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SOME ASPECTS OF THE MECHANICAL BEHAVIOR OF FABRIC SUPPORTED PAINTINGS

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FABRIC SUPPORTED PAINTINGS

I. Introduction

The deterioration of "fabric supported" oil paintings has generated perhaps as much debate during the last four hundred years as have the paintings themselves. In many cases the causes of damage are obvious; accidental tears, biological attack and saturation with water usually are easily identifiable. Not as apparent, however, are the causes of persistent cracking and flaking even after relatively recent conservation treatment. An historically long list of painters have commented on the effects of using excessive animal skin glue,[1] while recent writers have stressed the hygroscopic nature of the fabric support.[2] Some have discussed the effects of stretchers, while others have further compounded the problem by introducing the concept of paint film behavior with the associated idea that paint films become brittle with "age",[3] or more precisely, with oxidation and polymerization of the oil films. If artists used oil paint directly, perhaps fewer forms of deterioration and destruction would occur, since the addition of dryers and resins alters the mechanical properties of the design layer. Clearly the number of variables is large enough that a systematic analysis of all mechanisms of deterioration of fabric supported oil paintings will take considerable time and resources.

Over the years the general concensus has been reached that environmental moisture plays a significant role in the mechanical deterioration of paintings, based on the assumption that artists' materials expand and contract due to gain and loss of water associated with changes in environmental moisture.

Expansion and contraction have become designated as the primary sources for the cracking and flaking of paint from the fabric support. As a result, attempts are made to stabilize the moisture content of the air in most museums.

The magnitude of environmental moisture content (water vapor present in the air) is usually indicated by the term "percent relative humidity" (%RH), and although an increase in relative humidity might suggest an increase in the water vapor present, this is not always so. A decrease in ambient temperature can cause an increase in RH while the actual amount of water vapor present remains the same.[4] Relative humidity provides a good way to relate the moisture content of a material specimen to the condition of the surrounding air at a given temperature.

An example of a material influenced by environmental moisture is wood, which swells with an increase in RH and shrinks when RH decreases.[5] This motion has long been considered the source of destruction of paint on a panel painting. When the panel contracts in excess of the paint's ability to do so, the paint cleaves under compression. Does the wood also expand so much during high RH that the paint film is "stretched" and found to crack under tension? Although the precise mechanisms of the behavior of panel paintings due to RH are yet to be fully determined, a basic principle apparently is at work. A material swells or contracts in an attempt to relieve stress generated within that material. Expansion and contraction are stress release mechanisms. If a material cracks (due to tension) or crushes and cleaves (due to compression), then it has been unable to completely relieve stress by expanding or contracting and by definition has failed due to excessive stress. In a material such as wood, stress can result from the development of internal force, such as swelling due to water vapor absorption when the wood is restrained, or of external force, such as bending or pulling, or from a combination of both. Similarly, the paint on a fabric supported oil painting cracks because of excessive unrelieved stress, whether the source of the stress is internal or external to the paint. The key questions for the conservator are: what are the sources of the stress, and how does it relate to environmental moisture?

The study of stress development within a material falls under a broad area of investigation called mechanics, which can be further broken down into 1) the study of the mechanical properties of the materials themselves, and 2) the stress analysis of the structures formed by the materials.

All materials found in the traditional oil painting (wood, fabric, glue and oil paint) gain and lose moisture with changes in environmental moisture. To the degree that they do this, they change both dimensionally and in their mechanical properties. The amount of moisture uptake is normally plotted in equilibrium moisture isotherms (EMI). The putrified bast fibers of flax, used to weave linen, are approximately 95% cellulose, while cotton fibers are about 97-99% pure cellulose.[6] Because of their similar compositions, and since the EMI for cotton is well established (considerably more research has been done on cotton), it is presented here (fig. 1) as a general indication of the EMI for flax, and gives a good description of water content (moisture regain) versus RH. The moisture content is described in terms of moisture regain -- the percent weight of water versus weight measured when the fibers are bone dry.

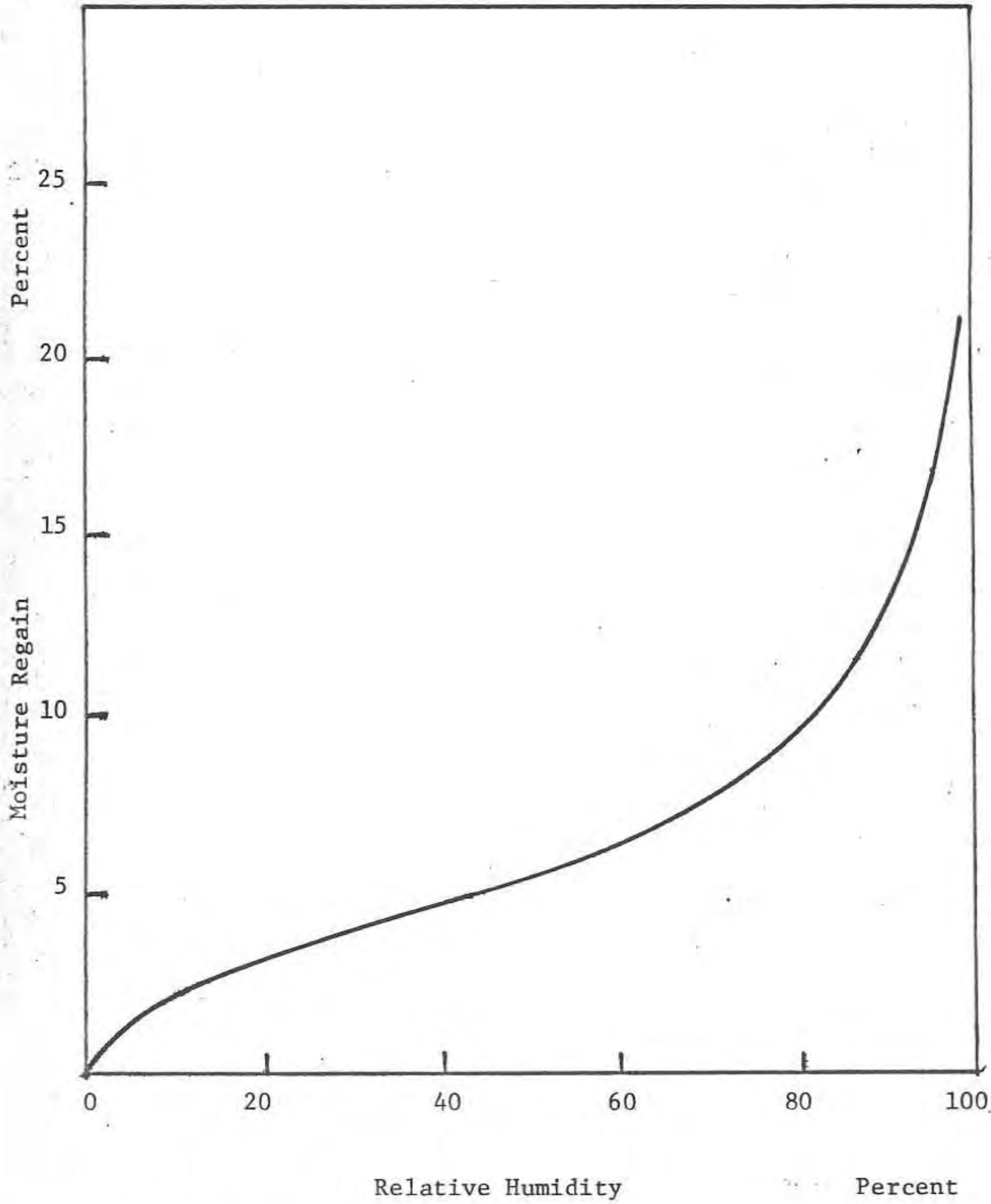


Figure 1. Sorption Isotherm for Cotton at 20° C

From J.W.S. Hearle, R.H. Peters, Moisture in Textiles (New York: Textile Book Publishers, Inc., Division of Interscience Publishers, Inc. Manchester and London, The Textile Institute, Buttersworth Scientific Publications), 1960, p. 18, fig. 8.

