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Development of craquelure patterns in paintings on panels

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Abstract

Panel paintings are multi-layer structures composed of humidity-sensitive materials. Preventing or limiting stresses in these structures, generated by the loss or gain of moisture, requires an understanding of the relevant processes and risks. A three-dimensional elastic model of a panel painting was used to analyse surface stresses and understand how crack patterns are developed in the two-layer structure of the pictorial layer—the gesso and the paints. Two historically important paint types were considered—egg tempera and oil paints, laid on a gesso produced following historical procedures. Two scenarios of stress development were analysed: permanent cumulative drying shrinkage of paints or gesso, owing to gradual loss of water or evolution of the molecular composition of the binders, and moisture-induced cyclic swelling of the wood substrate. Ratios of distances between cracks in the tangential and longitudinal directions of a wood panel to the layer thickness were estimated for increasing magnitudes of materials' dimensional change in the two scenarios. The critical values of the ratios for which stress in the midpoint between the cracks dropped below the value inducing strain at break in the materials and saturation of the crack patterns occurred, was approximately 3–4 or 5–6 for the paints and the gesso, respectively. The critical distance normalized to the gesso thickness between cracks parallel to the wood grain induced by cyclic swelling of the wood substrate due to relative humidity variation in the range of 50–70% was 6. The study demonstrated that crack spacings in the fully developed crack systems remain sensitive only to the thicknesses of paint or gesso layers which, therefore, can be derived from the crack pattern geometry. Existing flaws in gesso were found not to increase the risk of new crack development.

Keywords Paintings, Wood panels, Oil, Tempera, Gesso, Cracking, Craquelure patterns, Fracture saturation

Introduction

This is the third of a series of papers analysing a model of panel paintings to elucidate the structural response of their pictorial layers with a network of cracks under environmental loadings [1, 2]. The issue is of key importance in developing evidence-based environmental specifications for museums and historical buildings as panel paintings are amongst the objects most vulnerable to relative humidity (RH) and temperature fluctuations.

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Panel paintings are multi-layer structures composed of wood support sized with animal glue and a pictorial layer consisting of a preparatory layer of gesso—a mixture of animal glue and white inert solid, paints, and varnishes on the top. All materials constituting the structure are humidity sensitive: they swell when they gain moisture and shrink when they lose it, which generates stresses owing to materials' different dimensional responses to the loss or gain of moisture. Preventing or limiting the stresses requires a thorough understanding of the relevant processes and risks, including the role of complex crack patterns called craquelures.

The phenomenon of fracturing in layered materials is commonly observed in man-made and natural materials. The formation of a new crack in layered materials is due to stress transfer from the substrate to the cracked layer in the area between neighbouring cracks [3]. If the load increases, the tension in the middle between two fractures reaches the maximal value. If the strength of the material is exceeded, a new crack nucleates. In consequence, the stress-transfer theory predicts that for infinite tensile stresses, the spacing between fractures decreases to an infinitesimal value. However, observations of the layered rocks and experimental results indicate that saturation spacing between fractures is achieved [4]. Wu and Pollard postulated that, in case of a very small distance between cracks, an additional load did not initiate new fractures but resulted in the opening of existing cracks [5]. An alternative explanation was given by Bai et al. [6, 7]. The authors used numerical simulation based on a finite element model to show that if the fracture spacing was small, the stress in the centre between two adjacent fractures was no longer tensile but became compressive, independently of the value of applied stress. More recently, first studies in the field of heritage science were also reported [8–10]. The craquelure patterns in a painting are engendered by drying shrinkage of the materials and the environmental impacts which the painting experiences in its history. Bucklow used the terms 'drying' and 'ageing' cracks to describe the two categories, respectively [11].

In the most recent study, environmentally induced stresses in the gesso layer were analysed, as cracking of this layer, resulting from the mismatch in the moisture response of gesso and wood, inevitably leads to cracking of the entire pictorial layer [2]. Wood is anisotropic and its moisture-related dimensional change varies in its principal anatomical directions: longitudinal—or parallel to the grain, radial, and tangential. The most pronounced moisture response is in the tangential direction, it halves in the radial direction, whereas, for practical purposes, wood can be considered dimensionally stable in its longitudinal direction. The developed three-dimensional structural model of a panel painting with a cracked gesso layer was used to analyse two loading modes of the gesso layer—cyclic moisture response of a wood panel and permanent cumulative drying shrinkage of gesso. It was found that moisture-related expansion of wood, approximated by a physical stretching of the panel, explained the formation of cracks parallel to the grain. For moisture response of a tangentially cut wooden panel, the ratio of spacing between cracks to gesso thickness in the saturated crack pattern for which stress in the midpoint between the cracks dropped to zero, was between 6 and 2.4 depending on gesso stiffness. For the radial cut, this value was about 10% higher. The permanent cumulative drying shrinkage of the gesso layer restrained by the dimensionally stable wooden substrate produced almost square cracks of aspect ratio 4:5 in the tangential to longitudinal directions. The ratio of spacing between cracks in the saturated crack pattern to gesso thickness ranged between 4.5 and 5, and 3.5 and 4, in the two directions, respectively. The modelling results were cross-checked with crack patterns obtained on a mock-up of a panel painting exposed to several extreme environmental variations in an environmental chamber. The outcome of the study confirmed that the gesso layer, after reaching a certain level of crack density, is much less vulnerable to tensile loading.

This paper reports on the crack pattern development in the two-layer structure of the pictorial layer—the gesso and the paint. As previously, analysis of surface stresses in a three-dimensional fully elastic model was used to understand how cracks along and perpendicular to the wood grain were formed. In particular, ratios of distances between cracks in both tangential and longitudinal directions to the paint or gesso layer thickness were systematically estimated for increasing magnitudes of the material's permanent cumulative shrinkage or increasing moisture-induced swelling of the wood substrate. In the latter case, the modelling took into account the real response of the system to RH changes and not the response approximated by a physical stretching of the panel as previously. A further, less severe criterion for the new crack formation was considered, namely that tensile stress in the midpoint between the cracks merely exceeds the level at which the strain at break is induced in the material rather than zero. Two historically important paint types were considered—egg tempera and oil paints, laid on a gesso produced following historical recipe and procedure. Two wood species historically widely used in Europe as substrates for paintings were selected: poplar preferred in Italy, and lime/linden favoured in Central Europe.

