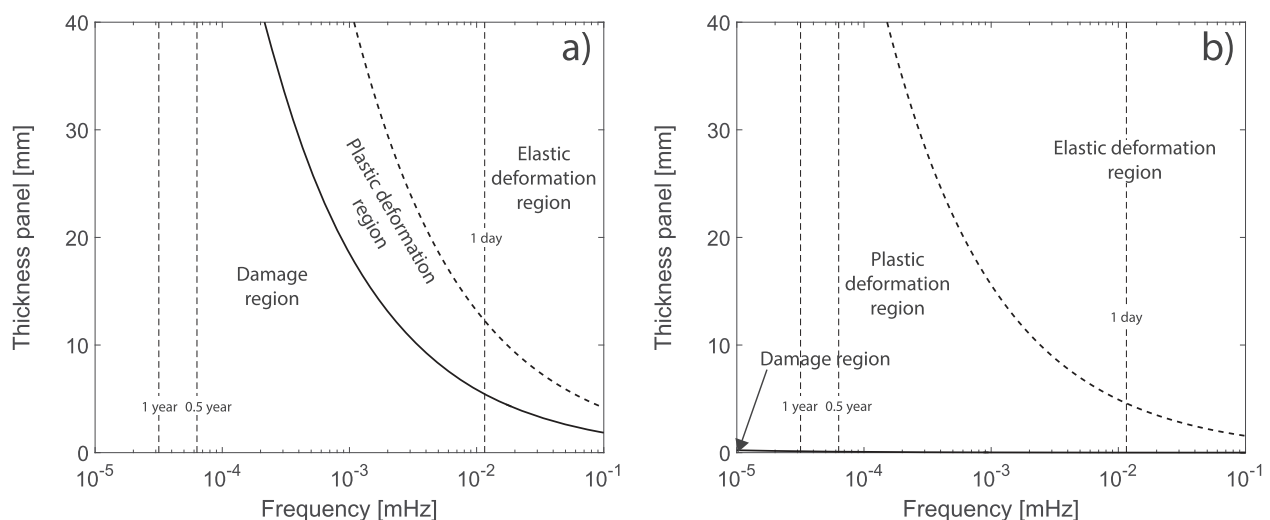
Figure 7. Frequency versus panel thickness plot for an unrestrained oak panel with a finishing layer containing gesso, indicating three different regions (elastic deformation, plastic deformation, damage) for two different RH amplitudes: (a) 30% and (b) 10%.
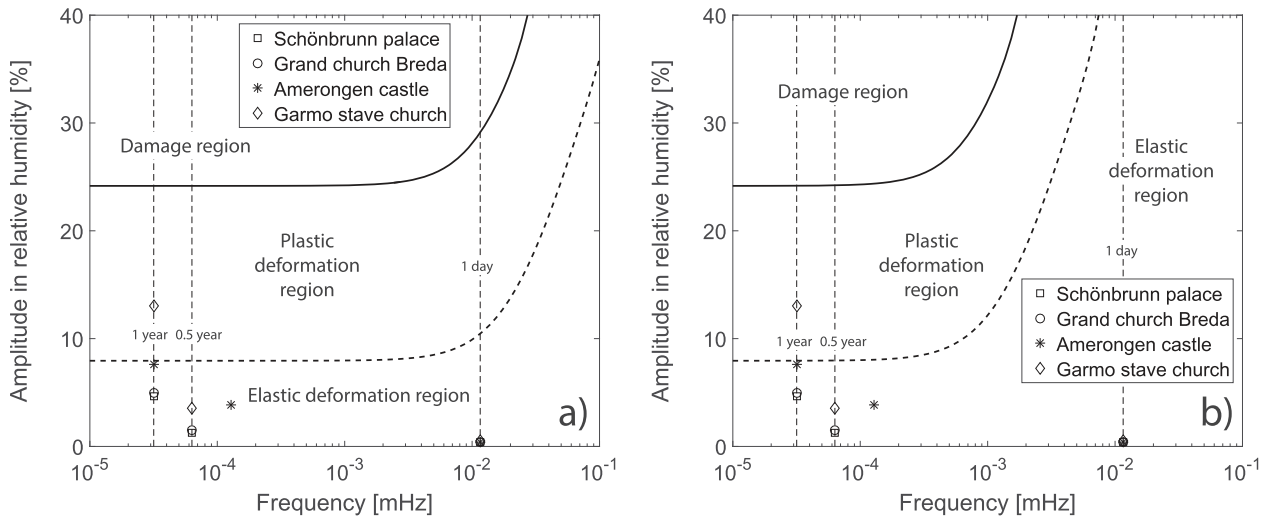
Figure 8. Frequency versus amplitude plot for an unrestrained oak panel with a finishing layer containing gesso, indicating three different regions (elastic deformation, plastic deformation, damage) for two different board thicknesses: (a) 5 mm and (b) 20 mm. Markers are added to illustrate four different indoor climates.