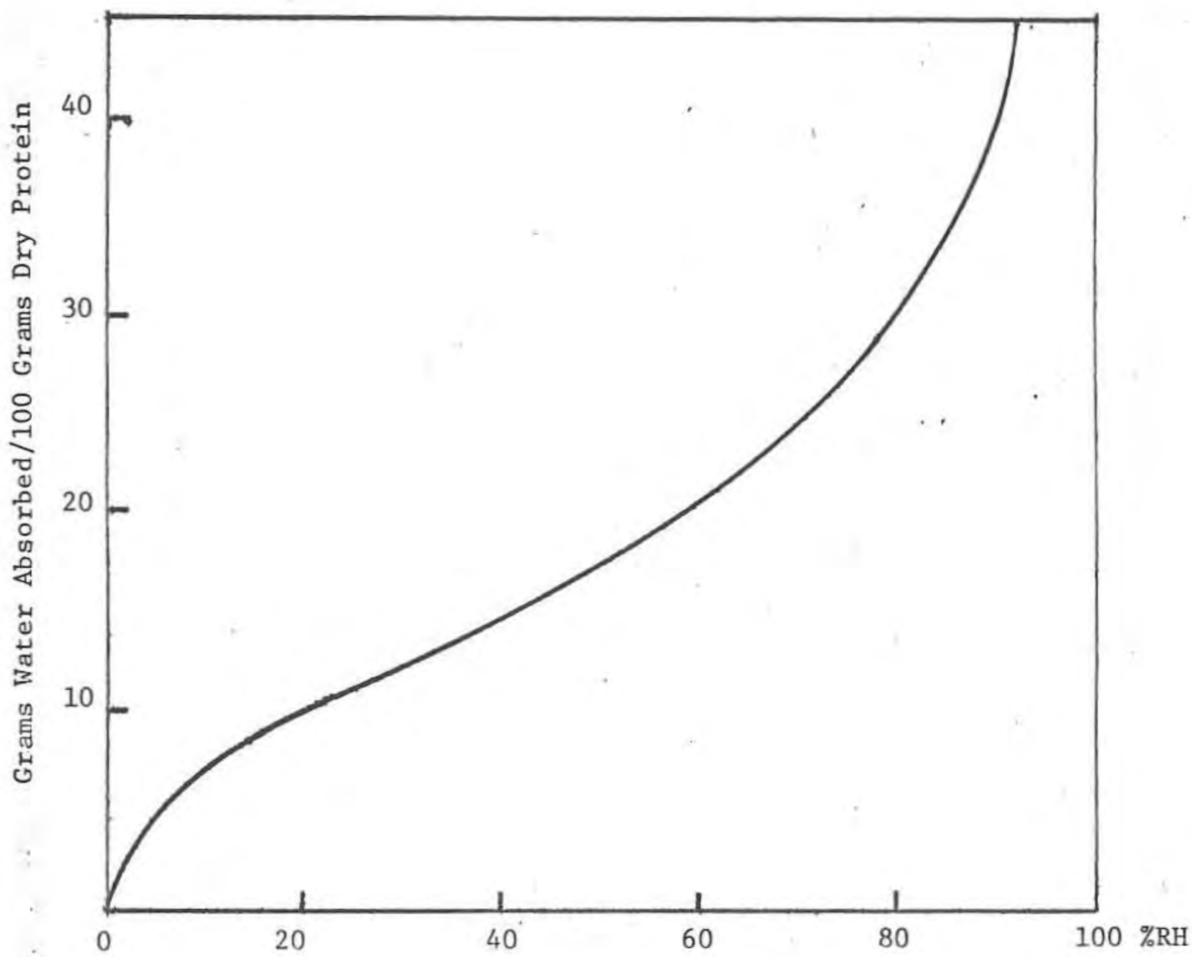


Figure 2. Absorption of Water Vapor by Collagen

From F. Haurowitz, Chemistry and Biology of Proteins (New York: Academic Press), 1950, p. 91, fig. 24.

The principal constituent of hide glue is collagen, the fibrous connective tissue found in mammals and fish.[7] Dry collagen absorbs water from the atmosphere, and the amount of water it can absorb is related to RH (fig. 2).

In both cellulose and collagen the amount of water absorbed can be large, affecting their mechanical behavior. In addition to their ability to absorb, their rate of moisture uptake significantly increases from about 75% RH to 100% RH. This will have some important implications later in the discussion.

Much has been written about the moisture permeability of oil paints, while little research has been done on their actual moisture content. Preliminary research suggests, however, the variability and importance of moisture content. For example, a 42-month old specimen of flake white oil paint (lead carbonate) weighing 0.2520 grams at 5% RH gains 0.0040 grams of water at 98% RH. This is an increase of only 1.6% water by weight, but different pigments and drying times probably affect the amount of water gained. In this particular specimen the change in moisture content was small, yet its effect on the paint was dramatic; this effect will be described below.

Since so much has been written on wood behavior and moisture content, I refer the reader to various texts listed in the endnotes.

As these artists' materials gain and lose moisture they tend to change dimensionally, to expand and contract, which will be described in detail below. A frequently encountered misconception is that this movement is the sole source of stress development and hence of cracking of the material, but this movement is not sufficient, for stress is only developed if the material is either partially or fully restrained during changes in moisture content. For fabric supported oil paintings, this restraint can come either from the various layers of the painting or from the stretcher.

II. Dimensional Changes (Expansion and Contraction)

Straightforward observation of the dimensional behavior of the artists' materials as a function of moisture content reveals useful data. Figures 3a through 3d show the changes in length of four different paint samples versus RH. Each sample had been aged 36 months in an environmentally uncontrolled interior room. All samples were taken from tubes as commercially available from various manufacturers and represent a much larger group of specimens. All paint and glue samples were isolated and free of any substrate. Tests were run over a period of several weeks, with samples cycled from low to high humidity and back again (or vice versa) several times. Some full cycles required nearly a week because the samples were allowed to equilibrate at a particular RH for about twelve hours before the corresponding measurement was taken. Shown here are plots of the fifth cycle. By this time the cycles had become regular, contrasting early cycles during which many specimens sagged considerably at high humidity.

The white lead, titanium dioxide and vermillion changed only slightly in total length, while the burnt umber changed dramatically with the variation in RH. These differing dimensional changes among types of paint probably effect the overall structure of the painting, but the present discussion is confined to differences among classes of materials, for example, between paint and glue. The behavior of the "vermillion", an artificial azo pigment,[8] seemed typical of this kind of pigment. When gaining moisture all specimens increased in rate of expansion at about 75-80% RH.

Fig. 4 demonstrates the rather massive dimensional changes of rabbit skin glue. This specimen was representative of many cast from granular rabbit skin glue mixed according to the manufacturer's directions. Of all the artists' materials glue demonstrates the greatest change in length, and it can be cited as the prime source of stress development in paintings.

The dimensional changes in fabric are more difficult to observe in a cyclic fashion, for once the free-hanging fabric enters a period of high RH the yarn configuration is altered so that the specimen shrinks (fig. 5a,b). This shrinkage alters the behavior of the free-hanging specimen. Therefore, for a free-hanging specimen, the first pass from low to high RH, before the change in yarn configuration happens, is the only one that reflects the behavior of a stretched fabric. A general picture of force developing behavior in the stretched fabric is more accurately observed from fig. 11a (showing tangent modulus vs. RH) and from tests of restrained linen (fig. 12).

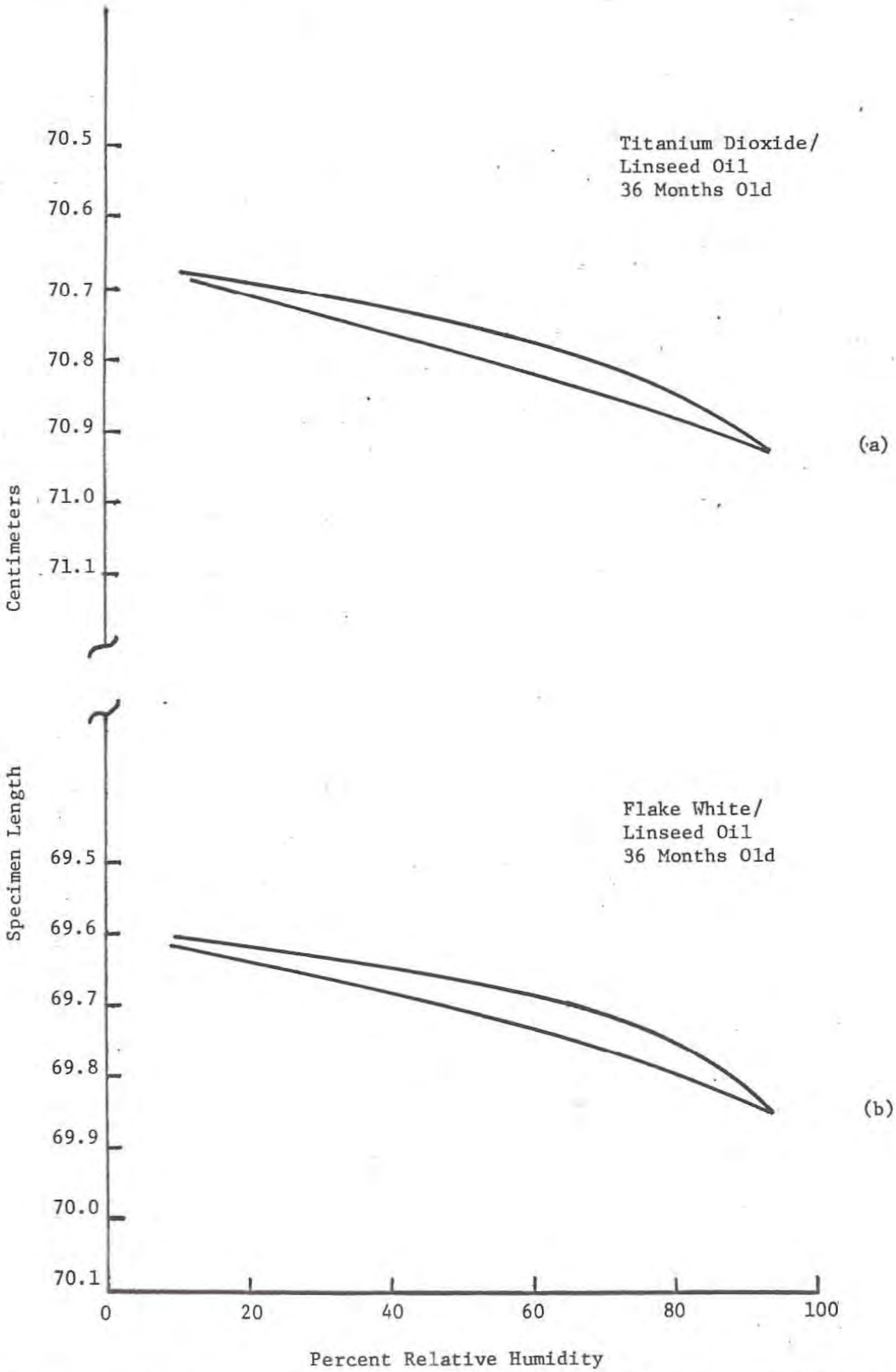


Figure 3 a, b. Unrestrained Dimensional Change in Oil Paint vs. Relative Humidity at 70° F

