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Hygromechanical study of a 16th century painted wooden panel: in-situ experiments to quantify the mechanical effect of the frame and the cradle.

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Abstract

In order to prevent damage to painted wooden panels from the cultural heritage sector, curators and conservators must provide the hygroscopic and thermal conditions necessary for their conservation. Furthermore, the design of physical reinforcements such as frames or cradles has to be considered. In this paper, experiments were designed to determine the kinematic response of a painting to hygrometric variations both before and after remedial conservation treatments were undertaken. This study was carried out in the Fabre Museum, Montpellier on the panel painting “*La Sainte Trinité couronnant la Vierge*” (« *The Coronation of the Virgin by the Holy Trinity* »), which was placed in a climate controlled showcase in a museum exhibition space. A glass panel on either side allowed visitors to see both sides of the panel during the experiment. At the same time, two stereoscopic devices allowed us to follow the relief, the shape deformation and strain of the panel on its front and back sides. First, the mechanical effect of the frame and cradle was studied. The majority of the deformation was found to be due to the cradle; initially the panel had a complex warp (-5 to 10 mm), decreasing to (-1 to +2 mm) when the cradle was removed. The continuous monitoring (two images per hour) was carried out to assess the behaviour of the panel during imposed relative humidity (RH) variations of about 13% RH (between 65% RH for the maximum and 52% RH for the minimum) for both the absorption and desorption phases. The global mechanical effect on the curvature was very clear with an opposite direction of deflexion between absorption and desorption phases. A comparison of the behaviour of the panel with and without the cradle showed that the change in curvature was about twice as great (4 mm) without the cradle, and its direction moved from an initial slight negative curvature state to a positive one. In terms of strain on both the surfaces, we observed a horizontal shrinkage of about -0.1% during the desorption phase and a swelling of about +0.1% during the absorption phase for both the front and back sides of the panel. A further local study allowed us to assess the mechanical phenomenon for each board with the local determination of cupping angles and strains. This local study highlighted the change in behaviour of the panel without the cradle. On both sides, the local strains were decomposed into the mean strain and the deviation from the mean strain. The study highlighted the fact that the intensity of the mean strain (local swelling or shrinkage due to the hygroscopic changes) was the same for each configuration and was about 0.1%. Nevertheless, in

the case of the panel without the cradle, the variation of relative humidity was smaller (8% RH instead of 13% RH), thus we could have expected a slightly higher mean strain compared to the case with a cradle. This study of the hygromechanical behaviour of the panel painting over five years has been a great success in terms of innovative development and multidisciplinary research within the Fabre museum.

Keywords: Wood, Panel painting, Strain measurement, Moisture-induced strain, Remedial conservation

Highlights

Continuous monitoring in a museum setting of the relief, deformation and strain of a painted wooden panel of cultural significance.

Shape deflexion and strain are linked to moisture variations and structural reinforcements (frame and cradle).

A painted wooden panel of cultural significance is placed in a climatic showcase to assess its hygromechanical behaviour.

Experimental study of the hygromechanical response of a wooden panel by using a non-contact optical technique,

To raise public awareness of the conservation of artworks and the interaction between cultural heritage professionals and academics.

1. Introduction

Wooden objects of cultural significance are usually complex structures, subjected to deformations induced by environmental hygrothermal variations, which evolve over time and sometimes present irreversible damages. Conservation professionals regularly draw up condition reports to describe the evolution of the work over time, in order to prevent possible damage.

Conservators empirically evaluate the impact of their structural work, but it is rare to obtain quantitative data about this process. However, analytical techniques and digital methods developed for technical objects can also be applied to works of art, facilitating preventive conservation research. Therefore, the conservation community seeks to collaborate with scientists to gain a deeper understanding of the short- and long-term behaviour of these works of cultural significance. The monitoring of the structural behaviour which took place before, during and after structural work on the wooden panel painting in the Fabre museum is essential to this research discipline. Few other studies have been carried out using this methodology [1 - 3], and there is a growing demand for research involving diagnostic tools and a more integrative approach in the field of preventive conservation [4].

In 2018, the Fabre museum organised the exhibition “Dans le Secret des oeuvres d’art” (*« Inside the secrets of art works »*) where the conservation treatments of five objects was highlighted [5]. This event was the perfect opportunity to study the panel painting “*La Sainte Trinité couronnant la Vierge*” by an anonymous artist. This painting had never been restored since it arrived in the museum collection in 1961. Usually, when an artwork is studied before its conservation treatment, only visual characterisation is carried out. The assessment of its structural integrity is often limited to a recording of a crack map and the shape of the painting. However, with this study a group of curators, conservators and diverse scientific researchers collaborated to set-up a study to investigate the structural integrity of this panel painting before conducting the conservation treatment (both structural and pictorial).

More and more initiatives are taking place around the world (CollectionCare [6, 7], VirtEx [8], Impastow [9], Climate4Wood [10 - 12], HERIE [13], etc.[14 - 16]) to introduce a global approach towards the understanding of wooden panel behaviour over time as a function of environmental conditions (exhibition and storage spaces...). Mechanical behavior of each layer of the painting is studied and can be modeled giving a digital twin in an attempt to predict their probable future structural deterioration. [14-19]. These initiatives require experimental data and case studies on hygro-mechanical properties of a work of art on a wooden panel support. As each panel is unique in terms of structure, materials and its stress-loading history (i.e. mechanical and hygrothermal), it is difficult, where inappropriate or misleading, to use the measurements and results obtained on one panel and to apply them to another. Each case therefore requires its own specific survey. Different structural 3D monitoring techniques have been applied to paintings. Rapid dimensional change has been investigated in previous research using digital coherent out-of-plane interferometry [20] and digital holographic speckle pattern interferometry [21]. However, these techniques, using LASER technology, scan only a limited area of the painting over a short timescale, which does not allow the diagnosis of the overall behaviour of the painting subjected to climatic variation throughout the year. It is necessary to assess a painting's overall behaviour due to the heterogeneity of the painting's structure: assembled from several boards of wood, with different cut orientations; the deformation of the shape of the overall panel can be very different to that of a single board. Other techniques have emerged in the last 20 years, such as digital image correlation and its derivative (i.e. mark tracking techniques), which allows the user to monitor large areas for a long period of time [22 - 24]. This technique has been used for the present study and explained in a previous article [24].

