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Original research or treatment paper

Mechanism of craquelure pattern formation on panel paintings

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The drying shrinkage accumulation from exposure of freshly prepared gesso layers to relative humidity (RH) cycles was determined to elucidate the mechanism of craquelure pattern formation on panel paintings. The progressive drying shrinkage of the gesso is observed only under the cycles going to high RH levels which bring about transitions from brittle to ductile state of the material. The first incidence of fracture on the gesso layers occurred after a limited number of cycles ranging between a few and 100 for a range of layer thickness between 0.5 and 1 mm. The craquelure patterns stabilised also after a limited number of cycles (30 for the 1-mm thick layer). Upon increase in the gesso layer thickness, the strength of the layer is reduced and the spacing of shrinkage fractures increases. The study demonstrated that craquelure patterns, mimicking historical ones, can be realistically produced in laboratory conditions. Such studies would provide useful information for preparing specimens simulating historic panel paintings and would inform the current efforts on automatic, computer-aided classifications of crack formations on paintings.

Keywords: Craquelure pattern, Crack formation, Fracture saturation, Panel paintings, Gesso layer, Dimensional change, Drying shrinkage, Relative humidity cycles

Introduction

The craquelure patterns in a painting are related to drying shrinkage of a pictorial layer produced by the artist, and to environmental and physical impacts which the painting experienced later in its history. The terms ‘drying’ and ‘aging’ cracks are used to describe the two groups of patterns, respectively (Bucklow, 1997).

The formation of environmentally induced ‘aging’ cracks in panel paintings has been extensively analysed and is quantitatively understood in terms of the complex dimensional response of a multi-layered structure of a painting to variations of relative humidity (RH) in its environment. The moisture-related dimensional changes of the individual layers of the structure – wood, animal glue, gesso, and paints induce stresses, which can cause cracking of the ground and paint layers. The wood substrate itself is anisotropic because its moisture-related dimensional changes vary in its three principal anatomical axes –

longitudinal, or parallel to grain, radial, and tangential. Wood can be considered dimensionally stable parallel to the grain. Its most pronounced moisture response is in the tangential direction and that response halves in the radial one. In the direction across the grain, moisture-related movement of a wood substrate may completely override the less responsive ground and paint layers, which has been identified as the worst-case condition for their fracturing induced by RH variations (Mecklenburg *et al.*, 1998). The condition has provided the basis for establishing the allowable ranges of climatic variations which the painted wood can endure without damage (Bratasz, 2013).

The formation of ‘drying’ craquelure patterns resulting from an overall shrinkage of the gesso during drying has been less investigated. Generally, as the shrinkage is restrained by the wooden substrate especially in the longitudinal direction, the drying gesso experiences an increase in tensile strain and stress, resulting in particularly pronounced cracking running perpendicular to the grain (Bucklow, 1997). Obviously, the drying craquelure patterns are related to the materials and methods employed by the artist

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and the craftsmen preparing the wooden substrate. The permanent shrinkage engendered in the gesso during drying from the slurry, as-prepared state was termed an initial drying strain (Michalski, 1991). Gesso was found to undergo further permanent shrinkage, termed an ‘annealing’ shrinkage, when exposed subsequently to high RH. The material continued to exhibit additional, but smaller annealing shrinkage after having been subjected to subsequent cycles of exposure to high RH levels (Mecklenburg, 1991). To the permanent drying shrinkage, a reversible shrinkage or swelling is added as gesso is a hygroscopic material which loses or gains moisture when RH decreases or increases, respectively. Changes in moisture adsorption of the gesso cause changes in the dimension.

Karpowicz (1989) investigated shrinkage behaviour of films of rabbit-skin glue – which is the component in gesso responsible for moisture-related dimensional changes. The glue shrank at high RH as a result of recovery of strains formed during drying after preparation. The author estimated the ultimate permanent drying shrinkage of the glue to be 5.5% achieved after repeated cycling to high RH levels. The mechanism was discussed in terms of structure and ordering of protein network during gelation and drying.