Further, the effect of flaws (air bubbles) in the gesso layer on the crack saturation was analysed taking into account varying sizes and positions of a flaw that might propagate causing further infilling between cracks. In the earlier paper, fracture toughness determined experimentally for the gesso layer was used as a 'failure criterion' [1]. Comparison of the energy release rate calculated for the two-dimensional model of the gesso laid on a wooden substrate with the fracture toughness, allowed the fracture saturation to be determined for varying sizes and positions of defects. The same approach was used in this study; however, a three-dimensional model was expected to elucidate how cracks are formed with respect to the three anatomical directions in the wood substrate.

Methods

Model

The model of a panel painting used in this study is shown in Fig. 1. Calculations were performed with the use of the finite element analysis assuming a fully elastic behaviour of all materials. Therefore, the modelling neglected relaxation of stresses over time, providing, in this way, the highest possible, worst-case estimation of the cracking risk. It was assumed that wooden support was made of wood cut in the tangential direction ϕ and its thickness in the radial direction ρ was 40 mm. The thickness of the gesso and paint layers was 1 and 0.1 mm, respectively. A periodic crack pattern of rectangular islands with cracks parallel to the tangential and longitudinal directions, ϕ and z, were embedded into the gesso and paint layers. Each crack was introduced as a discontinuity in the material at a given plane that was assumed to penetrate uniformly the entire thickness of the layer. The distances between the cracks were denoted S and L in the directions ϕ and z, respectively, with the subscripts g and p further denoting respectively gesso and paint (*po* and *pt*, for oil and tempera paints, respectively).

The mechanical properties of the components building up a painting are detailed in Table 1. As RH markedly affects the mechanical properties, the relationships between the tensile moduli of elasticity of the materials and RH were obtained by fitting polynomial or sigmoid Boltzmann functions to the experimental data for wood or gesso and tempera paints, respectively. As the mechanical properties of egg tempera paints were found in a recent study to significantly depend on pigments present in their composition, blue paint with azurite as a pigment was selected for the modelling as the plot of modulus of elasticity versus RH for this paint was between the same plots for two other paints investigated with yellow ochre (stiffer) and lead white (more flexible) as pigments [12]. In turn, oil paint with lead white as a pigment was selected. Janas et al. demonstrated that the modulus of elasticity and the strain at break of oil paints naturally aged for approximately 30 years continued to increase or decrease, respectively, with drying time [13]. The correlation between the two parameters is illustrated in Fig. 2 and described by a two-segment dashed line for oil paint with lead white. As the evolution of mechanical properties of paints with drying time reflects changes in the molecular composition of oil binder, it was assumed that changes in the mechanical properties were paralleled by increasing permanent drying shrinkage owing to evaporation of low-molecular-weight organic components and subsequent diffusing out free volume locked in the material. The assumed magnitudes of permanent cumulative drying shrinkage were indicated in Fig. 2 to increase from 0.5%—measured for the paint aged for 30 years—to 9%—derived from the analysis of the shrinkage of paint in a historic painting dated to the seventeenth century [13]. The assumed ranges of an increase in the modulus of elasticity and a decrease in the strain at break on paint ageing were 1–10 GPa and 1–0.1%, respectively.

Two scenarios of stress development in the pictorial layer listed in Table 2 and diagrammatically shown in Fig. 3 were considered.

Stress development in the paint and gesso layers due to permanent cumulative drying shrinkage of the materials restrained by the wood substrate (gesso) or the wood substrate covered with the gesso (paint) was the first

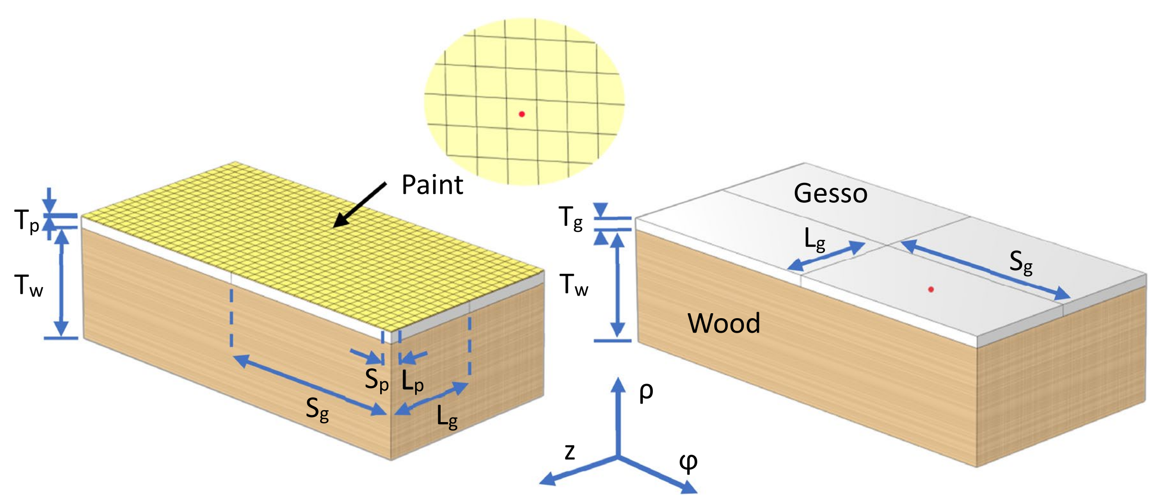

Fig. 1 Model of a panel painting with a periodic craquelure pattern of rectangular islands in layers of paint (left) or gesso (right) with cracks parallel to the tangential (φ) and longitudinal (z) directions in the wood. The dots indicate the points at the surfaces of the layers, in the middle of the paint or gesso islands, at which the stress components in the two directions were calculated

Table 1 Moduli of elasticity *E*, Poisson's ratios *υ*, and shear moduli *G* for wood, gesso, and paints used in the modelling

Material	Property	Value or formula		Units	Source
		Poplar	Lime		
Wood	E_φ	356–1.79RH	872–18.16RH + 0.2RH^2–0.0014RH^3	Pa	[14]
	E_ρ	1124–4.39RH	1649–34.83RH + 0.48RH^2–0.0023RH^3	Pa	[14]
	E_z	1.2×10^{10}	1.1×10^{10}	Pa	[15]
	$G_{\varphi\rho}$	1.7×10^8	2.1×10^8	Pa	
	$G_{z\rho}$	9.0×10^8	6.2×10^8	Pa	
	$G_{z\varphi}$	8.3×10^8	5.1×10^8	Pa	
	$\upsilon_{\rho\varphi}$	0.70	0.91	–	
	$\upsilon_{z\rho}$	0.32	0.36	–	
	$\upsilon_{z\varphi}$	0.39	0.41	–	
Gesso	E_g	$6840\left[\frac{0.53}{1+e^{\frac{RH-24.44}{16.81}}}+\frac{0.47}{1+e^{\frac{RH-71.84}{5.99}}}\right]$		Pa	[16]
	υ_g	0.2		–	
Oil paint	E_{po}	1×10^9–1×10^{10} (varying with the drying shrinkage, Fig. 2)		Pa	[13]
	υ_{po}	0.3			
Tempera paint	E_{pt}	$24.4\left[\frac{87.39}{1+e^{\frac{RH-78.88}{10.22}}}-1\right]$		Pa	[12]
	υ_{pt}	0.2 (assumed)			