Quantifying the deformation undergone by a panel during variations in relative humidity, or during structural conservation treatment (eg the removal of the cradle), allows us to improve our insight into the behaviour of panels and their pictorial layers. This information is of the utmost importance in order to determine the environmental specifications of an exhibition space for panel paintings. Many studies have been carried out on environmental specifications for museums [25 - 27]. The cultural heritage community is working towards the improvement of the international climate regulation in museums, galleries and archives, known as ASHRAE [28]. However, these regulations need more specific data on climate related damage of fragile objects such as panel paintings.

In regards to cupping deformation [17], the main cause lies in the variations in relative humidity (RH) of the environment in which the artwork is located. This is due to the hygroscopic nature of wood, which exchanges moisture with its surrounding environment in order to reach equilibrium. This moisture exchange can result in both transient and permanent deformation. Transient deformation is caused by fluctuations in humidity and temperature and tends to stabilise when the wood reaches equilibrium with its environment. The causes of permanent deformation can be categorised into four types: the orientation of the cut of the board [29, 30], compression set [31, 32], the ageing of the wood [33], and the mechanical asymmetry of the panel [34, 35]. The cutting orientation and compression set result in permanent cupping. The loss of hemicellulose over time and the mechanical asymmetry of the panel with paint on one side only, also contribute to warping.

2. Research aim

This study aims to determine the experimental mechanical response of the panel painting “*La Sainte Trinité couronnant la Vierge*”, in terms of curvature and strain, before and after remedial

conservation, related to variations in relative humidity between 52 and 65% at 20 °C, using stereovision and mark tracking monitoring. This technique allows a continuous measurement of the relief, the shape deformation and the strain of both the front and back faces of the panel by recording two images per hour throughout the experiment. The innovative techniques used over five years to monitor this painting also included aspects of its conservation. This project was truly multidisciplinary resulting from a collaboration of professionals from the museum, academic researchers in engineering and panel painting conservation. In this paper, the hygromechanical response of the panel is assessed in the presence or absence of the frame and the cradle. A future study will investigate the behaviour of the panel following conservation treatment with a new design of flexible cradle.

3. Material and methods

This article is a follow-up to the article [24] in which the structure of the panel was studied and the measurement methods used were described in detail. We recall here the essential elements for understanding this study and refer to the previous article for more details.

The subject of this study is “*La Sainte Trinité couronnant la Vierge*”, an oil painting on a wooden panel dating from the 16th century, whose unframed dimensions are 1370 mm high and 980 mm wide, and whose thickness varies between 10 and 13 mm. It was presented in a 135 mm wide and 40 mm thick softwood frame (Fig. 1a). The panel consists of four oak (*Quercus* sp.) boards joined vertically: the first one from the left, as seen from the front, is flat sawn (tangential), while the other three are quarter sawn (radial). A wooden cradle, in fir (*abies* sp.), consisted of seven horizontal bars of 35 mm by 15 mm cross-section glued to the back of the oak boards, and six vertical uprights of identical cross-section nailed to them forming half-lap joints. The vertical uprights at the extreme right and left were in one piece, while the other four were divided into six pieces (Fig. 1b). The entire back face of the panel and cradle was covered with a layer of brown paint which had undergone microchemical analysis. (analyse chimique Marina ?)

The joints between the four boards making up the panel, had mostly degraded. Several vertical cracks had been detected on the three quarter-sawn boards which had provoked the rupture (flaking) of the paint layer. The panel had two different levels of curvature in the upper and lower parts.

The panel was installed in a humidity-controlled display case. It was placed vertically on a balance that allowed the measurement of variations in the mass of water adsorbed or desorbed by the wooden structure, when the relative humidity of the environment varied. The upper edge of the panel was held using a ball joint link which allowed the panel to curve freely.

In order to measure the panel deformations on both sides simultaneously, two stereovision systems each with two cameras permanently installed on the walls of the exhibition room recorded pairs of images every 30 minutes [24]. Two principal methods were employed to analyse these images: the mark tracking technique and digital image correlation depending on the tonal contrast of the panel surface. The mark tracking technique consists of detecting and tracking the displacement of dots (black or white) on the surface, during loading. The correlation method requires a certain degree of surface texture (in our case, the texture of the paint surface) in order to track the displacement of several small areas by local matching between two images of different mechanical states. In this study, the natural contrast was insufficient to obtain an accurate measurement on both the back and front sides [24], so only the mark tracking technique was used. Small round dots composed of Japanese paper reversibly glued with a weak adhesive were attached to both

sides at regular intervals. The displacement measurements were then accurate to 0.03, 0.04, 0.06 mm in x,y,z directions respectively and the strain measurements were then accurate to about 10^{-4} [24]. The « drift » of the panel or of the cameras was measured with the help of marks put on the support and were subtracted from the panel displacement measurements.

In addition, three Deformometric Kits (DK), consisting of two transducers were mounted between two axes fixed to the back of the panel and perpendicular to its plane [36, 17], which measured local deformations and curvatures at three locations over time. The correlation between the DK measurements and those obtained by stereo-correlation was verified and found to be accurate [24], thus we present here only the results obtained by stereo-vision.



Fig. 1. “*La Sainte Trinité couronnant la Vierge*” with the original frame in the humidity-controlled display case. Markers in the form of round dots positioned on the front (a) and back (b) sides allowed displacement to be measured by stereovision of images, using 4 cameras installed on the walls of the exhibition room.

The experimental set-up allowed us to follow the deformations of the panel during hygrometric variations, and to deduce the strains in the wood and paint layer. But it also allowed us to compare the shape of the panel in different configurations, and thus to evaluate the effect of physical elements such as the original frame or the cradle on the panel. In addition, each board is considered independently, by subtracting its individual inclination and by calculating the shape and

displacement of the reference system attached to it. This allowed us to obtain the local curvature angles and the local displacements [24] of the wooden boards.