This study seeks to refine – in two aspects – understanding of the mechanism of gesso’s cumulative drying shrinkage leading to craquelure. First, changes in gesso’s properties were studied experimentally over a wide range of RH so that effects related to changes of the material from brittle to ‘gel-like’ when going from low- to high-moisture content are taken into account. Secondly, the shrinkage accumulation due to a large number of cyclic exposures to high RH was considered for gesso films of varying thickness. The ultimate intent of the study is to improve understanding of the distinct features of the drying craquelure patterns observed on the surface of panel paintings and the mechanism leading to their formation.

Material

For this study, all gesso samples were made using rabbit-skin glue and ground chalk. The ratio of the chalk, ‘the pigment’, to the glue is expressed as the pigment volume concentration (PVC)

$$\text{PVC} = \frac{P}{P + B} * 100\%$$

where P and B are volumes of the pigment and the dry glue binder, respectively. The mechanical properties of the gesso are affected by both the strength of the glue and the PVC. PVC values ranging between 85 and 95% were suggested as typical recipes of usable gessesoes (Mecklenburg, 1991; Michalski, 1991). The rabbit-skin glue used in this study had a high Bloom

strength value of 380–420 g, defined as the force required to make a specific depression into a gel sample prepared from the glue under standard conditions. Therefore, a rather high PVC value of 92% was selected as it produced gesso layers of very good mechanical properties and, at the same time, accepted by a restorer as matching gessesoes commonly used to restore panel paintings.

Experimental details

To determine moisture-related dimensional change and tensile properties of the gesso, strip specimens $6 \times 6 \times 80 \text{ mm}^3$ were machined from a 10-mm thick stock material prepared by a professional restorer. The fresh gesso mixture was applied with a brush and dried on a flexible support (a polyethylene film) to allow restraint-free drying shrinkage of the material and thus produce undamaged, stress-free material. Then subsequent layers of the gesso slurry were similarly laid and dried, until the desired thickness of 10 mm was attained.

The specimens used in the tests were mounted in a Universal Testing Machine – UTM (Inspekt Table 10 kN) using flexible joints to ensure a linear alignment of the specimen (Fig. 1). The displacement was measured using a 50-mm base extensometer and the force was measured by a transducer which was a part of the UTM itself. The rate of the tension loading was $3.3 \mu\text{m/m/s}$. The specimen was placed in a sealed box connected to a climatic chamber, which allowed temperature and RH to be precisely controlled during the testing.

To measure the moisture-related swelling and shrinkage of the gesso, the specimen was mounted in the UTM, which was programmed to keep it unloaded as RH was cycled between 30 and 90% during 20

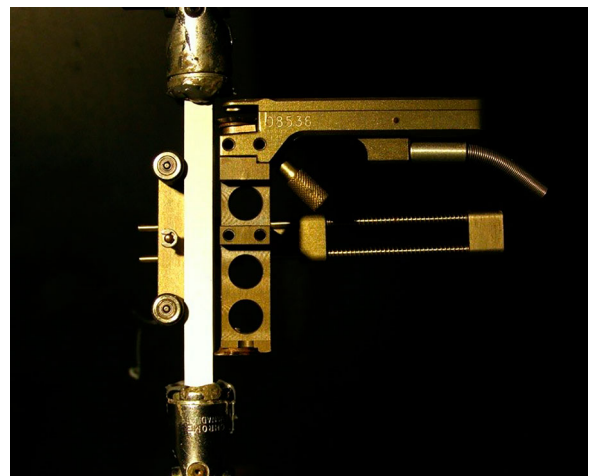


Figure 1 The experimental set up for the measurement of tensile properties and moisture-related dimensional change.

hours of test period. The dimensional change was monitored using the extensometer.

Results

Stiffness of the gesso

The stiffness of gesso was periodically measured at 22°C for an RH range between 45 and 98%. RH in the climatic box surrounding the specimen was increased at a rate of approximately 1.4% RH per hour. During each hourly step of the RH increase, the specimen was stretched to a strain of 0.02% (well below the elastic region limit) and released. The relationship between the initial tensile elasticity modulus, determined from the steepest slope of the stress–strain curve, and RH is shown in Fig. 2.

As one can see, gesso experiences a dramatic loss of stiffness at high RH range. The material's glass transition, which is from the brittle to ductile (gel-like) state is observed at approximately 75%. Above this RH level gesso becomes easily deformable and elongation at break increases at least by an order of magnitude when compared with the values below the glass transition point (Rachwał et al., 2012).