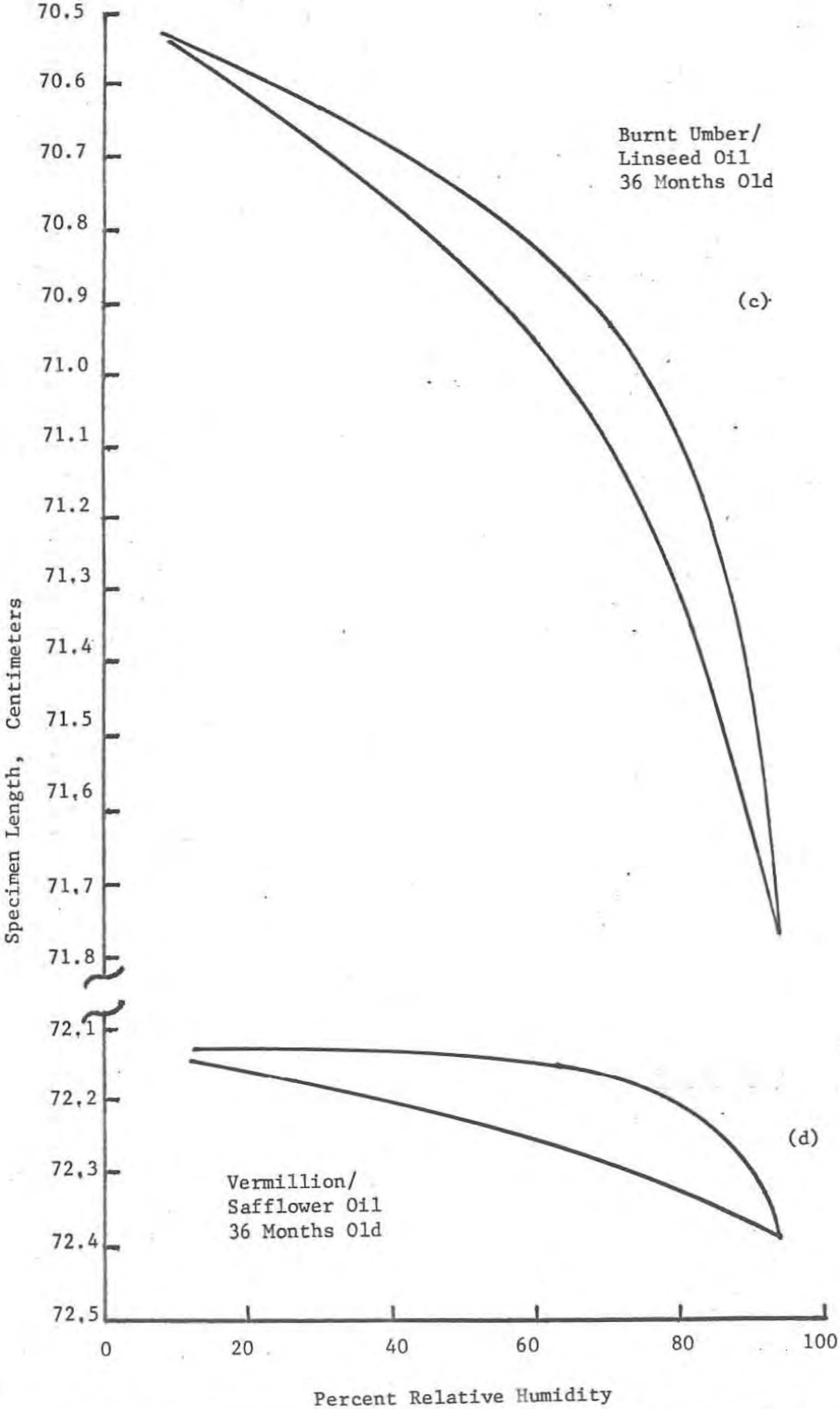
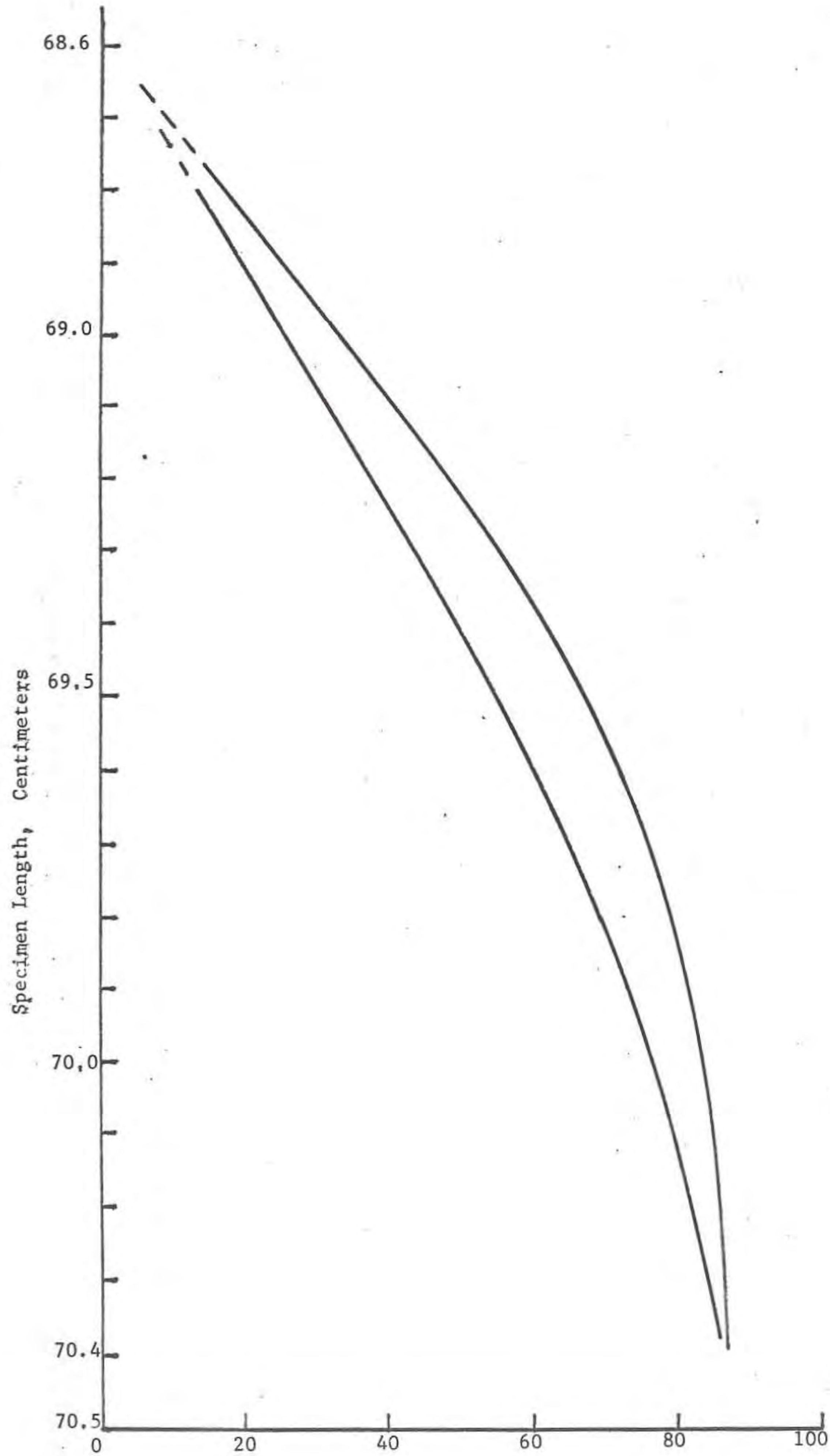


Figure 3 c, d. Unrestrained Dimensional Change in Oil Paint vs. Relative Humidity at 70° F