For this purpose, a set of experiments was conducted on the panel, described in figure 2, as a function of time. In the first experiment the hygroscopic equilibrium of the panel with its original frame at 52% RH was obtained after a certain lapse of time, stabilisation state named S0. This stabilisation was determined from the mechanical curve, corresponding to a quasi-constant strain variation lower than 10^{-4} over 7 days. After that, a rapid increase in relative humidity to reach 65% RH was applied and maintained until the stabilisation of the panel, state named S1. At this point the original frame was removed, and the panel without its frame was returned to the showcase with an holding device adapted to secure the panel without its frame. The panel was then stabilized at three different levels of relative humidity in the following sequence: 65% RH, state named S2, then 52% RH, state named S3 and 65% RH, state named S4. Next, a structural conservation treatment which consisted in removing the whole fir cradle, disassembling the four boards of the panel in order to perfectly clean the glue joints, and then accurately re-glueing the four boards back together. A further stabilisation at 65% RH led to a state named S5. A polyester film was laid on the front side of the panel to prevent the exchange of humidity through this side, and thus simulate the effect of a varnish layer filling the cracks which could inhibit moisture transmission. A decrease of relative humidity to 56% gave the last presented state, S6, after stabilisation of the panel. A new auxiliary cradle was designed and positioned on the back of the panel (state named S7). However, this state and the following ones are not presented in this paper, which focuses on the various states of the panel before the full conservation treatment.

The previous article [24] presented some preliminary results concerning the first phase of the study, i.e. the movement and deformation of the panel in its original frame when it was stabilised at 52% RH (S0) and then underwent a rapid increase in relative humidity until its stabilisation at 65% RH (S1). The purpose of this subsequent article is to analyse the results obtained from the same panel; with the frame and cradle, with the cradle only and lastly without the cradle. Particular attention is paid to a comparison of the two desorption phases: the panel with the cradle and the panel alone without the cradle.

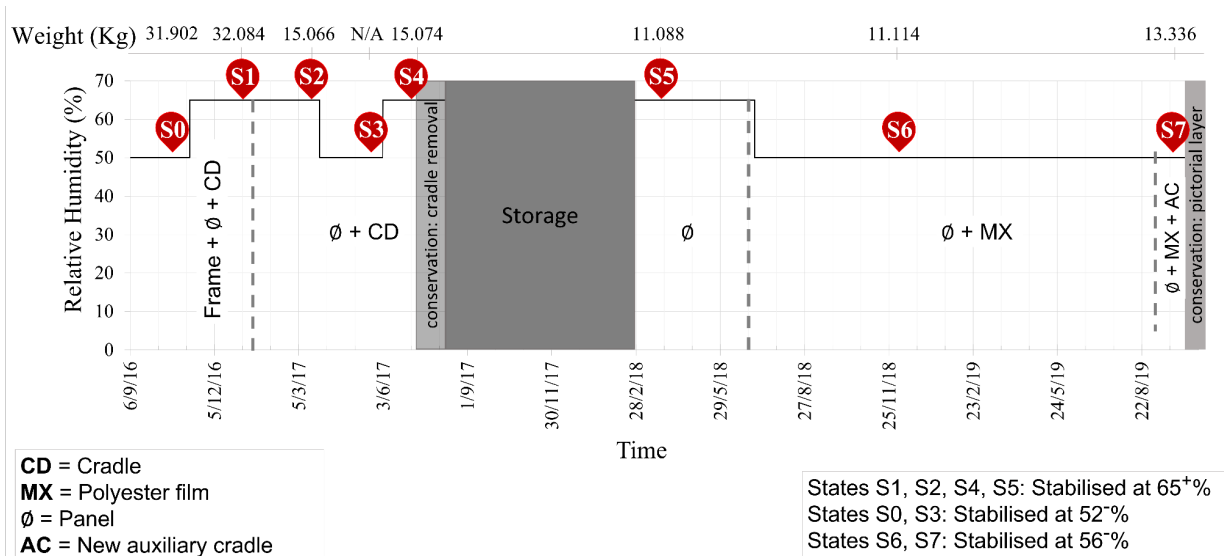


Fig. 2. Presentation of the different states of the panel over time, and applied relative humidity variations. S1 to S7 labels refer to the different states.

4. Results and discussions

4.1. Effect of the softwood frame and the original cradle on the mechanical state of the wooden panel

The first experiment, begun in September 2016, investigated the effect of the softwood frame on the panel. When the panel with the frame and the original cradle was stabilised at 65% RH, it reached a weight of 32.084 kg. In this state it had a concave shape with a maximum deflection of about 15 mm located in the upper part of the panel (Fig. sm1a in supplementary material). The removal of the frame allowed us to evaluate its mechanical influence on the panel. The new weight was 15.066 kg for S2. The frame alone was heavier than the panel and thus contributed to approximately half of the mass variation. However, the shape of the panel varied very little before and after removal of the frame (see Fig. sm1b in supplementary material). On fig. 3a (S4-S1), the variation of the relief between these two states is shown amplified by x50 to allow the reader to see the deformation clearly, the maximum out-of-plane displacement was 2 mm for the upper left corner with a small twist movement around the vertical axis.

In July 2017, the original cradle was removed during structural conservation that took place over three days in the Atelier Tournillon workshop [37]. The panel freed from the original cradle, which weighed approximately 4 kg, was then reinstalled in the display case, stabilised at a relative humidity of 65% RH, reaching a weight of 11.088 kg (S5). It can be observed that it had flattened considerably: the strong curvature of the upper part (-5 to 10 mm) had almost disappeared (-1 to +2 mm) and had given way to a lighter, opposite curvature in the lower part of the panel (Fig. sm1c in supplementary material). The variation in curvature (with a range of 11 mm) seemed to be fairly homogeneous over the whole height of the panel, with a slightly stronger evaluation value in its centre (Fig. 3b (S5-S4)). The loadings imposed by the frame or the cradle on the panel induced opposite curvatures with respect to the action-reaction principle. Therefore, we can consider that the shape change induced by the removal of the cradle reflected an elastic return of the removed forces, where the final shape was only affected by the remaining permanent deformation in the panel.

