A Parametric Analysis of Relative Humidity Effects on Traditional Panel Paintings

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ABSTRACT

A finite element analysis was performed on panel painting structures subjected to changes in relative humidity. Measured Young's modulus values and humidity expansion coefficients were used to define the properties of materials characteristic to northern and southern European panels. Models of northern panels simulated white oak with two layers of oil paint, while models of southern panels simulated cottonwood with gesso and two oil paint layers. In both cases, the properties of the oil paints were input for lead white and Naples yellow respectively. Influence of radial/tangential grain orientation, panel thickness, and structural support were investigated through various humidity changes. Results are presented in the form of stress in the wood, gesso, and paint layers as well as curvature of the painted surfaces. Methods of reducing panel curvature with structural support are discussed, which involve applying a frictionless cradle, wood battens, or verso gesso layer. Verification of the model was performed with a derivation of general stress equations for a cradled painting with no friction between the slider-bars and the panel. A comparison of derived and parametric results confirms accurate behavior of the model.

INTRODUCTION

Finite element analysis (FEA) is a powerful tool used in a wide range of mechanical and civil engineering applications. Software packages are specifically designed for structural mechanics as well as heat transfer and fluid mechanics. Little work has been performed with FEA on works of art due to the need for measured material properties. In the scientific analysis of art and archaeology objects, the use of FEA has largely been confined to the study of load distributions in historic buildings [1,2]. Years of research at the Smithsonian Center for Materials Research and Education (SCMRE) have provided the means for developing accurate finite element models of a wide range of artistic works. Material properties such as Young's modulus, thermal expansion coefficient, and moisture expansion coefficient are now defined for various woods, gesso formulations, oil paints, acrylic paints and many others. Mecklenburg [3] has described the method for determining the material properties required for finite element models. A previous analysis with this method has illustrated the stresses that develop in photographs and fabric supported paintings [4]. In this paper, the application of FEA has been extended to an investigation of relative humidity effects on panel paintings. The method for determining material properties and constructing computer models is identical to that shown in former work [2,3]. A brief description of the technique is presented here, and further background information is readily available from FEA and mechanics of materials texts [5,6,7].

The physical structure of a panel painting typically consists of a wood panel layered with gesso and paint layers, or solely paint layers. The difference in the moisture expansion coefficients between materials causes stress to develop between the layers. As relative humidity

(RH) increases or decreases, each material attempts to expand or shrink by an amount defined by the respective expansion coefficient. The presence of internal stress results in panel bending, which is generally viewed as unacceptable due to the change in aesthetic quality. In the past, a series of wood battens or a cradle system was commonly applied to the back face of panels to decrease warping [8]. Many examples of restrained panels have shown severe warping and cracking [9]. Richard D. Buck [10], a pioneer in the study of RH effects on panel paintings, questioned the use of cradling at a time when FEA was first being developed. The tools are now available to quantify the stresses in panels and identify damaging conditions. The following section describes the construction and testing of a parametric model, followed by an analysis of the stresses that develop in unsupported and restrained panel paintings.

EXPERIMENT

Building the Model

Prior to constructing a finite element model, the properties of each material were measured. Stiffness values and moisture expansion coefficients were obtained from experiments performed on artists' materials at the Smithsonian Institution. Wood behaves as an orthotropic material; therefore, each property was defined in the radial, tangential, and longitudinal directions. Paint and gesso layers are isotropic, and thereby possess only one stiffness value and moisture expansion coefficient. Table 1 lists the properties at different RH levels for each material used in the finite element models. The composition (by weight) of the clearcole gesso was 2:1:0.63 of rabbit skin glue (10% stock soln.), water and chalk respectively [11]. Naples yellow and lead white oil paints were made from cold-pressed linseed oil and all films were naturally aged.

Table 1 Material properties measured for the parametric models.