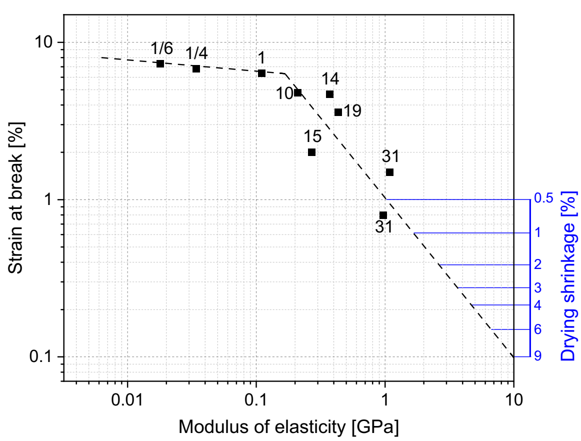

Fig. 2 Modulus of elasticity and strain at break for oil paint with lead white as a pigment dried for increasing time indicated in years. Data from [13]. Permanent cumulative drying shrinkage magnitudes related to the evolution of the mechanical parameters as assumed in this study are indicated

scenario considered. The drying shrinkage was assumed to be isotropic, that is to say, the related tensile strain ε was the same in the directions ϕ and z, $\varepsilon_z = \varepsilon_\varphi$. Therefore, this path of stress development was denoted as mode (1,1). In turn, stress development in the gesso layer caused by the moisture expansion of wood across the grain i.e. in the tangential and radial directions ϕ and ρ of a panel due to an increase in RH was the second scenario considered and denoted as mode (1,0).

Components of stress tensor σ_ϕ and σ_z were calculated for a point at the top of the paint surface in the middle of a paint island where stresses were largest for varying distances S_p and L_p between the cracks (Fig. 1a). Bai et al. showed that the stress in the direction normal to the developing fracture would reach its maximum in the centre of each 'island' for large ratios of spacing between cracks S_p or L_p to paint layer thickness T_p, that is to say, the islands tend to form cracks in the middle [7]. For decreasing S_p/T_p or L_p/T_p, no new cracks perpendicular to the directions ϕ and z can develop starting from the surface, if the stress components σ_ϕ and σ_z drop below stress σ_0 inducing the strain at break ε_0 ($\sigma_0 = E_p \times \varepsilon_0$). The critical values of S_p/T_p or L_p/T_p are defined by conditions $\sigma_\varphi = \sigma_0$ and $\sigma_z = \sigma_0$ in the point of stress calculation. A further 'absolute' criteria of crack saturation were also calculated, namely the S_p/T_p or L_p/T_p, values for which the stress components σ_ϕ and σ_z dropped to zero. Below these values, the stresses were becoming compressive.

The identical approach was used to calculate the components of stress tensor σ_ϕ and σ_z for a point at the top of the gesso surface under the layer of cracked tempera paint with S_{pt}/T_{pt} and L_{pt}/T_{pt} having the critical values, in the middle of a gesso island for varying dimensions S_g and L_g of the island (Fig. 1b). Such geometry of the model

Table 2 Two scenarios of stress development in the pictorial layer used in the modelling

Mechanism	Maximum strain in the φ-direction ε_φ [%]	Maximum strain in the z-direction ε_z [%]	Mode (φ,z)
Ultimate drying shrinkage			(1,1)
Oil paint	9 [13]	9 [13]	
Tempera paint	8*	8*	
Gesso	1 [17]	1 [17]	
Expansion of wood support in the tangential direction on an increase in RH	0.8	0	(1,0)

* This work, see section *Crack patterns in the paint layers induced by drying*

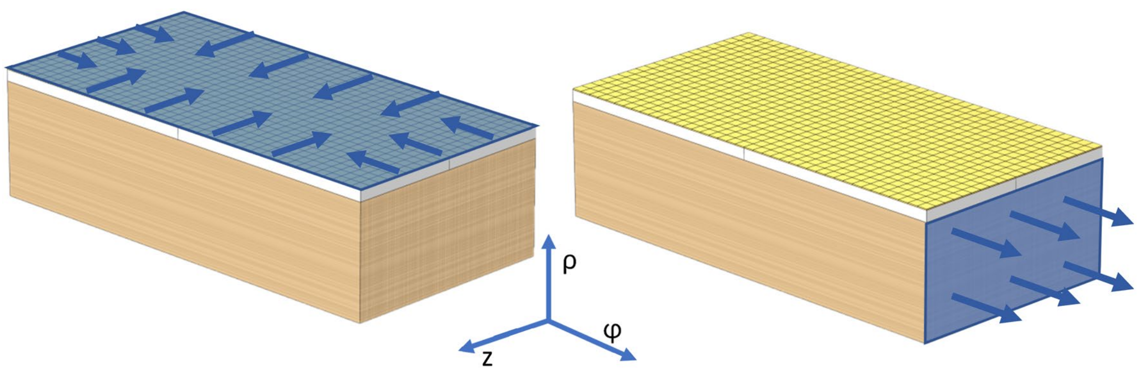

Fig. 3 Two scenarios of stress development in the pictorial layer detailed in Table 2: caused by isotropic gesso or permanent cumulative paint shrinkage on drying denoted as mode (1,1) (left), uniaxial loading of the pictorial layer caused by moisture expansion of wood in the tangential direction denoted as mode (1,0) (right)

is based on the analysis of tempera paintings including the one considered in this study (see section *Crack patterns in the paint layers induced by drying*). The critical crack spacings in the gesso layer normalized to the layer thickness S_g/T_g or L_g/T_g were determined for the two loading modes (1,1) and (1,0).

COMSOL Multiphysics® software Version 6.0 from COMSOL AB (Stockholm, Sweden) with coupled solid mechanics and heat transfer modules was used to compute static solutions of deformation problems for a fully elastic solid body (the painting), induced by humidity variations. Static solutions of shrinkage-induced deformation problems were obtained in a similar manner. Free triangular controlled extremely fine mesh patterns were used to discretize object geometry with a total number of computational nodes between 0.3 and 2 million. Higher mesh density was reserved for thin layers. The finest mesh was around the point of stress calculation or a 'penny-shape' flaw described below.

