COMPUTER MODELING OF THE EFFECTS OF TEMPERATURE AND RELATIVE HUMIDITY ON STRESSES IN THE LAYERS OF CULTURAL MATERIALS.

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Mechanical Properties of Artists' Materials Under Long-term Conditions

Paintings are composite structures with organic coatings in layers. Typically, a painting has a stretched canvas layer coated with a rabbit skin glue layer or size. Over the glue are highly pigmented oil paint layers including the ground and the design layers. The response of these coatings to the environment is of considerable interest to museums if the long term care of the collections is to be addressed. Change in the ambient environment can be a result of transporting a painting or simply a lack of environmental control in the museum. If one is to examine the environment's role on the structural behavior of these materials, it is necessary to determine the appropriate mechanical and dimensional properties. Because the time required for artists' materials to equilibrate with new environments is relatively long, the mechanical properties of artists' materials must be examined under long-term conditions. Paintings can hang on a gallery wall for years before being moved to another location. Under these circumstances it is most probable that a painting will have equilibrated to the mean ambient environment of its location. It is the long term mechanical properties and their response to environmental changes that are of interest to art museums.

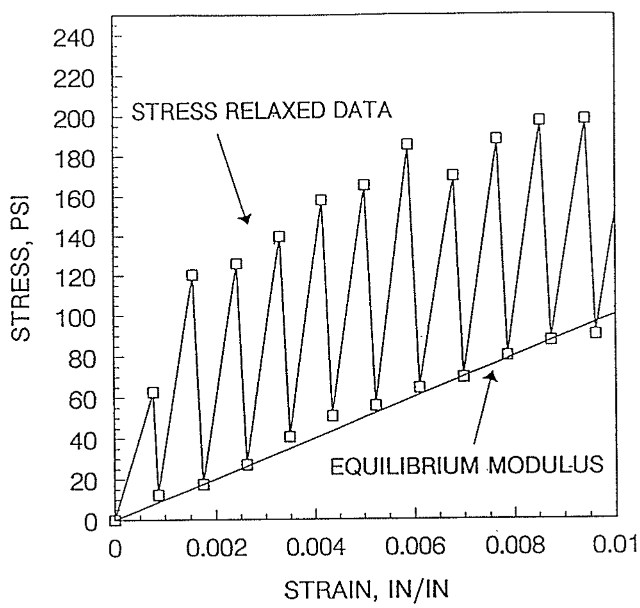

Fig. 1. The determination of the equilibrium modulus for Naples yellow oil paint.

Mechanical Test Procedure

Several artists materials, including oil paints, hide glues and textiles were mechanically tested under long-term loading conditions. [1] All of the paints tested were cast in March 1978 and tested in 1991 as free, unsupported films. The tests were conducted by applying a small strain to the test sample, about .007, and allowing it to stress relax fully. Once full stress relaxation was attained, a subsequent increment of strain was applied and the stress was allowed to relax fully again (Figure 1).

The time to relax fully the paints was typically between five and ten days, depending on the paint. This process was repeated until the specimen broke and its strength was recorded. The test procedure took several months to be completed. Typically, three samples were tested to check for consistency of results. The modulus (E) was determined by taking the slope of the locus of relaxed points from the equilibrium test. In this case, for Naples yellow, a tinted lead carbonate oil paint, the modulus was 10,000 pounds per square inch (10 ksi), (68.9 Mega-pascals (MPa)) at 23°C, 50% RH. This is only about one-tenth of the modulus of the same material when tested rapidly in the same environment. The strength of the paint at this environment is only about .18 ksi (1.24 MPa).

Temperature Effects

In general, if the thermal coefficient of expansion and the equilibrium modulus of a material is known, the stress levels resulting in cooling a restrained material can be predicted. The method of calculating this stress increase can be derived directly from the basic equation 1, relating stress to strain; $E = \sigma/\epsilon$ Eq. 1

where; E is the elastic modulus, σ is the stress in the sample and ϵ is the strain of the sample. Equation 1 can be rewritten as:

$$\sigma = E \times \epsilon. \quad \text{Eq. 2}$$

To include the temperature effects, it must be recognized that both the modulus, E, and the strain, ϵ, are functions of temperature and therefore: $\sigma(T) = E(T) \times \epsilon(T)$ Eq. 3

where T represents temperature.