	Clearcole Gesso		Lead White (oil)		Naples Yellow (oil)		Cottonwood						White Oak					
RH	**Modulus**	**M. Exp. Coeff.**	**Modulus**	**M. Exp. Coeff.**	**Modulus**	**M. Exp. Coeff.**	**Modulus**			**Moisture Expansion Coefficient**			**Modulus**			**Moisture Expansion Coefficient**		
(%)	**(MPa)**	**(strain/ %RH)**	**(MPa)**	**(strain/ %RH)**	**(MPa)**	**(strain/ %RH)**	**(MPa)**			**(strain/%RH)**			**(MPa)**			**(strain/%RH)**		
							Long.	**Rad.**	**Tan.**	**Long.**	**Rad.**	**Tan.**	**Long.**	**Rad.**	**Tan.**	**Long.**	**Rad.**	**Tan.**
30	1035	1.0E-04	272	2.6E-05	303	2.57E-05	8962	440	240	1.0E-06	2.0E-04	4.0-04	12400	1735	785	1.0E-06	1.7E-04	3.5E-04
40			219		164			420	220					1680	730			
45			193		145			411	211					1652	702			
50			167		126			400	200					1625	675			
55			141		106			391	191					1597	647			
60			115		87			380	180					1559	609			
70			62		49			360	160					1504	554			

Temperature is another important factor that influences the properties of painting materials. The stiffness of each material increases with decreasing temperature, and thermal expansion has the same effect as moisture expansion in developing stress. That is, stress will occur in layered materials during temperature or RH changes due to differences in thermal expansion or moisture expansion coefficients. The materials will strain (by compression or expansion) until a balance of forces is reached if the degree of expansion is not equal in each layer. The scope of this analysis was exclusively the influence of RH fluctuations on panel paintings. Properties used in constructing the models were all determined at an ambient temperature of 21°C.

After defining the materials and their corresponding properties, the next stage involved constructing the geometry and boundary conditions using ANSYS™. Each layer of material was created using eight-node brick elements (solid45), which gave a linear strain and constant stress distribution between nodes. The length and width of the panels consisted of 100 elements, while the thickness of the wood, gesso, and paint layers were divided into 10, 4 and 2 element layers respectively. One face of the panel was defined as a plane of symmetry to decrease the computation time required by the software. The model was designed to simulate a small section of a larger panel painting. Figure 1 illustrates the layering of materials and specifies the dimensions used in the model.

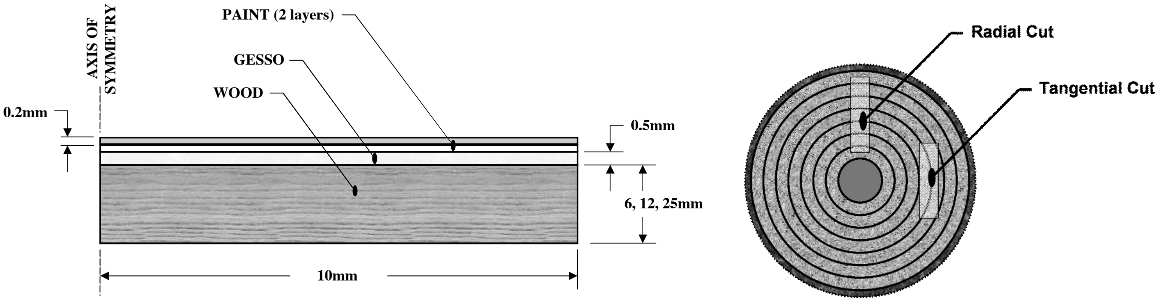

Figure 1 Panel geometry used in constructing finite element models.

Test Conditions

Mesh geometries were created for panels that were 6, 12 and 25mm thick, with and without the gesso layer present. This provided six models for entering different material properties. The flow chart in Figure 2 illustrates the conditions that were considered in the investigation. White oak and cottonwood were selected to represent typical panels in northern and southern Europe respectively. Each wood type was studied with consideration given to structural support, grain orientation, panel thickness and RH change. The number of combinations possible from the list of conditions was extremely large; therefore, only select cases were examined in depth. Models of greater complexity, involving rigid support on the back surface of panels, were studied after an extensive analysis of the conditions in Figure 2.

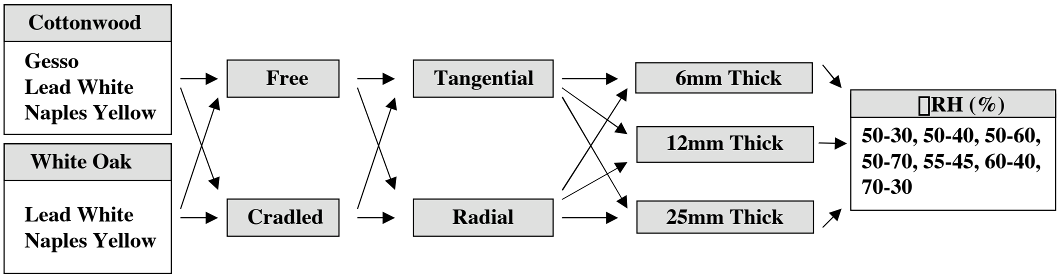

Figure 2 Flowchart of considered test conditions.