68.6
69.0
69.5
70.0
70.4
70.5
Specimen Length, Centimeters
0
20
40
60
80
100

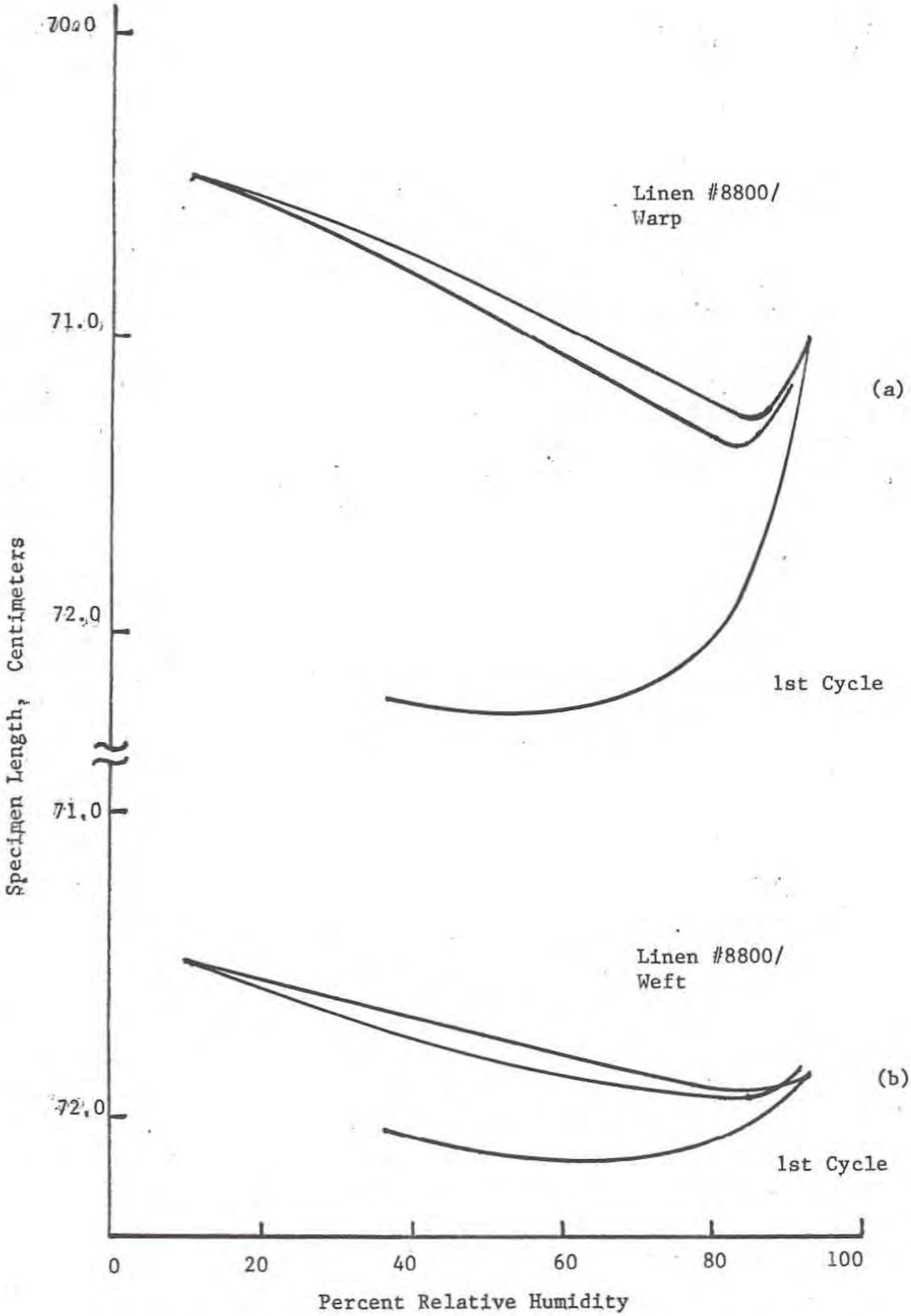


Figure 5 a, b. Unrestrained Dimensional Change in Linen Fabric vs. Relative Humidity at 70° F

III. Change in Modulus

To understand the behavior and deterioration of fabric supported paintings we must determine why paint and glue develop forces at all and why a thin layer of glue develops so much more force than does a paint layer ten times as thick. Actually, two materials with identical dimensional responses to moisture, upon being restrained, can develop very different forces. From a mechanical point of view, this is because the materials have different "mechanical properties". The modulus of one material is greater than the modulus of the other. The modulus of a material expresses the relationship between stress and strain, where stress is the distribution of force within the material and strain is the material deformation with respect to the undeformed dimensions. (For further definitions, see Glossaru.)

The concept of the modulus is fundamental to the interpretation of material behavior; it is the quantity that allows us to determine the magnitude of stress a material will develop if it is strained (expanded or contracted). Mathematically the modulus is defined as the ratio of stress to strain,

$$E = \sigma / \epsilon \qquad \text{in which} \qquad E = \text{modulus}$$

$$\sigma = \frac{\text{force}}{\text{area}} = \text{stress}$$

$$\epsilon = \frac{\text{deformation}}{\text{unrestrained length}} = \text{strain}$$

One way of looking at the force developed by shrinkage is to imagine that a specimen of material which would normally be restrained from shrinkage is allowed to contract. The amount of contraction is its deformation, δ, that is, the contracted length subtracted from the restrained length, $\delta = L_r - L_c$. The strain of the specimen then becomes the deformation divided by the contracted length, $\epsilon = \delta / L_c$. The stress of the restrained specimen is σ_r and is equal to the strain times the modulus, that is,

$$\sigma = \epsilon \times E = \left(\frac{\delta}{L_c}\right) \times E = \left(\frac{L_r - L_c}{L_c}\right) \times E$$

The total force (F) measured is then equal to the stress of the restrained specimen times its cross-sectional area ($F = \sigma \times A$, where A is equal to its width times its thickness). These relationships show that as the thicknesses of the glue and paint increase so does the total force. A higher modulus also increases the total force.

If a history of the stress-strain behavior of the materials discussed in this paper (glue, paint and fabric) were recorded, it would show that the properties of these materials are influenced by moisture content as well. While glue and paint show very low values of E (modulus) at high humidity, they have very high values of E at low humidities.

Figures 6 through 11 illustrate the general stress-strain behaviors of oil paint, glue size and fabric. While the absolute magnitudes of the various properties may vary somewhat, the overall performance is the same within each group of material.

For the paint, interpretation of the stress-strain curves (figs. 6a,b,c,d) explains important aspects of its behavior. At very high humidity the paint is quite <u>flexible</u> and exhibits very <u>plastic</u> behavior. It <u>creeps</u> to the point where it will completely release any applied stress within a short period of time, usually within a few hours. In addition, the <u>breaking stresses</u> of the paint are extremely low, while the <u>breaking strains</u> are high.

Since the paint exhibits such plastic behavior, tensile failure is extremely unlikely at very high humidity except under extraordinary circumstances. However, as the RH decreases the paints exhibit more elastic behavior and demonstrate less creep. At very low humidity the paint also becomes quite brittle and while the breaking stress is the highest, the breaking strain is the lowest. The paint's ability to accomodate dimensional changes is significantly altered by dessication. The transition point from a generally plastic to a generally elastic behavior seems to occur at about 60% RH, 71° F, though this can vary slightly from pigment to pigment and with the age of the paint. Note that for the burnt umber (fig. 6d) breaking stress does not show on the graph because the breaking strain, even at extremely low RH, was very large.

With increased oxidation and polymerization of the paint a general increase in the modulus will occur at all levels of RH and a general decrease in breaking stress follows. When the paint is most brittle and cannot appreciably creep at low RH it has the highest potential for developing stress and thus for becoming itself part of the support of the painting.

Fig. 7 shows the tangent moduli of the paint samples. The tangent modulus conveniently displays the change in modulus of the four paint samples as RH changes.

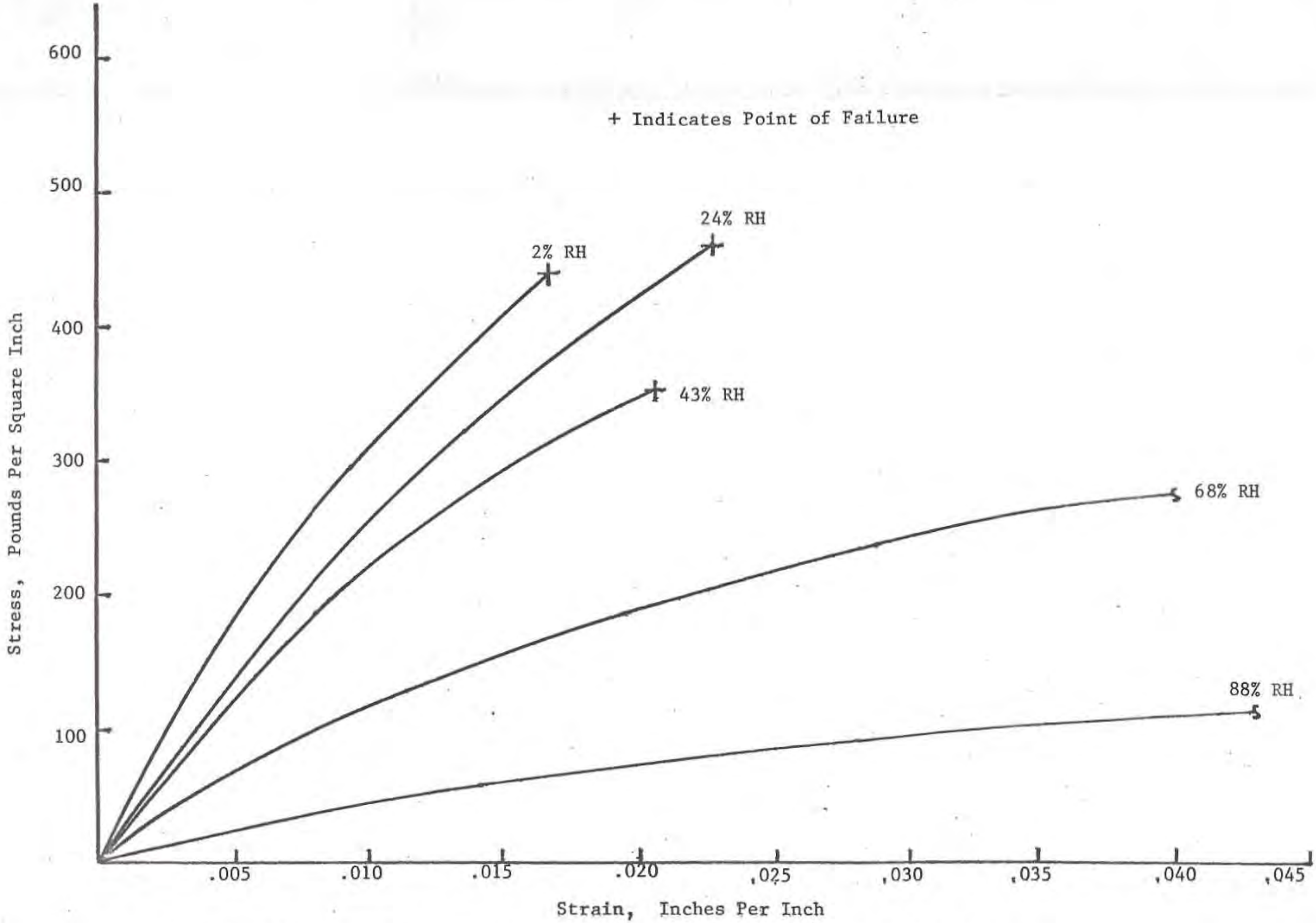


Figure 6 a. Effect of Relative Humidity on Stress-Strain Properties of Flake White in Linseed Oil, 36 Months Old, at 70° F

