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ALLOWABLE MICROCLIMATIC VARIATIONS FOR PAINTED WOOD: NUMERICAL MODELLING AND DIRECT TRACING OF THE FATIGUE DAMAGE

Keywords: painted wood, gesso, relative humidity, microclimate variations, fatigue damage, finite element modelling

ABSTRACT

Painted wood is a multi-layer structure composed of materials which swell or shrink differently in response to the sorption and desorption of moisture. The allowable levels of strain of the gesso layer were determined experimentally by subjecting specimens imitating historic panel paintings to mechanical stretching, and monitoring the development of cracks. These strain values were translated into the magnitudes of cyclic RH fluctuations allowable for unrestrained panel paintings, which depend on cycle duration, panel thickness and the configuration of moisture exchange of a panel with the environment. Panel paintings do not respond significantly to diurnal or shorter fluctuations irrespective of the panel thickness. The panels respond more and more significantly when the duration of the fluctuations increases until the panel fully responds to each cycle. The approach for calculating the accumulated fatigue damage from real-world climatic variations, being combinations of climatic cycles of various durations and amplitudes, was demonstrated.

RÉSUMÉ

Le bois peint est une structure multicouche composée de matériaux qui enflent ou rétrécissent différemment en réaction à la sorption et la désorption d'humidité. Les niveaux admissibles de déformation pour la couche de gesso ont été déterminés de manière expérimentale en soumettant des spécimens imitant des peintures anciennes sur panneau à un étirement mécanique, pour surveiller la formation de craquelures. Ces valeurs de déformation ont été traduites en magnitudes admissibles des cycles de fluctuation de l'HR pour des peintures sur panneau sans contrainte, qui dépendent de la durée du cycle, de l'épaisseur

INTRODUCTION

Reviewing environmental standards for cultural heritage collections has been much debated in the last two years. The debate derives from a growing movement to *green* museums, that is, finding low-carbon, cost-effective energy solutions for museums while at the same time maintaining high standards of collection care (IIC 2010, Hayton 2010). There is universal agreement that the development of environmental guidelines for cultural heritage needs to be informed by growing scientific understanding of how changes in environmental conditions ultimately affect real artefacts.

This paper focuses on advances in research on the response of paintings on wood – one of the most vulnerable category of historic objects – to variations in the environment. Painted wooden objects are complex, multilayer structures composed of humidity-sensitive materials – wood, animal glue, gesso and paints – which respond to environmental variations by gaining moisture and swelling when relative humidity (RH) is high and losing moisture and shrinking when the surrounding air is dry. The mismatch in the dimensional response of gesso and wood in unrestrained panel paintings, especially in the most responsive tangential direction of the wood, has been identified as the worst case condition: upon desiccation, the shrinkage of wood overrides that of the gesso which experiences compression, whereas upon wood swelling, the gesso layer experiences tension (Mecklenburg et al. 1998). If the uncontrolled changes in the moisture-related strain go beyond a critical level, the gesso can crack or delaminate.

This study further refines the understanding of painted wood response to environmental variations. Specimens simulating historic panel paintings were subjected to cycles of mechanical stretching to imitate repetitive dimensional change of unrestrained panel paintings induced by RH fluctuations in the environment and the development of cracks in the design layer was directly monitored. In this way, the critical strains causing damage were determined experimentally with great precision for the entire complex structure of painted wood as a function of the number of strain cycles and thus the vulnerability of the design layer to fatigue fracture – a consequence of the cumulative strain effects – was assessed. The necessity to correct critical strains due to fatigue from multiple fluctuations has been stressed already (Michalski 2009), as the continuous accumulation of slight changes also accounts for the deterioration of painted wood observed in museums.

du panneau et de la configuration de l'échange d'humidité d'un panneau avec l'environnement. Les peintures sur panneau ne réagissent que faiblement aux fluctuations diurnes ou brèves, quelle que soit l'épaisseur du panneau. Le panneau réagit de plus en plus lorsque la durée des fluctuations augmente jusqu'à ce qu'il réagisse complètement à chaque cycle. La méthode de calcul des dommages dus à la fatigue accumulée lors des variations climatiques en situation réelle, caractérisées par des combinaisons de cycles climatiques de durée et d'amplitude variables, a été démontrée.

