19147

Structural Response of Painted Wood Surfaces to Changes in Ambient Relative Humidity

Marion F. Mecklenburg, Charles S. Tumosa, and David Erhardt

Fluctuations in ambient relative humidity (RH) produce changes in the materials that make up painted wood objects, altering their dimensions and affecting their mechanical properties. The use of wood as a substrate for paint materials presents a particular problem. In the direction parallel to the grain of a wood substrate, applied paint materials are considered to be nearly fully restrained because wood's longitudinal dimension remains essentially unchanged by fluctuations in relative humidity. In the direction across the grain, however, moisture-related movement of an unrestrained wood substrate may completely override the less responsive paint layers. In this situation, stresses induced in the ground and paint layers due to changes in RH are completely opposite to the stresses parallel to the grain.

To quantify the effects of RH fluctuations on painted wooden objects, tests were conducted to determine the individual swelling responses of materials such as wood, glue, gesso, and oil paints to a range of relative humidities. By relating the differing swelling rates of response for these materials at various levels of RH, it becomes possible to determine the RH fluctuations a painted object might endure without experiencing irreversible deformation or actual failure (cracking, cleavage, paint loss) in the painted design layer.

Painted wooden objects are composite structures. They may incorporate varying species of wood, hide glues, gesso composed of glue and gypsum (calcium sulfate) or chalk (calcium carbonate), and different types of paints and resin varnishes. Paint media can include wax, egg tempera, oils, and combinations of these. These materials have differing mechanical properties and varying responses to moisture fluctuations. Painted wood surfaces also vary in complexity. The simplest consist of paint applied directly to wood, but more complex examples, such as early Italian panel paintings in tempera, may have a layer of fabric glued to the wood, a gesso ground to produce a smooth painting surface, paint applied above the gesso, and a clear varnish.

For the past four centuries, oil paint, rather than tempera, has been the most commonly used pigmented coating for wood. Therefore, oil paint on a wood substrate will serve as the focus of this chapter. Hide glue and gesso—materials with distinctive mechanical behavior—will also be included, since they are often incorporated into painted wooden objects. Properties of the individual materials will be discussed here first, followed by aspects of the painted wooden object as a composite structure.

Regarding the effect of RH fluctuations on painted wooden objects, there are three basic conditions of concern. The first, a common construction problem, is built-in restraint that prevents joined wood from naturally swelling and shrinking across its grain in response to RH fluctuations. A variation of this occurs when wood acts as its own restraint (uneven moisture penetration can induce strain into both the dry and wet regions of otherwise unrestrained wood). A second condition of concern is restraint placed on the paint (and any other components of the design layer) by the wooden substrate in the direction parallel to the wood grain (the longitudinal direction). A third and equally important condition involves the RH response of the design layer itself in the direction perpendicular to the grain of an unrestrained substrate. Here, differences in the rate of response of the various materials to changes in ambient RH become especially significant. The following examines these three conditions and identifies the worst cases.

The Wood Support

Over the centuries, many species of wood have been used as paint substrates, with each geographic region favoring certain woods for reasons of fashion, ease of use, and availability. For example, painters from northern Germany and Holland preferred oak while those in southern Germany favored such woods as pine, fir, larch, linden, and ash. In Italy, poplar and cypress were used. American woods, such as cottonwood and mahogany, were imported into Europe for use as supports (Doerner 1962).

Wood responds to moisture by swelling and shrinking with increases and decreases in ambient RH. But wood is anisotropic, meaning that moisture-related dimensional changes vary in its three principal axes—longitudinal (parallel to the grain), radial, and tangential (see Hoadley herein). The most pronounced moisture response is in the tangential direction, where wood may swell up to eighty times as much as in its negligibly responsive longitudinal direction. In the radial direction, wood swells about half as much as it does tangentially (*Wood Handbook* 1974).

If restrained during changes in relative humidity, wood can develop high stresses and strains. If the change in environmental moisture is extreme, the wood may be plastically (permanently) deformed, a condition that can lead to cracking. How much change in relative humidity is necessary to bring about plastic deformation and failure in fully restrained wood and paint materials? The following sections outline experimentation and analysis designed to answer this question.

Mechanical Testing of Woods

Recent research into the response of wood to changes in RH examined the cross-grain mechanical properties of tangentially sawn wood samples of several species (Mecklenburg, Tumosa, and McCormick-Goodhart 1995). Using this testing program, the yield point (the amount of strain necessary to produce permanent plastic deformation) and strength (the amount of stress necessary to cause breakage) of each wood sample could be established. Figure 1a, b shows the stress-strain plots of different samples of cottonwood and white oak, tested at a range of relative humidities. The samples were all incrementally loaded across the grain, and tests were conducted allowing 30 seconds of stress relaxation at each loading point. In this way, time-dependent variations in behavior were greatly reduced. Disparities in the starting points of the tests reflect changes in cross-grain

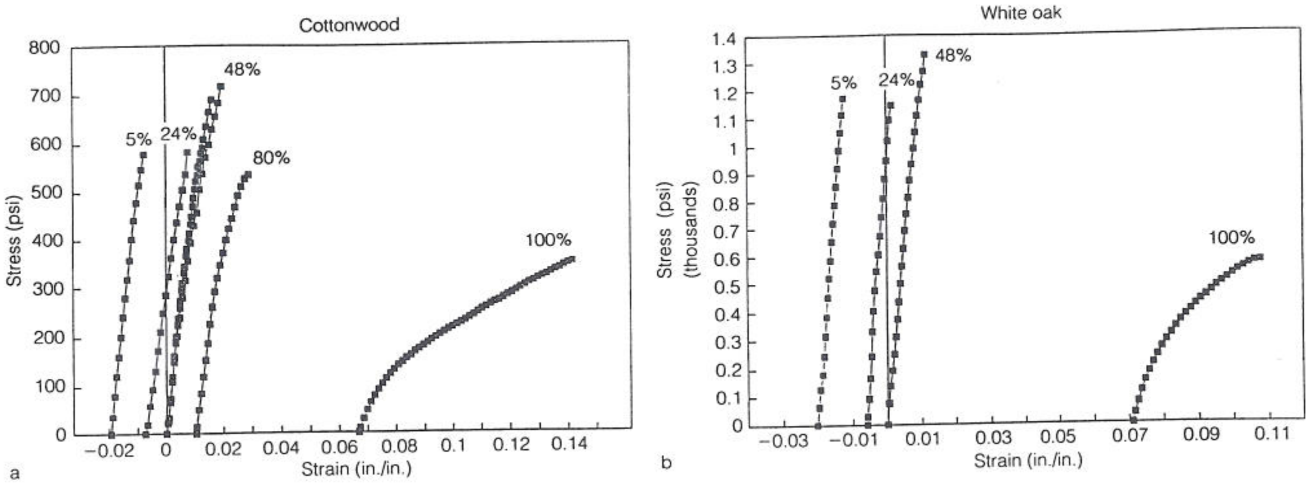


Figure 1a, b

The stress-strain curves for cottonwood (a) and white oak (b), tested at various relative humidities. The space between each plotted test relates to stress-free dimensional change in the sample when the ambient RH is raised or lowered.

dimension, due solely to RH-dependent differences in the moisture content of the wood. The test temperature was approximately 22 °C in all cases. The strengths of the woods are the stresses noted at failure—the end point of each test. Cottonwood, white oak, and American mahogany are strongest at around 50% RH. White oak has the highest strength at around 1340 pounds per square inch (psi).[1]

The amount of strain required to go beyond the elastic (reversible) region to the plastic (irreversible) region can be determined by unloading the specimen at different strain intervals. Testing shows that the yield point of most polymers, including wood, is about 0.004. Figure 2 shows that cottonwood has an initial yield point of 0.004 but, when strain-hardened, it stretches farther.

Environmentally Induced Strains

One can easily recognize that if a hygroscopic material is restrained and desiccated it will experience an increase in stress. What is not so evident is that there is an increase in strain. Too often strain is associated with external deformation when, in fact, no external movement is necessary for strain to occur. Consider a hygroscopic specimen that is allowed to shrink freely from an initial length (L_i) to a final length (L_f) when desiccated from a high relative humidity (RH_h) to a low relative humidity (RH_l). If, under

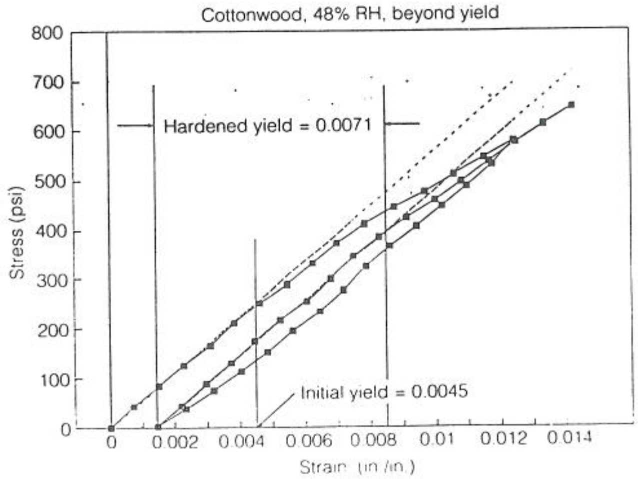


Figure 2

The stress-strain plot of cottonwood that is loaded beyond its yield point of 0.0045 at around 48% RH. After unloading, this specimen exhibits a plastic deformation strain of approximately 0.0014. Reloading indicates an increased yield point of 0.0071.

equilibrium conditions, the specimen is now stretched back to its original length (L_i) it will clearly undergo an increase in stress and strain. It is, however, at the lower relative humidity (RH_l). This new state of stress, strain, and relative humidity is no different from that of a specimen restrained at L_i and RH_h, then desiccated to RH_l without being allowed to shrink (Mecklenburg and Tumosa 1991). The specimens reach identical states following the two different experiments, ending with the same cross-grain dimension and the same relative humidity. The restrained test specimen does not exhibit dimensional change, although it was subjected to an increase in strain. Now it is necessary to determine the amount of change in RH that will cause strains approaching the yield point when a material is fully restrained. If the yield point is not exceeded, then a fully restrained specimen may be subjected without damage to strain induced by variations in RH.