Moisture-related dimensional change

The moisture-related strain for the RH change between 30 and 90% did not exceed 0.2% (Fig. 3). Strain is calculated as change in length divided by the specimen original length, in this case the length of the dry sample. The moisture coefficient of dimensional change was obtained by the linear regression of the central part of the plot and is 3.2×10^{-6} per 1% of RH. In the earlier work (Rachwał et al., 2012), the value of 9.4×10^{-6} per 1% of RH was obtained for the same gesso preparation from the moisture coefficient of dimensional change of the pure glue using Michalski's microscopical model of gesso (equation 8 in Michalski, 1991). As the value

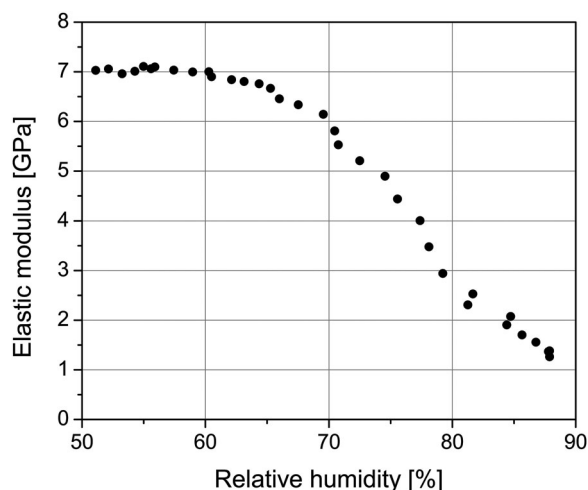


Figure 2 The modulus of elasticity of the gesso plotted as a function of RH.

calculated from the model was an estimate of the parameter, it is assumed that the value obtained directly from the experiment in this study is more accurate.

Cumulative drying shrinkage

In the first experiment, a freely dried gesso specimen was mounted in the UTM and RH in the climatic box was raised to 90% to transform the material into the gel-like state. Then the specimen was subjected to a strain of 2% under an applied force of 24 N. The strain, as for all subsequent strain values, was calculated as change in length divided by the specimen length at 50% RH. The specimen was allowed to dry at RH of 50% under the same loading. Finally, the loading was released, and the specimen was subjected to RH variations of varying ranges. The experiment was aimed at measuring the cumulative, permanent drying shrinkage induced by RH changes in the gesso subjected to a considerable, uniform, uniaxial stretching in the material's wet, ductile state. Fig. 4 shows RH and dimensional changes recorded.

During the initial drying the specimen underwent a decrease in strain (shrinkage) of 0.4%, that is, the specimen dried at 50% RH retained 80% of its gel-like state dimension even without any external force applied. When the RH cycles between 20 and 80% RH were subsequently applied, the specimen was undergoing reversible increases and decreases in strain (cycles of expansion and shrinkage) of approximately 0.2% according to material's moisture coefficient of dimensional change. However, once RH in the cycles exceeded 90%, a significant permanent cumulative decrease in strain was observed reaching 1.3% after 20 cycles. Thus, the specimen experienced a total permanent decrease in strain (drying shrinkage) of 1.7%, or retained merely 15% of its gel-like state dimension.

A subsequent experiment aimed at measuring the cumulative drying shrinkage induced by RH changes

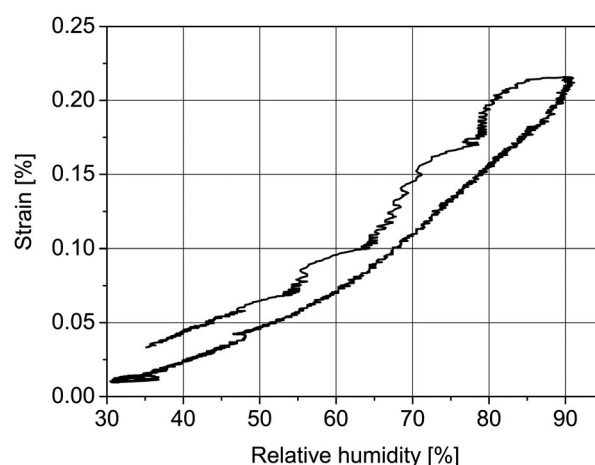


Figure 3 The moisture-induced dimensional change (swelling and shrinkage) of the gesso.