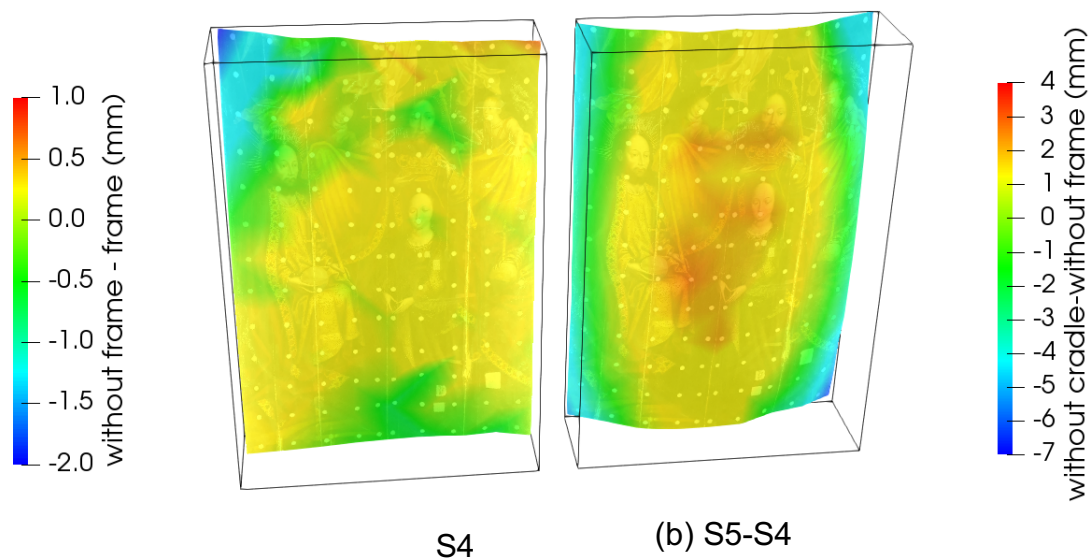
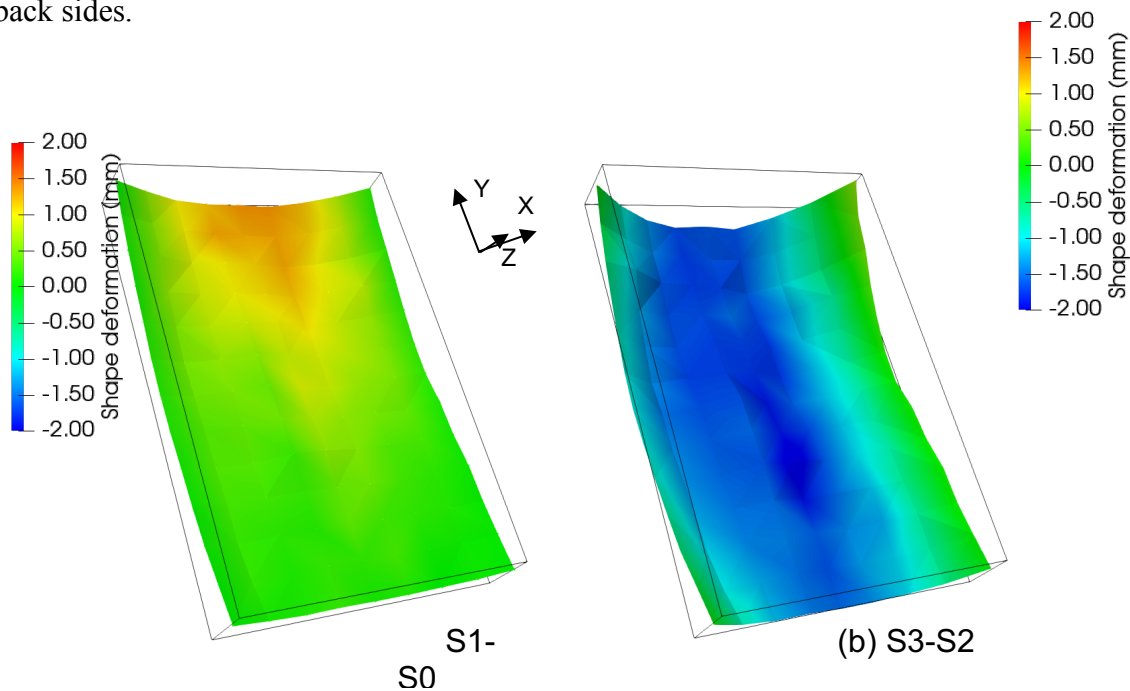


Fig. 3. Mechanical effect of the frame and the original cradle on the panel. Variation of the relief (shape deformation): (a) due to the frame (state 4-state 1) (amplified by x50) (b) due to the original cradle (state 5-state 4) (amplified by x20), viewed from the front side.

4.2. Effect of an absorption phase on the wooden panel with the original frame and the cradle (S1-S0)

An increase of 52 to 65% RH lowered the maximum deflection of the panel with the frame and original cradle by about 2 mm (Fig. 4a (S1-S0)). The order of magnitude of this variation was four times lower than the mechanical effect of removing the original cradle (Fig. 3b (S5-S4)), and principally localised at the top of the panel. Concerning the horizontal strain evolution (ϵ_f^h) for the front side of the panel, the increase in humidity led to a global swelling, whose average order of magnitude was 0.06 to 0.1% (Fig. 5a (S1-S0)). The global results obtained on the back side (ϵ_b^h) are close to those obtained on the front side in all cases, and can be seen in figures sm2 to sm5 in the supplementary material. Nevertheless, the local evolution of the strains in two particular areas are presented in the following sections to highlight the small differences between the front and back sides.