The Swelling Isotherm and the Moisture Coefficient of Expansion

The amount a material swells or shrinks can be expressed as strain (a ratio of the dimensional change of the material to its initial dimension) versus RH. This simply entails holding the temperature constant, measuring the cross-grain dimension (L_{RH}) of a specimen at different RH levels, then establishing an initialized length (L_O), usually the dry length. The strain (ϵ) is calculated as

$$\epsilon = (L_{RH} - L_O)/\ L_O \tag{1}$$

This form of displaying the dimensional response of a material to changes in moisture is useful in relating dimensional properties to mechanical properties of materials. Figure 3a shows the swelling isotherm (at 22 °C) of cottonwood in the tangential direction. This plot shows significant dimensional response to moisture at the extremes of the RH scale and relatively little response to moisture in the region bounded by 30% and 70% RH. The implications are that moisture changes will have the greatest structural effect at extreme low and high RH levels and the least effect in the central RH regions.

It is necessary to determine the allowable RH fluctuations for cottonwood in any ambient RH environment: the RH changes that will not strain the wood beyond its yield point. To do this, one may use the swelling isotherm and simply measure the change in RH that will cause a strain no greater than 0.004 inch (0.01 cm) of dimensional change per inch of initial dimension (the yield point for cottonwood determined in Figure 2). Alternatively, one may determine the rates of dimensional change (d) experienced by a material across the entire range of RH from a polynomial fit of the swelling data. These rates, hereafter known as moisture coefficients of expansion (α) are calculated as

$$\alpha = d\epsilon/d\mathrm{RH} \tag{2}$$

The moisture coefficients of expansion for cottonwood are plotted in Figure 3b. Most texts on the swelling of wood report the moisture coefficient as a constant, but Figure 3b demonstrates that this is not the case. This figure also shows that the lowest values of the coefficient of expansion correspond to the flattest portion of the swelling isotherm, namely from 30% to 70% RH.

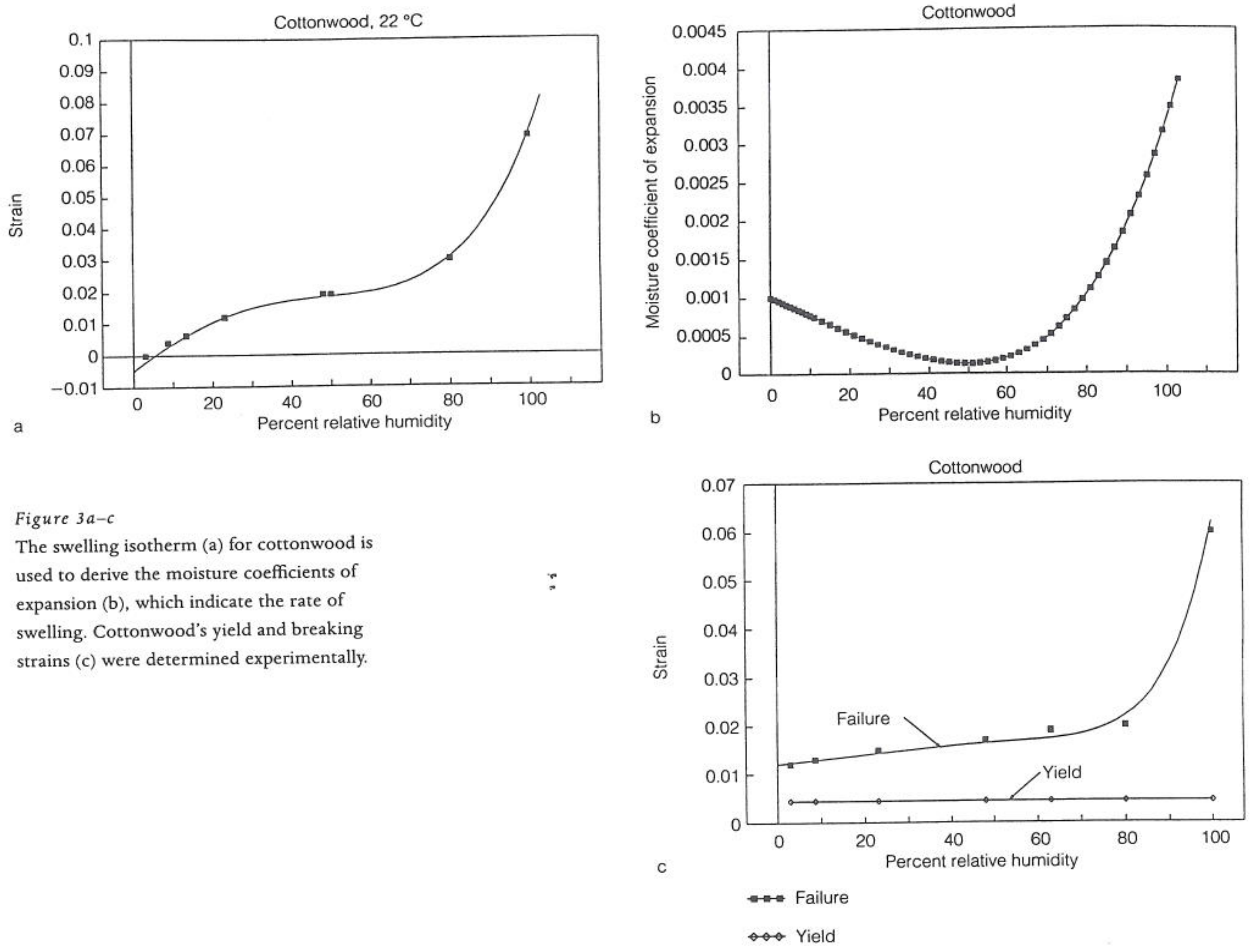


Figure 3a–c
The swelling isotherm (a) for cottonwood is used to derive the moisture coefficients of expansion (b), which indicate the rate of swelling. Cottonwood's yield and breaking strains (c) were determined experimentally.

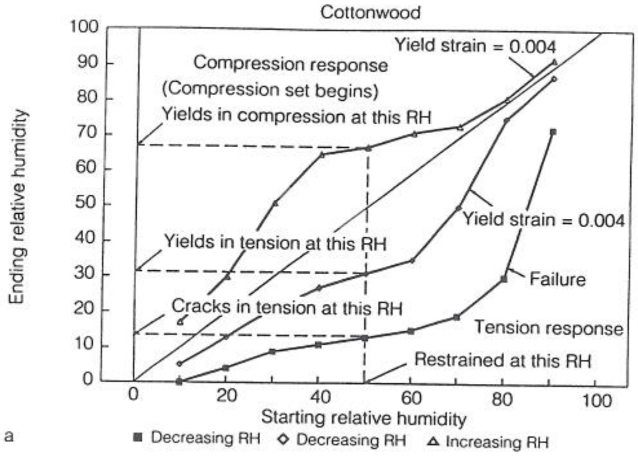
Using equation 2, the strain change ($\Delta\epsilon$) for any RH change can be calculated as

$$\Delta\epsilon = \int \alpha \, d\mathrm{RH} \tag{3}$$

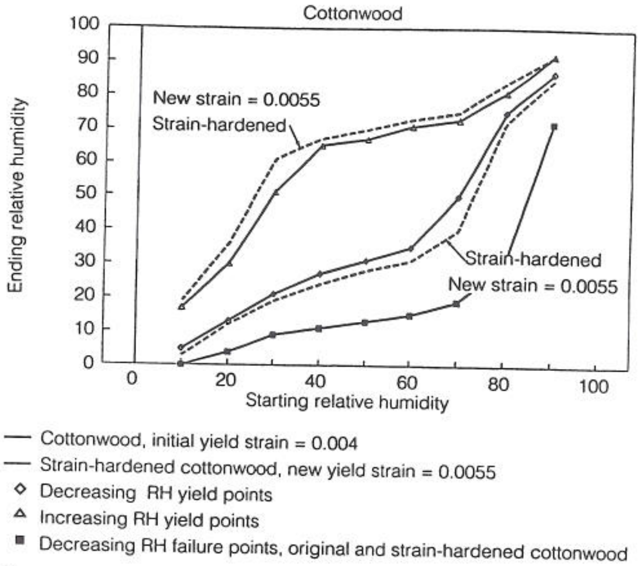
where $\alpha = d\epsilon/d\mathrm{RH}$.

To determine the effect of a given strain change on cottonwood, one must know the wood's yield point and the amount of strain necessary to cause it to break. These values are determined experimentally and are shown in Figure 3c. The yield point for new cottonwood is about 0.004 at all RH levels, and its breaking strains increase with increasing RH.