amplitude in RH. If we consider a yearly fluctuation with an amplitude of 30%, panels with all thicknesses considered here (up to 40 mm thickness) are in the damage region. On the other hand, all panel thicknesses considered here result in plastic deformation for a fluctuation of 15%.

Figure 10 is similar to Figure 7; the boundaries are shifted slightly due to different criteria (oak in Figure 10, gesso in Figure 7) and a different position along the thickness of the board (middle of board in Figure 10, unexposed surface in Figure 7). The damage region is marginally larger, at the expense of the elastic deformation region. In other words, fluctuations exist which are harmful for the finishing layer covering an unrestrained board, but not for a restrained board at half-thickness.

The fluctuation frequency versus amplitude plot for the second case is shown in Figure 11 for two different board thicknesses (5 and 20 mm). Again, the plot is

similar to Figure 8 for the unrestrained case. The boundaries have shifted vertically, due to the lower critical strains for gesso compared to oak. For the unrestrained board, the damage region is smaller, and thus more fluctuations can be considered safe.

The maximum allowable fluctuation for a 10-mm-thick board is shown in Figure 12, where a comparison is made for a restrained and an unrestrained board. As can be seen, the allowable fluctuation for the middle of the restrained board is larger than for the gesso in the pictorial layer in case the board is unrestrained. Nonetheless, the qualitative behavior is similar.