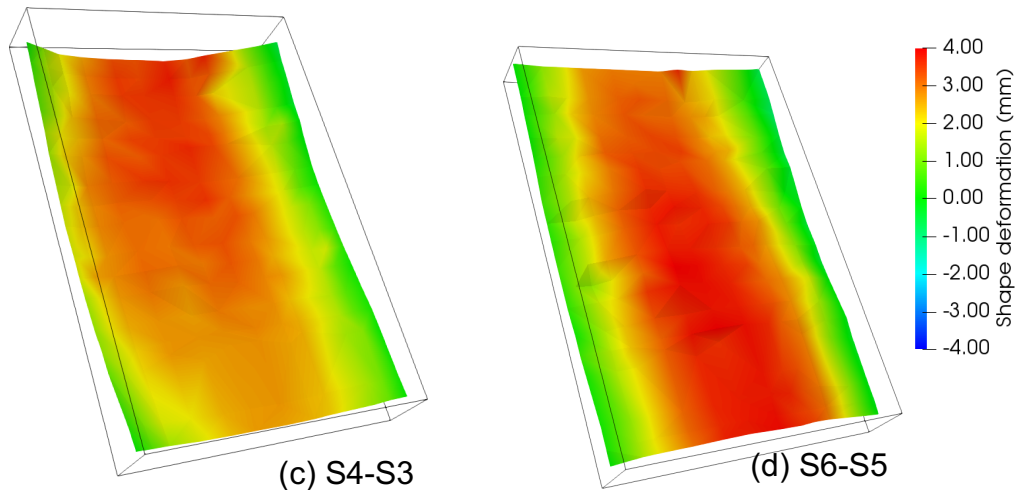


Fig. 4: Relief map (amplified by x10) and shape deformation of the front side: (a) Effect of an absorption from 52 to 65% RH on the panel with the original frame and the cradle (S1-S0), (b) Effect of a desorption from 65 to 52% RH on the panel with the original cradle (S3-S2), (c) Effect of an absorption from 52 to 65% RH on the panel with the original cradle (S4-S3), (d) Effect of a desorption from 64 to 56% RH on the panel alone (S6-S5).

4.3. Effect of a desorption phase on the wooden panel with the original cradle (S3-S2)

Under a decrease in relative humidity from 65% RH to 52% RH, the deflection of the panel with the original cradle increased by about 2 mm (Fig. 4b (S3-S2)) all along the height of the panel, contrary to the variations observed on the panel with its frame, located in the upper part.

Looking at the global behaviour of the panel, the horizontal shrinkage was about -0.1%, on the front side (Fig. 5b). A lower shrinkage on the back side of the panel was observed (Fig. sm3b), consistent with the increase of curvature. This can be explained by the fact that the crossbars of the cradle were glued to the back of the panel, thus the panel was forced to maintain material continuity in the transverse direction, with the crossbars of the cradle, so the joints between the boards were limited to very small movements. The longitudinal direction of the crossbars and that of the panel boards was parallel to the direction of their wood grain, which is the most rigid direction. The crossbars are located across the boards and were thus parallel to the radial or tangential directions of the panel's wood grain, in consequence the crossbars restricted the lateral shrinkage of the wood of the panel.

Considering the local strains over time, the horizontal shrinkage of area A, whose location is shown in figure 5, reached -0.11% for the front and -0.07% for the back sides (Fig.6). The panel was stabilised after 5 weeks. The horizontal shrinkage of area B, whose location is also shown in figure 5, reached -0.08% and -0.12% for the front and back sides respectively. We can notice by comparing these two areas that the strongest strain does not correspond to the same side of the panel (front side for area A, back side for area B). This can be explained by the opposite local curvatures in these two areas: -0.2° for the area A and $+0.2^\circ$ for the area B (Fig. 7).