Integrating equation 3 allows one to determine the change in RH that will produce a particular change in strain. One assumes a starting RH of 50% and integrates to another RH level associated with the strain change in question. In the case of cottonwood in the tangential direction, at 50% RH the yielding strain is 0.004, and the breaking strain is 0.017 (Fig. 3c). The associated RH changes required to induce these strains for a sample of cottonwood restrained in the tangential direction (Fig. 4a) are from 50% to 30% RH for yielding in tension, 50% to 67% for yielding in compression, and 50% to 14% for complete failure in tension. No line for complete compression failure is shown in Figure 4a, as compression failures take different forms, from the crushing of the cell walls to buckling



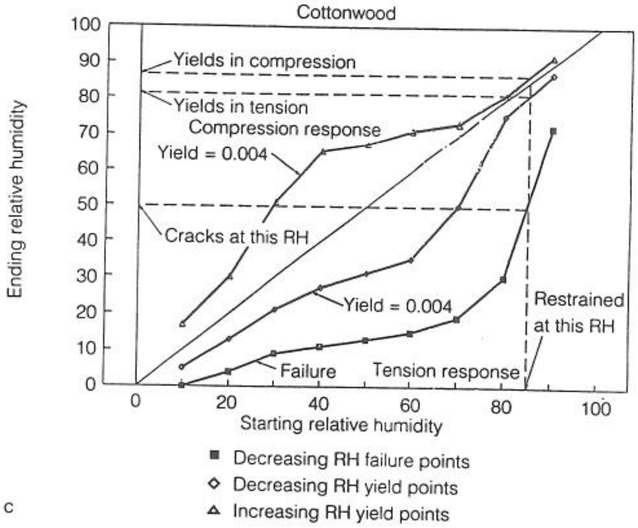
a



b

Figure 4a–c

The domain of allowable RH fluctuations (a) for cottonwood fully restrained in its tangential direction. Yield lines represent the upper and lower limits of RH change at any given ambient RH, with permanent wood deformation occurring beyond these limits. If an RH fluctuation extends below the line of failure, the wood will break. Dashed lines illustrate the effects of strain hardening (b): since the yield point is increased, the domain of allowable RH fluctuations is enlarged. The effects of compression set (c) on tangentially-restrained cottonwood. When wood is reinitialized to a high RH—in this case, 85%—minimal desiccation produces tensile yielding. The wood is likely to crack if desiccated below 50% RH.



c

of the panel itself. Buckling is influenced by the geometry (thickness) and restraint (boundary conditions) of the panel.

Allowable RH Fluctuations

Figure 4a effectively establishes the allowable RH fluctuations cottonwood restrained in the tangential direction may sustain without damage. The tension and compression yield lines set the RH limits (ending RH) from which the ambient RH (starting or equilibrium RH) can deviate. The area between these lines can be viewed as the allowable RH zone. Since the data relate to the wood's tangential direction, this represents the worst-case condition for cottonwood. If the wood were tested in the radial direction, the allowable RH fluctuations would be greater. This is because the yield point is still at least 0.004, but the moisture response of cottonwood in the radial direction is about half that in its tangential direction.

If the wood were wholly unrestrained, Figure 4a would not be pertinent, but in real-world conditions one assumes there is restraint. Restraint may result from basic construction techniques (e.g., wood components are often securely joined with grains mutually perpendicular). Bulk wood also experiences internal restraint when the exterior responds more quickly than the interior to an RH change. Battens and locked cradles on the backs of panels restrain them from freely expanding and contracting. Even under the worst structural circumstances, however, the tests indicate that cottonwood can endure significant RH fluctuations if the ambient RH is centered between 35% and 60%. At higher or lower RH the allowable fluctuations are dramatically reduced. Cottonwood forced beyond the allowable range will experience yielding. If the excursion is severe enough, it is possible that the material cannot return to the central zone without breaking.

If the wood has been strain-hardened, which is probably the case for all old woods, the RH change required to reach the yield point increases. Figure 4b shows the plots for tension and compression when the yield points have increased from 0.004 (solid lines) to 0.0055 (dashed lines). In effect, the allowable elastic or reversible RH fluctuations have been increased. It is important to point out, however, that neither the breaking strength of the material has changed, nor the associated change in RH sufficient to cause cracking.

If a cottonwood sample is restrained at 50% RH and the humidity is increased to 85% RH, the wood will experience plastic deformation in compression, or *compression set*. The wood now has been effectively shortened, and upon desiccation from 85% it begins to experience tension. In effect, the wood has been reinitialized to a restrained condition at 85% RH. Figure 4c shows that, upon desiccation from 85% to about 81% RH, the sample has already attained yield in tension. Upon returning to 50% RH, the sample will most likely crack. This illustration explains why restrained wooden objects subjected to very high humidities or stored outside in equally humid environments often suffer damage when brought into a well-controlled museum environment. The degree of control of the museum environment is thus not the issue. The substantial change from the high humidity to a moderate environment is the cause of failure.

Since wood is most dimensionally responsive in its tangential orientation, tangentially restrained wood is the most vulnerable to RH-induced strain development. Therefore, if one wishes to set a criterion for the allowable RH fluctuations for a restrained panel, one should examine strain development in the tangential direction as the worst case condition. Figure 5 shows the allowable fluctuation plots for white oak in the tangential direction. It is quite similar to the cottonwood plot (Fig. 4a).

The Effects of Wood Variability within a Single Species

Wood samples of the same species can vary considerably in their mechanical properties. It is of interest to know how this variability affects the material's response to fluctuations in the environment. Samples of spruce obtained from two different sources were tested mechanically, with respect to their dimensional response to moisture. The difference in their mechanical behavior was substantial. In Figure 6a, results from tensile tests are plotted as stress-strain curves conducted at 50% RH and 22 °C. The sample A spruce was 4.5 times as stiff and twice as strong as sample B. This difference was more or less consistent over the whole RH range. The yield points for new samples of both woods were 0.004, but the breaking strains were substantially different, as shown in Figure 6b. Even though sample A was stronger, it broke at strains one-third as great as those for sample B, over the entire RH

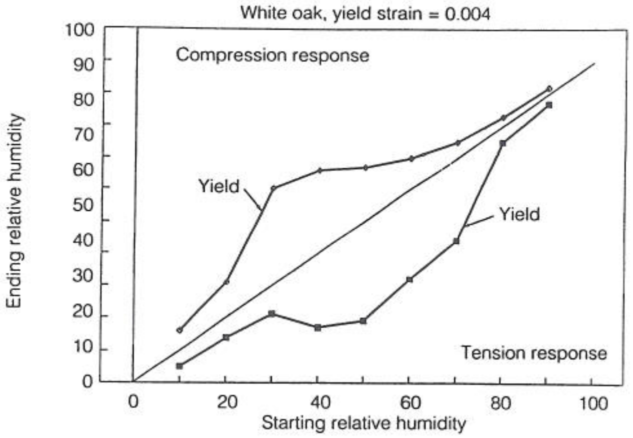


Figure 5
The domains of allowable RH fluctuations for white oak, fully restrained in their tangential directions.

range. When measuring the swelling behavior, the two materials showed little difference, and the moisture coefficients of expansion were quite similar (Fig. 6c). Computing the RH fluctuations that are required to induce yield strains (Fig. 6d) in either compression or tension showed insignificant differences. In addition, these RH fluctuations were greater than those for woods discussed previously in this article. Differences occurred in the RH fluctuation that was required to cause failure in tension. Sample B acted quite

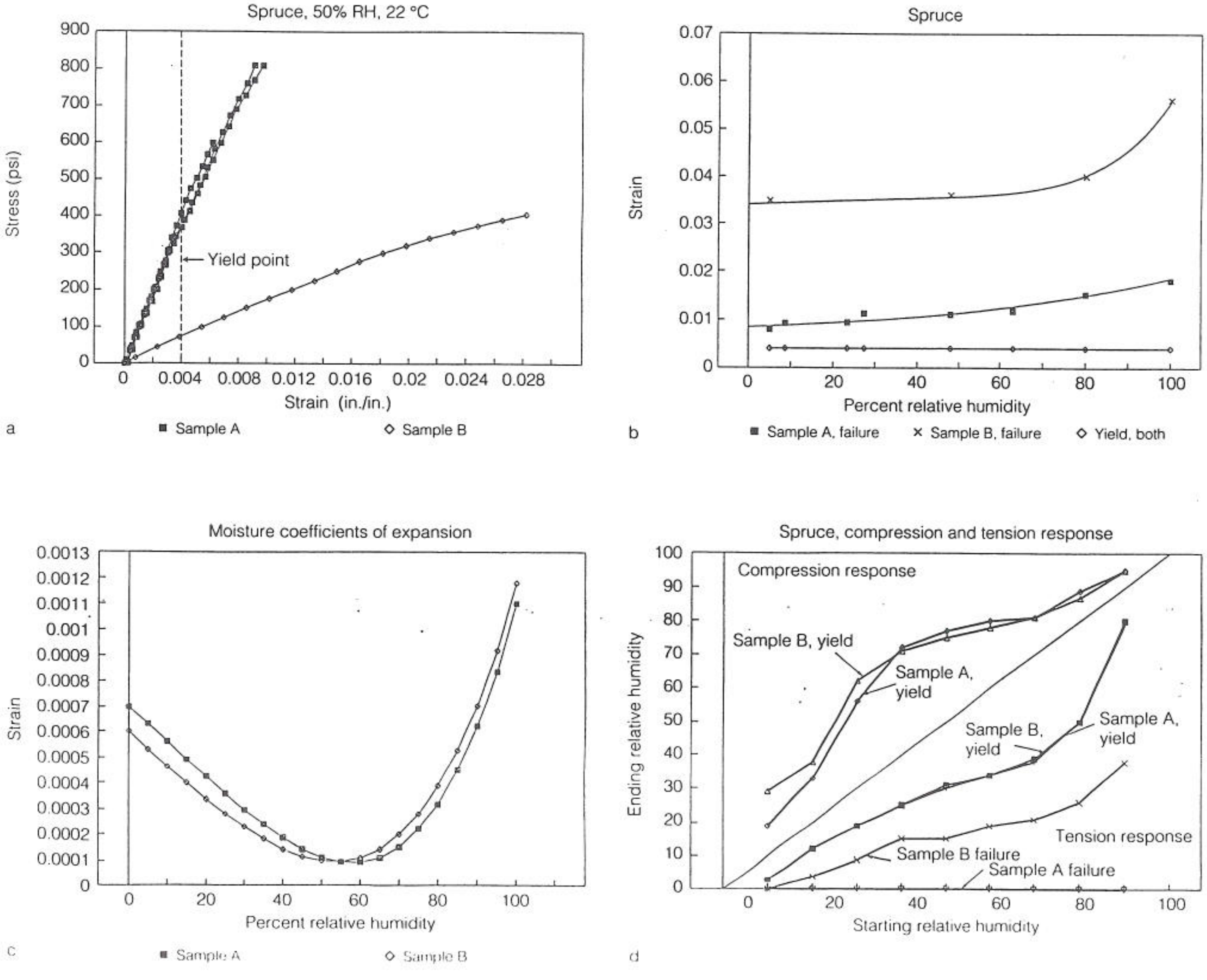


Figure 6a–d
The stress-strain plots (a) and the experimentally measured yield and breaking strains (b) for two samples of tangentially-restrained spruce show substantial variations in mechanical properties. However, the moisture coefficients of expansion (c) and the domains of allowable RH fluctuations (d) are nearly identical.