To model the crack infilling process in the pictorial layer on loading, J-integral was calculated using the formalism described in Ref. [18]. Fully elastic behaviour of all materials was assumed, so the J-integral allowed the energy release rate on the initiation of a crack at a flaw in the gesso layer to be evaluated. As the calculated deformations were small, they were related to the original dimensions of a sample, and the 'geometric nonlinearity' option was switched off. A flaw was introduced as a discontinuity in the material in the form of a thin disk—a 'penny-shape' flaw (Fig. 4). The flaw was perpendicular to the ϕ direction and was placed at various depths h in a gesso layer covered with a cracked tempera paint layer. The stresses in the gesso layer with a flaw were engendered by the (1,0) mode corresponding to the moisture expansion of the panel in the ϕ direction. The worst-case scenario for the infilling process was evaluated involving the flat geometry of a panel painting and the largest flaws in the gesso layer of 0.2 mm in diameter, determined in a typical historical gesso with the use of the X-ray computer microtomography [1]. J-integrals were calculated for three directions of crack propagation—the vertical direction (up and down) and the horizontal direction in Fig. 4. The maximum value of the energy release rate was selected as representative of the given flaw configuration.

The experimental work on the determination of fracture toughness of gesso revealed a significant uncertainty of the measurements, indicating large variability in gesso samples across each set tested at the given test conditions

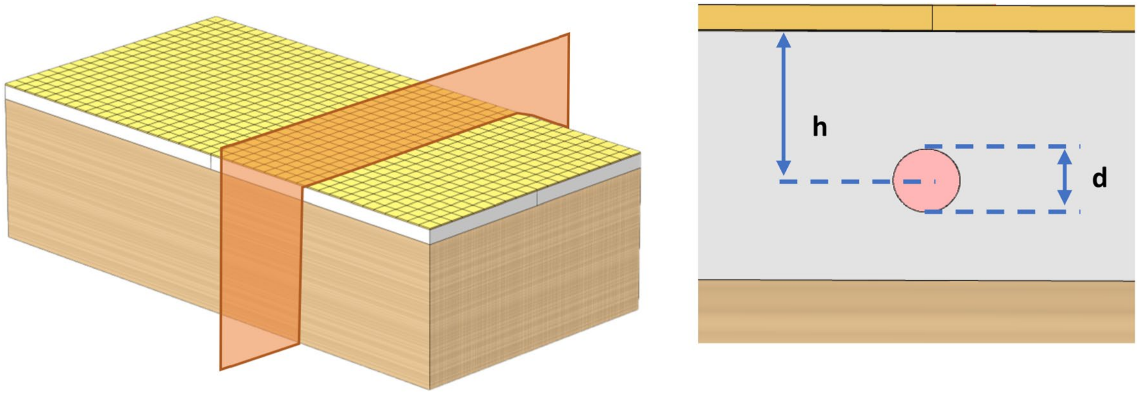

Fig. 4 Configuration of a subsurface flaw in the gesso layer

(Fig. 3 in ref. [1]). 36 N/m was the minimum value of the uncertainty range of measurements for usable gessoes with pigment volume concentration (PVC) of 92%, where PVC = P/(P + B), and P and B are volumes of the pigment and the dried glue binder. The value was used in this study as a very conservative 'failure criterion' for gesso, that is to say, it was assumed that cracking in the loaded material may initiate when the energy release rate induced by tensile stress exceeds 36 N/m.

Results and discussion

Crack patterns induced in the gesso layer by drying

As discussed in the introductory section, the formation of a new crack in layered materials is due to stress transfer from the substrate to the cracked layer in the area between neighbouring cracks. When the gesso layer irreversibly contracts owing to the accumulating drying shrinkage, the tension in the middle between two cracks reaches the maximal value. If the strength of the material is exceeded, a new crack nucleates. When the distance between cracks becomes small, an increasing tensile load does not initiate any new cracks as the stress in the centre between two adjacent cracks is no longer tensile but becomes compressive, independently of the value of applied load [1, 6–8].

Stresses engendered in the gesso layer by its permanent cumulative drying shrinkage—the mode (1,1) loading—were calculated in the modelling as a function of the magnitude of shrinkage. Domains of tolerable magnitudes of the gesso's permanent cumulative drying shrinkage, producing stress components in the middle of a gesso island smaller than those inducing the strain at break, are shown in Fig. 5 in the directions φ and z. The ultimate permanent shrinkage of gesso was assumed to be approximately 1% as determined for a gesso layer restrained by a glass substrate and subjected to repeated cycling RH between low and high levels [17]. The strain

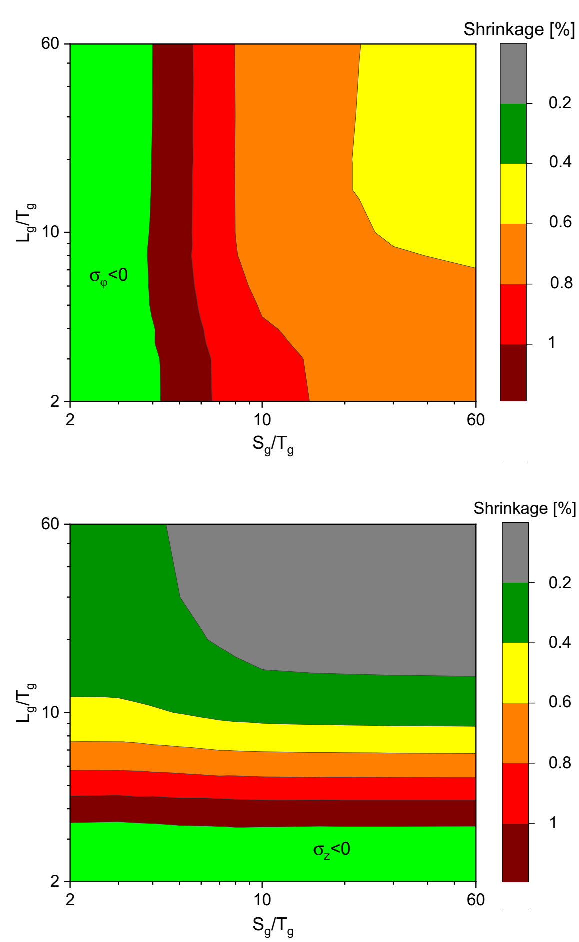

Fig. 5 Domains of tolerable magnitudes of the gesso's permanent cumulative drying shrinkage producing stress components that induce strains in the middle of a gesso island smaller than the strain at break in the directions φ (top) and z (bottom). With increasing permanent shrinkage, the stress components ultimately fall below zero (light green domains)

at break of gesso was determined to be around 0.2% at the RH mid-range in studies of usable grounds with PVC values ranging between 85 and 95% [16, 19]. Such preparations match grounds commonly used to produce or restore paintings. With increasing permanent shrinkage, the stress components ultimately fall below zero—become compressive—and $L_g/T_g=3.4$ and $S_g/T_g=4.1$ for such conditions.