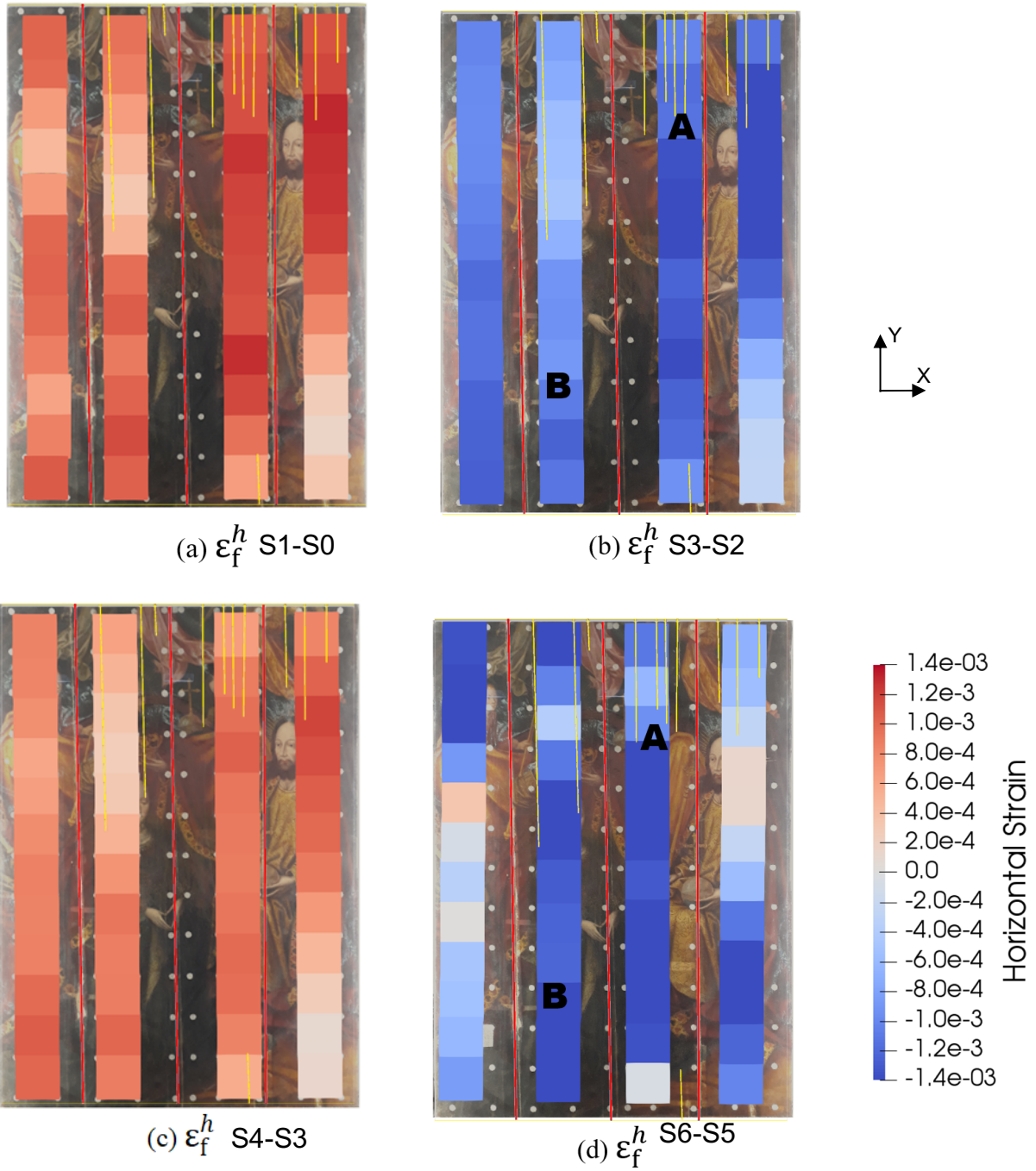


Fig. 5. Horizontal strain of the front side : (a) Effect of an absorption from 52 to 65% RH on the panel with the original frame and the cradle, (S1-S0), (b) Effect of a desorption from 65 to 52% RH on the panel with the original cradle (S3-S2), (c) Effect of an absorption from 52 to 65% RH on the panel with the original cradle (S4-S3), (d) Effect of a 64-56% RH desorption on the panel alone (S6-S5)

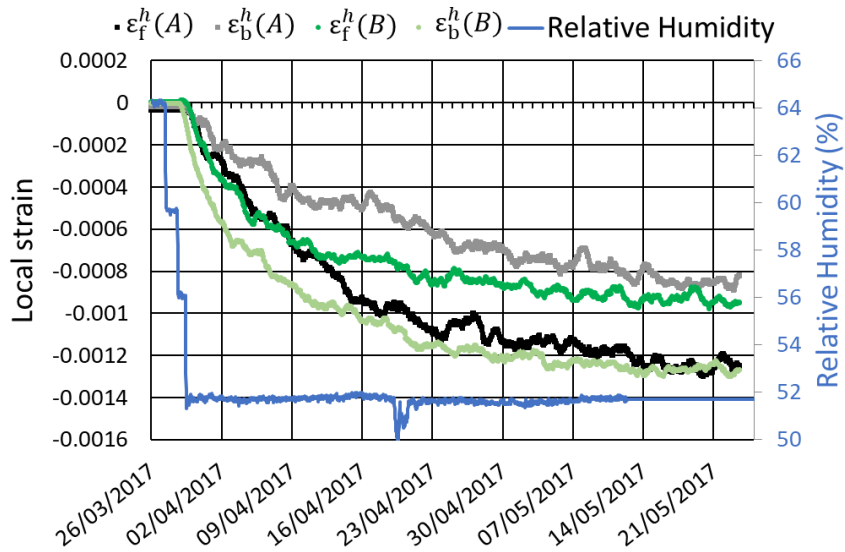


Fig. 6. Effect of a desorption from 65 to 52% RH on the panel with the original cradle (S3-S2). Local horizontal strain on area A and Area B.

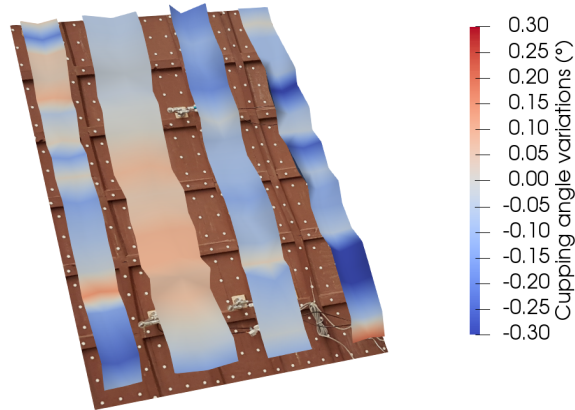


Fig. 7. For each board, out of plane displacement (amplified by x400) and **cupping** angle variations for the S3 state, view from the front side.

4.4. Effect of an absorption phase on the wooden panel with the original cradle (S4-S3)

During a 52-65% RH absorption phase, the deflection of the panel with the original cradle decreased by 2 mm, slightly more strongly in the upper half of the panel (Fig. 4c). The horizontal swelling reached a practically homogeneous 0.1% on the front side (Fig. 5c). These strain values are very similar to those obtained in the case of the panel with the cradle and the frame (Fig. 5a).

4.5. Effect of a desorption phase on the wooden panel alone (S6-S5)

Under a desorption from 64 % RH to 56% RH, the deflection of the panel alone varied by about 4 mm (Fig. 4d (S6-S5)), twice that of the deflection of the panel with the original cradle. This

humidity variation decreased the initial slight negative curvature, which then became positive. The direction of the curvature was thus inverted.

The horizontal shrinkage was in the same order of magnitude as in the case of the panel with the original cradle (Fig. 5b), about -0.1%, but was less homogeneous (Fig. 5d). The local value of the strain of the areas A and B over time are plotted on Fig. 8. These two local strains reached similar values, about -0.12% on the front side and -0.1% on the back side and seemed to be stabilised four weeks after the change in humidity. It was noted that in this phase the moisture control was less stable than in the other phases, with a slight increase 3 weeks after the change of the set point. The device did not reach the target of 52% RH, instead the environment stabilised at about 56% RH.

Two phenomena were likely to have modified the deformation kinetics of the panel: on the one hand, the back side of the panel was free of the cradle, and thus revealed bare wood areas where the cradle had been for which the local permeability was higher than elsewhere due to the presence of the brown paint layer. On the other hand, the front side was covered with a polyester film, which prevented moisture exchange on this side. These two phenomena tended to increase the asymmetry of the transient moisture gradient in the panel, which could therefore only be stabilised due to the moisture flow on the back side.