similarly to the three previous woods, while sample A is difficult to break with any RH change. The interesting aspect of this comparison of two samples of spruce is that mechanical properties, such as stiffness and strength, do not necessarily influence the restrained specimen's yield points (the amount of RH-induced strain required to cause plastic deformation). By contrast, stiffness and strength do influence the restrained specimen's points of failure (the amount of RH-induced strain required to break the sample).

Hide Glue

Hide glue is a material often associated with painted wooden objects, whether used to join the components, to size the surface prior to painting, or as an ingredient in gesso applied to prepare a smooth painting surface. Hide glue is one of the materials most dimensionally responsive to moisture. The swelling isotherm for a particular type of hide glue (rabbit-skin glue) was developed from two separate samples of the same material (Fig. 7a). The newly cast material shrinks freely when initial high RH levels are reduced (Mecklenburg and Tumosa 1991). The total shrinkage can be as much as 6% when desiccating from 90% to 10% RH.

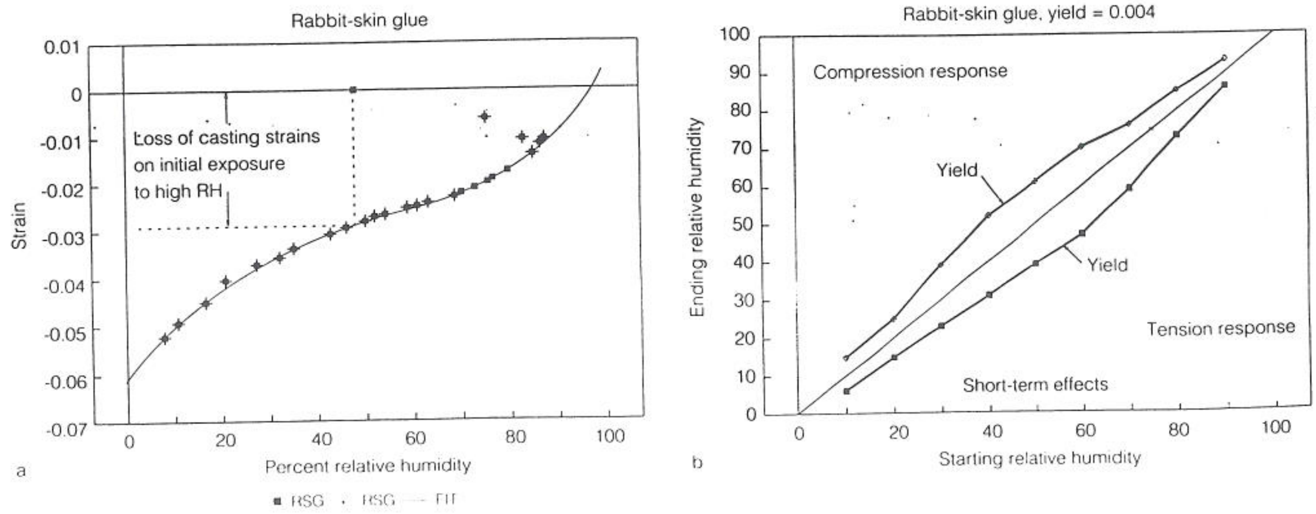
Over short time spans—days to weeks—one can measure a yield point of about 0.004 to 0.005 for rabbit-skin glue (the breaking strains are measured at approximately 3% to 4%—strains of 0.03 to 0.04—in extremely slow tests). For changes in RH that occur within these short periods, it is possible to determine the RH fluctuations that will induce yield strains in restrained hide glue (Fig. 7b). In effect, at 50% RH, the short-term RH fluctuations may range ±11% before yield point is reached. Since hide glue has no covalent cross-links, it is prone to stress relaxation over periods ranging from six to twelve months, depending on the RH level (Mecklenburg and Tumosa 1991). Therefore, over a long period of time any induced stresses may relax. If subjected to excessive RH (over 85%), however, the glue reactivates; as the reactivated glue desiccates with decreases in RH, extremely high stresses develop.

Hide glue response when attached to an unrestrained wood support

Theoretically, rapid extreme changes in RH could cause significant damage to objects sized with glue, due to the resulting high stresses. While such

Figure 7a, b

The swelling isotherm for rabbit-skin glue (a) and the domain of allowable RH fluctuations for fully restrained rabbit-skin glue (b) at any given ambient RH.



damage is common in paintings on sized canvas, the mass of the substrate in a glue-sized painted wooden object provides substantial resistance to stresses developing in the relatively thin layer of glue. Since wood has a very small dimensional response to moisture in its parallel-to-grain (longitudinal) direction, wood in this axis essentially serves as a full restraint for all materials attached to it—glues, fabrics, gessoes, and paint.

Across its grain, unrestrained wood will change dimensionally with RH changes. If the moisture coefficients of expansion of all materials attached to a wood substrate were the same as the wood, then RH changes would induce no cross-grain stresses in the attached layers. In reality, the expansion coefficients of the different materials vary considerably, but by comparing them it is possible to explore the effects of RH changes in the cross-grained direction of an unrestrained painted panel. Figure 8a compares the expansion coefficients of cottonwood and hide glue. At approximately 70% the plots intersect: at this RH, both wood and glue swell or shrink at the same rate. In the RH range from 35% to 60%, the glue attempts to swell or shrink at a slightly higher rate than the wood substrate. In this region, glue applied to cottonwood will develop stresses, but only a fraction of those that result from full restraint, since the shrinking or swelling of the wood approximates that of the glue. This is an example of partial rather than full restraint. In effect, the wood's movement provides greater RH tolerances for the hide glue. The strains in the glue can be calculated using the following equation:

$$\Delta\epsilon_G = [(1 - \int\alpha_S dRH) - (1 - \int\alpha_G dRH)]/(1 - \int\alpha_S dRH) \qquad (4)$$

where α_S is the coefficient of expansion of the substrate, and α_G is the swelling coefficient of the hide glue.

This equation can be used for any material applied to any substrate in any direction. For example, assume that the coefficient of expansion for the substrate is zero. In that case, Equation 4 simplifies to Equation 3. In the examples to follow, cottonwood will be the substrate since it is one of the most dimensionally responsive woods.

The calculated increase in RH tolerance for hide glue size on a wood substrate is illustrated in Figure 8b. Here, the hide glue is applied to an unrestrained cottonwood support, and the glue strains are plotted

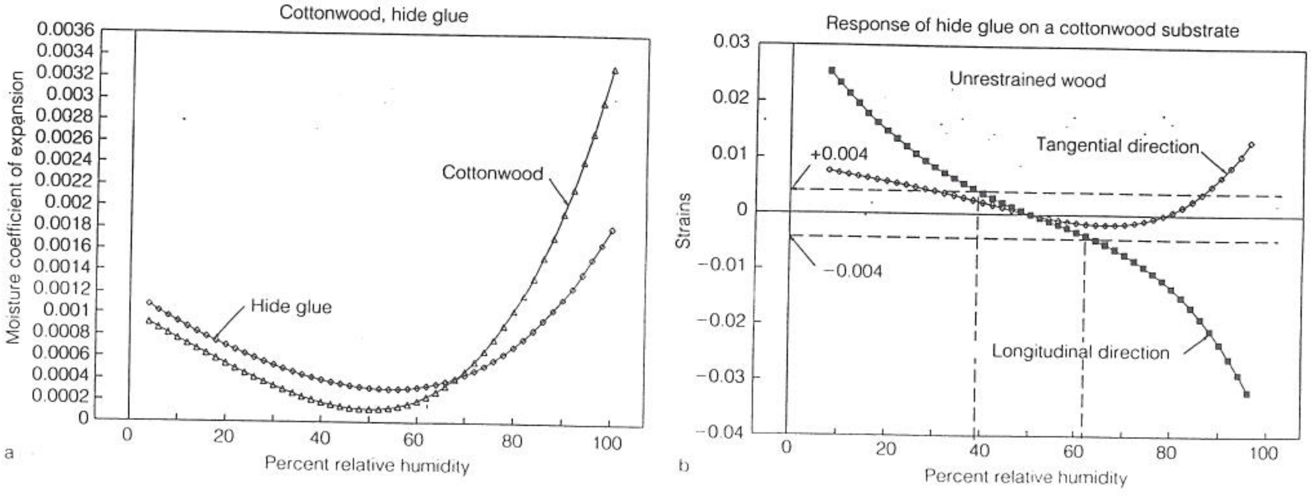


Figure 8a, b

A comparison of the moisture coefficients of expansion (a) for hide glue and cottonwood. Using Equation 4, these values enable one to determine the strain interaction of the glue with the cottonwood substrate (in both tangential and longitudinal directions) over the complete range of RH (b).

against RH in both the tangential and longitudinal directions. The longitudinal direction, in which the glue is essentially fully restrained (the wood's coefficient of expansion in that direction is assumed to be zero), is plotted by integrating Equation 4 from 50% RH going in both increasing and decreasing directions. The strains are as one would expect for fully restrained glue: high in tension (positive values) upon desiccation, and high in compression (negative values) upon increases in humidity. To determine the strains in the glue in the wood's tangential direction, Equation 4 was integrated again, now using cottonwood's tangential coefficients of expansion, shown in Figure 8a. In this direction, the wood substrate and the glue respond similarly to the moisture changes, significantly reducing the strains in the glue layer. With desiccation, the glue strains are in tension but are less than half those in the longitudinal direction. This is because from 50% to 0% RH, the glue coefficient is greater than that for the wood. Increasing the humidity from the 50% RH starting point produces different results. At about 68% RH, the wood coefficient becomes greater than the glue; the swelling of the wood actually overrides that of the glue, and the wood begins pulling the glue layer into tension.