The map of the ratio of the stress components σ_z/σ_ϕ shows that for $L_g/T_g>6.8$ stress along the z axis is higher than stress along the ϕ axis (Fig. 6). It means that the formation of cracks perpendicular to the longitudinal direction of wood is more favourable than cracks perpendicular to the tangential direction during the initial phases of crack formation. By way of example, a network of cracks with comparatively large spacings between cracks is marked as point A on the σ_z/σ_ϕ map. With increasing permanent shrinkage on drying, cracks perpendicular to the z direction will densify reaching the L_g/T_g values at points B, C, and D for the shrinkage magnitudes of 0.2, 0.4, and 0.6%, respectively. Then, crack densification will bring L_g/T_g and S_g/T_g parameters from point D along a red line to points E and F for the shrinkage magnitudes of 0.8 and, ultimately, 1% with $(S_g/T_g)_{critical}=6$ and $(L_g/T_g)_{critical}=4.4$.

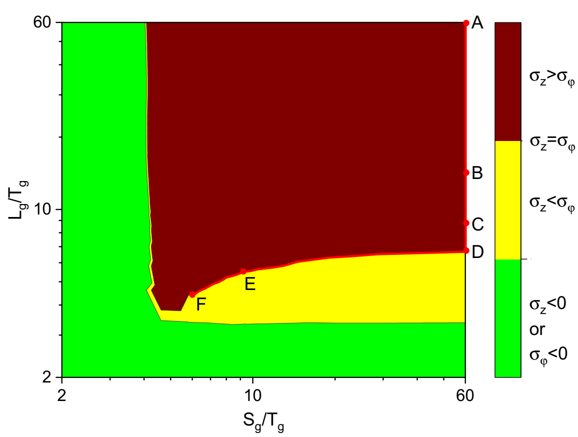

Fig. 6 Stress components σ_φ and σ_z engendered in the gesso layer by permanent cumulative drying shrinkage of the gesso. Coordinates of the points: A (60;60), B (60;14.1), C (60;8.7), D (60;6.8), E (9.3;5.5), F (6;4.4)

Crack patterns induced in the gesso layer by the moisture-related expansion of the wood substrate

Figure 7 shows an oil painting on wood in which 'ageing' cracks predominantly parallel to the wood grain induced by swelling of the wood substrate are observed. In the modelling, moisture-related expansion of wood was calculated as the change in length divided by the panel's length at 50% RH which is the midpoint of the full RH scale between 0 and 100% and the most typical value recommended for museums. The expansion of wood was considered in the range of 50–70% RH for two reasons. First, gesso is a mixture of animal glue and inert solid. Collagen glue and, in consequence, gesso, experience a dramatic loss of stiffness at RH exceeding 70% [20]. This loss of stiffness corresponds to the plasticization of the collagen by water thus reducing the glass transition temperature to below the ambient temperature, which cannot be modelled in the formalism used in this study. Secondly, an RH of 70% is a precautionary upper limit at which mould germination is expected to occur, and the risk of irreversible physical change increases. The average tangential hygroscopic expansion coefficient of poplar and lime is approximately 0.038% per 1% RH so the wood's expansion is approximately 0.8% at 70%.

Fig. 7 Craquelure patterns in a fragment of *The Last Judgment*, Hans Memling, c. 1467–1471, oil on wood, the National Museum in Gdańsk, Poland. Predominantly parallel cracks were induced in the gesso by swelling of the wood substrate. Photo: Piotr Frączek and Michał Obarzanowski

A map of stresses engendered in the gesso layer covered with a dried cracked layer of tempera paint by the expansion of the wood substrate of up to 0.8%—the mode (1,0) loading—is shown in Fig. 8. The stress was normalized to the stress σ_0 inducing strain of 0.2% in the gesso layer at which the material fractures ($\sigma_0=E_g(RH)\times 0.002$). No new cracks nucleate in the middle of a paint island if the normalized stress drops below 1. Change of gesso's modulus of elasticity E_g with RH was taken into account making use of the relationship provided in Table 1. The second vertical axis in the diagram indicates RH levels which induced the ε_ϕ strain in the gesso layer through moisture-related expansion of wood in the tangential direction. The diagram reveals that the network of cracks

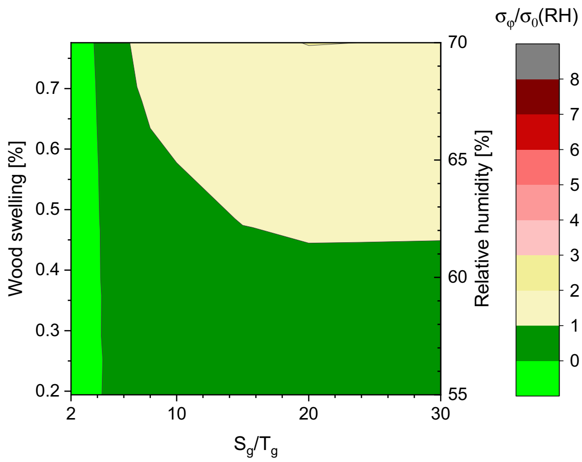

Fig. 8 Normalized stress components σ_φ engendered in the gesso layer by moisture-related expansion of wood in the tangential direction as a function of S_g/T_g and RH

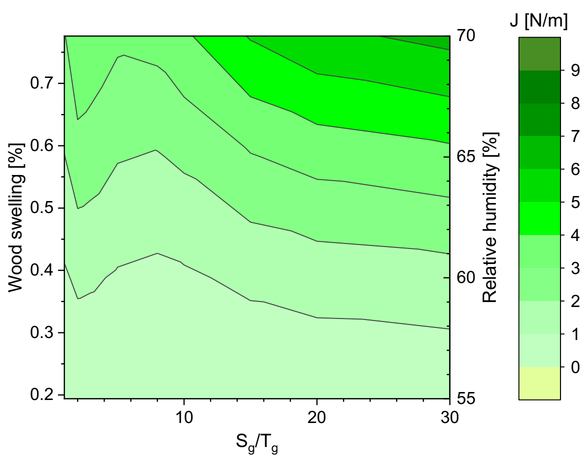

Fig. 9 Energy release rate *J* for the flaw position h of 0.8 mm as a function of the moisture-related expansion of the wood support in the tangential direction and S_g/T_g

parallel to the grain densifies as the strain increases and for the maximum assumed RH variation from 50 to 70%, the S_g/T_g value is 6 for the normalized stress of 1. In turn, the S_g/T_g for which the stress component σ_φ falls to zero slightly diminishes from 4.8 to 4 with increasing RH, the effect being an outcome of decreasing gesso's modulus of elasticity. It is worth noticing that the values obtained are similar to the S_g/T_g values in crack patterns induced by gesso's permanent cumulative drying shrinkage.