The equilibrium modulus for Naples yellow was measured at 23°C, 5% RH to be 47.5 ksi (327 MPa) and at -3°C, 5% RH it was found to be 150 ksi (1,034 MPa). It was assumed that E varies linearly over this temperature range and a linear function for E(T) was fitted and stated as:

$$E(T) = 138.5 - 3.8(T) \quad \text{Eq. 4}$$

where the units are ksi for the modulus and temperature is in degrees Celsius. It can be shown that for a restrained material, the strains resulting from cooling are:

$$\epsilon(T) = -(\gamma \times \Delta T)/(1 + \gamma \times \Delta T). \quad \text{Eq. 5}$$

where: ΔT is the change in temperature and, γ is the thermal coefficient if expansion. The negative sign indicates that positive tensile strains are resulting cooling. The thermal coefficient of expansion for the Naples yellow was measured as γ=.000052. The stresses for a fully restrained specimen are now the product of Equations 4 and 5. Experimentally, it is not easy to measure the stress of a "fully" restrained specimen since the "load cell," the device that measures the stresses, is "compliant", meaning the cell "gives" a bit as force is applied. This load cell compliance effectively relieves some of the restraint on the specimen and the stresses measured are actually less than if fully restrained. This compliance can, however, be included in the calculations that allow the prediction of the behavior of the specimen subjected to restrained temperature changes. The compliance of the test device is a function of the total force and is measured during the test of the specimen. The value of the compliance, measured in units of length, is the raw data output, AO, times a compliance constant, KD. KD is determined for each load cell. It is now possible to correct for the compliance of the load cell and calculate the expected stresses in the experimental restrained test where:

$$\sigma(T) = E(T) \times (\epsilon(T) - AO \times KD/L_T) \quad \text{Eq. 6}$$

Where; L_T is the free length of the specimen at the specified temperature. The results of this calculation are presented in Figure 2 as the lower continuous line. Also on that figure is the actual test data (squares) for the Naples yellow paint. There is a substantial correlation between the predicted and the actual measured stress levels at the different temperatures while the relative humidity is held at 5%. Also in Figure 2 is the data (crosses) for restrained rabbit skin glue. If, as before, the modulus is assumed to vary linearly with temperature, then a prediction for all of the temperature-related stresses is possible. This is shown on Figure 2 as the solid line overlaying the rabbit skin test data.

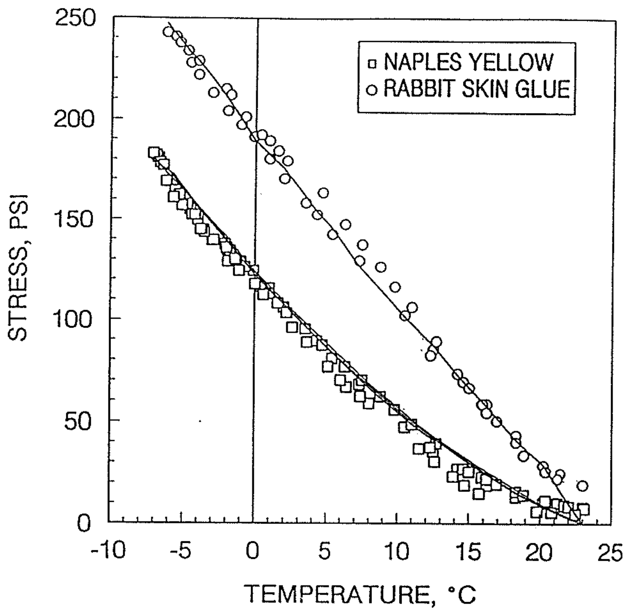

Figure 2. Stress resulting from the restrained cooling of Naples yellow oil paint and rabbit skin glue.

Relative Humidity Effects

The effects of relative humidity on the artists' materials are analogous to those of temperature. Stress development in restrained materials subjected to desiccation can be treated in a manner similar to those subjected to decreases in temperature. The mathematics for relative humidity behavior would be: $\sigma(RH) = E(RH) \times \epsilon(RH)$ Eq. 7
where; $\epsilon(RH) = -(\alpha \times \Delta RH)/(1 + \alpha \times \Delta RH)$ Eq. 8
and ΔRH is the change in relative humidity,
with α the "moisture" coefficient of expansion.

Two paints, Naples yellow and flake white were restrained at 66% RH and 23°C, and desiccated to 5% RH. Using equation 7 (corrected for load cell compliance), it was possible to calculate the expected stresses. The measured value, α_s = .0000257 was used for both the Naples yellow and the flake white. The equations for the modulus of the materials were:
for Naples yellow, E(RH) = 51.8 - .85(RH) and
for flake white, E(RH) = 63.9 - .85(RH), where the units are in ksi and percent relative humidity. The results of the calculations are shown in Figure 3 as the solid lines passing through the data points. The test data stresses are only about 15% less than that expected if the specimens were fully restrained. The magnitude of stress reached for the Naples yellow, (.066 ksi (.455 MPa)), at a desiccation from 66% RH to 5% RH, is considerably less than that reached (.185 ksi (1.27 MPa)), when cooled from 23°C to -3°C.