Regarding allowable RH fluctuations, the strains upon glue in wood's fully restrained, longitudinal direction are the most severe, but it is clear that severe desiccation could cause cracking in the glue in both of the wood's directions. In addition, extreme humidification simultaneously subjects the glue to significant tension in the wood's tangential direction and severe compression in its longitudinal direction—both strains potentially leading to failure. Similar diagrams will be used to examine the response of gesso and paint layers attached to wood substrates.

Gesso

Gesso is a mixture of a hide glue and gypsum or ground chalk, used to prepare a smooth, paintable surface on wood. Sometimes other inert materials, such as zinc white and clay, are incorporated. The ratio of inert solids to hide glue has a dramatic influence on the mechanical and dimensional properties of the gesso. This ratio can be expressed in the pigment-volume concentration (PVC). The higher the concentration of inert filler (higher PVC), the weaker, stiffer, and less dimensionally responsive to ambient moisture a gesso becomes, due to the smaller relative amount of glue. Figure 9a plots the dimensional response against RH for two gesso mixtures: PVC = 58.3, and PVC = 81.6. The lower PVC gesso has a maximum change of about 1.5% (strain = 0.015) over the entire RH range. The higher PVC gesso changes only about 0.6% over the same RH range, which is about one-tenth that of pure hide glue (in effect, PVC = 0) which swells as much as 6%. With the increased PVC, gesso will reach yield point and experience failure at dramatically lower strains, and the reasons for this were discussed in a recent study (Michalski 1990). Figure 9b shows the difference in the moisture coefficients of expansion for the two gessos. Both show lowest values (representing the lowest rates of dimensional response) between 50% and 60% RH.

As with all the materials examined, RH affects the mechanical properties of gesso. Tensile testing of one of the gessoes (PVC = 58.3) shows a dramatic loss of strength with increasing RH (Fig. 9c). Here the low RH strains for the gesso tested are actually higher than those determined in the midrange RH tests. The yield strains are about 0.0025, and

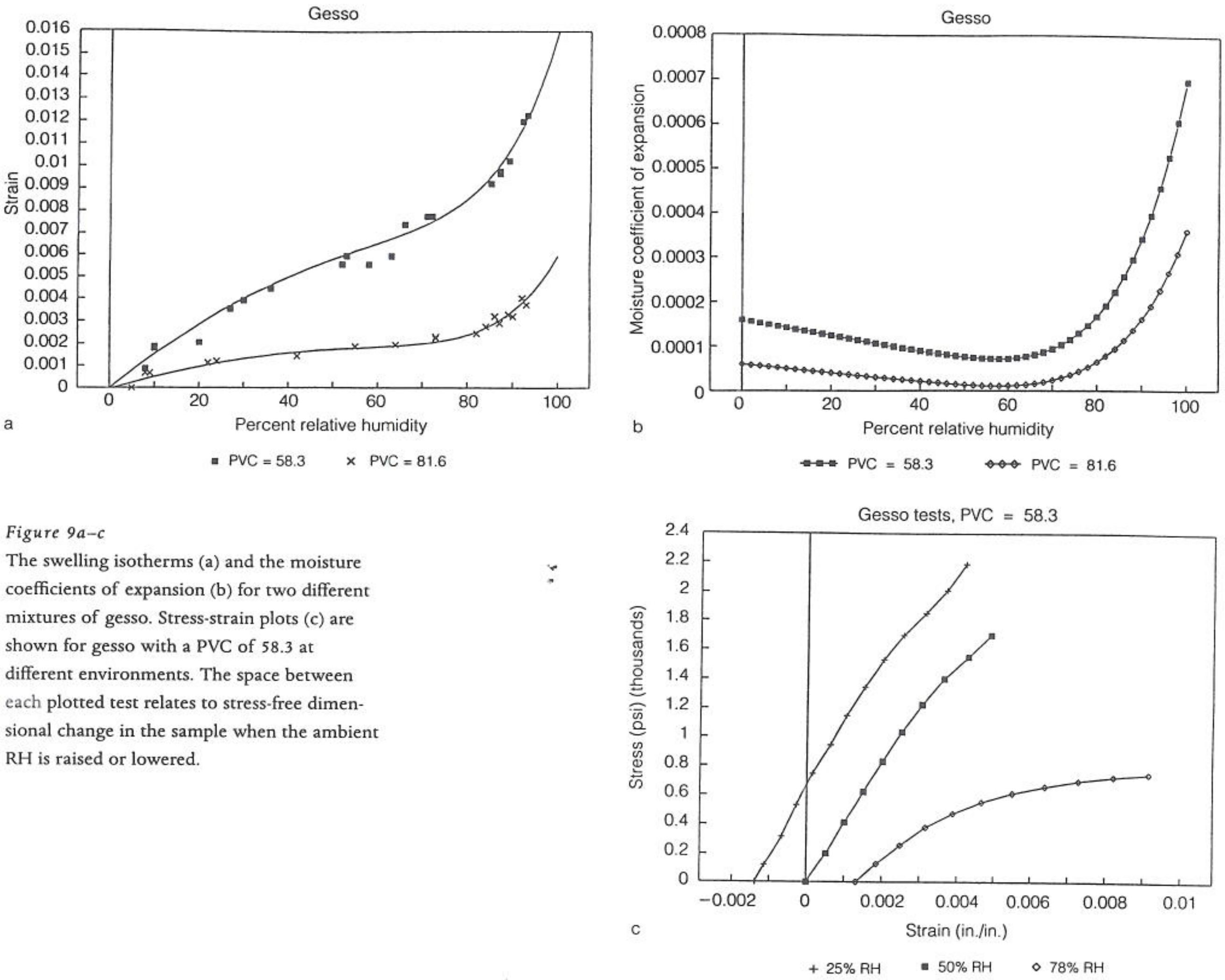


Figure 9a–c

The swelling isotherms (a) and the moisture coefficients of expansion (b) for two different mixtures of gesso. Stress-strain plots (c) are shown for gesso with a PVC of 58.3 at different environments. The space between each plotted test relates to stress-free dimensional change in the sample when the ambient RH is raised or lowered.

the breaking strains again vary with RH but are generally lower than those for other materials associated with painted wood.

In spite of its low yield and breaking strains, gesso can be subjected to greater RH changes than most of the other materials under consideration before reaching its yield points. Figure 10a shows the RH changes required to induce yield and cracking in gesso (PVC = 58.3) fully restrained in the longitudinal orientation of a wood substrate. For example, beginning at an ambient RH of 50%, fully restrained gesso can desiccate to 26% RH before attaining yield in tension. The RH can go as high as 76% before yield is reached in compression. This is a direct result of the gesso's low moisture coefficient of expansion.

Figure 10b compares the swelling coefficients of gesso with those for cottonwood in its tangential direction. Here, the swelling coefficients of the cottonwood and the gesso are not only very low but nearly identical in the 40–60% RH range. This means that an unrestrained cottonwood panel and its applied gesso are swelling and shrinking very little and at almost exactly the same rate in this RH region; there is effectively little structural interaction.

Deviation from the mid-RH zone, however, has quite dramatic effects. Equation 4 was again integrated in order to explore the composite