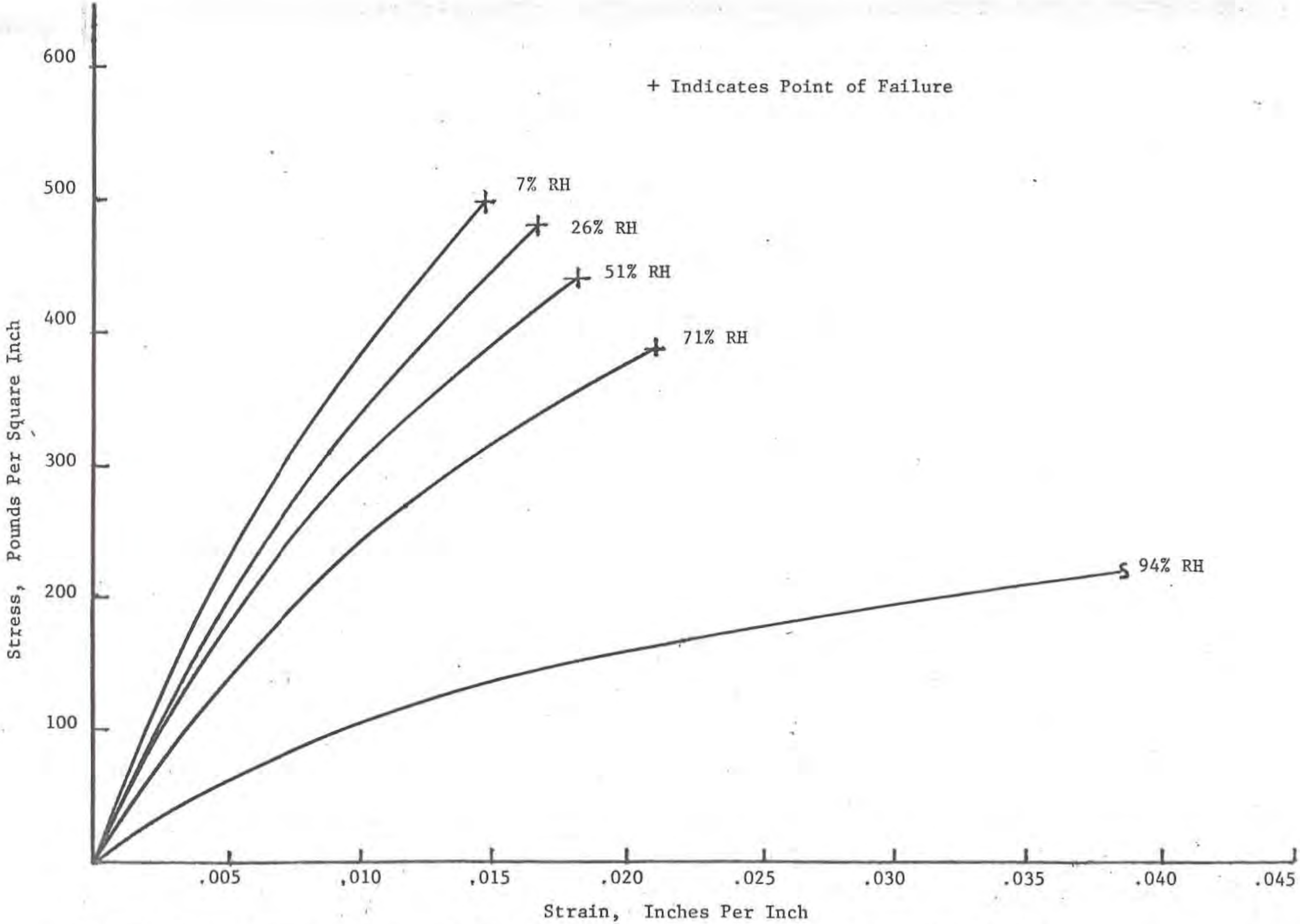
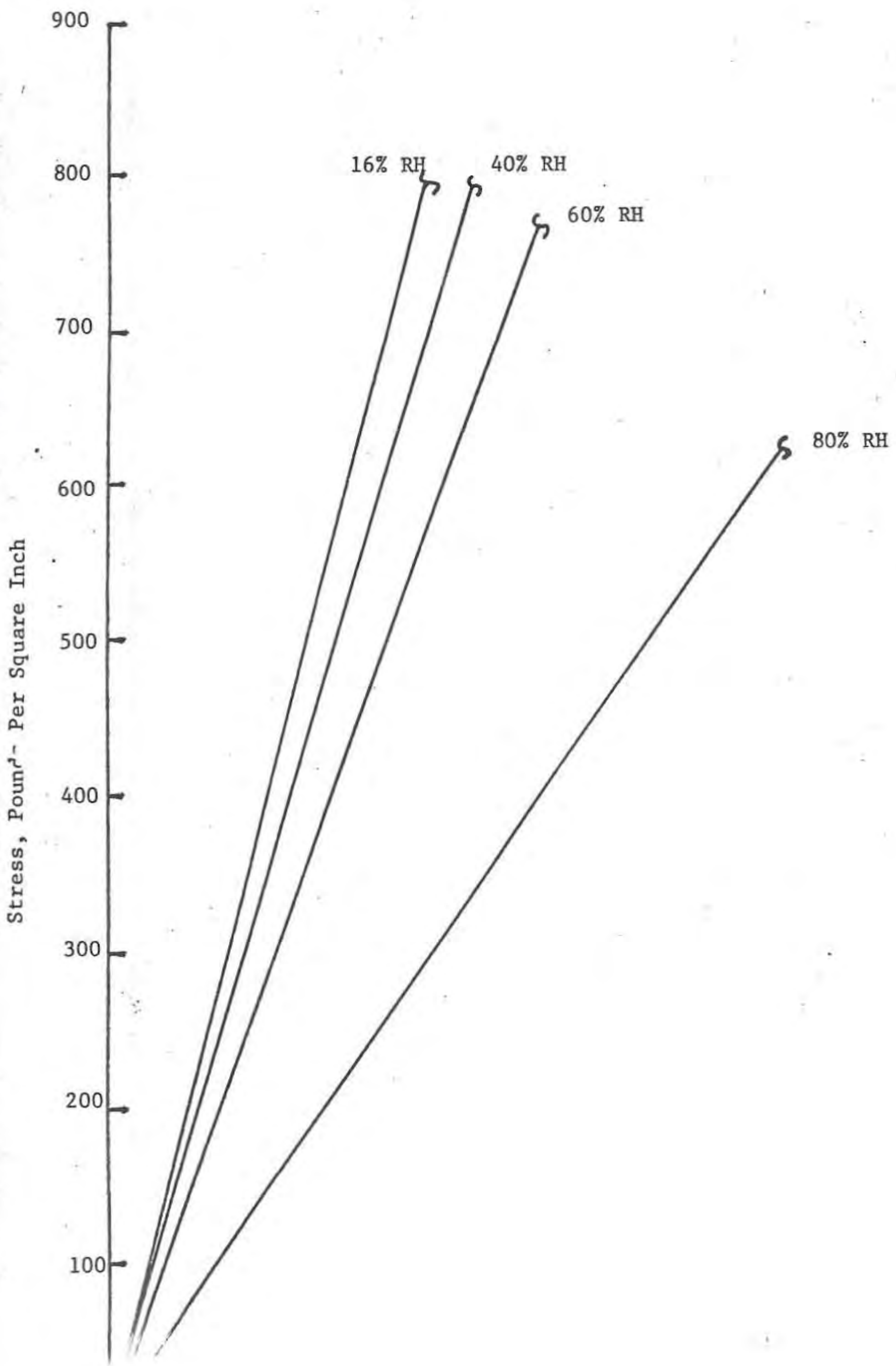


Figure 6 b, Effect of Relative Humidity on Stress-Strain Properties of Titanium Dioxide in Linseed Oil, 36 Months Old, at 70° F


900
800
700
600
500
400
300
200
100
Stress, Poun'- Per Square Inch
16% RH
40% RH
60% RH
80% RH

The hide glue, in this case rabbit skin glue, demonstrates the greatest changes in mechanical properties with varied moisture content of all the materials (fig. 8). At about 95% RH the material is quite flexible and has a modulus of 4000 psi; at 10% RH the modulus is nearly 400,000 psi. Of all the materials found in a painting, glue has the highest modulus, and it has a breaking strength approaching 10,000 psi. At about 75% RH its material properties change tremendously, corresponding to the most significant change in its moisture content. Fig. 9 shows this change while relating the modulus to RH.