RESUMEN

La madera pintada es una estructura con múltiples capas compuesta por materiales que se hinchan y encogen de manera diferente, en respuesta a la adsorción y desorción de humedad. Los niveles permitidos de deformación de la capa de yeso se determinaron de manera experimental, sometiendo muestras que imitaban pinturas sobre tabla antiguas a estiramientos mecánicos, y monitoreando el desarrollo de grietas. Estos valores de deformación se tradujeron en magnitudes de fluctuaciones cíclicas de HR permitidas para pinturas sobre tabla sin control, que dependen de la duración del ciclo, del grosor de la tabla y de la configuración del intercambio de humedad de un panel con el ambiente. Las pinturas sobre tabla no responden de manera significativa a las fluctuaciones diurnas o más cortas, independientemente del grosor de la tabla. Las tablas responden cada vez más cuando la duración de las fluctuaciones aumenta hasta que la tabla responde completamente en cada ciclo. Se demostró el acercamiento para calcular el daño por fatiga acumulada provocado por las variaciones climáticas del mundo real, es decir combinaciones de ciclos climáticos de duración y amplitud variadas.

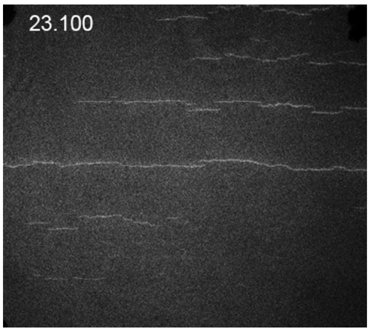


Figure 1
Interferogram showing crack pattern development after 23,100 cycles at a strain of 0.025, obtained with the use of the laser speckle decorrelation technique (note: the images obtained by this technique are, by nature, intrinsically grainy)

METHODS OF STUDY

To produce specimens imitating historic painted wood, 10-mm-thick lime wood substrates were sized with rabbit-skin glue and coated with gesso composed of the same glue and ground chalk at a pigment-volume concentration commonly used in the restoration of panel paintings: the thickness of the dried gesso layer was approximately 1 mm.

Cycles of strain were produced by mechanical stretching and compressing of the specimens using a universal testing machine at selected amplitudes which simulated the dimensional changes of unrestrained panel paintings induced by repetitive fluctuations of RH. The frequency of the strain cycles was approximately 0.3 Hz and the specimens were subjected to up to 100,000 cycles. The experiments were conducted under a constant RH of 50% maintained in the laboratory. The specimens were taken out after a pre-determined number of strain cycles and the fracture development in the gesso was recorded using the speckle decorrelation technique capable of monitoring physical damage at the micro-level (Lasyk et al. 2011).

The finite element method was used to model moisture movement and strain in a wood panel coated with a layer of gesso in response to changing climate conditions – temperature and RH. The material properties of lime wood and gesso used in the modelling – water vapour sorption isotherms, moisture diffusion coefficients, mechanical properties and swelling/shrinkage responses – were determined experimentally (Rachwał 2011).