Model Verification

The parametric model was verified using two different methods. First, the model was constructed with only the wood layer present and was tested with a change in RH. A manual calculation of the expansion in each direction matched exactly with the displacement data output from the software. The second method was more laborious, which involved setting up a system of equations to solve the exact solution for a frictionless cradled panel with three interacting layers (wood and two oil paint films).

A frictionless cradled panel allows for the assumption of equivalent strains in each layer, which gives the pair of equations in Figure 3a. The subscripts 1, 2, and 3 refer to the white oak, lead white, and Naples yellow materials, while the axes x, y, and z refer to the longitudinal, tangential and radial directions respectively. A balance of forces provides two additional equations that are shown in Figure 3b. These forces are a result of the different expansion coefficients of each material. In the thickness direction, no force develops due to the free expansion of the panel. Summing the strains in each material for both the x and y directions gives the equations in Figure 3c. Each equation represents a sum of the strains caused by the primary stress in the specified direction, the effect of Poisson's ratio from the opposite stress, and the moisture expansion coefficient.

a. Equivalent Strains

$$\square_{x1} = \square_{x2} = \square_{x3}$$
$$\square_{y1} = \square_{y3} = \square_{y3}$$

b. Balance of Forces

$$\square_{y1}A_1 + \square_{y2}A_2 + \square_{y3}A_3 = 0$$
$$\square_{x1}A_1 + \square_{x2}A_2 + \square_{x3}A_3 = 0$$

c. Strain Equations (modified from Hooke's Law with thermal expansion)

$$\square_{x1} = \frac{\square_{x1}}{E_{x1}} \square \frac{\square\square_{y1}}{E_{y1}} + \square_{x1}\square RH \quad \square_{x2} = \frac{\square_{x2}}{E_2} \square \frac{\square\square_{y2}}{E_2} + \square_2\square RH \quad \square_{x3} = \frac{\square_3}{E_3} \square \frac{\square\square_{y3}}{E_3} + \square_3\square RH$$

$$\square_{y1} = \frac{\square_{y1}}{E_{y1}} \square \frac{\square\square_{x1}}{E_{x1}} + \square_{1y}\square RH \quad \square_{y2} = \frac{\square_{y2}}{E_2} \square \frac{\square\square_{x2}}{E_2} + \square_2\square RH \quad \square_{y3} = \frac{\square_{y3}}{E_3} \square \frac{\square\square_{x3}}{E_3} + \square_3\square RH$$

d. Symbol Definitions (considering a radial cut white oak panel with two oil layers)

$\square_{x1}$ - white oak strain, longitudinal direction
$\square_{x2}$ - lead white strain, longitudinal direction
$\square_{x3}$ - naples yellow strain, longitudinal direction
$\square_{y1}$ - white oak strain, tangential direction
$\square_{y2}$ - lead white strain, tangential direction
$\square_{y3}$ - naples yellow strain, tangential direction

E_{x1} - white oak modulus, longitudinal direction
E_{y1} - white oak modulus, tangential direction
E_2 - lead white modulus
E_3 - naples yellow modulus

A_1 - white oak cross-sectional area
A_2 - lead white oak cross-sectional area
A_3 - naples yellow cross-sectional area

$\square_{x1}$ - white oak stress, longitudinal direction
$\square_{x2}$ - lead white stress, longitudinal direction
$\square_{x3}$ - naples yellow stress, longitudinal direction
$\square_{y1}$ - white oak stress, tangential direction
$\square_{y2}$ - lead white stress, tangential direction
$\square_{y3}$ - naples yellow stress, tangential direction

$\square_{x1}$ - white oak moisture exp. coeff., long. dir.
$\square_{y1}$ - white oak moisture exp. coeff., tan. dir.
$\square_2$ - lead white moisture expansion coefficient
$\square_3$ - naples yellow moisture expansion coeff.

□ - poisson's ratio
□RH - change in RH

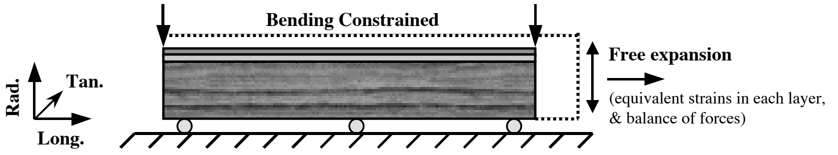

Figure 3 Equations for solving stresses in the frictionless cradled panel.