Fabric exhibits more complex behavior because it is not a homogeneous material; it is a structure fabricated by weaving yarns of spun flax fibers. Nevertheless some general observations can be made. With respect to the stress-strain curve (fig. 10a,b), at low strain much of the behavior simply results from straightening crimped yarns (crimp removal zone at strains below 0.025). After crimp removal the actual yarn behavior takes over. Although increased moisture influences the modulus by making the crimp more difficult to remove, moisture affects the actual yarn behavior to a lesser degree, and thus the yarn behavior contributes less to the modulus of the fabric. Very high moisture content appears to lubricate the fibers so that slippage occurs, and a lower yarn modulus results as the strain increases, i.e., more elongation results from less stress.

In general, when testing isolated fabric specimens the warp and weft directions show obvious differences. Stretched fabrics found on paintings seem to behave similarly in both directions and similarly to the warp of an isolated test fabric. These similarities are due to stretching the fabric before painting. Raw fabric weft yarns have very little crimp, but upon stretching, the warp yarns induce more crimp into the weft yarns (crimp transfer), making the stretched fabric more orthotropic. Visual examination of actual painting fabrics and of figures 16 and 17 bear this out.

Equally important is that although a fabric, upon being stretched, appears to lose some of the yarn crimp (is strained beyond the crimp removal zone), the first time the fabric is subjected to high humidity the yarn fibers slip and the fabric relaxes and returns to the crimp behavior zone. In fact, to maintain a high strain on a fabric and subject it to high humidity without losing much of the fabric tension seems impossible.

Having now discussed the dimensional changes and the modulus changes of the materials, their comparison becomes of interest. In the paint specimens characteristic behavior exists: paints that develop the high modulus undergo small dimensional changes; paints with generally low modulus behavior undergo fairly large dimensional changes. If restrained, the paints with high modulus are the ones that will develop high stress (e.g., titanium dioxide and artificial vermillion). Very low modulus paints maintain such plastic behavior that little or no stress develops (e.g., burnt umber). As an oil film oxidizes and polymerizes, the modulus increases, so higher stress development should be expected in older, restrained films. Unfortunately, strength of the film is not necessarily maintained as time passes.

The glue film exhibits both high modulus development and large dimensional changes, and if restrained, should show very high stress

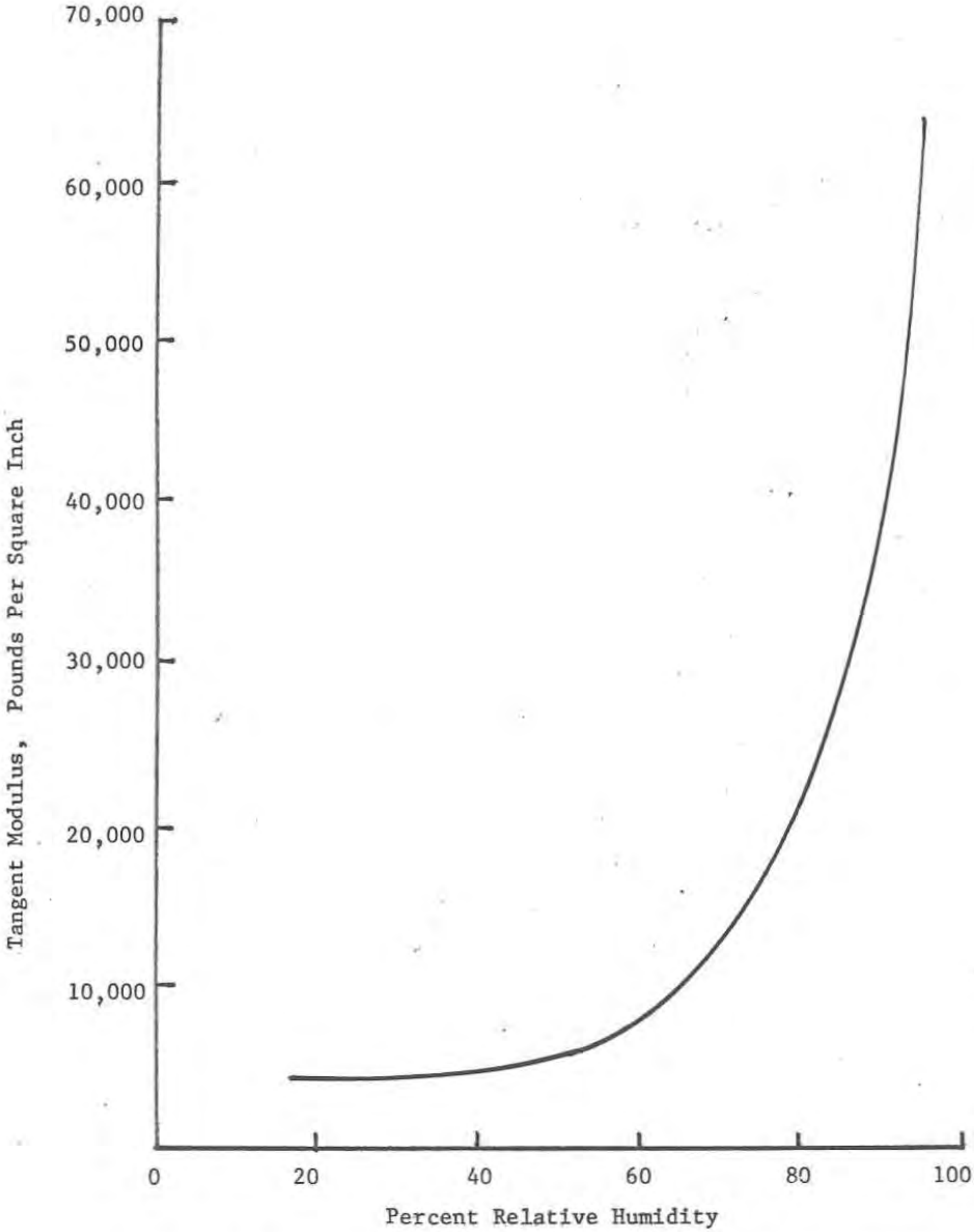


Figure 11 a, Effect of Relative Humidity on Tangent Modulus of Linen in Warp Direction, Medium Weight, 32 Yarns Per Inch (#8800 Ulster), at 71° F

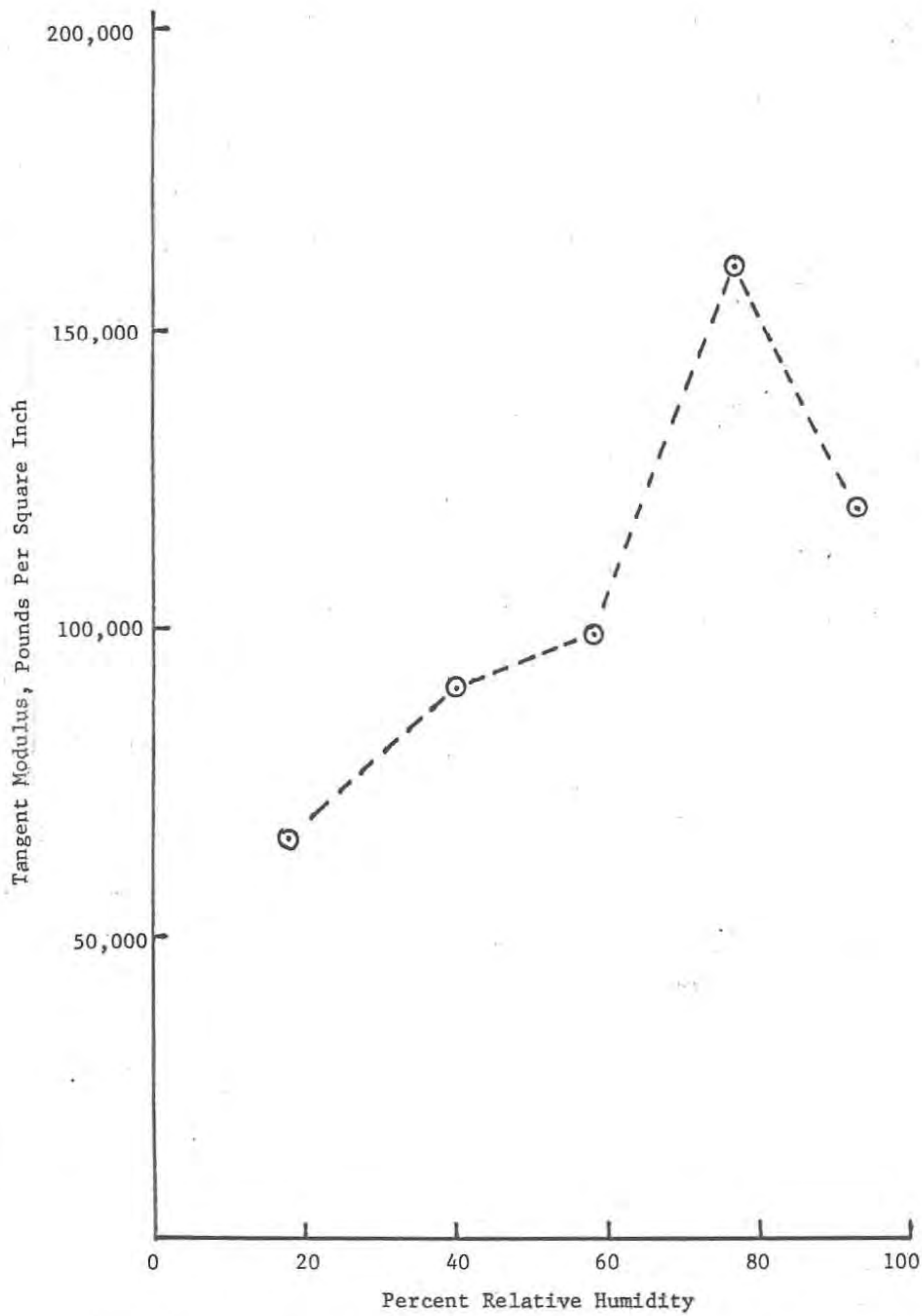


Figure 11 b. Effect of Relative Humidity on the Tangent Modulus of Linen in Weft (Fill) Direction, Medium Weight, 30 Yarns Per Inch (#8800 Ulster), at 71° F. (Preliminary Results) development. This phenomenon will be discussed later.