Discussion

Guidelines for indoor climates hosting panel paintings were proposed before by Mecklenburg, Tumosa, and Erhardt (1998) and Mecklenburg (2007), where allowable changes in the RH were based on the initial and
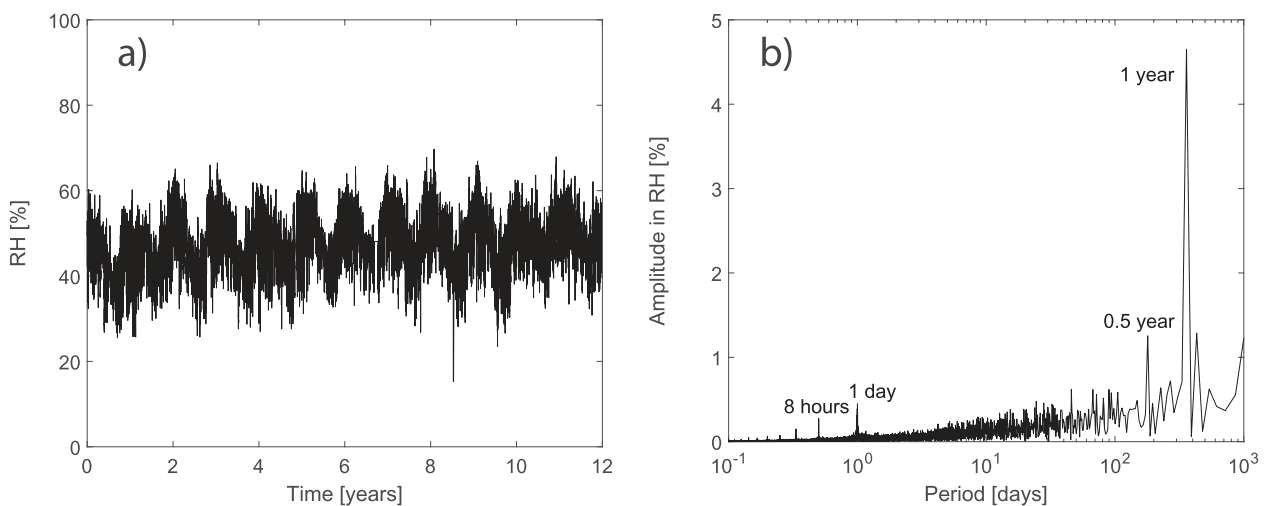
Figure 9. (a) Time-domain RH data of the Spiegelsaal of Schönbrunn palace in Vienna, and (b) its frequency spectrum, with dominant fluctuations highlighted.
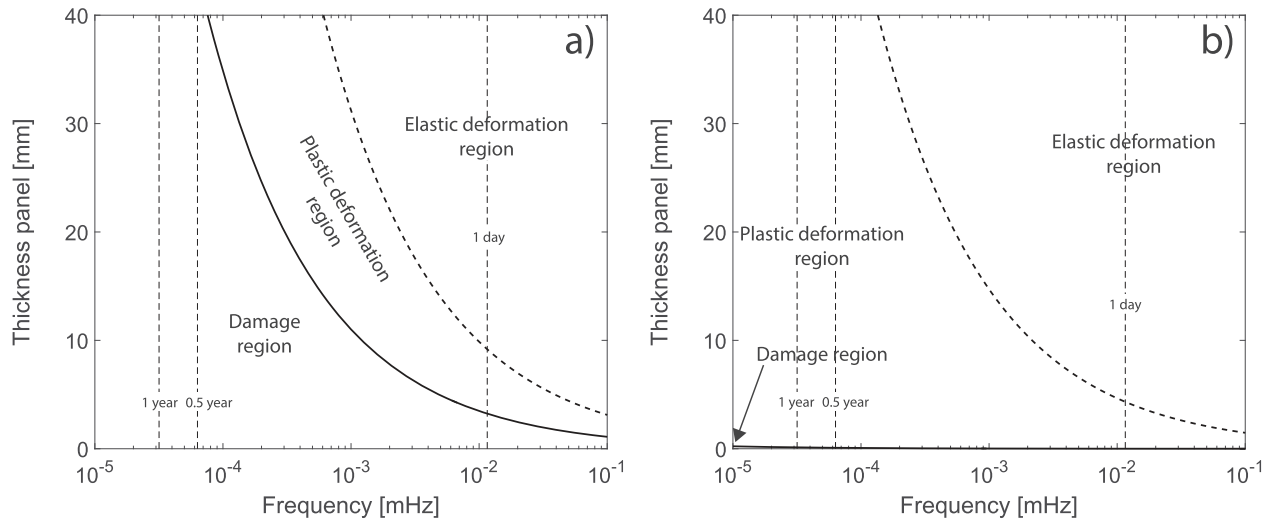
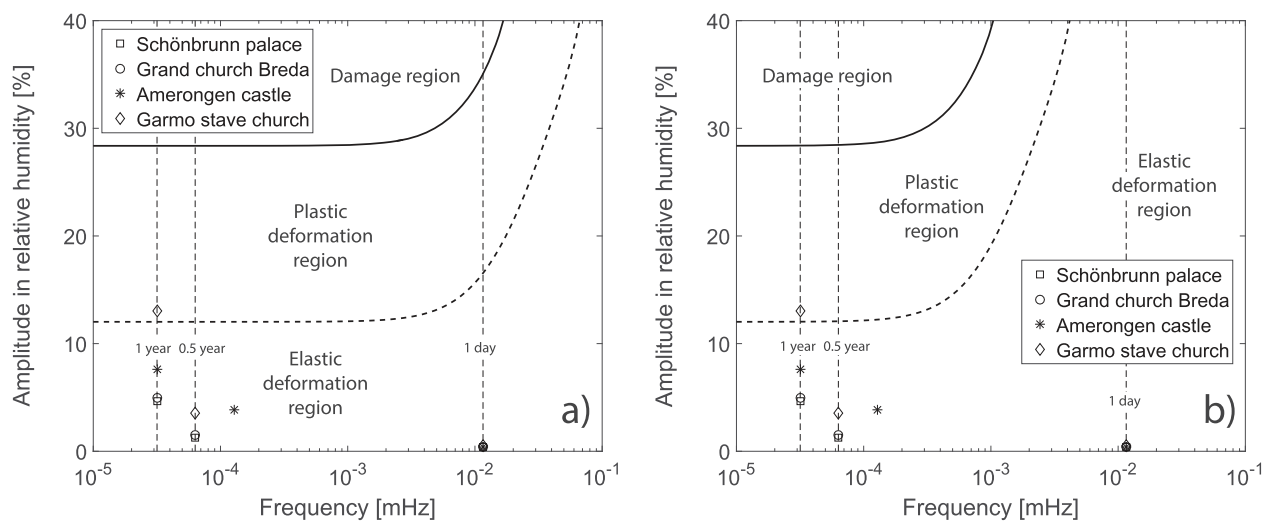**Figure 10.** Frequency versus panel thickness plot for a restrained oak board, indicating three different regions (elastic deformation, plastic deformation, damage), for two different RH amplitudes: (a) 30% and (b) 15%.