Crack infilling in the pictorial layer on loading

Figure 9 shows the map of the energy release rate for the flaw position h of 0.8 mm calculated for the moisture-related expansion of the wood substrate of up to 0.8% induced by the RH change from 50 to 70%. As indicated in section *Model,* it was assumed in this study that cracking initiates when the energy release rate reaches the critical value of 36 N/m—the conservative minimum value of fracture toughness determined experimentally for usable gessoes [1]. One can see that the wood expansion cannot generate cracks starting from the sub-surface flaws independently of the S_g/T_g ratio as the energy release rate is smaller than 36 N/m. This outcome of the modelling indicates that generally existing flaws in gesso do not increase the risk of the development of new cracks.

Crack patterns in the paint layers induced by drying

Analysis of historic paintings on wood generally reveals distinct categories of the craquelure patterns which reflect the intrinsic evolution of artistic materials and their interaction with environmental agents throughout time from the moment the given painting was created. Figure 10 shows an oil painting on wood in which two craquelure patterns were induced just by permanent cumulative shrinkage of the gesso and the oil paint on drying. No long cracks parallel to the wood grain that could have been induced by swelling of the wood substrate are observed.

A pronounced periodic crack pattern of semi-rectangular islands with cracks approximately parallel to directions along and across the grain is associated with the cracking of the gesso ground on drying. Clearly, these cracks formed first. Krzemień et al. demonstrated that attaining the ultimate permanent drying shrinkage of the gesso was achieved after a limited number of RH cycles between low and high levels (30 for a 1 mm thick layer), which can be explained by diffusing out free volume locked in the material until the equilibrium state [17]. Therefore, drying cracks in gesso can be assumed to develop fully after a relatively short period of probably no more than several years after the painting was executed and exposed in a building with unavoidably uncontrolled climate.

In contrast to gesso, drying oils used as binders in oil paints solidify and harden through chemical reactions with oxygen. The molecular system of oil paints is continually evolving even after 30 years of drying under room conditions, and oil paints not only get stiffer and more brittle with the drying time but also experience increased permanent shrinkage [13]. In consequence, a secondary pattern of thinner, irregular cracks in the paint layer observed in the painting within the islands of cracked gesso must have developed later in the painting history with the slowly progressing evolution of the paint.

Two different crack pattern categories are evident in a tempera on panel (Fig. 11). One isotropic 'mud crack pattern' composed of thin cracks separated by distances of

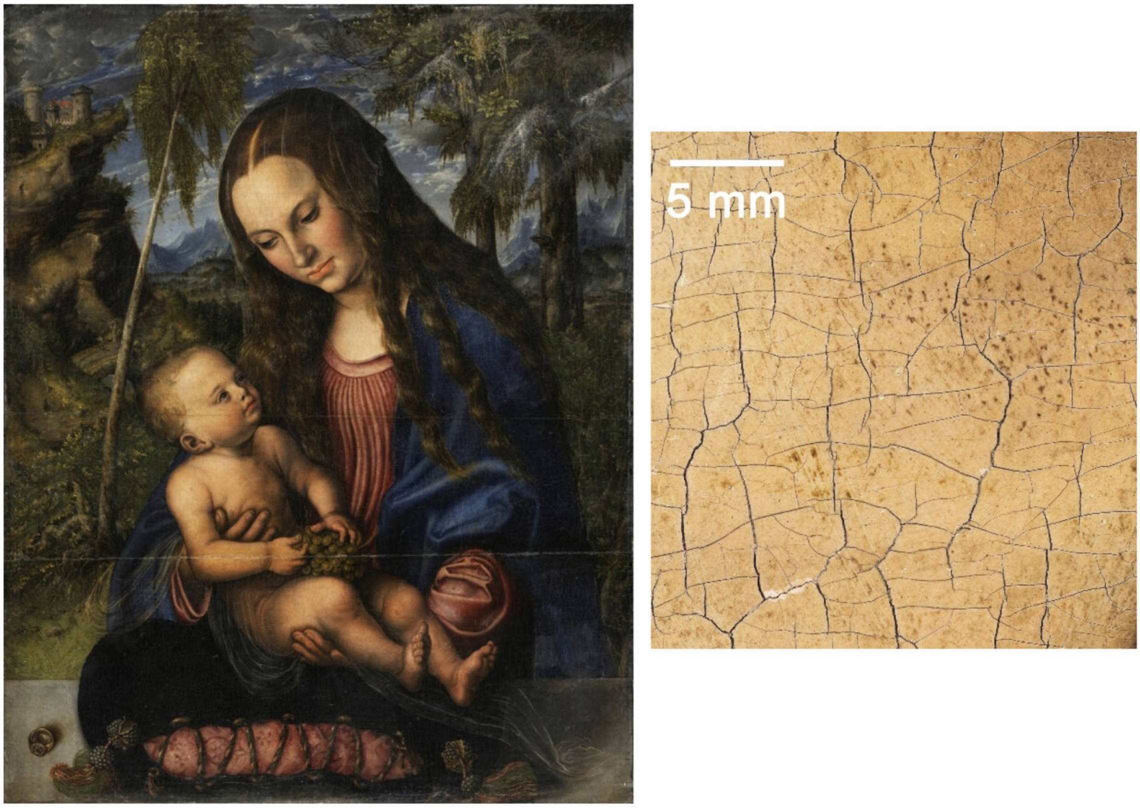

Fig. 10 Craquelure patterns in *Virgin and Child under the fir trees*, Lucas Cranach the Elder, 1510, oil on panel, 70.5 cm × 56.5 cm, the Archdiocese Museum in Wrocław, Poland. Cracking of the oil paint occurred after wider cracks in the ground were formed (http://hirox.ikifp.edu.pl)

approximately 0.6 mm is associated with ultimate permanent drying shrinkage of the tempera paint layer, and the other anisotropic—oriented with respect to the anatomical directions of the wooden substrate, with wide cracks separated by much larger distances, is associated with cracking of the ground. It is evident that drying craquelures in the paint formed first after the paint layer had been laid on the uncracked gesso ground and they were disrupted by the secondary wide cracks in the ground.