The 12 equations in Figure 3c, involving 12 variables, were solved using Maple™ 9.5 to give a general solution that was too large to present here. Four solved systems are compared with the finite element model solutions in Figures 4. In this case a 6mm thick, tangential cut, white oak panel was studied with two layers of oil paint over RH changes of 50-30%, 50-40%, 50-60%, and 50-70% RH.

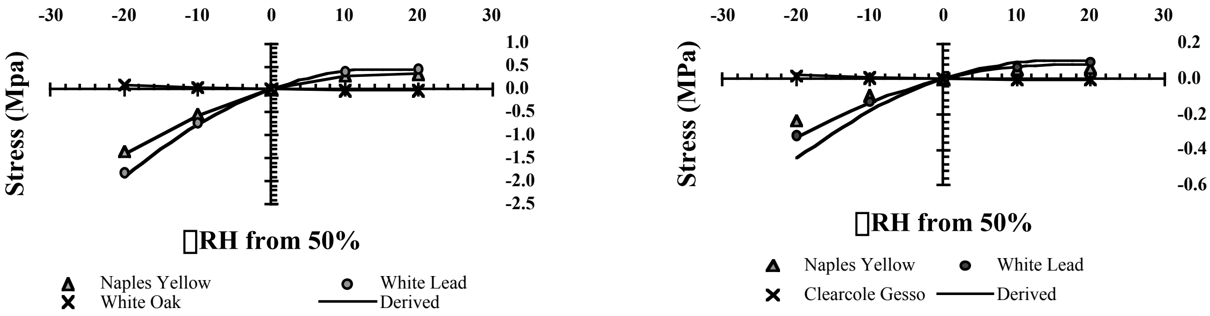

Figure 4 Finite element and derived stress solutions in tangential (left), and longitudinal (right) directions: white oak, 6mm thick, tangential cut.

RESULTS

Unrestrained and Frictionless Cradled Panels

The first investigated models were simple cases involving changes in grain orientation, panel thickness, and cradling. At this stage, the cradled panels were modeled for the ideal frictionless condition where the crossbars slide unhindered. Figure 5 summarizes the results for several geometries of white oak panels with no gesso present. In cases a, b and c the results were almost identical and the largest stress was approximately –1.5MPa (compressive) in the paint layers. Smaller stresses developed when the panel was radial cut as a result of the smaller coefficient of expansion in the radial direction of the wood layer.

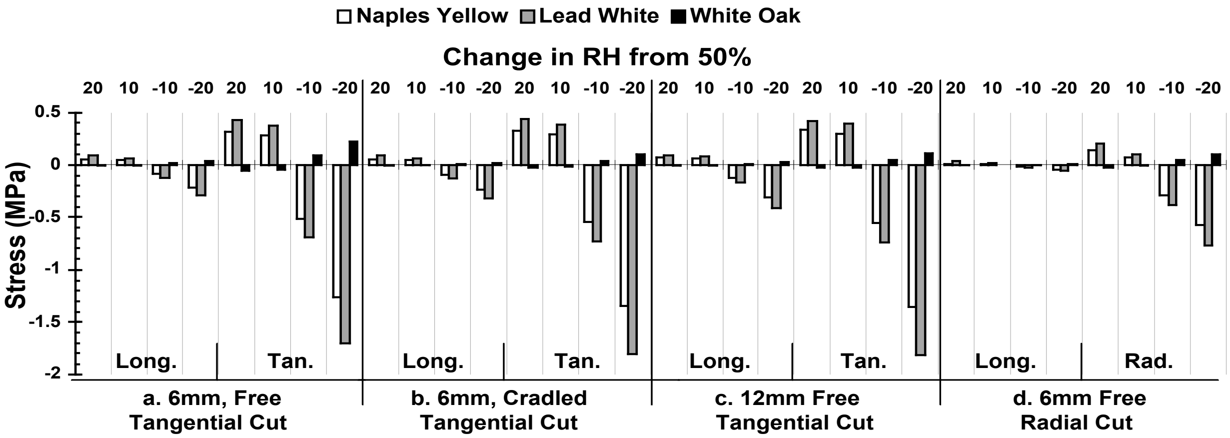

Figure 5 Stresses in white oak panel painting models.

