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Original article

Strains in gesso on painted wood panels during humidity changes and cupping

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ABSTRACT

Strain gauges were attached to both faces of 10 mm thick Poplar wood panels before applying a traditional gesso-based ground layer and varnish on only one face. The application and setting of the ground layer left high strains on both faces of the wood panels. Later measurements, followed by geometrical calculations, showed that for step-humidity changes the strains in the outer surface of the gesso ground layers were small. These results were followed by numerical calculations to indicate the behaviour of thicker panels and with different stiffnesses. These indicated that the strain levels in the ground layer are strongly dependent on the ratio of the thicknesses of the ground layer to the wood, and also weakly dependent on their stiffness ratios. Further calculations showed that the prevention of cupping by mechanical restraint can increase by many times the strains in the ground layer surface, but this also is dependent on the panel thickness. In this paper, the authors have tried to provide some background information about the strains that can result either from moisture changes or from external restraints; to help the conservators make a decision in any specific case.

1. Research aims

This research is part of a study of the curvature, or 'cupping', of historical paintings on wood panels. A big problem with such a study is that there are known to be several causes of cupping, and in order to study each cause, care must be taken to isolate them in order to study and measure one at a time. The part of the study presented here aimed to isolate the contribution of the relative stiffnesses, and of the different expansion coefficients, of the wood panel and the surface layer which consists of gesso, canvas and glue; and the consequent effects of moisture changes that result in dimensional changes. This study provides an original insight into the mechanical functioning of the composite system formed by the wood and ground layers, and also provides rational basic information to be used by conservators of historic panel paintings having to design and implement new restraining frames for panels.

2. Introduction

Old paintings, especially those painted before about the end of the 16th century, were generally painted on wood panels. The traditional preparation of these wood panels was that the wood was well seasoned, smoothed, and then was coated with a grounding layer, which included a substantial coating of gesso, prior to the painting of the actual picture by the artist [1–3]. However, there were

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[1] Deceased author.

[2] It is with great regret that the co-authors announce the death of David Hunt on 16 October 2016. David was a lecturer and researcher at South Bank University (UK) until his retirement but remained active and productive until the end. In the past few years, he was associated with the University of Reading for a while and later became Visiting Researcher at the GESAAF Department of the University of Florence, pursuing his research interests. He was an engineer by training with expertise in the mechanical behaviour of wood. He was well-known for his work in mechanosorption and viscoelastic behaviour of wood, a topic he had researched and contributed to very significantly since the 1980's. Aged almost 86 he was still working on ageing of wood and on painted wood panels in collaboration with the Universities of Florence and Montpellier. Research over the years has resulted in a considerable number of scientific papers and an international reputation in the field; he was invited to be an external examiner for many PhD candidates in several countries. In addition to his scientific career, he has also worked during the last 20 years on translations and analysis of folk literature from the Caucasus Mountain Area. This has resulted in numerous papers, books and presentations at academic conferences, for which he was awarded an Honorary PhD by the State University of the Karachayevo-Cherkessian Republic, Russia. In spite of his academic achievements, David remained a modest and approachable person, willing to help students and colleagues. His family and all the friends he has made over the years will miss him. Reported by Joseph Gril, George Jeronimidis and Luca Uzielli.

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significant differences between the various geographical areas, periods and painting 'schools'.

It is well-known that with moisture changes wood swells and shrinks a substantial amount, especially perpendicular to the grain direction. Since the ground layer is stiffer than the wood and swells less in this transverse direction, the swelling and shrinkage of the wood results in curvature of the panel transverse to the grain direction, known as 'cupping'. There are several different mechanisms and aspects of cupping, some of which are described below.

When this cupping is observed, the observer naturally worries about its effect on the somewhat brittle layer of gesso and the valuable paint layer on its surface. Experience shows that tensile strains can result in cracking, whilst compressive strains can result in buckling and flaking of the surface [4].

If the ground layer is of poor quality (originally or as a result of anomalous events such as wetting), damage of the paint layers can occur even for smaller strains of the underlying wood. Recent research [5] speculated that the damage may also depend on the phenomenon of fatigue; i.e. over a long period the dimensional changes of the wood subject the ground layer and the paint layers to fatigue loading, which can lead to failure at lower strain levels than would be required for static loading. These strains are superimposed on the effects of phenomena related to aging, taking place in the paint and the ground layers.

2.1. Outline of the tests carried out and of related phenomena

In order to study the problems of cupping and damage, two experimental panels were produced according to the materials and techniques used during the Renaissance in Central Italy [1,6]. These were subjected to small-step-humidity changes accompanied by various measurements, including the monitoring of strains and dimensions. These measurements were then analysed and studied with the help of stress calculations.