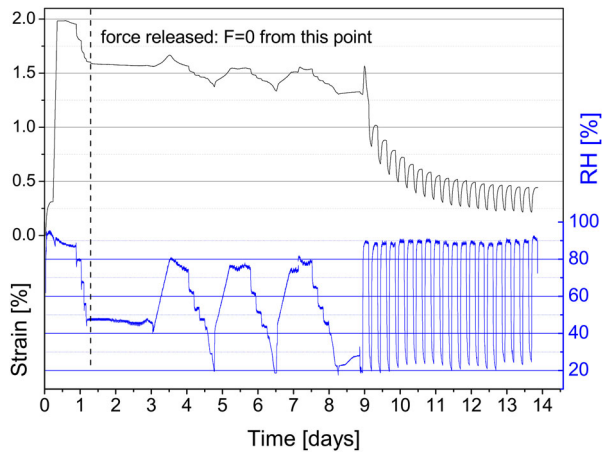


Figure 4 The strain in the gesso specimen subjected to RH changes.

in the 10-mm thick gesso specimen prepared as described earlier by applying subsequent layers of the gesso mixture with a brush and drying, but this time on a glass plate providing a full substrate restraint (in two directions) to the drying shrinkage of the gesso layer. The dried specimen was removed from the glass support, placed in a climatic chamber and subjected to RH cycles of varying ranges. Dimensional change was recorded using the extensometer.

The gesso specimen thus prepared expanded and shrank reversibly according to gesso's moisture coefficient of dimensional change (Fig. 5). However, a step-wise accumulation of high level permanent drying shrinkage occurred when the upper RH level in the cycles exceeded 90%. The specimen experienced a cumulative drying shrinkage of 0.2% after approximately 40 such cycles – the largest shrinkage of 0.04% being observed on the first cycle to high RH level. The experiments clearly demonstrated that only the upper limit of the RH cycles was of critical importance – the gesso did not experience any permanent shrinkage for cycles in which RH did not exceed 80%. In contrast, the lower RH limit is not critical to

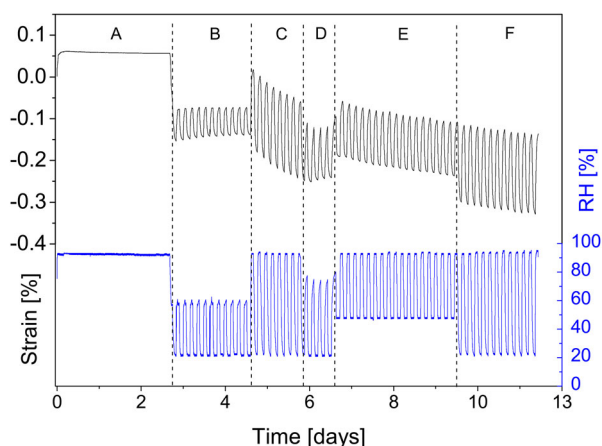


Figure 5 The strain in the gesso specimen laid on a glass plate, dried and removed, and then subjected to RH changes.

the phenomenon observed – cycling RH in the range of 95–50% or 95–20% produced the same steps of the permanent shrinkage. The measured total drying shrinkage of the gesso shows good agreement with the value of 0.15% calculated from Michalski's microscopical model (equation 8 in Michalski, 1991) using the ultimate permanent drying shrinkage of 5.5% determined for the glue (Karpowicz, 1989).

Formation of craquelure on a restrained gesso layer

Considerable drying shrinkage experienced by the gesso subjected cyclically to high RH levels indicates that, if the material is restrained by a stable substrate, it will ultimately fail via fracture. To determine the number of cycles producing failure for gesso layers of varying thickness, three gesso samples were produced on a single 500 × 500 mm² glass plate by applying with a brush a single layer, five, and ten layers of the gesso slurry; each layer application was allowed to dry at 50% RH. Glass was selected as the substrate as it offered a perfect uniform restraint to the gesso layer. In contrast, gesso on wood would experience a complex strain pattern owing to a varying degree of moisture-related dimensional change of wood depending on the anatomical directions. Selecting glass as the substrate allowed the effect of drying shrinkage of the gesso to be clearly distinguished from strains induced in the gesso by dimensional response of a wooden substrate. The ten-layer gesso sample was about 1-mm thick. Gesso layer thickness values ranging between 0.5 and 1 mm were documented as typical for the historical panel paintings. A systematic study of about 50 Italian panels painted before the sixteenth century revealed the gesso thickness range between 0.3 and 1.9 mm, however, concentrated for most paintings to a domain slightly below 1 mm (Martin et al., 1992). Each sample was applied partially on clean glass and partially on glass covered by animal glue (Fig. 6). The plate was