While the paints are not so responsive to changes in relative humidity, the rabbit skin glue is extraordinarily so. Figure 4 plots (symbols) the results of restrained desiccation tests where the initial restraint was at 72%, 50%, and 30% RH. The continuous lines are the plots of a single mathematical function derived as described above. These stresses are extremely high and this glue layer is the source of much RH related damage in paintings.

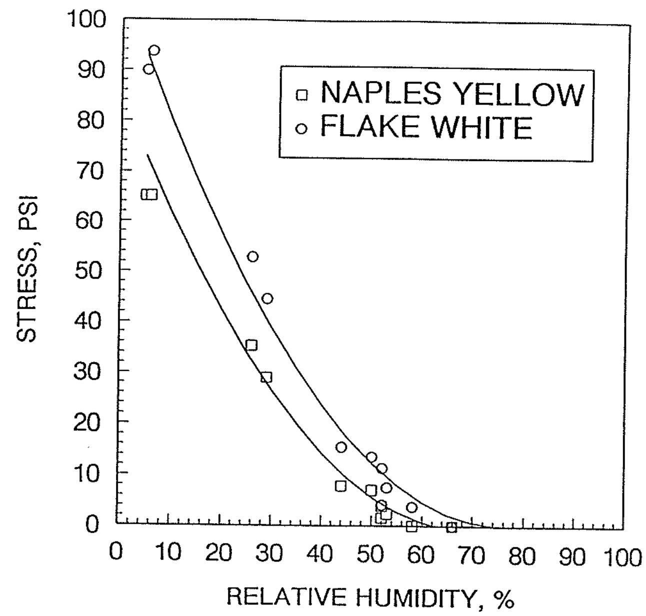

Fig. 3 Stresses resulting from the restrained desiccation of artists' oil paints.

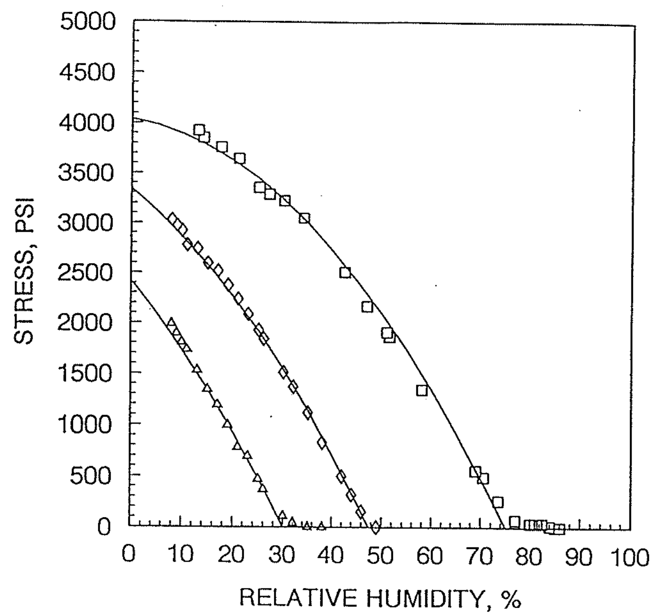

Fig. 4. Stresses resulting from the restrained desiccation of rabbit skin glue.

While traditional paintings have linen fabric supports, this textile has very little effect on the other layers of the structure during desiccation or cooling of the painting. Some fabrics only have a significant influence if the RH gets above 85%. The fabric layer was, however, included in all computer analysis.

Computer Modeling

Once the mechanical and dimensional properties of the materials are established, a structural analysis of a painting's response to environmental changes can be conducted using Finite Element Analysis (FEA) software on a standard PC. This is possible by programming the material's thermal and moisture coefficients as well as the modulus' E(T) and E(RH) which are functions of temperature and relative humidity respectively. The program used is this study was Ansys version 4.4a on a 80386 PC with 4 megabytes of ram and a 150 megabyte disk drive.

A 30 x 40 in. (76 x 102 cm) sample painting having a medium weight linen fabric, a .002 in. (.0058 cm) glue layer and a .003 in. (.0076 cm) Naples yellow paint layer was modeled and subjected to temperature changes. The linen was modeled as a layer .025 in. (.015 cm) thick layer. The painting was initialized at 5% RH. The temperature was changed from 23°C to -3°C. The results, Figure 5, showed that the paint film stresses were uniform in magnitude and exceeded the fully restrained breaking strength of the paint, around .250 ksi (1.72 MPa).