final RH. The timescale on which changes in the ambient RH occur was not taken into account; all changes in RH, regardless of the frequency, were treated equally. This is accurate for a thin layer near the exposed surface, but for the rest of the panel only at low frequencies, when the moisture penetrates all the way through. Moisture penetration into the board was taken into account by Rachwal *et al.* (2012a) and Bratasz (2013). Rachwal *et al.* (2012a) numerically calculated the amplitude in RH as a function of the period which causes a critical strain of 0.002 in the tangential direction of a 10-mm-thick lime wood panel. Results are qualitatively comparable to the boundary between the elastic and plastic deformation region in Figure 8. The diffusion coefficient used by Rachwal *et al.* (2012a) is a function of the moisture content, and higher than the average diffusion coefficient found in this study ($\sim 5 \times$

10^{-11} m^2 s^{-1}). As a consequence, the line is shifted along the frequency axis compared to Figure 8. The critical amplitude in RH of 6%, however, is comparable to the value found in this study (8%).

Our results show that the allowable amplitude in RH is dependent on the frequency of the fluctuation, due to the relative penetration depth of moisture. Fast, daily fluctuations only cause significant bending in very thin boards; thicker boards do not appreciably bend as to exceed the critical strain in the finishing layer or in the wood itself, when restrained. Slower, yearly fluctuations are allowed with a smaller RH amplitude due to the large relative penetration depth of moisture. We now have provided a first quantitative estimate of the allowable RH fluctuations when assuming a certain panel structure and critical strain levels from the literature. This can be used to assess certain situations, e.g. fast fluctuations in RH in the form of visitors passing by periodically


Figure 11. Frequency versus amplitude plot for a restrained oak board, indicating three different regions (elastic deformation, plastic deformation, damage), for two different board thicknesses (a) 5 mm and (b) 20 mm. Markers are added to illustrate four different indoor climates.
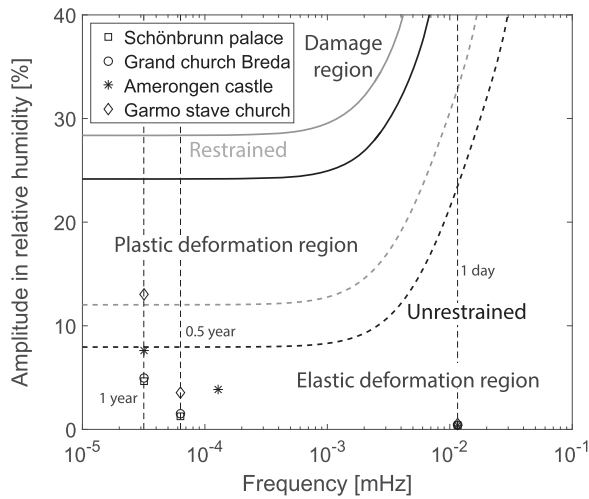
Figure 12. Frequency versus amplitude plot indicating the three different regions (elastic deformation, plastic deformation, damage) for a board thickness of 10 mm, comparing a restrained oak board and an unrestrained oak board with a finishing layer containing gesso. Markers are added to illustrate four different indoor climates.