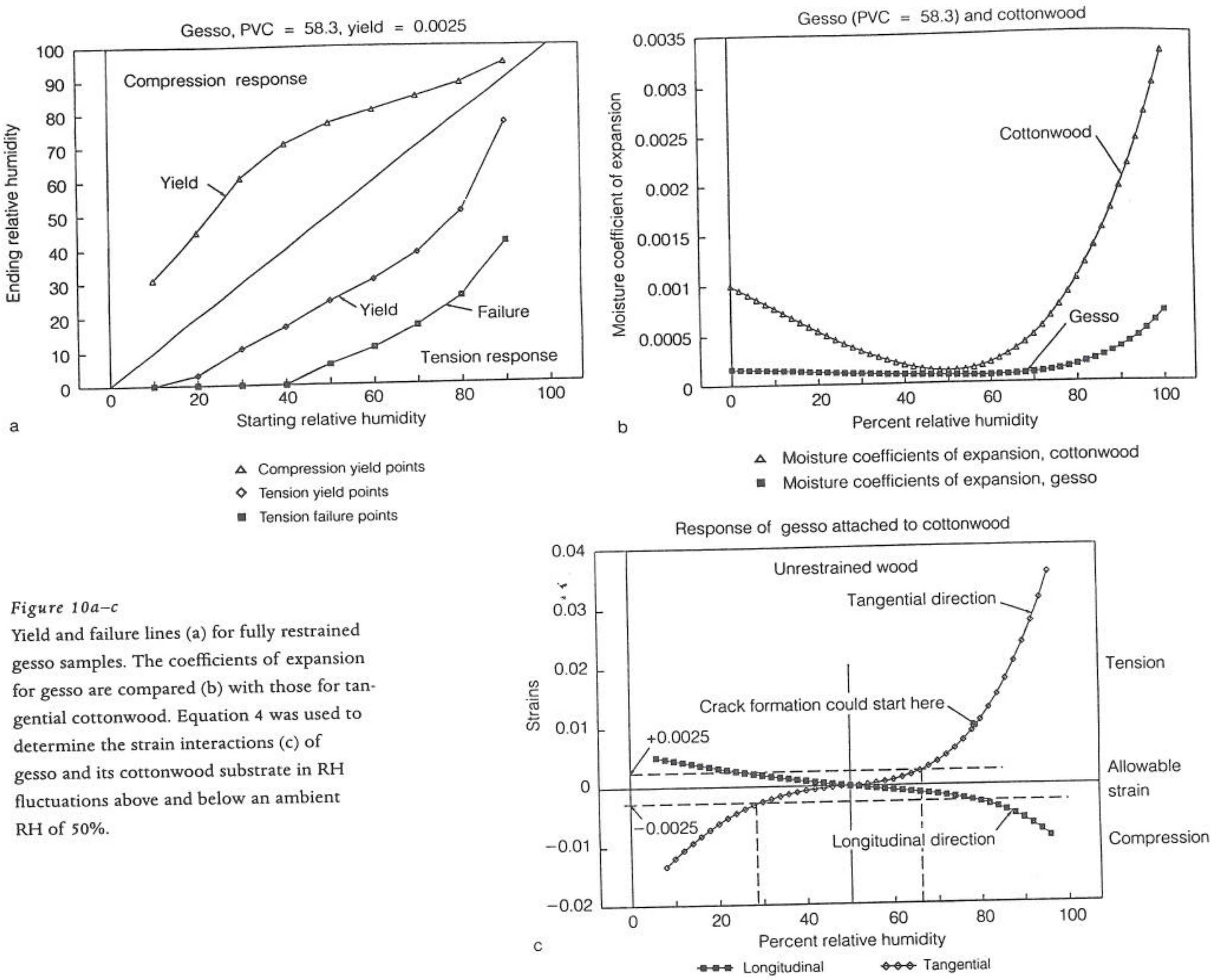


Figure 10a–c

Yield and failure lines (a) for fully restrained gesso samples. The coefficients of expansion for gesso are compared (b) with those for tangential cottonwood. Equation 4 was used to determine the strain interactions (c) of gesso and its cottonwood substrate in RH fluctuations above and below an ambient RH of 50%.

effect when the gesso is bonded to a cottonwood panel, using a starting point of 50% RH. The results of this analysis are illustrated in Figure 10c, where gesso strains associated with both the tangential and longitudinal directions of the wood support are plotted against RH. In the longitudinal direction, full restraint is again assumed, and the RH fluctuations needed to induce yielding are quite large—from 50% to 26% RH in tension upon desiccation and from 50% to 76% RH in compression upon humidification. In the tangential direction, the mismatch of swelling coefficients for the wood and the gesso worsens dramatically as the high and low extremes of the RH range are approached (Fig. 10b). Consequently, Figure 10c demonstrates that desiccation will induce severe compressive strains in the gesso layer (which can cause cleavage and buckling), while raising the RH from 50% to 80% can actually cause the gesso layer to crack. Thus, the range of allowable RH fluctuation is more limited for the tangential direction than for the longitudinal direction. Nonetheless, from a starting point of 50% the RH can range downward to 28% or upward to 66% without causing the gesso to yield in the tangential direction. Even in this worst-case example, the gesso/wood composite can survive significant fluctuations in RH.

The Paint Layers

To study stiffness, strength, and response to relative humidity fluctuations, mechanical tests were carried out on fifteen-year-old oil paints under true equilibrium conditions (several weeks of stress relaxation occurred prior to any subsequent incremental loading). Figure 11a, b shows the tensile test results for two of these paints. Although the yield points for nearly all the paints remained at about 0.004 throughout the tests, the breaking strains varied from one paint to another when tested at the same RH and temperature. For example, at 48% RH and 22 °C, flake white in safflower oil attained a breaking strain of 0.02 (Fig. 11a); titanium dioxide in safflower oil broke at 0.01 (Fig. 11b). When the same paints were tested at different relative humidities, it became apparent that RH plays a considerable role in modifying the mechanical properties. Flake white in safflower oil is a fairly flexible paint that was not seriously affected by the change in RH from 48% to 5% (Fig. 11a). Meanwhile, titanium dioxide in safflower oil lost nearly all its stiffness and strength when the RH was raised from 48% to 80% (Fig. 11b). In general, increasing the RH decreased the strength of a paint but increased its breaking strain, while lowering the RH increased its strength but lowered the breaking strain.

Typically, oil paints are far less dimensionally responsive to moisture than are hide glues or wood. Flake white in safflower oil, for instance, shows a total change in length of only about 0.5% when the RH is raised from 20% to 90%. A plot of the moisture coefficients of expansion (Fig. 12) demonstrates that this is one of the least dimensionally responsive materials presented in this discussion.

Effects of solvents on paint

Leaching out the soluble components of oil paints has a dramatic effect on the mechanical properties. Two fifteen-year-old paints, cadmium yellow in safflower oil and cadmium yellow alkyd artist's paint, were soaked in toluene for a week, then allowed to dry for eight weeks. Figure 13a, b shows results of equilibrium tensile tests before and after toluene treatment for the oil and alkyd paints, respectively. Surprisingly, the yield points of the toluene-treated paints were no different than those for the untreated paints. After treatment, however, each paint experienced a

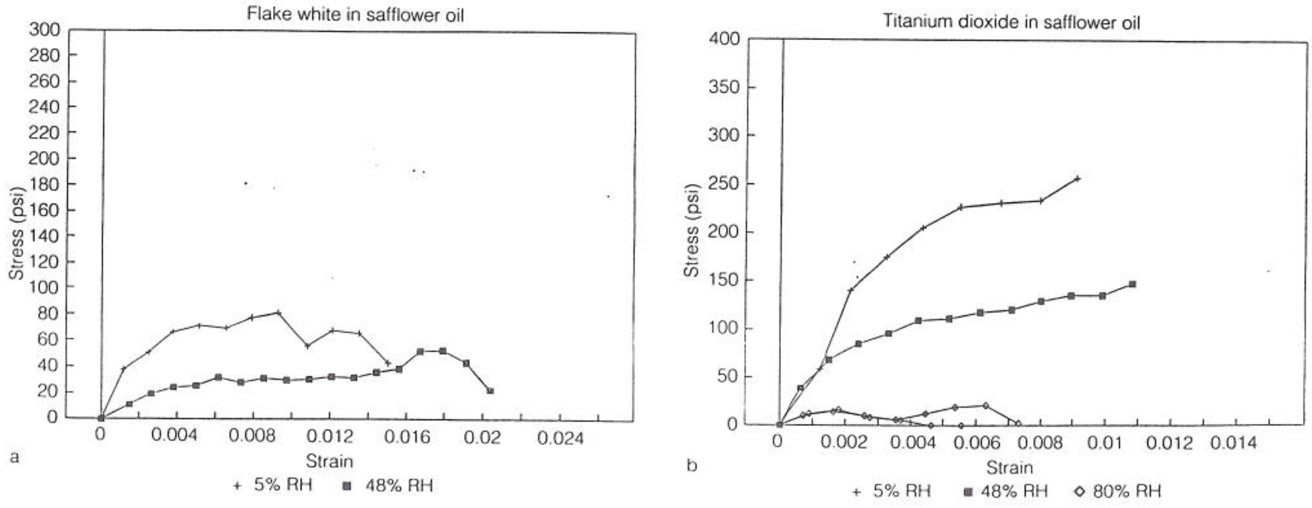


Figure 11a, b

The equilibrium stress-strain plots at different environments for flake white (a) and titanium dioxide (b), both in safflower oil.

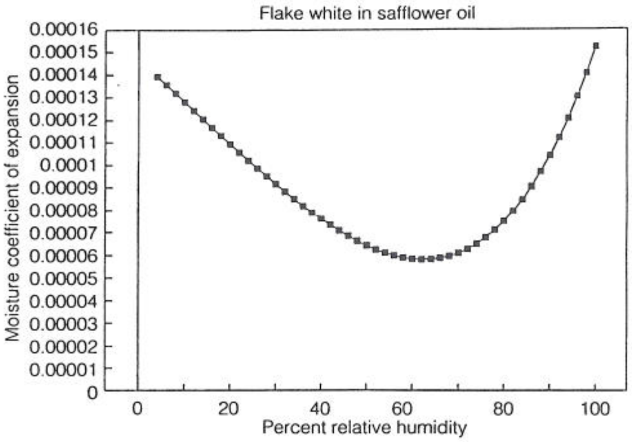


Figure 12

The moisture coefficients of expansion for flake white in safflower oil are the lowest of any included in this study.