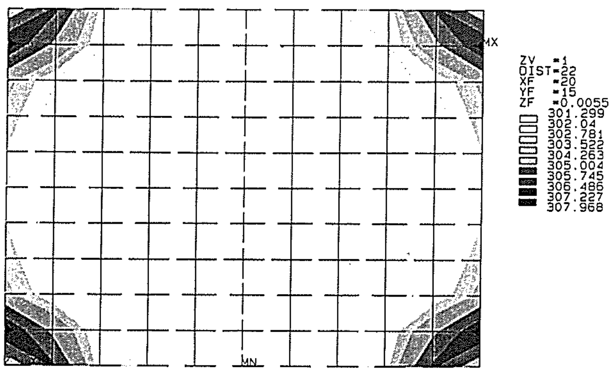

Fig. 5. The computed paint stress magnitude resulting from the cooling of a model painting.

The computed direction of the stresses allowed the prediction of the crack pattern as shown in figure 6.

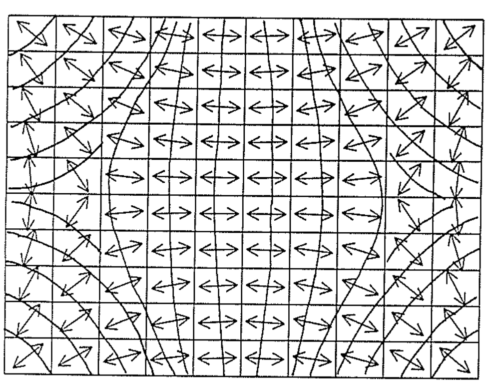

Fig. 6. The stress directions and crack prediction from cooling a model painting.

This pattern is found in American paintings quite frequently. It is important to recognize that the paint film itself in response to the temperature change is failing. If the same painting is subjected to a change in relative humidity from 70% to 10% at 23°C, the stresses in the paint film reach a maximum of .117 ksi (.8 MPa) only at the corners. The central part of the painting has relatively low stresses. In the presence of a thicker glue layer, twice as large as before, the paint film stresses increased to .28 ksi (1.9 MPa) with the same environmental change. Again the high stresses are confined to the corners and should failure occur, the predicted crack pattern is as shown in figure 6. This occurs on a large proportion of paintings and is more common than the crack pattern seen due to temperature changes. In America, many commercially prepared artist's canvases had poor quality canvases and thick glue layers.

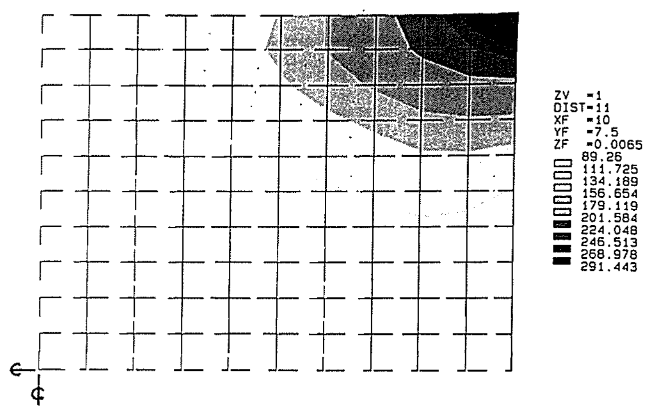

Fig. 7. The computed paint stress magnitude resulting from the desiccation of a model painting.

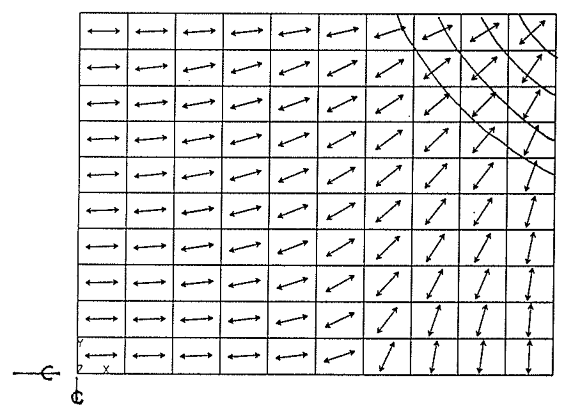

Fig. 8. The stress directions and crack prediction from desiccation a model painting.

Summary

The computer model helps define the different effects of temperature and relative humidity on paintings. It also helps explain the role of the different layers when responding to environmental changes. The oil paint layers are particularly susceptible to drops in temperature while the glue layer is susceptible to drops in relative humidity and responsible for cracking the overlaying paint layers.

Footnotes

1. M.F.Mecklenburg and C.S.Tumosa, "Mechanical Behavior of Paintings Subjected to Changes in Temperature and Relative Humidity," Art in Transit: Studies in the Transport of Paintings, M.F.Mecklenburg, ed., National Gallery of Art, Washington (1991) 173-216.