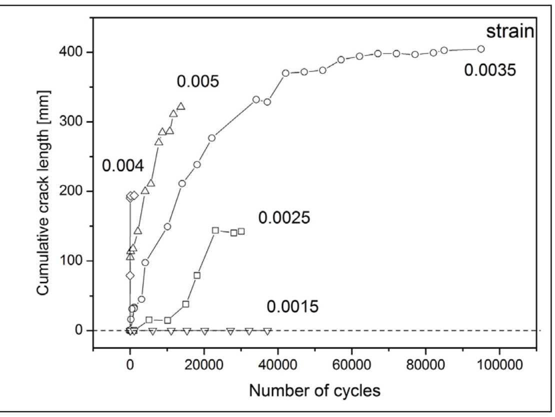
EXPERIMENTAL RESULTS

The speckle decorrelation technique can provide quantitative information about the number of cracks in the surface layer and their length (Figure 1). Plots of the cumulative crack length versus the number of stretching cycles were determined for a range of strains between 0.0015 and 0.005. For a strain of 0.0015, no fracture in the gesso appeared after the 36,500 cycles applied, equivalent to 100 years of diurnal strain cycles, whereas a strain of 0.0025 produced first cracking after only 5000 cycles (Figure 2). Though a strain of 0.0035 caused a first fracture in gesso after just a hundred or so stretching cycles, approximately 50,000 further cycles were necessary to bring the crack growth to 'saturation'. The results obtained allow plotting of an S-N curve where S is the strain leading to fracture and N is the number of cycles causing the first incidence of fracture at that strain (Figure 3). As each test consisting of a large number of stretching cycles proved very time-consuming, it was possible to test only a few specimens (no more than three) at each strain level. Such small numbers of measured specimens do not allow for an experimental uncertainty analysis to be performed. However, the difference between the first and the second points (3 and 11 cycles, respectively) in Figure 3 provides some estimation of the uncertainty of the measured quantity. The general curve shape is sigmoid, starting from the strain to fracture in a single cycle or a few cycles, and dropping to a plateau where cyclic strain can be tolerated for up to 36,500 cycles. The strain of 0.002 was assumed to be close to that value. Thus, the strain tolerable at the maximum number of cycles was approximately 1/2 of the single-cycle fracture strain.

The critical strain values of the S-N curve were translated into the critical magnitudes of RH variations necessary to cause these strains using the numerical modelling of the dimensional response of the panels. When the RH variations last much longer than the response time of a panel, that is, when the panel can reach the new values of equilibrium moisture content, and the corresponding strain, at each instant of a variation, the critical strains of the S-N curve in Figure 3 correspond to a mismatch in the moisture-related responses of the unrestrained wood substrate and the gesso layer. This mismatch can be recalculated into the magnitude of RH variations causing the respective strains in the wood substrate and the gesso, using the swelling isotherms of both materials. Moisture expansion coefficients for the gesso and lime wood – in the most responsive tangential direction – were derived experimentally by taking into account the hysteresis in the dimensional response of wood when subjected to alternating processes of adsorption and desorption (Rachwał 2011).

When the duration of RH variations decreases, a panel experiences moisture change in its outer parts only. The overall dimensional response of the panel, and its damaging impact on the gesso, is consequently reduced, as the outer part will be restrained from dimensional change by the underlying core which is unaffected by the fast RH variations. To illustrate the effect, RH variations were represented in the calculations at first by a sine function. Each sinusoidal RH cycle of a given amplitude and duration causes a certain strain cycle in a panel which impacts on the gesso layer. The amplitude of the strain cycle depends on the panel thickness and the configuration of moisture exchange by a panel with the environment. Two extreme situations were considered: a free moisture exchange through both faces of a panel, or through one of the two faces only, to simulate the extreme effect of a gilded or varnish layer completely impermeable to moisture flow (Allegretti and Raffaelli 2008). The allowable amplitude of an RH cycle for a given panel was calculated as a value causing cyclical critical mismatch between the moisture-related responses of the unrestrained wood substrate and the gesso respectively which leads to the first fracture on the virgin gesso after 100 years of cycle occurrence; the critical mismatch values were read on the S-N curve shown in Figure 3. 100 years was considered an appropriate time interval for risk assessment in the cultural heritage field.

Relationships between the allowable amplitude of an RH cycle thus defined and the cycle duration were obtained for panel thicknesses varying between 5 and 40 mm and the moisture flow through one or both faces (Figure 4). Typically, the original thickness of panels ranged from 30 to 45 mm (Uzielli 1998). However, straightening of deformed panels which involved planning them to a fraction of the original thicknesses before the application of new supports became a common practice in the 19th century. Therefore, the substrates of panel paintings surviving to our times can