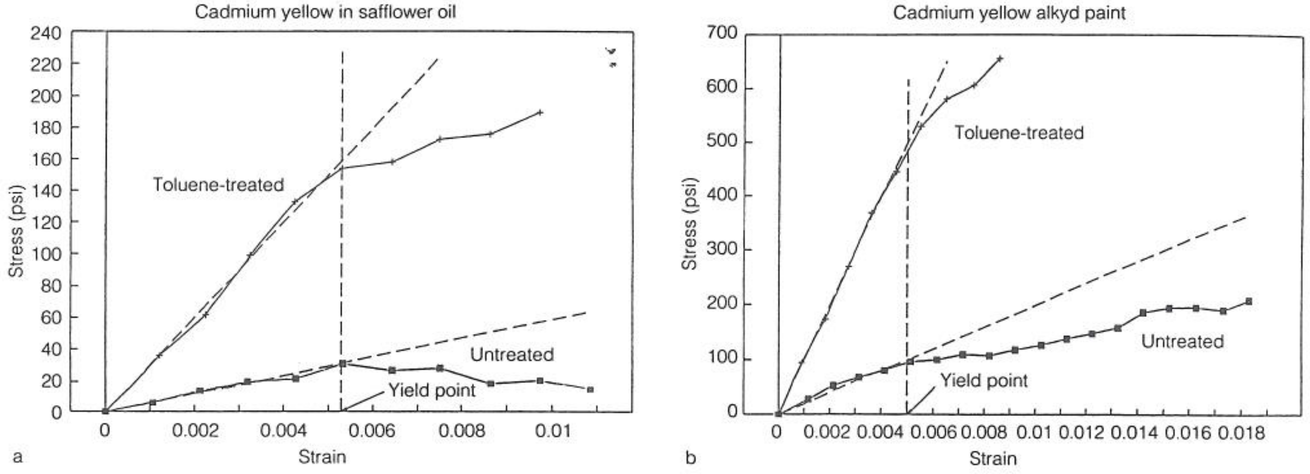


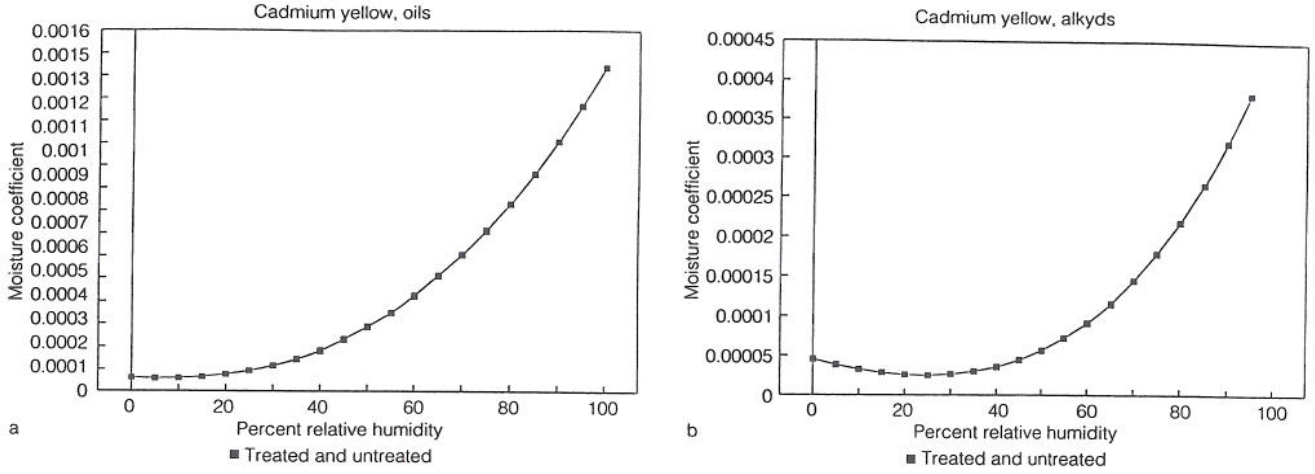
Figure 13a, b

The equilibrium stress-strain curves for cadmium yellow in safflower oil (a) and in alkyd (b), before and after soaking in toluene for one week.

fivefold increase in stiffness and at least a threefold to fourfold increase in strength. Obviously, the soluble components leached out by the toluene had been acting as plasticizers. Solvent leaching simulates one of the possible aging processes of oil paints that results in increased stiffness and strength: the slow evaporation of free fatty acids and other volatile, low molecular weight components (Michalski 1990; see also Erhardt herein).

There is no difference in the swelling characteristics of the treated and untreated paints. The moisture coefficients of expansion in treated oils and alkyds do not change from their untreated values (Fig. 14a, b).

Using the strain-to-yield values and integrating the expansion coefficients for the paints tested, it is possible to establish the allowable RH fluctuations for several restrained paints. Figure 14c shows the acceptable ranges for cadmium yellow in oil (toluene-treated and untreated), cadmium yellow in alkyd (treated and untreated), flake white in oil, and titanium dioxide in oil. Since the toluene treatment altered neither the yield points nor the expansion coefficients of the paints tested, the allowable RH fluctuations are no different for treated and untreated paints. The difference, if any, will be reflected in any changes in strain to break caused by the solvent.



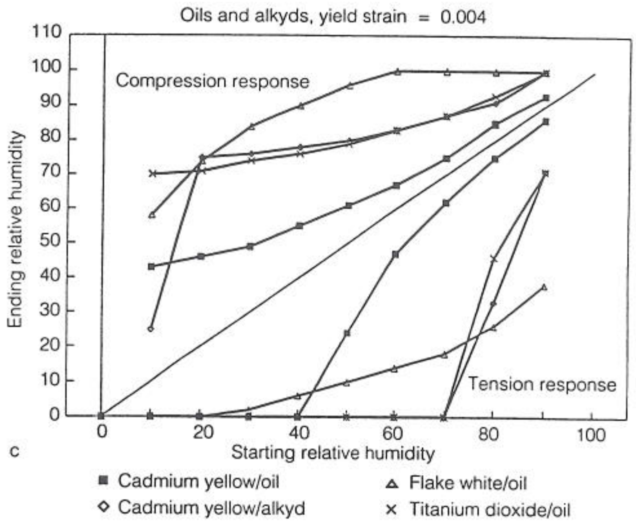


Figure 14a–c
The moisture coefficients of expansion for cadmium yellow in oil (a) and in alkyd (b) are identical before and after solvent treatment. Yield lines (c) for several fully restrained paints indicate their domains of allowable RH fluctuations over the range of ambient RH. With the exception of the cadmium yellow oil paint, these paints safely sustained wider fluctuations in RH than any of the other materials examined.

Response of a composite painted wood surface

For purposes of comparison, the moisture coefficients of expansion for cottonwood, hide glue, gesso, and flake white oil paint are plotted in Figure 15a. The very low coefficients of oil paint and gesso are almost identical, except the coefficients for gesso rise a bit in the range from 70% to 100% RH, while those for the paint stay nearly flat. As with the gesso, the paint—when applied to an unrestrained wood substrate—will experience a serious swelling mismatch outside of the midrange RH. This mismatch can be demonstrated by using equation 4 to calculate the strains expected in a composite of cottonwood, and flake white in oil. Figure 15b shows the flake white strains initialized at 50% RH. In the longitudinal direction, the allowable fluctuations for the paint are quite large. With desiccation from 50% RH, the RH can drop to about 10% before the paint reaches yield point. With humidification above 50%, the RH can rise safely to about 95% RH. In the tangential direction, desiccation to 26% RH will cause compression yielding; beyond that, buckling and cleavage can occur. Increasing the RH to 70% will cause yielding in tension, with possible cracking at extremely high RH levels.

Flaking and the Adhesion of the Design Layers

Normally, the physical separation of the design layer from the support (i.e., peeling, curling, or flaking) manifests after a crack has occurred. There are occasions, however, when the paint layer separates from the wooden support without an associated crack. In art conservation this is usually referred to as *blind cleavage,* while the paint industry calls it *blistering* of the paint. On exterior painted wooden (and metal) surfaces, blistering may result from the solar heating of soft, freshly painted surfaces, from the penetration of excessive amounts of moisture, or from the generation of a gas beneath the paint layer (Hess 1965:102–4; *Wood Handbook* 1987:16–21; Houwink and Salomon 1967:51; Van Laar 1967). In all probability, poor preparation of the substrate also contributes to interlayer or blind cleavage caused by exposure to excessive moisture. Lean (insufficient glue) gesso grounds are particularly susceptible to blind cleavage because of the low cohesive and adhesive strength of the material.

A great number of causes have been proposed for the flaking of a previously cracked paint film. Exterior paints may flake because of exposure to frequent cycles of wetting (by rain) and drying. Too little oil binder may cause poor adhesion of the paint, as may contamination of the prepared surface with dirt, wax, fats, nondrying oils, or grease. Cold temperatures may also cause flaking. As Hess states (1965:242):

> It is widely known that elasticity, adhesion, and shock resistance of most paints and varnishes, even those of very long-oil length, suffer badly during cold weather. The temperature need not necessarily be below freezing point and susceptibility already exists for some coatings at about 50 °F (10 °C). As long as the films are on rigid structures and do not crack the failure does not become permanent and is hardly apparent at all.