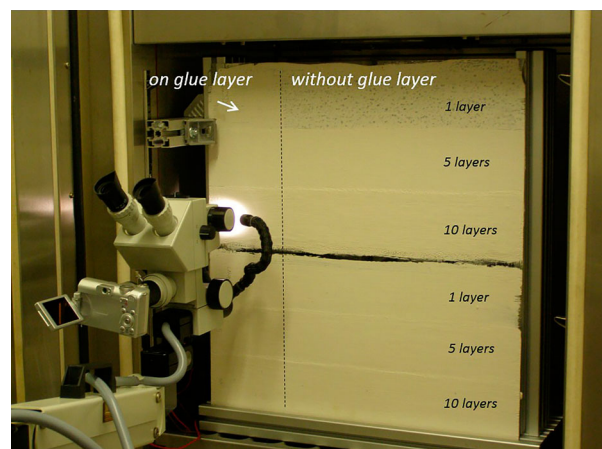


Figure 6 Glass plate with different gesso sample thicknesses subjected to RH cycles in a climatic chamber.

placed in the climatic chamber and subjected to RH cycling. The crack formation on the surface was monitored using macrophotography.

A single RH cycle consisted of a slow increase of RH to 90% (during ten hours) and exposure at this RH for two hours, followed by a slow decrease of RH to 20% (also during ten hours) and exposure at this RH for two hours. A slow increase and decrease of RH was maintained to allow uniform moisture penetration on RH changes and, thus, to prevent stresses due to possible non-uniform dimensional response of the samples.

First cracks appeared in the thickest gesso samples (10 layers) after four to five RH cycles. After three or four additional cycles the surface of the thick gesso sample was highly cracked. The same gesso behaviour was observed whether or not glue had been initially applied to the glass substrate. The samples consisting of one layer and five layers did not crack at all under these test conditions. The observation indicated that the critical level of the tensile stress, at which the thickest gesso layer cracked, was reached quickly after a few cycles to high RH level.

As the thickest gesso layer – in which moisture gradients were more probable – cracked under the very slow cycling described, it was concluded that moisture gradients were not a driving force for the gesso cracking. Therefore, additional ‘fast’ RH test cycles consisted of instantaneous RH increases to 90% and exposure at this RH for three hours, followed by instantaneous drops of RH to about 20% and exposure at this RH for three hours. After 90 fast cycles the first cracks on thinner gesso sample consisting of five layers were observed. The craquelure pattern on the surface of five-layer gesso was denser than in case of the ten-layer sample. The single layer gesso was still undamaged when the experiment was terminated. Thus, the thinner five-layer gesso proved to be much more fracture resistant than the ten-layer specimen. Also, the number of the RH test cycles which caused fracturing of the thinner five-layer specimen was much higher than that bringing about the ultimate permanent drying shrinkage of the unrestrained gesso specimens. The experiments were repeated for further gesso samples on glass produced by applying up to 22 layers of the gesso slurry and the results are shown in Figs. 7 and 8.

It was observed that the crack width increased with consecutive RH cycles resulting in the formation of crack-free ‘islands’. After 30 fast RH cycles, the cracks width stabilised at about 0.2 mm and the size of the crack-free ‘islands’ at about 10 mm for the thickest gesso sample. The experiments with the various gesso samples on the glass supports showed that the crack density is related to the thickness of the gesso layer (Figs. 7 and 8).