The fabric develops both high modulus and dimensional change at humidities above 80%, and as expected, most force development appears in this range.

IV. Restrained Testing

The foregoing discussion alludes to the development of a tensile stress within a material when that material, which would otherwise contract with a loss of moisture content, is restrained from contraction. If the dimensions of the specimen of material are known, then that stress is measurable. If these dimensions are not easily obtained, as in a sample of fabric, then the total force developed at one end of the specimen is measurable.

Tests were run on strips of linen (comparable to that found in a given painting), having dimensions 7 X 0.5 inches with a 32 X 32 thread per inch count; on cast strips of rabbit skin glue with the same length and cross-sectional area of 0.000483 square inch; and on cast strips of paint 7 inches long with a cross-sectional area of 0.00243 square inch. The individual specimens were restrained to a near constant length and the force developed by each specimen while changing the RH at a constant temperature was measured, to observe the relative behavior of each material.

Taking the warp direction sample of the linen first, a record was made of force versus RH (fig. 12). In this case two distinct sections of the graph are apparent: from zero to 85% RH; and from 85% to 100% RH. The graph is relatively flat with a slight increase in total force as the specimen is dessicated, but at 85% RH and above, a rapid and marked increase

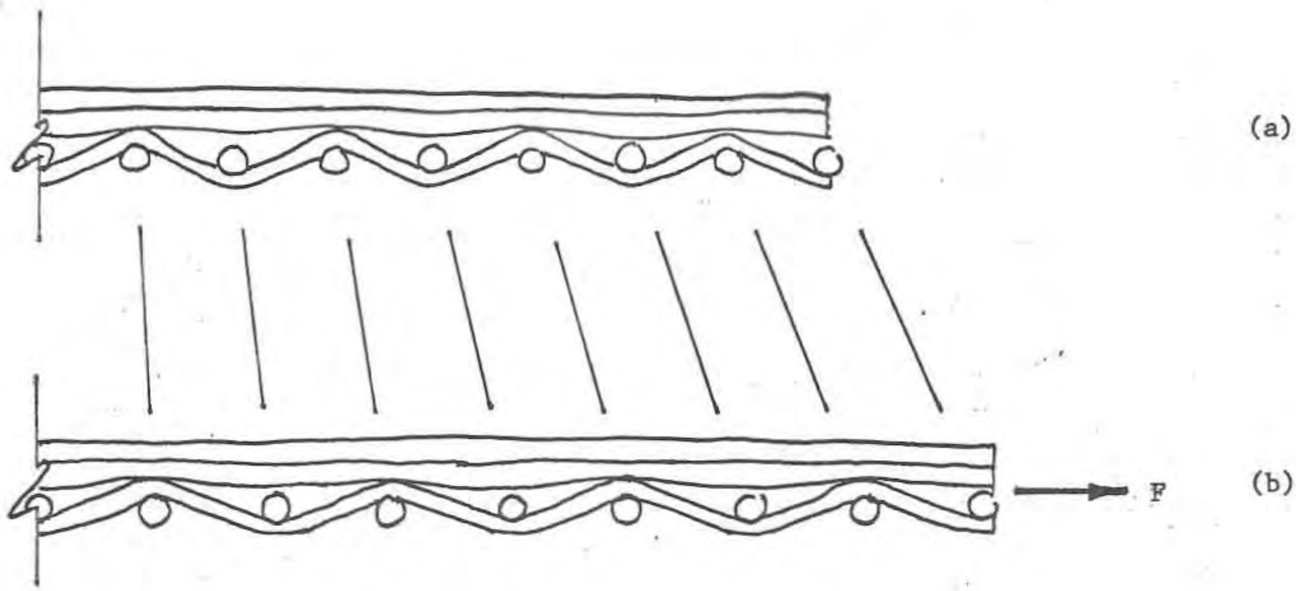


Figure 18. Expansion of a Painting Due to Either Stretching or Stretcher Expansion. All layers are therefore strained.

in total force is observable. This behavior was measured during a cycle of four days duration and was repeated during several following cycles. Above 95% RH the total force becomes even higher, reaching the point where some fiber slippage occurs and resulting in a net decrease in force on the specimen.

Next a cast strip of rabbit skin glue was tested. It was actually somewhat thicker then the layer normally found in a painting, so the recorded forces were mathematically corrected to those for a film 0.00048 inch thick and 0.5 inch wide. The plot of the total force versus RH is shown in fig. 13. The complete cycle lasted three days. This plot clearly shows the remarkably high force development in rabbit skin glue. From 96% RH to about 80% RH relatively little total force is developed, while from 80% RH to 5% RH massive force is developed. (Note that going from low RH to high RH a different path is followed.)

Finally a strip of paint was tested. It was 42 months old and chosen for its degree of drying.[9] The pigment was an azo pigment, vermillion, in safflower oil and showed nearly twice the modulus of white lead and titanium dioxide paints after comparable drying time. As with the rabbit skin glue, the dimensions were corrected, this time to 0.0048 inch thick and 0.5 inch long. Fig. 14 shows that above 75% RH no force developed in the specimen, but from 75% RH to 5% RH force developed and at a faster rate than that of the fabric tested. At humidities of 75% and above, the paint creeps, losing all ability to maintain a force.

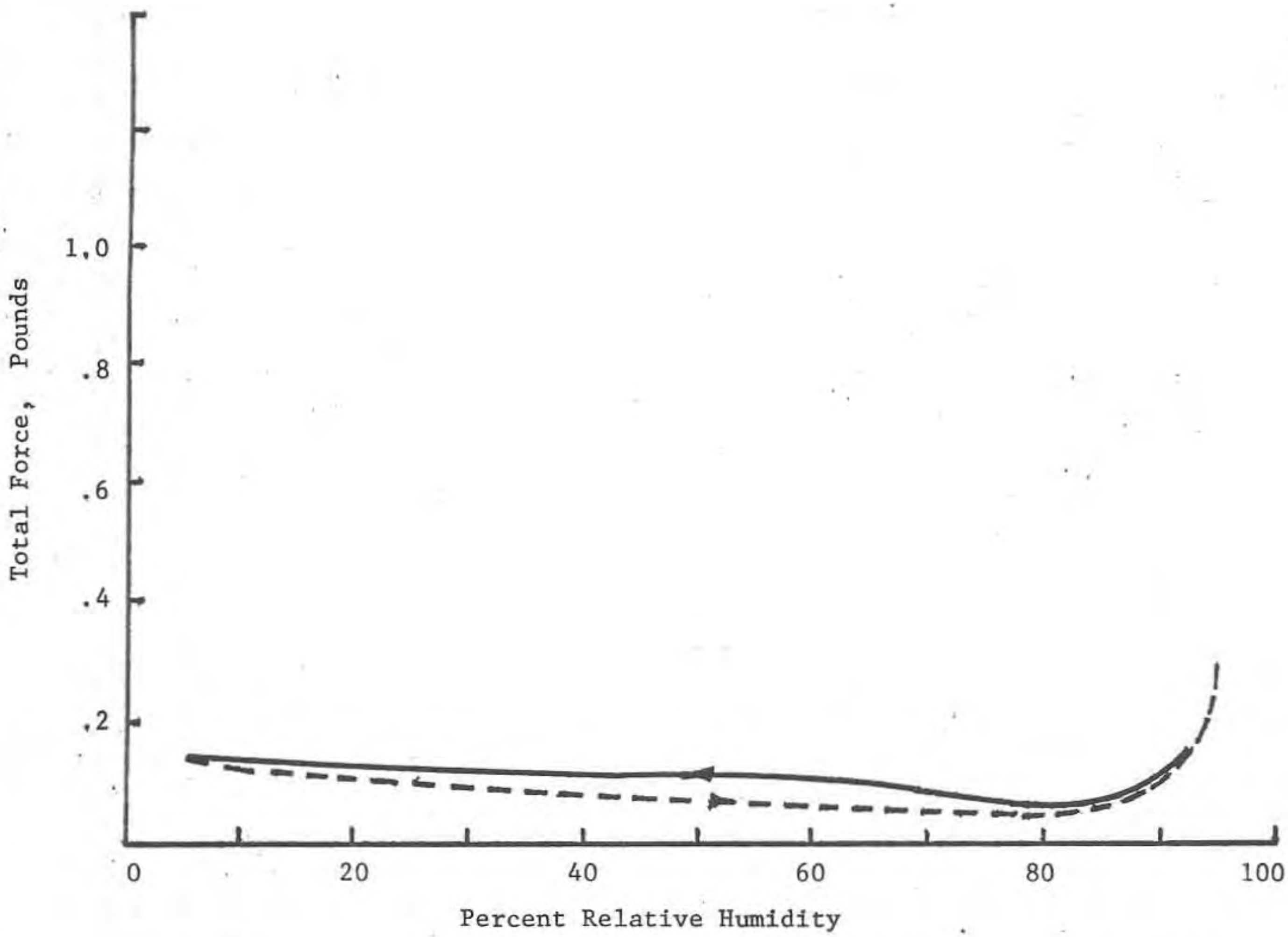


Figure 12. Restrained Specimen Force Development vs. Relative Humidity at 71° F for Linen in Warp Direction (#8800 Ulster). Length 7 inches. Width 0.5 inch (16 yarns).