Certain woods accept and hold paint better than others. Cedar, cypress, and redwood are excellent woods for painting, while red and white oak, elm, chestnut, and butternut are considered poor choices. In fact, many of the woods historically used as paint substrates for art objects, such as cottonwood, basswood, and yellow-poplar, are not recommended as suitable for exterior painted finishes in the *Wood Handbook* (1987:16–21), one of the standard industrial texts. One of the factors affecting the permanence of a painted surface is moisture-related dimen-

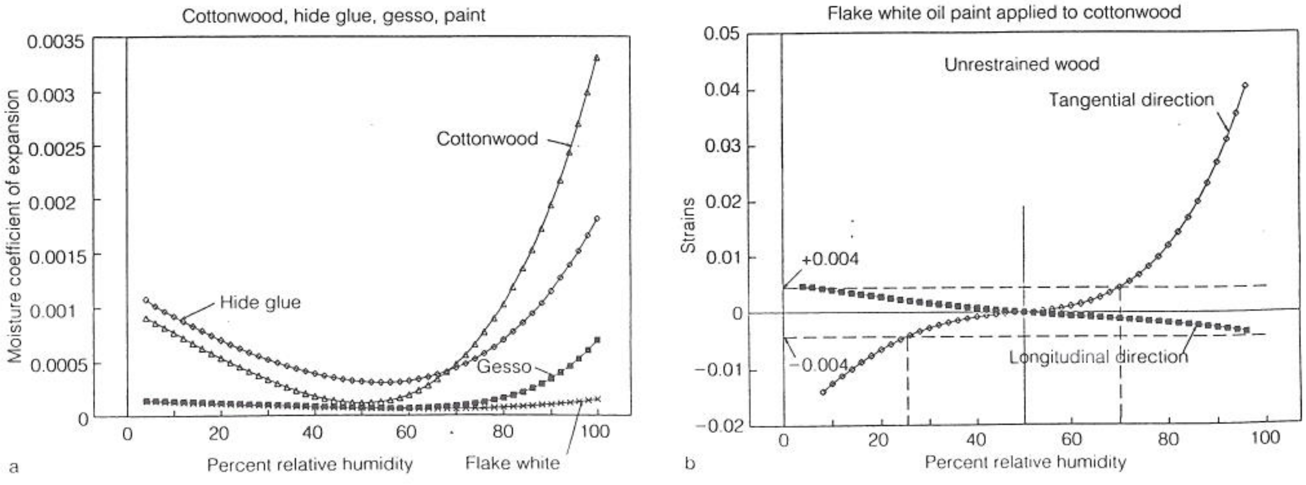


Figure 15a, b

A comparison of the moisture coefficients of expansion (a) of cottonwood, gesso, hide glue, and flake white oil paint. Equation 4 was used to determine the strain interactions (b) of flake white in oil and its cottonwood substrate in fluctuations above and below an ambient RH of 50%. At extreme low RH, the paint endures simultaneous compressive strain in the wood's tangential direction and tensile strain in the longitudinal direction. These strains are reversed at extreme high RH.

sional stability, and woods that retain paint well tend to be the most dimensionally stable. Obviously, this is the reason radially sawn boards hold paint better than tangentially sawn boards. Other than dimensional stability, density seems to be the chief factor in wood's ability to retain paint, with less dense (more porous) woods likely to be better paint substrates. This explains the tendency for paint to adhere better to earlywood in species with pronounced earlywood-latewood differences; the lower density and greater porosity of the earlywood helps it to retain paint (Marian 1967). This correlation of wood density with paint adhesion suggests that the wood-paint bond is largely mechanical.

Nonetheless, there are convincing arguments that van der Waals forces contribute significantly to the adhesion of paints to wood (Marra 1980; Salomon 1967; Kaelble 1971:45–82; Pocius 1986; Parker and Taylor 1966). Current theory suggests that the adhesion mechanisms are a combination of chemical bonding and mechanical attachment. While increasing the porosity (or surface texture) of a substrate may encourage a better mechanical grip, it is also true that more chemical bonding sites are exposed. Whether or not the adhesion is mechanical or chemical, both bonding mechanisms are seriously affected by wood's affinity for water. While moisture can seriously affect an existing paint-wood bond line, fracture testing of bonded joints suggests that the presence of moisture in the wood at the time of paint application can also seriously weaken the resulting bond (Kousky 1980).

Moisture represents one of the most important factors in the delamination of a paint film, glue size, or gesso ground. High moisture content disrupts the adhesion bond, and subsequent desiccation separates the materials physically. High moisture content in wood can result from liquid sources such as rain, condensation on walls, or groundwater from wet foundations. It may also result from a vapor source (persistent high relative humidity).

Conclusion

Fluctuations in relative humidity cause strains in the materials used to construct a cultural object. Quantifying the moisture response of each of the materials permits one to determine the allowable RH fluctuations—the RH changes an object can safely endure. In the example presented in this study (a painted panel composed of cottonwood, hide glue, gesso, and oil paint), several conditions were examined to assess the RH-related behavior. Theoretically, the hide glue size was found to be the material limiting the allowable RH fluctuations of the panel. Because of its low yield point and its great capacity for expansion in response to moisture, the glue should limit the panel to an allowable RH fluctuation of 50% ± 11%. Because glue stresses relax over time, however, the glue actually has little influence on the overall response of the panel.

The maximum allowable RH fluctuation for a particular object is ultimately determined by examining the independent RH response of each of the materials making up an object, determining the effects of the composite nature of the object on each material's response, then adopting the composite worst-case responses as the factors that truly limit the allowable RH fluctuations. Assuming that an ambient RH of 50% is desirable, the painted panel can endure maximum allowable RH fluctuations of 16% above 50% RH (the tension yield point for the tangential wood substrate) and 22% below 50% RH (the compression yield point for gesso in the wood's tangential direction). As a structure, then, the panel may endure considerable fluctuations in the environment.

Equally important, the research shows the *type* of damage most likely to occur, given a particular set of circumstances. For example, cracking is most likely in the gesso and paint layers when a panel is expanding in response to a severe increase in RH. These cracks will run parallel to the grain of the substrate (longitudinally). Cracking might also occur in the gesso and paint under extreme desiccation, but these cracks will run perpendicular to the grain of the substrate (across the grain). During severe desiccation, the gesso and paint layers may even suffer compression cleavage and ridging, but the ridges will invariably run parallel to the substrate's grain.

The research also shows that if a painted panel becomes equilibrated at an extreme high or low RH, it cannot be returned to the moderate RH regions without damage. This is because the domain of allowable RH fluctuation narrows at extreme high or low levels of ambient RH, permitting very little RH change without yielding and failure.

From the standpoint of structural stability, the optimal environmental baseline for most objects is in the middle RH region (45% to 55%), since nearly all materials experience their lowest rates of RH-induced dimensional response (i.e., their lowest moisture coefficients of expansion) in this region.

Note

1 Because the authors' tests were performed in pounds per square inch and the graphs provide data in the same units of measure, conversions to kilograms per square centimeter were not done.

References

Doerner, M.
1962 *The Materials of the Artists and Their Use in Paintings . . . With Notes on the Techniques of the Old Masters*. New York: Harcourt, Brace, and World.

Hess, M.
1965 *Paint Film Defects*. 2d ed. New York: Reinhold.

Houwink, R., and G. Salomon, eds.
1967 *Adhesion and Adhesives*. Vol. 2. Amsterdam, N.Y.: Elsevier.

Kaelble, D. H.
1971 *Physical Chemistry of Adhesion*. New York: Wiley-Interscience.

Kousky, J. A.
1980 Recent results on fracture toughness of bonded wood. *Proceedings of 1980 Symposium, Wood Adhesives—Research, Application, and Needs*, 189–94. Madison, Wis.: U.S. Forest Products Laboratory,

Marian, J. E.
1967 Wood, reconstituted wood and glue laminated structures. In *Adhesion and Adhesives*, vol. 2, ed. R. Houwink and G. Salomon, 167–70. Amsterdam, N.Y.: Elsevier.

Marra, G. G.
1980 The role of adhesion and adhesives in the wood products industry. In *Proceedings of 1980 Symposium, Wood Adhesives—Research, Application, and Needs*, 1–8. Madison, Wis.: U.S. Forest Products Laboratory.

Mecklenburg, M. F., and C. S. Tumosa

1991 Mechanical behavior of paintings subjected to changes in temperature and relative humidity. In *Art in Transit: Studies in the Transport of Paintings*, ed. M. F. Mecklenburg, 173–216. Washington, D.C.: National Gallery of Art.

Mecklenburg, M. F., C. S. Tumosa, and M. H. McCormick-Goodhart

1995 A general model relating externally applied forces to environmentally induced stresses in materials. In *Materials Issues in Art and Archaeology IV, Materials Research Society Symposium Proceedings*, vol. 352, 285–92. Pittsburgh, Pa.: Materials Research Society.

Michalski, S.

1990 A physical model of the cleaning of paint. In *Cleaning, Retouching and Coatings: Preprints of the Contributions to the Brussels Congress, 3–7 September 1990*, ed. J. S. Mills and P. Smith., 85–91. London: International Institute for Conservation of Historic and Artistic Works.

Parker, R. S. R., and P. Taylor

1966 *Adhesion and Adhesives*. Oxford, N.Y.: Pergamon Press.

Pocius, A. V.

1986 Fundamentals of structural adhesive bonding. In *Structural Adhesives, Chemistry and Technology*, 33–75. New York and London: Plenum Press.

Salomon, G.

1967 Adhesion. In *Adhesion and Adhesives*, vol. 1, ed. R. Houwink and G. Salomon, 1–128. Amsterdam, N.Y.: Elsevier Publishing.

Van Laar, J. A. W.

1967 Adhesion and paint technology. In *Adhesion and Adhesives*, vol. 2, ed. R. Houwink and G. Salomon, 459–64. Amsterdam, N.Y.: Elsevier.

Wood Handbook: Wood as an Engineering Material

1974 Agricultural Handbook No. 72. Madison, Wis.: Forest Products Laboratory, U.S.D.A.

1987 Agricultural Handbook No. 72. Madison, Wis.: Forest Products Laboratory, U.S.D.A.

Painted Wood: History and Conservation

Proceedings of a symposium organized by the
Wooden Artifacts Group of the American Institute
for Conservation of Historic and Artistic Works
and the Foundation of the AIC, held at the Colonial
Williamsburg Foundation

Williamsburg, Virginia
11–14 November 1994

Edited by Valerie Dorge and F. Carey Howlett

THE GETTY CONSERVATION INSTITUTE
LOS ANGELES