with wet clothes. This probably has little effect on the bending of most panel paintings.

So far, the critical strain was assumed to be constant. It has, however, been shown experimentally that fracturing in gesso is dependent on the number of cycles undergone (Kozlowski *et al.* 2011). Damage in gesso occurred only after ~5000 cycles of successive mechanical stretching and compression for a strain of 0.0025. Two cases can thus be compared: a constant critical strain of 0.0025 (Mecklenburg, Tumosa, and Erhardt 1998), and a critical strain dependent on the number of cycles in a period of 100 or 1000 years (Kozlowski
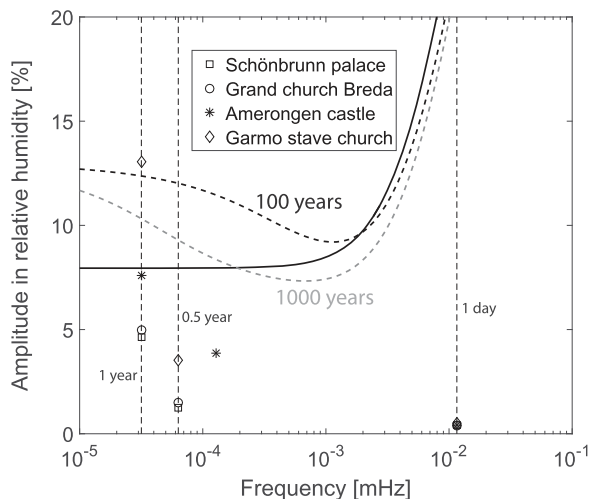
Figure 13. Amplitude in RH which produces a critical strain in the gesso layer of a 10-mm-thick board as a function of frequency. A comparison is made for a constant critical strain of 0.0025 (Mecklenburg, Tumosa, and Erhardt 1998) and a critical strain dependent on the frequency (Kozlowski *et al.* 2011), which the gesso layer can safely sustain for either 100 or 1000 years. Markers are added to illustrate four different indoor climates.

et al. 2011). The allowable amplitude in RH as a function of fluctuation frequency is shown in Figure 13 for a 10-mm-thick panel, for both cases. For high frequencies, it can be seen that the difference between the two curves is minor. Towards lower frequencies, the allowable amplitude in RH increases, due to the fewer cycles at that frequency occurring over a period of 100 or 1000 years. Yearly fluctuations considered harmful with the constant critical strain are considered safe with the critical strain dependent on the number of cycles (Schönbrunn and Breda). Adding this effect raises an additional question: how long do we wish to preserve panel paintings? As can be seen, if we wish to preserve the painting for 1000 years instead of 100 years, the maximum allowable amplitude in RH shifts to lower values. In the limit, i.e. for infinitely long preservation and thus an infinite number of cycles, the critical strain attains a constant value of 0.0015 (Kozlowski *et al.* 2011), lower than the constant value found by Mecklenburg, Tumosa, and Erhardt (1998). In other words, the maximum allowable amplitude in RH will be even lower than the 8% for slow fluctuations found in this study.