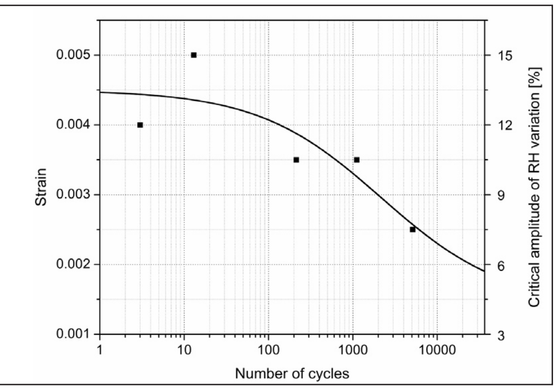
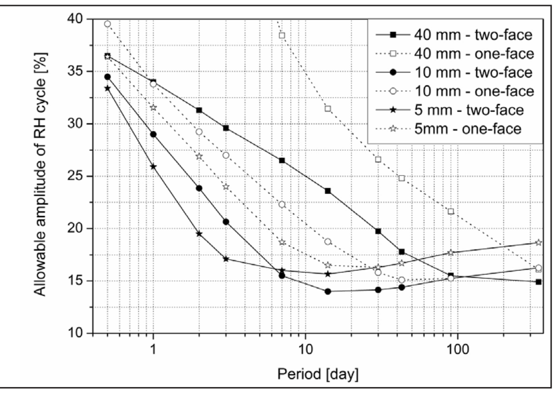


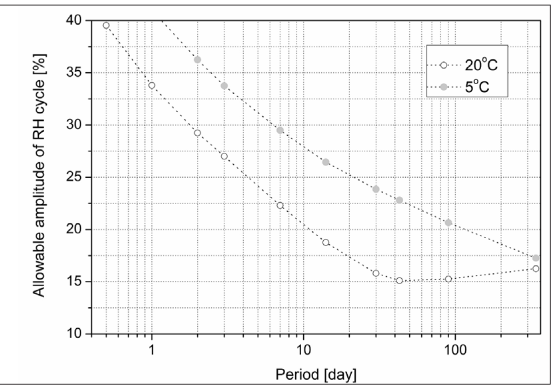
Figure 2

The cumulative crack length in gesso versus the number of strain cycles

Figure 3

Strain, and corresponding amplitude of RH variation, leading to fracture in gesso versus number of cycles causing fracture at that strain. The most responsive tangential direction in wood was considered and each RH variation was assumed to cause a full response of an unrestrained panel. Amplitude of RH variation was calculated assuming a starting point of 50% RH





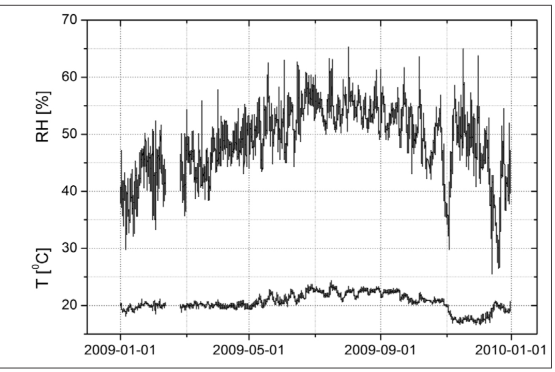


Figure 4
Allowable amplitude of the sinusoidal RH cycles as a function of the cycle duration for unrestrained panels of thicknesses between 5 and 40 mm and for a moisture exchange through one or both the faces at 20°C. The most responsive tangential direction in wood was considered

Figure 5
Allowable amplitude of the sinusoidal RH cycles as a function of the cycle duration for an unrestrained panel of 10 mm thickness and a moisture exchange through one face at 5 and 20°C. The most responsive tangential direction in wood was considered

Figure 6
Indoor climate in 2009 in one of the galleries of the National Museum in Krakow, Poland as plots of temperature and RH recorded every 10 minutes

be merely a few millimetres thick. Though such thin panels were always backed by a new support usually restraining their dimensional response, they are included in the present modelling to show their response if freed from their supports.

