Climate induced deformation of Panel Paintings: experimental observations on interaction between paint layers and thin wooden supports

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Abstract. This work describes the experimental evidence of the deformation induced on a XVI century panel painting by climate uncontrolled fluctuations and on structural replicas under controlled laboratory conditions. The objects under measurement have a very thin wooden support (6 mm), caused by thinning and cradling of the original artefact during a restoration made at the beginning of the XX century. This kind of artefacts are very susceptible to suffer mechanical damage.

The data of experiments carried out on the panel and in laboratory conditions show a characteristic behavior, similar to bimetallic strip warp and an interaction between hygroscopic asymmetry and mechanical asymmetry, inducing a peculiar stress dynamic in the interface wood-paint layer during climate fluctuations.

In collaboration with the conservators involved in the restoration process, the effect of buffer hygroscopic systems on the warping has been studied.

1. Introduction
The possible anisotropy due to the anatomical cutting of the planks of the panel is a common factor influencing its cupping trend as a consequence of sorption phenomena.

However the cupping trend is also influenced by other factors. A panel painting is a composite made of a wooden panel and of painting layers on the front face (gesso-glue preparation, paint layers, varnishes). These layers cause hygroscopic and mechanical asymmetries.

The hygroscopic asymmetry is due to the vapor barrier effect, causing a vapor flux reduction throughout the painted layers from wood to the surrounding atmosphere. The consequence of the different moisture content (MC) between front and rear face during a Relative Humidity (RH) change is a typical cupping trend already described [1][2]. It is characterised by a transitory cupping which after a peak tends to decrease as the MC gradient decreases.

The mechanical asymmetry is due to the stiffness of the paint layers and to their shrinkage/swelling properties that, differently from wood, are not significantly affected by hygroscopic variations. As a consequence, the whole composite wood + layers is prone to a warping behaviour comparable to the bimetallic strip (bs) (Figure 1).
Figure 1. Effect of asymmetries on cupping strain ($\varepsilon$) of a panel painting under RH change.

The influence of the $bs$ effect is affected by the materials involved, but mostly by the support thickness and by the ratio between the support's and layers' thicknesses.

The $bs$ phenomenon is generally hidden by the hygroscopic asymmetry and by the anisotropic cupping but it can be significant or critical in thin panel paintings, such as the ones who underwent the (not recommended and no longer performed) thinning technique. In this case, thinning – usually coupled with cradling – creates high warping tendencies, restrained by the cradle. The result is a high stress level with risk for the integrity of the object. These well-known and largely investigated phenomena [3,4] had led conservators to attempt different intervention approaches aiming to reduce the asymmetries, like various kinds of buffer systems affixed on the back face [5,6,7].

In this research strain measurements have been carried out on an XVII panel painting before and after the restoration in uncontrolled climatic conditions. The experimental results highlighted the stiffening effect of the cradle and the influence of the buffer barrier placed on the rear side of the panel during its restoration.

2. Materials and methods
2.1. Experiments on the Panel Painting
The case of study is an oil painting on oak ($Q. petraea$ L.) support (“Baccanale”, XVII century, attributed to the school of Jacob Jordaens and part of the Grezler collection, Trento, Italy, Figure 2).

The identification of the wooden species has been performed on small samples by means of anatomic microscopy. The support (103 x 71 cm) is composed by four sawn boards 5-6 mm thick glued together along the edges. The very little support thickness was caused by thinning and associated cradling (Figure 3) of the original artifact during a restoration made at the beginning of the XX century. In 2015 it was withdrawn from the exhibiting site and sent to restoration because of extended detachments of the painted layers.

The observation of the rings in the transversal sections of the boards at the edges allowed the dendro-chronology dating and to assess their anatomical orientation, their distance and position from the log’s pith, the minimum diameter of the log (Figure 4). The anatomical orientation is a fundamental piece of information in order to calculate the fraction of cupping tendency due to anisotropy.
Figure 2. The “Baccanale” painting

Figure 3. Left: picture of the rear side of the panel with the cradling structure. Right: the rear side of the panel after the restoration: the cradling has been kept but modified in order to improve the cross beams slideability and stiffness. A vapor buffer composed of collapsible squares composed of wooden sticks was affixed on the panel surface among the cradling spaces. The DK transducers mounted are also visible.