2.2. Wood dimensional changes leading to cupping

Wood being a hygroscopic material, changes in the relative humidity (RH) of the surrounding environment lead to changes in its moisture content (MC), by a process of diffusion. Moisture diffuses into the unpainted back of a painted panel fairly easily and quickly, but it has also been found to diffuse through the ground layer surface fairly rapidly too [5,7], although surface layers of paint can make moisture penetration somewhat slower than through the wood. Any difference in the diffusion rates through the two surfaces can cause a temporary differential moisture gradient, which results in a time-dependent and mainly reversible cupping [8]; however, this paper only considers the steady-state cupping taking place after the moisture gradients have faded. Also, there are other causes of cupping, some of which are transient and some are more permanent.

Four of the other important causes of cupping are:

- 'aging' of the wood, resulting in a permanent (or perhaps semi-permanent) shrinkage of the exposed back [9];
- 'compression set' of the exposed back, resulting from accidental wetting and/or from numerous drying/moistening cycles [10];
- internal stresses between the hygroscopic wood panels and the relatively inert but stiff ground layer [11];
- the effects of the tree-ring orientation of the panel [12].

2.2.1. Aging of the exposed wood back

It has been found that moisture changes can eventually result in a permanent reduction in hygroscopicity of the wood, so that at any given level of RH the MC is lower than it was in the freshly-cut wood [9]. The loss of moisture results in smaller dimensions of the back-face region relative to the core region, which is likely to result in cupping of the panel.

2.2.2. Compression set

Compression set can follow after exposure to high humidity or wetting, and is caused by the stresses set up in the moist wood that is trying to expand, but is prevented by the resistance to swelling of the adjacent layer of wood that is still dry. Since wood at high moisture content creeps more than dry wood, the differential stresses result in a size reduction of the wetted and compressed layers, usually known as 'compression set'. A type of compression set can also result from regular RH cycling, since the resulting cyclic surface-moisture levels and their consequent internal tension-compression stress cycles mean that the compression stresses tend to coincide with the higher MC, with the result that the surface layers are compressed [13]. Compression set is part of a phenomenon in wood that is known as 'creep' and 'stress relaxation', and is known to be at least partly recoverable. Recovery takes place over a period of time, especially with reduced or zero stress, but can also be speeded up by a process known as 'mechanosorption', involving moisture content changes at reduced stress [14,15].

2.2.3. Stiffness of ground layer

The hygroscopic expansion and shrinkage of wood relative to the ground layer can lead to the temporary curvature of the composite panel, with high moisture environments leading towards a concave paint face and low moisture towards a convex paint face. If viscoelastic effects are ignored, this effect can be considered as reversible. If the wood and ground layer behaved in a purely elastic manner, this reversibility would be *quantitatively* true. Because of the rheology of the wood, the reversibility is only true *qualitatively*, but not quantitatively. However, the application of the ground layer can introduce a large amount of water, which if still in place after the ground layer has set hard, can result in a permanent convexity of the front face after the panel has returned to a normal environment if this is not prevented. This effect can be seen in the numerical data of Section 3 of this paper, and is likely to be more extreme in thinner wood supports such as the 10 mm panels used here. However, it was shown in [6] that with time the ground layer suffers a small permanent shrinkage as well as changes in other properties.

For older panels (roughly up to the 14th to 15th century) the wood face was traditionally covered with a layer of linen canvas, in order to protect the paint layer from defects in the wood and possible movement at joints. At later times, canvas was only applied on critical parts (e.g. joints and knots), or sometimes not at all. This was then covered with several layers of gesso, a mixture of gypsum and animal glue. The composition and properties of gesso are discussed in depth by Mecklenburg [6,16]. These properties included measurements of stiffness at various humidities and the effects of large humidity cycles on the stiffness and dimensions of various compositions of gesso. Some strength and stiffness properties of gesso were measured by Rachwal et al. [5].

2.2.4. Tree-ring orientation

Because wood swells and shrinks nearly twice as much in the tangential direction as in the radial direction, and also because of the curvature of the growth rings, wood panels always take on curvature (cupping) during moisture changes, unless the panels are cut with their width orientated perfectly radially. The greater the ring curvature, the greater the cupping [17].

3. Test materials and procedure

The test pieces consisted of two panels, designated 9A and 10A, of white Poplar (*Populus alba* L.) of nominal dimensions 85 mm in the longitudinal grain direction by 10 mm by 289 mm. The longest

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