As individual plots for each panel of a given thickness and moisture exchange configuration reveal, the panels respond less and less significantly when the duration of the fluctuations decreases, which is expressed in an increasing allowable amplitude of the fluctuations. Also, when the duration of the cycle goes beyond the response time of the panel, its allowable amplitude increases as fewer cycles would occur in the period of 100 years considered. As expected, a decrease in thickness reduces the allowable amplitude of RH fluctuations at the same duration of a cycle. However, the dimensional response of thin painted panels becomes subject to restraint by the applied layer of gesso. Therefore, the 5 mm panel free to exchange moisture through both faces can tolerate a slightly higher amplitude of ± 16% RH at the duration of 14 days than that of ± 14% RH determined for the 10 mm panel at the same duration. Consequently, the 10 mm panel with two faces permeable to the water vapour flux subjected to fluctuation cycles lasting 14 days represents the ‘absolute’ worst case of the study performed.

The allowable amplitude increases if the temperature at which the panel painting is displayed is lowered, as illustrated in Figure 5. The decrease in temperature lowers the moisture diffusion coefficients in wood and hence increases the time of the panel’s response. The effect can be one of the factors accounting for the frequent observation that low-temperature storage of wooden works of art – for example in unheated historic buildings – favours preservation.

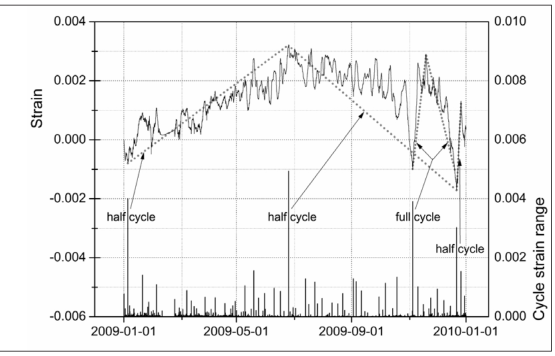
The modelling allows the calculation of the accumulated fatigue damage from real-world climatic variations consisting of combinations of climatic cycles of various duration and amplitudes. Such climatic variations produce irregular strain-versus-time histories for the panels which can be reduced mathematically into simple strain cycles of various sizes. By way of example, relative humidity and temperature data recorded in 2009 in one of the galleries of the National Museum in Krakow, Poland are used to illustrate the approach (Figure 6). The temperature was maintained at approximately 20°C throughout the year with periods of slight increases or decreases in summer and winter respectively. Though average RH was about 49%, a distinct low-high RH cycle was caused by heating in winter. The seasonal cycle is accompanied by shorter irregular variations in RH. The two most pronounced falls in RH recorded at the end of the year were due to spells of cold dry weather, when the outdoor air drawn into the museum was heated to the set temperature but insufficiently humidified by the air-conditioning system.

The variations in the indoor climate are reflected in a strain-versus-time history calculated for an unrestrained 10 mm panel free to exchange moisture through both faces, selected as a case study (Figure 7). The strain variations are a combination of one yearly swelling-shrinkage cycle of the overall range close to 0.005 – the cycle strain range being defined as an algebraic difference between the largest peak and the smallest valley in the strain-time history analysed – and many short-term strain cycles of variable range. Simple cycles of various ranges were obtained using the rainflow counting method (ASTM 2005) and are shown in the bottom part of Figure 7 as a vertical line graph. The detailed procedure is not covered here but it can be seen how the method separates strain cycles of various duration embedded in the complex strain-time history. Each vertical line is placed at a beginning of a simple cycle identified by the procedure and the cycle range is represented by the height of the line. The yearly swelling-shrinkage cycle is counted as two one-half cycles corresponding to swelling by 0.004 from the smallest valley in January to the largest peak in the summer and to shrinkage by 0.0049 from the same largest peak in summer to the smallest valley in December, respectively. Two shrinkage episodes in the cold period are counted as a full cycle and a one-half cycle of ranges 0.4 and 0.3, respectively. The remaining short-term cycles have declining ranges.