Figure 4. Scheme of the end sections of the planks 1–4 and their distance from the pith. The dashed circles represent the minimum circumscribed circumference. The figure also indicated the position of the two couples of displacement transducers on the rear side of the panel.
The environmental-deformometric survey on the panel painting was carried out in the restoration laboratory before and after the restoration operations. The parameters measured were the following:
- Environmental Relative Humidity (RH) and Temperature (T) measured near the panel;
- Deformations of the panel in plane (shrinkage/swelling) and out of plane (cupping) in two zones of the panel using a total of 4 transducers.

The monitoring was set on a 5 minutes sample rate for a total period of 161 days.

The monitoring took place according to the following steps described in the table below:

| STEP | start       | end         | Days | Heating | Cradle | Buffer |
|------|-------------|-------------|------|---------|--------|--------|
| A    | 09/08/16    | 08/10/16    | 60   | OFF     | original | none   |
| B    | 08/10/16    | 28/10/16    | 20   | ON      | original | none   |
| C    | 28/10/16    | 12/11/17    | 15   | ON      | none    | none   |
| D    | 12/11/17    | 17/01/17    | 66   | ON      | new     | yes    |

The deformation measurements were performed thanks to two couples of DK transducers, according to the methodology described in [8,9]. The measurement system was able to detect the cupping and the differential shrinkages or swellings (Def%) between the rear (R) and the front (F) of the panel.

Other different approaches to out-of-plane warping measurement are available and some new cheap techniques have been successfully developed [10].

Cupping deformations are here expressed as the inverse of the radius of curvature (1/r) (m⁻¹). Negative cupping values (-1/r) indicate a concavity on the back of the painting that occurs when R<F and vice versa.

A simple linear regression analysis was used to examine the correlation between RH and the dependent deformations. Results of the analysis are reported in terms of:
- $r^2$: linear correlation index. ($r^2 > 0.55 - 0.6$ is considered correlated).
- $m$: the slope of the regression line, describing how much the deformation under test varies under the variation of 1% of RH. The higher the absolute value of $m$, the higher the warping sensitivity of the support as the RH changes.

2.2. Experiments on samples in laboratory conditions

In order to better understand the influence of the different asymmetries on the cupping trend of the original panel painting some preliminary laboratory tests were carried out in controlled climatic conditions on dummies (structural replicas) made by the restorer.

Radial planks (quarter sawn planks) free of visible defects with a thickness of 5.9 mm (in the tangential direction) x 189.5 mm x 243 mm were obtained from a seasoned radial table of oak (density of 670.7 kg/m³). Thickness and material reflect the average characteristics of the Bacchanal panel painting as measured previously. The choice of radial anatomical orientation of the boards is dictated by the need to avoid the interference of a cupping due to the anisotropic component.

The 4 edges of all the boards have been sealed with aluminium foil glued with vinyl glue in order to avoid the edge effect.

The specimens used for the tests were prepared and named as described below:
- **OO**: “bare” plank without any layer affixed on both the major faces, used as a reference for free deformations (data not shown in the results).
- **Al**: one face has been sealed with aluminium foil and with vinyl glue in order to allow the flux of vapor on only one of the two faces. The plank thus prepared had an exclusively hygroscopic asymmetry.
- **Ol**: one of the free faces was treated with gesso and glue preparation and subsequent layers of oil paint. The overall thickness of the affixed layers is 0.55 mm (support/paint layer thickness ratio=10.8). The other face was kept bare. The dummies thus prepared are expected to have both a hygroscopic and a mechanical asymmetry.

The specimens have been placed inside the climate chamber and underwent in-parallel cupping measurement during classical sorption tests characterised by RH step change followed and preceeded by steady RH periods (Figure 6).
A further Oak plank was placed in the climate chamber on a laboratory scale for the continuous measurement of its mass variation. The scale has a nominal resolution of 0.01 g which allowed to appreciate variations in average MC of the plank around 0.01%.