Figure 6 summarizes data from the same set of conditions presented in Figure 5, except with cottonwood and clearcole gesso supporting the paint layers. The highest stress occurred in the gesso layer under each condition. Of all cases, straightening the panel with a cradle system caused the greatest increase in stress. The cradled system in Figure 6b shows tensile stresses of 4MPa, and –4MPa in the gesso (tangential direction) for RH changes of +20% and –20% respectively. The lowest overall stresses were evident in the 6mm thick panel that was radial cut. Increasing the thickness of the panel increased stress in the gesso layer, although not to the same extent as cradling.

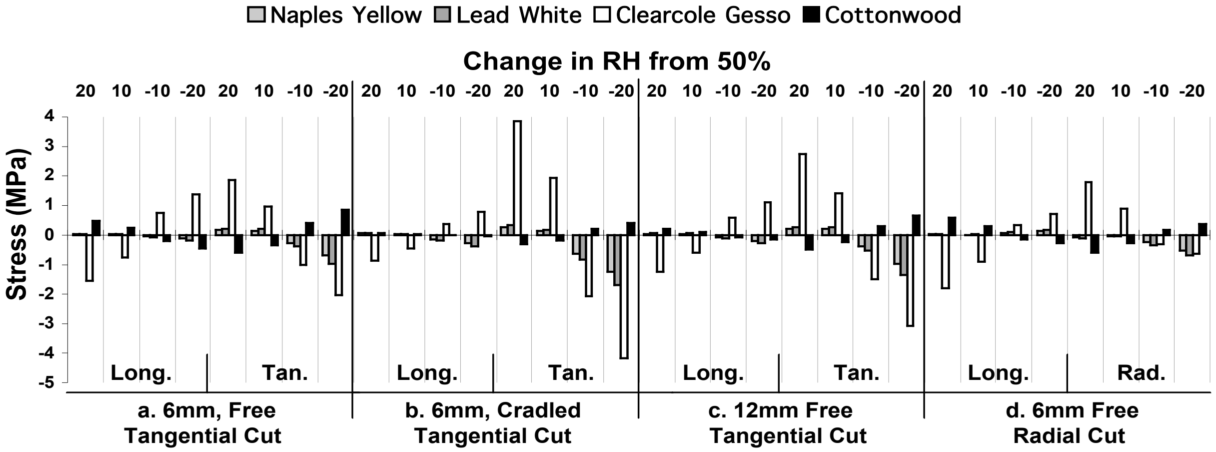

Figure 6 Stresses in cottonwood panel painting models.

The effect of the gesso layer on panel bending is shown in Figure 7 for a 6mm thick cottonwood panel. In Figure 7a, only the wood is present during a 20% decrease in RH and no bending occurs. With the gesso present, the panel bends convex in Figure 7b for an RH decrease, and concave in Figure 7c for an RH increase. Deflection of the panel results from the difference in moisture expansion coefficients between the wood and gesso. The large stiffness of the gesso increases the amount of bending due to its ability to restrain the swelling/expansion of the wood on the front face. The deflections in Figure 7 indicate that straightening a desiccated panel compresses the gesso layer, while straightening a moist panel applies tension. Together, Figures 5, 6, and 7 emphasize that panel paintings are sensitive to RH changes and stresses develop from the different expansion coefficients of the materials. The stress magnitudes were quite small in all of the investigated conditions.

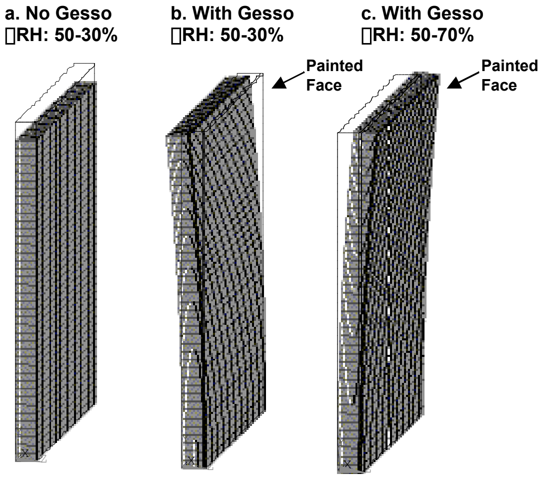

Figure 7 Bending of 6mm thick cottonwood panels during RH changes.