The results of the analysis are summarised in a histogram providing the number of times that cycles of various ranges occur (Figure 8). Miner's rule was then used to assess the combined effect of individual strain cycles on the gesso. The rule states that where there are k various strain ranges in the strain-time history, each contributing n_i cycles ($1<i<k$), then if N_i is the number of cycles to failure for a given strain cycle, the proportion of life of the material consumed by the strain-time history analysed is 1/C where C:

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C$$

The strain-time history analysed would bring about fracturing of the gesso within one year as it contains one large strain range of 0.0049 causing the gesso's failure in a single cycle (Figure 2). A mere reduction of this largest range to 0.004 would prolong the gesso's life to 114 years due to a dramatic increase in the number tolerable cycles with a decrease in the strain range.



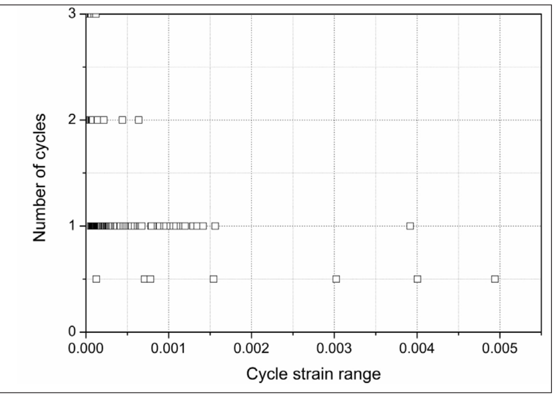


Figure 7
Strain experienced by the gesso layer on an unrestrained 10 mm panel with two faces open to moisture exchange and exposed to the climatic variations shown in Figure 6. The full strain-versus-time history (upper part) is compared with the set of simple cycles (bottom part) obtained by the rainflow analysis. Four simple cycles dominating the strain-versus-time history are marked with a dotted line

Figure 8
Histogram showing the number of times single cycles of various strain ranges, shown in Figure 7, occur

CONCLUSIONS

The experimental approach involving cyclic mechanical stretching of wooden specimens coated with gesso and monitoring the development of cracks in the gesso layer with the use of laser speckle decorrelation allowed determination of the critical levels of strain, above which damage in gesso appeared, as a function of the number of strain cycles. 0.002 was accepted as a very conservative criterion for the critical strain as no physical damage of the gesso layer on wood had been observed after 36,500 such strain cycles at 50% RH.

A numerical modelling of the moisture movement and strain in unrestrained wood panels coated with a layer of gesso subjected to changing climate conditions revealed that paintings do not respond significantly to diurnal or shorter fluctuations. The panels respond more and more significantly when the duration of the fluctuations increases until a certain critical duration at which the panel fully responds to each cycle. Further increase in duration diminishes the risk of physical damage as the number of fluctuations within the selected time period decreases. The critical, worst-case duration is 14 days for a panel 10 mm thick and the allowable amplitude of fluctuations for this worst case cycle was ± 14% RH. A decrease in panel thickness reduces the allowable amplitude of RH fluctuations at the same cycle duration. However, the dimensional response of panels thinner than approximately10 mm becomes subject to restraint by the applied layer of gesso. The allowable amplitude of RH fluctuations also increases if the temperature at which the panel painting is displayed is lowered

The time to the first incidence of cracking in the virgin gesso layer on an unrestrained 10 mm panel was calculated from yearly real-world climatic variations which consisted of combinations of climatic cycles of various duration and amplitudes. The demonstrated approach will be used to develop a prediction software that calculates doses of accumulated climate-induced damage to panel paintings caused by real-world environmental variations measured or forecast in museums and historic buildings. This will help in assessing the harmlessness or otherwise of current or future museum climates, which would inform strategies for reducing the environmental control needed to ensure adequate preservation of panel paintings.

It should be stressed further that real-world RH variations experienced in the past by polychrome wood often exceeded the ±15% RH band. Therefore, the design layers on wood are usually extensively cracked. The cracking has been considered an ‘acclimatisation’ process for painted wood with cracks acting as expansion joints and reducing the risk of further mechanical damage from fluctuations which do not go beyond the past pattern. Therefore, more experimental work is necessary to determine critical strains which would endanger cracked rather than virgin design layers.

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