The ultimate permanent shrinkage of oil paint with lead white as the pigment was determined for a specimen of panel painting dated to the seventeenth century with the use of X-ray computer microtomography [13]. The total coverage by the paint was 82% and the remaining part was covered by cracks. Therefore, a unit square area of 1 shrank to 0.82, and its edge of 1 to 0.91 (the square root of 0.82). The resulting change in length was 0.09 and divided by the original length of 1 gave the linear shrinkage of the paint of 9% after more than 300 years of drying. Similarly, the total coverage by the tempera paint, determined in this study from the high-resolution microscopic scans of the tempera on panel shown in Fig. 11, was 84% and the linear shrinkage of the paint was estimated to be 8%. The strain at break, at which the tempera paint fractured, was determined in mechanical tensile tests as approximately 0.1% at 50% RH [12]. The strain at break for the oil paint was assumed to decrease from 1 to 0.1% as the permanent drying shrinkage increased from 0.5 to, ultimately, 9% as indicated in Fig. 2 and explained in section *Model.*

Stresses engendered in the paint layer by permanent cumulative drying shrinkage of the paint—the mode (1,1) loading – were calculated in the modelling as a function of the magnitude of shrinkage. In Fig. 12, a map of the stress component in the ϕ-direction is shown as a function of S_{po}/T_{po} and permanent shrinkage of the oil paint reaching the ultimate magnitude of 9% for the case of square paint islands that is $L_{po} = S_{po}$. The stress was normalized to stress σ_0 inducing the strain at break in the paint ε_0 ($\sigma_0 = E_{po} \times \varepsilon_0$). As explained in section *Crack patterns induced in the gesso layer by the moisture-related expansion of the wood substrate*, no new cracks nucleate in the middle of a paint island if the normalized stress drops below 1. The map indicates that the critical value $(S_{po}/T_{po})_{critical}$ is decreasing with increasing shrinkage as paints become stiffer and more brittle but the parameter stabilizes at 4.3 for the shrinkage magnitude exceeding 2%. A very similar map of stress components in the

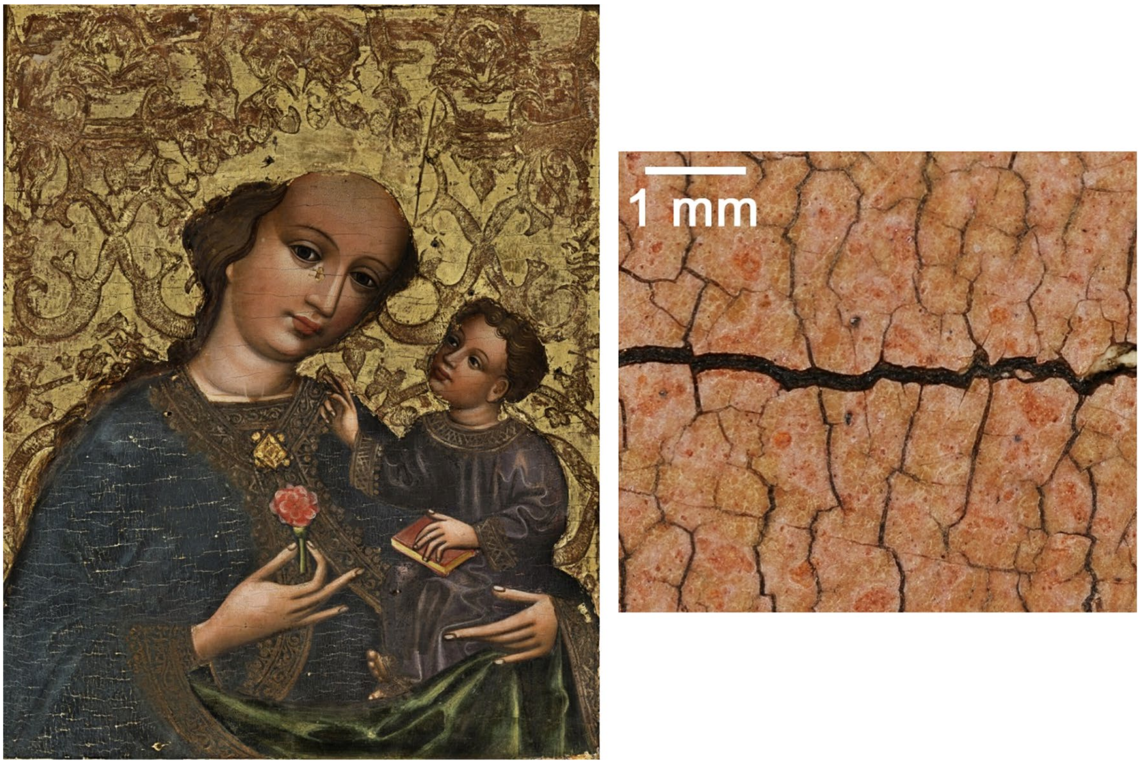

Fig. 11 Craquelure patterns in *Virgin and Child*, unknown author, fifteenth century, tempera on panel, 50 cm × 39 cm, St. Mary's Basilica, Krakow, Poland. Cracking of the tempera paint occurred before large cracks in the ground were formed (http://hirox.ikifp.edu.pl)

z-direction (data not shown) allowed the critical value $(L_{po}/T_{po})_{critical}$ to be determined also as 4.3. The identical values of the critical distance between the cracks in the directions ϕ and z in the paint layer point to the effective blurring of the anisotropic properties of wood by the layer of gesso. It was also verified that the critical spacings do not depend on the wood species used as the substrate—poplar or lime.