<u>Restrained Panels</u>

Restraining the dimensional changes of the wood increases the danger of material failure in a panel painting. This occurs if fixed battens are applied to the back surface, or a cradle system locks due to friction. A more advanced parametric analysis was performed on such support systems. Figure 8 shows a cottonwood panel (including gesso and paint layers) with a cradle applied to the back surface. Extreme bending occurred from the restraint imposed by the wooden support beam as the panel compensated for the immobile areas. Actual damage from a locked cradle, depicted in literature [9], matched exactly with that shown in Figure 8. The highest stress in the panel model was 25MPa where the back face of the panel and the batten intersect. The referenced photograph of a true panel shows cracks in this region.

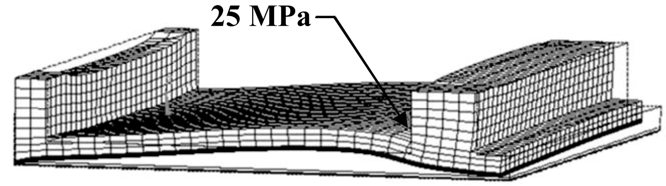

Figure 8 Cradled cottonwood panel, 6mm thick, with gesso.

Models were also constructed with battens added to the back of panels, which produced very high stresses in the wood. Stress levels were not as high as those caused by the fully seized cradle. Battens applied perpendicular to the grain restrained the deformation of the panel to a larger degree than the gesso on the front face. As a result, the panels bent in directions opposite to those shown in Figures 7b and 7c. In theory, a batten of the proper thickness will move the neutral axis to the center of the panel and produce a flat surface similar to Figure 7a. Figure 9 illustrates the out of plane deflection (left) and maximum stresses (right) of panels modeled with different depths of battens, compared to those with gesso on the back face. Gesso was added to the back of a panel model as a method for distributing support across the entire surface, similar to the layering on the front face.

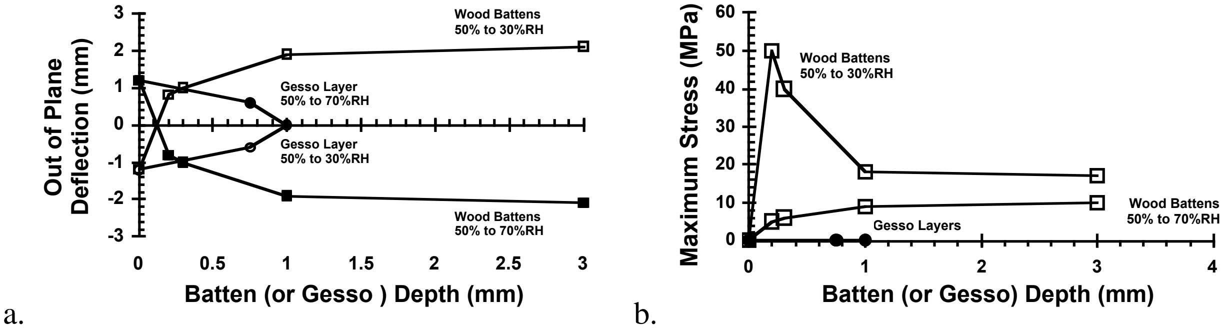

Figure 9 Effect of battens and a reverse gesso layer on **a.** panel deflection and **b.** maximum stress. 6mm thick, radial cut, cottonwood with clearcole gesso.

The plot of out of plane deflection in Figure 9a shows that a batten depth of 0.15mm, or back-face gesso thickness of 1mm, provides a flat surface for a 6mm thick cottonwood panel with 1mm thick front-face gesso and two paint layers. A comparison of stresses in Figure 9b indicates that a gesso layer applied to the back face of a panel painting produces much lower stress levels than battens.

CONCLUSIONS

Models of tangential cut white oak panels (without gesso) exposed to a wide range of RH values resulted in low stresses in the paint layers and very low stress in the wood layer. The models of tangential cut cottonwood panels (with gesso) showed higher stresses in the gesso layer and increased bending. The stresses were further increased by the frictionless cradle system, and increased panel thickness. The lower expansion coefficient in the radial direction of the wood caused lower stress levels when the panel was modeled with the properties of radial cut wood.

Panel models containing battens perpendicular to the grain, and also locked cradles, showed extremely high stresses that were past the fracture level of the wood. The deformed shape and the location of maximum stress correlated with a true case illustrated in literature. Careful selection of the batten or gesso thickness on the back face of a panel results in a flat surface profile. An overly thick batten produced reverse warping to that caused by the front gesso layer. Decreased warping with minimum stress was obtained by applying a 1mm thick layer of gesso to the back face of a 6mm thick cottonwood panel.

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