Balance, displacement transducers and temperature measurement probe (T) and Relative Humidity (RH) of the climate chamber are connected to a computer for data acquisition with a 5 minute sample rate.

Figure 5. Strain tests on dummies in climate chamber.

3. Results

Figure 6. Panel painting: time series of climate and of deformation (shrinkage-swelling and cupping) the during the for steps. Missing data at the end of the step C during the restoration process.
Figure 7. Panel painting: 3D plot of cupping deformation (vs. time and RH) during the C step (unrestrained deformation).

| Step   | R  | F  | cupping |
|--------|----|----|---------|
| Step A | 0.0048 | 0.0047 | 0.024 |
| r²     | 0.53 | 0.52 | 0.68    |
| Step B | 0.0046 | 0.0045 | 0.023 |
| r²     | 0.65 | 0.64 | 0.66    |
| Step C | 0.0073 | 0.0047 | 0.48  |
| r²     | 0.62 | 0.58 | 0.63    |
| Step D | 0.0063 | 0.006  | 0.049 |
| r²     | 0.72 | 0.7  | 0.86    |

Deformation ratios

|                     |     |     |     |
|---------------------|-----|-----|-----|
| cradling effect (m_B/m_C) | 0.6 | 1.0 | 0.05 |
| New buffer effect (m_D/m_C) | 0.9 | 1.3 | 0.1  |

Table 1. Panel painting: results of linear regression analysis of deformation as a function of RH. The amounts of shrinkage and swelling of rear (R) and front (F) side are expressed as \( m = \text{\%}/\text{\%} \) and cupping deformation \((1/r)\) as \( m = m^{-1}/\text{\%} \).

Positive correlation \((m > 1)\) are obvious for shrinkage/swelling for F and R. For cupping they are compatible with hygroscopic and mechanical asymmetry and with the anisotropy of wood in boards with pith towards R. The \( m \) ratio (calculated in single steps): B/C provides the constraining effect of cradling; D/C provides the constraining effect of the new cross beams+ vapor barrier.
Figure 8. Laboratory samples: sorption test with RH step change. Blue: normalized gravimetric MC curve; green: Al sample cupping (hygroscopic asymmetry only); red: Ol sample cupping (hygroscopic + mechanic asymmetry) vs. time.

Figure 9. hygro-mechanical FEM model: elaboration of expected deformation of a transversal section of the Baccanale panel due to anisotropy under a step change of RH (left absorption, right desorption). The model has been validated on the base of the data from the anatomical orientation observations and from the laboratory sorption tests on dummies.

4. Discussion and conclusions
1. The old cradling reduces the free deformation tendencies of the panel more than 20 times;
2. The panel painting with the new crosspieces and the buffering system has a cupping tendency two times wider than with the old cradle. The effects on the deformations produced by the vapor barrier systems on the back and by the stiffening cross members are very evident. It is important to stress that, although both reduce the cupping, their effect is very different because the crossbars are a mechanical constraint that contributes to the reduction of the cupping but, on the other hand, it generates a state of internal stress [11], while the vapor barriers balance or decrease the hygroscopic asymmetries, reducing both the cupping and the state of internal stress. The new system is a compromise aiming to reduce the deformation and the induced stress in the support.
3. The behavior of the samples in the laboratory tests confirm the trend of deformation and the effect of the new crosspieces and of the buffer system. Moreover, they allow to split the hygroscopic warping from the mechanical one. This experimental observation is somehow new and it should be object of future investigations. This research can be integrated in preventive conservation initiatives [12].
The experimental apparatus (Dew Point Climate Generator [13], the Deformometric Kits [8,9]) and the test methodology (programmed climatic loops) prove to be effective, simple to implement and reproducible and suggest the principles for the definition of a technical protocol for the development and certification of techniques and materials for restoration and conservation as systems of vapor barriers and crossbars.

Acknowledgments

The Authors would like to warmly thank Alberto Finozzi, the conservator who restored the panel painting and who provided the laboratory samples used in this work.

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