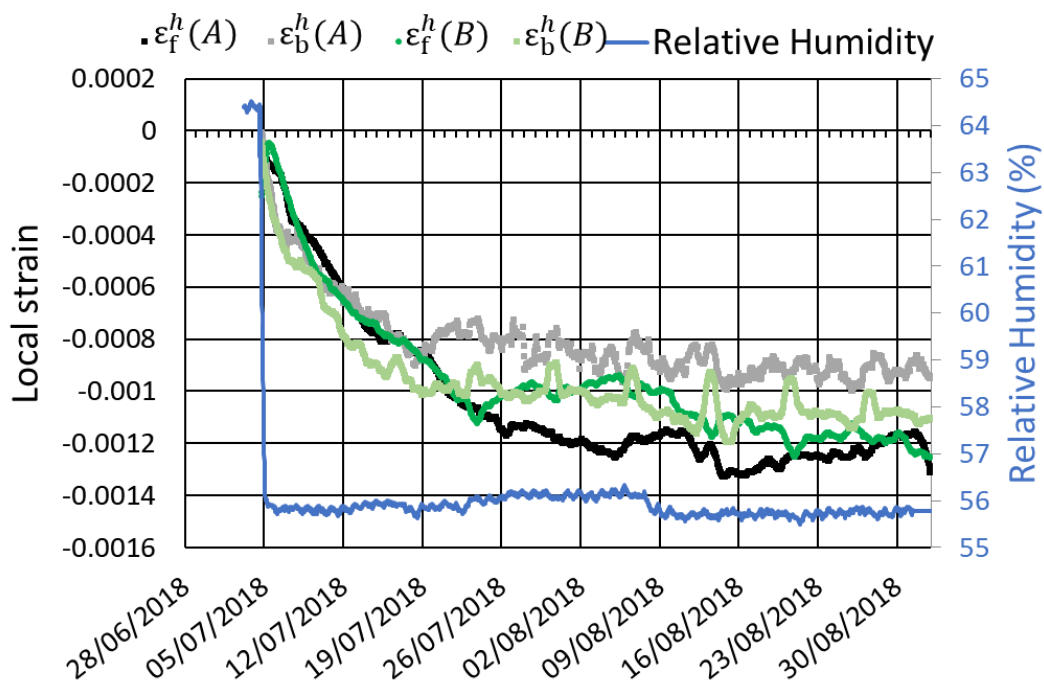


Fig. 8. Effect of a desorption from 64 to 56% RH on the panel alone (S6-S5). Local horizontal strains on area A and B.

The overall curvature of the panel was positive in state S6 (Fig. 4d), but if we look at the curvature of each board, the situation was a little more complex: two boards had positive curvature, while the curvature of the other two varied locally, with a negative curvature in some places (Fig. 9). The overall shape of the panel was flatter than in the case of the panel with a cradle, while the local curvatures were up to two times greater. The absence of a cradle allowed each board to curve more individually. The local curvatures of area A and B were respectively +0.2° and +0.4°, significantly different from the values of -0.2° and +0.2° in the case of the panel with a cradle.

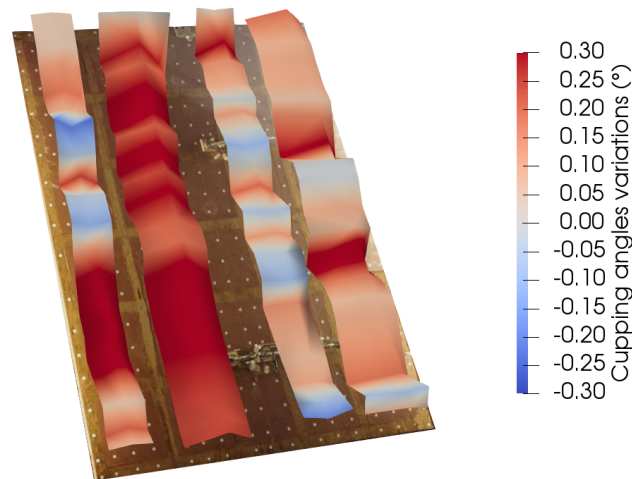


Fig. 9. For each board, out of plane displacement (x400) and curvature angle variations for the S6 state, view from the front side. The initial curvatures of each board have been subtracted from these results.

4.6. Strain analysis

The local horizontal strain calculated on each side, ε_f^h for the back side and ε_b^h for the front side, can be decomposed as the sum of two terms: (i) a so-called “mean strain” ε^{mean} , corresponding to the average of the strains of the two sides, which can be assimilated to an hygroscopic swelling or shrinkage, (ii) a so-called “deviation from the mean strain”, ε_b^{dev} and ε_f^{dev} , corresponding to the difference between the strain of the side considered and the average strain of the two sides, which can be assimilated to a bending strain (1). Figure 10 shows the evolution of the mean strain (red line ε^{mean}) and the deviation strains (black line ε_f^{dev} , grey line ε_b^{dev}) during the four hygrothermal loads experienced by the panel, with or without the frame and the cradle.

The mean strain ε^{mean} is always about three to four times higher than the deviation strain of each side (ε_f^{dev} and ε_b^{dev}). The intensity of the local mean strain, about -0.1%, does not depend on the presence or absence of the frame or cradle, suggesting that locally the wood can swell and shrink almost freely, perhaps due to the presence of cracks. Nevertheless, in the case of the panel without a cradle, the variation in relative humidity is slightly smaller (64-56% RH instead of 64-52% RH), we can thus expect a slightly higher mean strain compared to the case with a cradle.

In the previous paper [24], we calculated that this 10% variation in relative humidity, inducing a variation of 0.6% in moisture content, corresponds to a radial strain of 0.1%, in the case of unrestrained boards. The mean strain measured locally on both radial boards corresponds to this expected order of magnitude (area A and B). The deviation strain on each side is of the order of 0.02%.