In this study, gesso in the pictorial layer has been identified as the most vulnerable layer, and hence has been used in the determination of allowable RH fluctuations. In case the configuration of the board is different, or a different material is the most vulnerable, other critical strains can be adopted to determine allowable fluctuations. The same applies if more conservative values for the critical strains are preferred. Furthermore, the damage occurring now is due to cracking of the gesso layer. Damage may, however, also occur due to detachment of a layer which has been applied onto the oak board. In this case, other damage criteria may apply, changing the guidelines quantitatively.

Several assumptions have been made regarding the configuration of the board and the structure of the panel painting. The experiments are performed with moisture transport in radial direction and expansion in the tangential direction causing the bending. Although this configuration occurs in panel paintings, the reverse is common too. The guidelines will be qualitatively similar, but are probably shifted along the frequency axis due to slower transport in the tangential direction (Siau 1984). Furthermore, larger amplitudes in RH are allowable since expansion in the radial direction is smaller. The critical strain in the gesso layer will therefore be reached at higher amplitudes in RH.

Similarly, larger amplitudes in RH are allowable if moisture exchange at the back surface of the panel is hindered by e.g. a wall or a backbone structure. As a result, the bending response is delayed and attenuated due to a smaller asymmetry in the moisture content profile over time. Larger amplitudes in RH and slower fluctuations are allowed, dependent on the resistance

to moisture exchange of the back surface. An attenuation in the bending response also results if the finishing layer is more permeable to moisture than the silicone kit used in the experiments. The moisture content in the underlying layers may subsequently also change. The response of these layers, however, is generally low compared to wood (Mecklenburg, Tumosa, and Erhardt 1998). The influence is thus expected to be minor. Moreover, the finishing layer is presumed to play no part in the mechanics of the panel painting as a whole. In case the thickness of the board is small, the stiffness of the finishing layer may significantly contribute to the mechanics of the panel painting, and thus to the bending behavior. Bending experiments with boards and a thin finishing layer may provide insight into the role of this layer in the mechanics of the board.

Conclusions

A combined experimental–analytical method is presented to relate fluctuating environmental conditions to the response of oak panel paintings. We present insightful and simple plots for the assessment of indoor climates for panel paintings. The strength of the study is its experimental background; the bending behavior is determined experimentally simple and fast. Allowable RH fluctuations are assigned depending on board thickness and fluctuation frequency due to linear system behavior and the inherent scaling in the moisture-induced bending. Assessment of indoor climates is demonstrated, by Fourier transform of the time-domain data. The main implication is that fluctuations at high frequencies are allowed, since the penetration depth of moisture is too small to cause any significant bending. The allowable frequency is dependent on the board thickness; thicker boards can resist bending due to humidity changes better than thin boards. The four distinct indoor climates analyzed in this study show that the daily amplitudes, even for a poorly controlled indoor climate, do not reach values at which bending of a panel can potentially cause damage. Slower fluctuations with e.g. a period of one year can, however, result in exceedance of critical limits.

Since the configuration of the panel paintings in this study is simplified, so are the resulting allowable RH fluctuations. Specifically, the assumption that the back of the panel painting is free to exchange moisture affects the resulting recommendations pessimistically. A resistance to moisture exchange at the back surface impedes moisture transport and attenuates asymmetry in the board and thus the bending response. Moreover, the stiffness of the finishing pictorial layer is neglected, which results in an overestimation of the bending response and resulting strains. For these reasons, the presented guidelines for allowable RH

fluctuations can be considered as worst case conditions.

The strain criteria in this study are adopted from the literature. A valuable extension of the present work is therefore the experimental assessment of actual damage occurrence. Acoustic emission can for instance be used in experiments performed with different RH fluctuations to determine cracking in the wood (Quarles 1992; Jakiela, Bratasz, and Kozlowski 2007; Strojecki et al. 2014). Another possibility is the performance of bending experiments with a layer of gesso, covered with paint. Cracking in the paint layer can then be measured optically. A similar experiment is also expected to elucidate the effect of the stiffness of the finishing layers on the bending behavior. A disadvantage is the large number of cycles needed to cause damage at certain amplitudes in strain (Kozlowski et al. 2011).

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