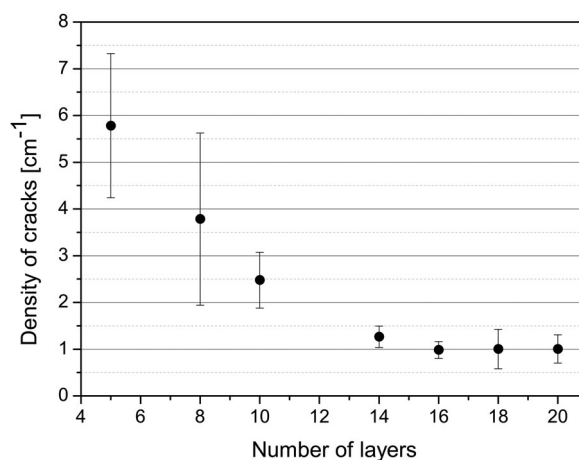


Figure 7 The crack density (number of cracks per cm) as a function of number of the fresh gesso layers laid on a glass plate.

The tests revealed two effects on the increase in the gesso layer thickness: decrease in strength and increase in size of the crack-free gesso islands. Both relationships are well-known in fracture of layered materials. The first effect – the strength size effect – arises from the observation that it is more likely to find a flaw in a thicker specimen than in a thinner one. Bubbles and voids have been frequently observed in the thick gesso samples and these voids appear to act as initiation sites for cracks. The second effect – the approximate proportionality of the fracture spacing to the thickness of the fractured layer – arises, in turn, from the observation that at a certain, critical ratio of spacing to layer thickness, no new fractures form – the fracture saturation is attained (Bai *et al.*, 2000). This is because any additional strain is accommodated by further opening of existing fractures. Also, for a given loading, a critical thickness of a layer exists below which no fracturing occurs.

Discussion

Observation of cracking of the gesso layer on the dimensionally stable support and analysis of the free dimensional response of gesso specimens to RH changes are consistent. They reveal a clear mechanism of the craquelure formation – the cumulative drying shrinkage of the gesso under cyclic RH changes bringing about transitions from brittle to ductile state. If the gesso layer is restrained by a dimensionally stable substrate, it ultimately fails via fracture.

A noteworthy observation in the study has been that the first incidence of fracture on a gesso layer occurred after a limited number of cycles to high RH levels ranging between a few and 100 for a range of layer thickness between 0.5 to 1 mm. Further, it was observed that the drying craquelure pattern stabilised after a limited number of cycles (30 for the 1 mm thick layer). The observations indicate that, typically,

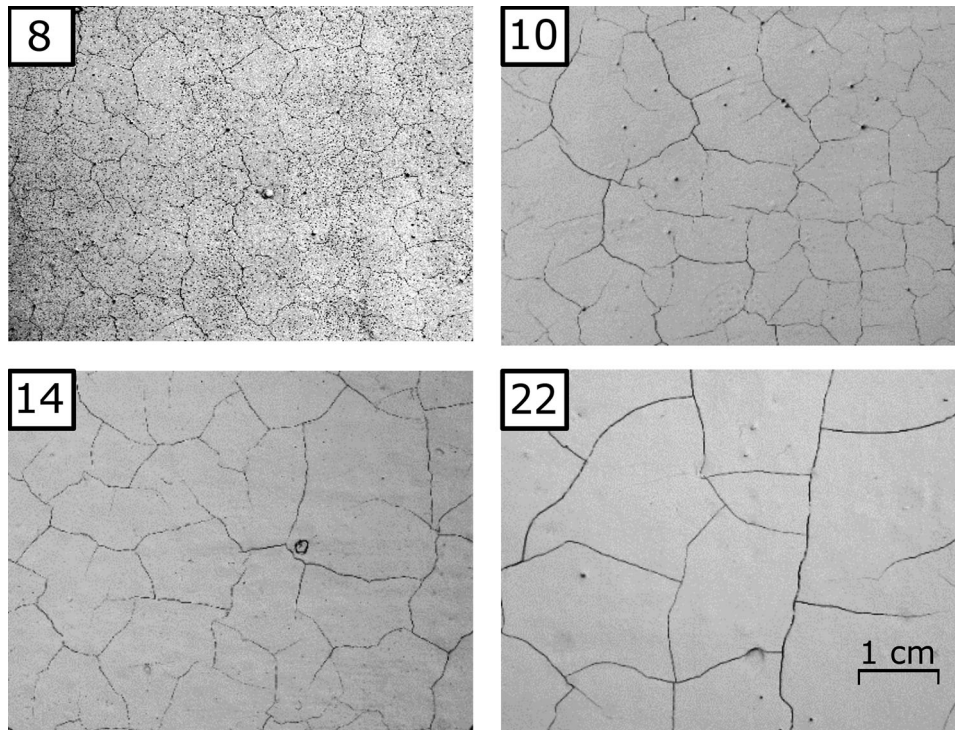


Figure 8 Final crack pattern in the gessoes of varying thickness laid on a glass plate after cycling RH between 20 and 90% (numbers of layers applied to produce the gessoes is indicated in the top left corner on each image).