According to the unpaired t-test with a p-value inferior to 0.0026 at 95% confidence, the deviation and mean strains are significantly different from each other (between area A and B, and between state S3-S2 and S6-S5). This can be explained because area A and B are located in two different boards, area A in the upper part of the board, and area B in the lower part. Comparing states S3-S2 and S6-S5, the difference between the strains is significant. Nevertheless, the decrease in

relative humidity of these two states is quite different (65%-52% RH for S3-S2 and 64%-56% RH for S6-S5), so we could expect even greater differences between the strains of the panel with and without the cradle for a similar decrease of humidity. The deviation strains are greater in the panel with the cradle (S3-S2), highlighting the constraining action of the horizontal crossbars on the boards.

$$\varepsilon_k^h = \frac{\varepsilon_f^h + \varepsilon_b^h}{2} + \left(\varepsilon_k^h - \frac{\varepsilon_f^h + \varepsilon_b^h}{2} \right) = \varepsilon^{mean} + \varepsilon_k^{dev} \text{ with } k = f, b \quad (1)$$

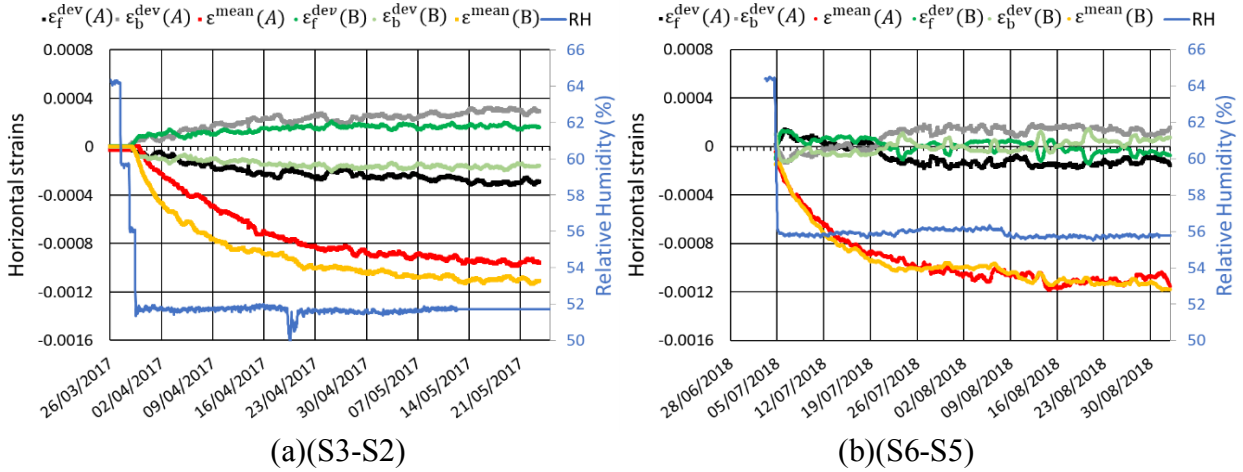


Fig. 10. Mean strain ε^{mean} (area A in red, area B in orange), deviation strain of the back side ε_b^{dev} (area A in grey, area B in light green) and of the front side ε_f^{dev} (area A in black, area B in dark green) for the 4 hygrothermal loadings (RH blue line): (a) panel with the frame (S3-S2), (b) panel alone (S6-S5).

5. Conclusion

“*La Sainte Trinité couronnant la Vierge*” is a painting on a wooden support, initially with a rigid cradle, cracks and damages had formed due to internal stresses. In order to understand its state of deterioration, we set up an experiment in the exhibition space of the Fabre Museum, Montpellier in full view of the public. This consisted of comparing the shape and the strains of the panel in different states such as: panel with cradle and frame, panel with cradle, panel alone after a conservation treatment, through the use of two stereovision devices in order to measure the displacements of the front and the back. We also measured the effect of controlled hygrothermal environmental variations on the shape of the panel in these different states.

These experiments produced measurements which quantified firstly the minimal effect of the frame on the mechanical condition of the cradled panel and secondly the principal role of the cradle. The remedial work that consisted of removing the cradle had a significant impact on the overall shape of the panel, which became much flatter despite the fact that each board

had an increased individual warp. Thus, even if a cradle induces stresses in the panel (the more the cradle is rigid compared to the panel, the more the stresses are high and the more the occurrence of cracking is probable), a specific flexible cradle is necessary to bring an uniformity to the panel. During a decrease in relative humidity, the behaviour of the panel without a cradle was very different from that with a cradle: the change in curvature was about double, as could be expected

and its direction was opposite, due to the restraining action of the cradle. In fact, the ability of the boards and the cradle to have relative movements in the plane of the panel produced a curvature opposite to that produced by the moisture gradients alone on a panel without a cradle. This caused the preparation and paint layers to shrink and the artwork to take on a general concave shape which appears to be the primary cause of the painting's damaged state. In the case of the panel without a cradle, the horizontal strain of the back side was generally higher and more homogeneous than in the case of the panel with a cradle. This can be seen especially in the deviation strains, which were greater in the case S3-S2 than S6-S5 despite the smaller decrease in humidity.

A global study allowed us to assess the overall shape deformation of the panel and the average strains, but a local study allowed us to understand the mechanical phenomenon for each board with the cupping angles, curvatures and strains. This local study highlighted the lack of uniformity in the behaviour of the panel without a cradle. Opposing local curvature of adjacent boards was observed, corresponding to the opposing strain evolution. Therefore, we can conclude that the primary function of the stiffening support for this panel painting is not only to limit inevitable cupping, but also to even out the cupping of individual boards within the overall cupping of the painting, whilst trying to limit the unavoidable mechanical stresses imposed on the panel.

Collaboration between conservators and engineers led to the design of a new cradle which limits the curvature of the panel whilst allowing shrinkage and swelling in its plane and thus reducing the mechanical stresses on the panel that cause the wood and paint layers to crack. The study of the mechanical response of the panel with this new cradle will be the subject of a future publication.

The procedure of measuring the strains and curvature of a painted wooden panel of cultural significance during a 10% variation in relative humidity can now be carried out "routinely" in the humidity-controlled showcase. It is a promising way of qualifying the reactivity of a work of art on panel to a variation in humidity, and of comparing the responses of different panels. Cultural heritage conservation professionals can thus detect those panels that are most sensitive to variations in humidity and then recommend the necessary precautions to be taken to ensure their optimal conservation.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:

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