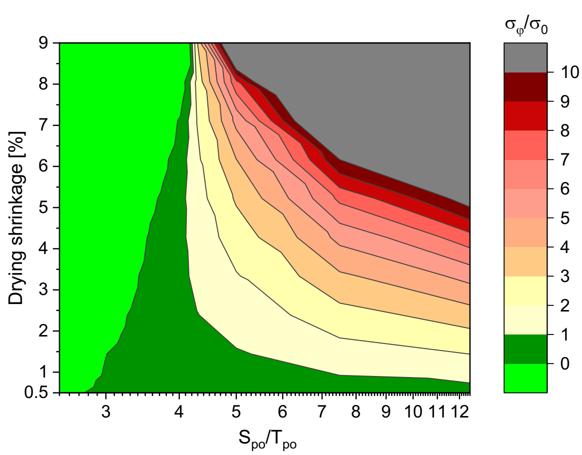

Fig. 12 Normalized stress components σ_φ engendered in the oil paint layer by permanent cumulative drying shrinkage of the paint as a function of S_{po}/T_{po} and shrinkage magnitude, for the case of $L_{po} = S_{po}$

In turn, the S_{po}/T_{po} for which the stress component σ_ϕ falls to zero increases from 2.7 for low shrinkage of 0.5% to 4.2 for the ultimate shrinkage of 9%, a tendency illustrating the increasing stiffness of the paint with drying time.

In turn, Fig. 13 shows a map of the stress component in the ϕ direction as a function of S_{pt}/T_{pt} and permanent shrinkage of tempera paint reaching the ultimate magnitude of 8%, again for the case of $L_{pt} = S_{pt}$. The stress was normalized to the stress σ_0 inducing strain of 0.1% in the paint layer at which the paint fractures ($\sigma_0 = E_{pt} \times \varepsilon_0 = 2$ GPa × 0.001 = 2 MPa). The critical $(S_{pt}/T_{pt})_{critical} = (L_{pt}/T_{pt})_{critical}$ stabilized at approximately 3 for shrinkage exceeding 2%. The limit of the domain at which the normalized stress falls to zero was 2.9, a value very similar to that obtained for the oil paint.

Conclusions

In the current study, a three-dimensional structural model of a cracked panel painting was further refined by considering the two-layer structure of the pictorial layer—the gesso and the paint.

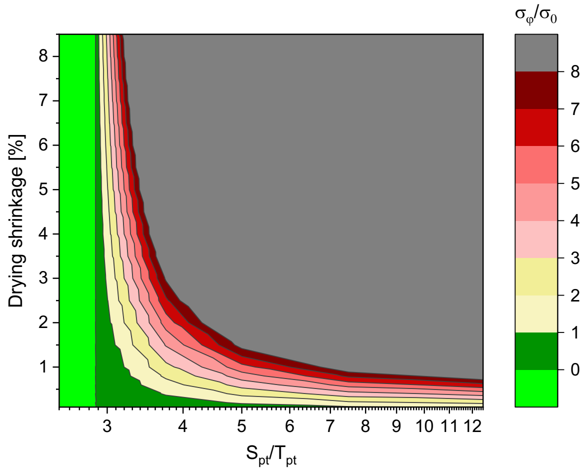

Fig. 13 Normalized stress components σ_φ engendered in the tempera paint layer by permanent cumulative drying shrinkage of the tempera paint as a function of S_{pt}/T_{pt} and shrinkage magnitude, for the case of $L_{pt} = S_{pt}$

Two historically important paint types were considered—egg tempera and oil paints. The model simulated stress fields induced in the paint layers by their permanent cumulative drying shrinkage owing to the gradual loss of water from the yolk binder in tempera paints or the evolution of the molecular composition of the oil binder, especially evaporation of low-molecular-weight organic components. The modelling revealed that the permanent cumulative drying shrinkage of paints produced cracks with identical distances between the cracks in the directions parallel and perpendicular to the grain which points to the effective blurring of the anisotropic properties of wood by the gesso/paint sandwich. The critical crack spacing normalized to the paint thickness, for which stress in the midpoint between the cracks dropped to below the level inducing fracture in the paint, was approximately 3 and 4 for tempera and oil paints, respectively. The modelling further revealed that crack saturation occurred at relatively low shrinkage magnitudes attained after the initial phase of drying (see Figs. 12 and 13). In consequence, the critical crack spacing is insensitive to the magnitude of advanced permanent drying shrinkage and remains sensitive only to the paint layer thickness which, therefore, can be derived from the geometry of crack patterns. As the parameters of the paints depend on pigments in their compositions, further steps in this research will encompass calculating the critical crack spacings for a broader spectrum of paints and validating model performance by comparison with craquelure patterns of panel paintings with known stratigraphy of their pictorial layers. Coupling characteristics of paint layers and their craquelure patterns to the geographical area and period in which the painting was created is the long-term aim of these research directions, also to support authentication of paintings.

Further, the modelling revealed that the permanent cumulative drying shrinkage of gesso produced semi-rectangular cracks with smaller distances between the cracks in the directions perpendicular to the grain along which wood is significantly stiffer. The critical crack spacing normalized to the gesso thickness, for which stress in the midpoint between the cracks dropped below the value inducing strain at break in the material, was approximately 4.5 and 6. Cracks parallel to the wood grain induced by swelling of the wood substrate due to RH variation in the range of 50–70%, exhibited the critical crack spacing – normalized to the gesso thickness—of 6. Finally, existing flaws in gesso were found not to increase the risk of the development of new cracks.

The obtained results also indicate that the cyclic swelling of wood support engendered by RH variations does not lead to new cracks in paintings with developed patterns of cracks related to the permanent cumulative drying shrinkage. Similarly to paints, the gesso layer thickness can be derived from the measurements of crack spacing if only the gesso crack pattern is close to saturation whatever mechanism inducing cracking. The modelling of fracture saturation in the gesso is believed to be especially robust for cracks perpendicular to the wood's grain owing to the dimensional stability of wood in the longitudinal direction. In contrast, wood across the grain is susceptible to permanent shrinkage which releases stress in the gesso in this direction, reducing or eliminating cracking. Attempts are undertaken to collect information on the permanent shrinkage of panels, especially the sequence of the shrinkage processes in the wood-gesso structure as revealed from the characteristics of crack patterns. Such observations will feed the model of cracked pictorial layers to yield realistic stress fields considering the combined effect of wood, gesso, and paint permanent shrinkage.

List of symbols

g	Subscript denoting gesso
RH	Relative humidity
PVC	Pigment volume concentration
p	Subscript denoting paint (po and pt, for oil and tempera paints, respectively)
ε	Strain
φ, z	Symbols denoting the tangential and longitudinal directions in the wood substrate, respectively
σ	Stress

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Author contributions
SA developed and validated the model, performed calculations, analysed and interpreted the data, and prepared the manuscript. LB conceptualized the model, developed the methodology, analysed and interpreted the results, and prepared the manuscript.

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Availability of data
All data needed to evaluate the conclusions in the paper are presented in the paper. Additional data related to this paper may be requested from the corresponding author.

Declarations

Competing interests
The authors declare that they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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