drying craquelure formed very early after the painting was produced, if one bears in mind a high probability of large RH variations in uncontrolled environments in which the paintings were historically displayed, stored, or transported. The observations demonstrate that drying craquelure patterns, mimicking historical ones, can be realistically produced in laboratory conditions for gesso layers in which important parameters like layer thickness, nature of the pigment or the medium, or pigment particle size could be controlled. The resulting data base of the drying craquelure patterns would inform the current efforts on automatic, computer-aided classifications of crack formations on paintings based on converting image-based representations into hierarchically structured numerical forms, and extracting meaningful features based on the orientation histograms and structural statistics (Abas, 2004; El-Youssef *et al.*, 2014). The laboratory-produced craquelure patterns would have the advantage of being free of noise and insignificant structures, or damage induced by environmental instability or mechanical impacts. In this way, they would facilitate extracting relationships between the craquelure and the materials and methods employed by the artist.

The study also provides useful information for preparing laboratory specimens simulating historic panel paintings, which are used in the experimental structural analysis of painted wood, crucial to the development of rational criteria for the control of climate in museums and historic buildings. As it

has been demonstrated in this paper and the earlier studies quoted, the craquelure pattern related to drying shrinkage of a pictorial layer produced by the artist was formed very early in the painting's history. Therefore, subjecting the as-prepared laboratory specimens to limited cycling to high RH levels to induce the drying shrinkage would bring the gesso layers to a state closer to that of the historical materials.

Supplier

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References

- Abas, F.S. 2004. Analysis of Craquelure Patterns for Content-based Retrieval. PhD thesis, University of Southampton.
- Bai, T., Pollard, D.D. & Gao, H. 2000. Explanation for Fracture Spacing in Layered Materials. *Nature*, 403: 753–56.
- Bratasz, L. 2013. Allowable Microclimatic Variations for Painted Wood. *Studies in Conservation*, 58: 65–79.
- Bucklow, S.L. 1997. The Description of Craquelure Patterns. *Studies in Conservation*, 42: 129–40.
- El-Youssef, M., Bucklow, S. & Maev, R. 2014. The Development of a Diagnostic Method for Geographical and Condition-based Analysis of Artworks using Craquelure Pattern Recognition Techniques. *Insight – Non-Destructive Testing and Condition Monitoring*, 56: 124–30.
- Karpowicz, A. 1989. In-plane Deformation of Films of Size on Paintings in the Glass Transition Region. *Studies in Conservation*, 34: 67–74.

- Martin, E., Sonoda, N. & Duval, A.R. 1992. Contribution à l'étude des préparations blanches des tableaux italiens sur bois. *Studies in Conservation*, 37: 82–92.
- Mecklenburg, M.F. 1991. Some Mechanical and Physical Properties of Gilding Gesso. In: D. Bigelow, E. Come, G.J. Landrey & C. van Horne, eds. *Gilded Wood: Conservation and History*. Madison: Sound View Press, pp. 163–70.
- Mecklenburg, M.F., Tumosa, C.S. & Erhardt, D. 1998. Structural Response of Painted Wood Surfaces to Changes in Ambient Relative Humidity. In: V. Dorge & F.C. Howlett, eds. *Painted Wood: History and Conservation*. Los Angeles: The Getty Conservation Institute, pp. 464–83.
- Michalski, S. 1991. Crack Mechanism in Gilding. In: D. Bigelow, E. Come, G. J. Landrey & C. van Horne, eds. *Gilded Wood: Conservation and History*. Madison: Sound View Press, pp. 171–81.
- Rachwał, B., Bratasz, Ł., Krzemień, L., Łukomski, M. & Kozłowski, R. 2012. Fatigue Damage of the Gesso Layer in Panel Paintings Subjected to Changing Climate Conditions. *Strain*, 48: 474–81.