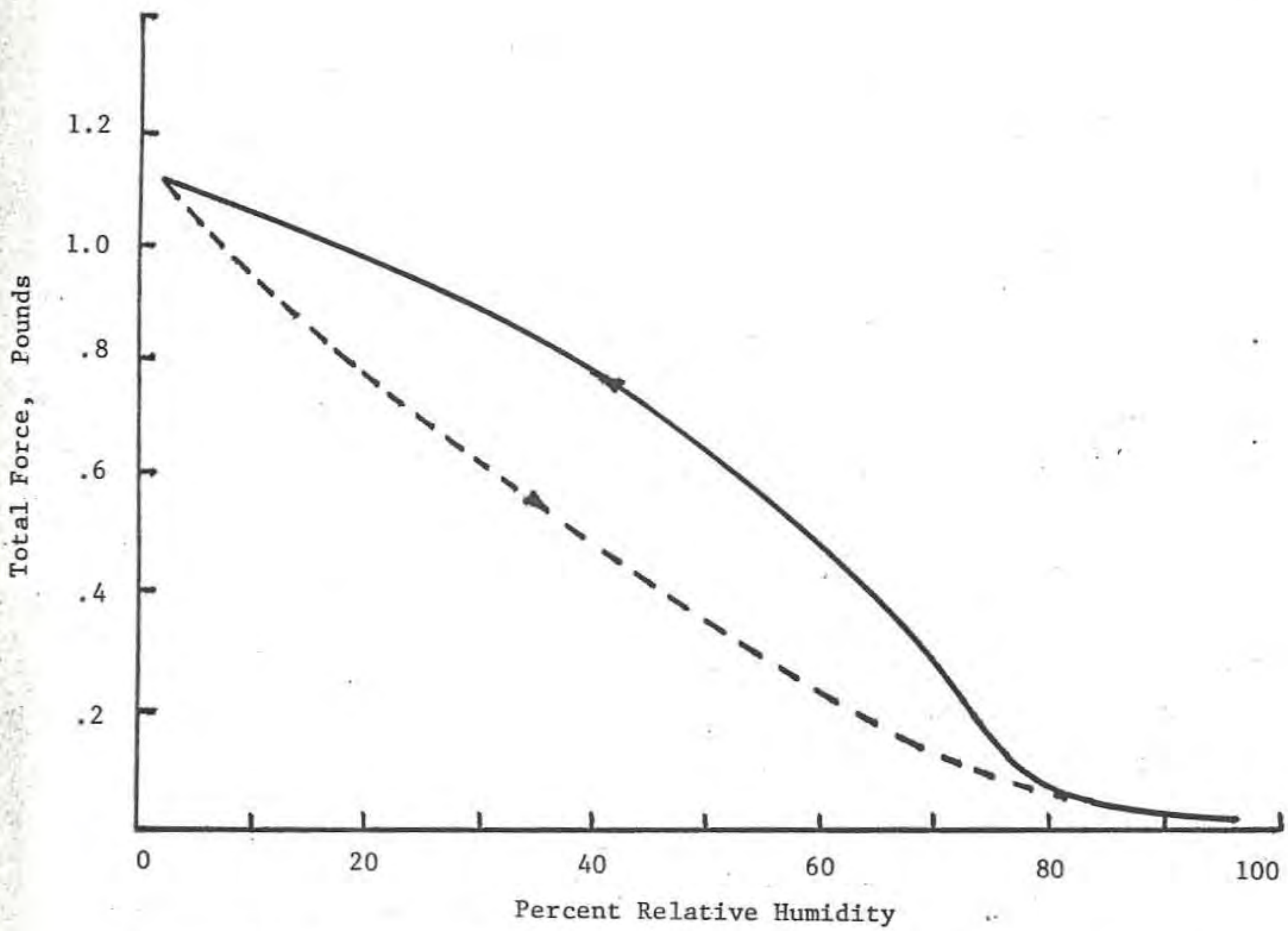


Figure 13. Restrained Specimen Force Development vs. Relative Humidity at 71° F for Rabbit Skin Glue. Length 7 inches. Width 0.5 inch. Thickness Adjusted to 0.00048 inch. Resultant Cross-sectional Area 0.00024 square inch.

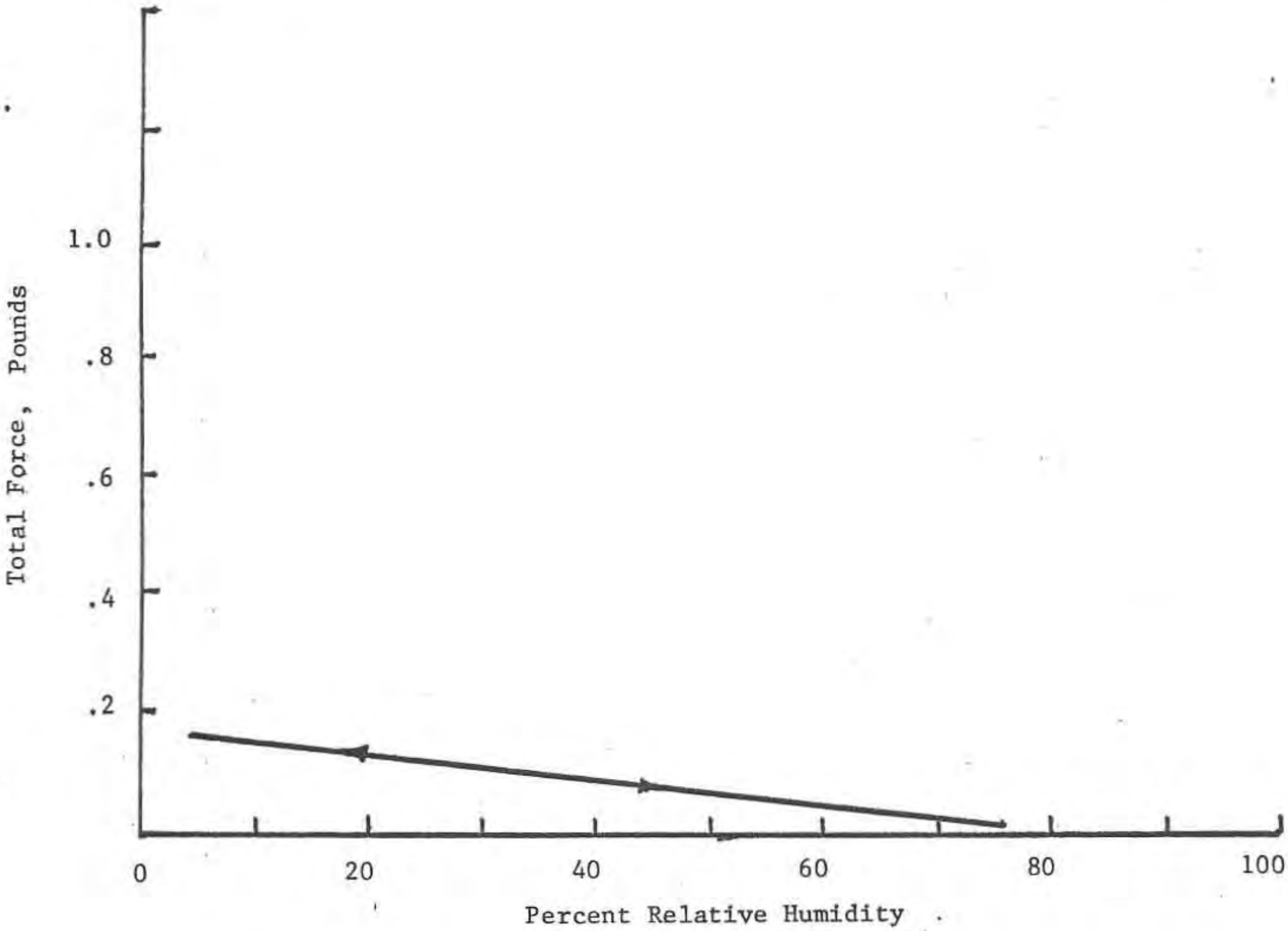


Figure 14. Restrained Specimen Force Development vs. Relative Humidity at 71° F for Artificial Vermillion in Safflower Oil. Length 7 inches. Width 0.5 inch. Thickness 0.0048 inch. Cross-sectional Area 0.00243 square inch.

Opinions have been expressed that a painting, composed of layered materials, is too complex for analysis and that research on its separate layers does not offer meaningful information for the total painting. Actually, the opposite is true, because the material behaviors of the individual materials can be summarized mathematically to project the performance of a total structure, in this case a painting. Therefore, if the forces developed by the separate materials are added together at each point of RH, a composite results. Fig. 15 shows the composite of the individual materials tested and indicates that the general character of each material is retained. This graph, then, predicts the behavior of an actual painting of similar construction.

To compare this theoretical analysis with the actual behavior of a painting, samples from a 1912 painting by the American artist Duncan Smith were tested. Test strips were cut in both the warp and weft directions, each 7 inches long and 0.5 inch wide. They were tested in the same manner as the specimens of individual materials, that is, they were held at a constant length during the full humidity cycle. The paint film was essentially uncracked having only microscopic fissures at the top of the weave pattern. The painting consists of a medium weight linen with layers of rabbit skin glue, white lead oil ground and a thin wash of ivory black paint totalling 0.017 inch in thickness.

The painting samples yielded similarly shaped curves (figs. 16 and 17) even though one curve illustrates the behavior of the warp direction and the other describes that of the weft (fill). Both curves compare to the mathematically projected composite plot of fig. 15. Even the magnitudes of

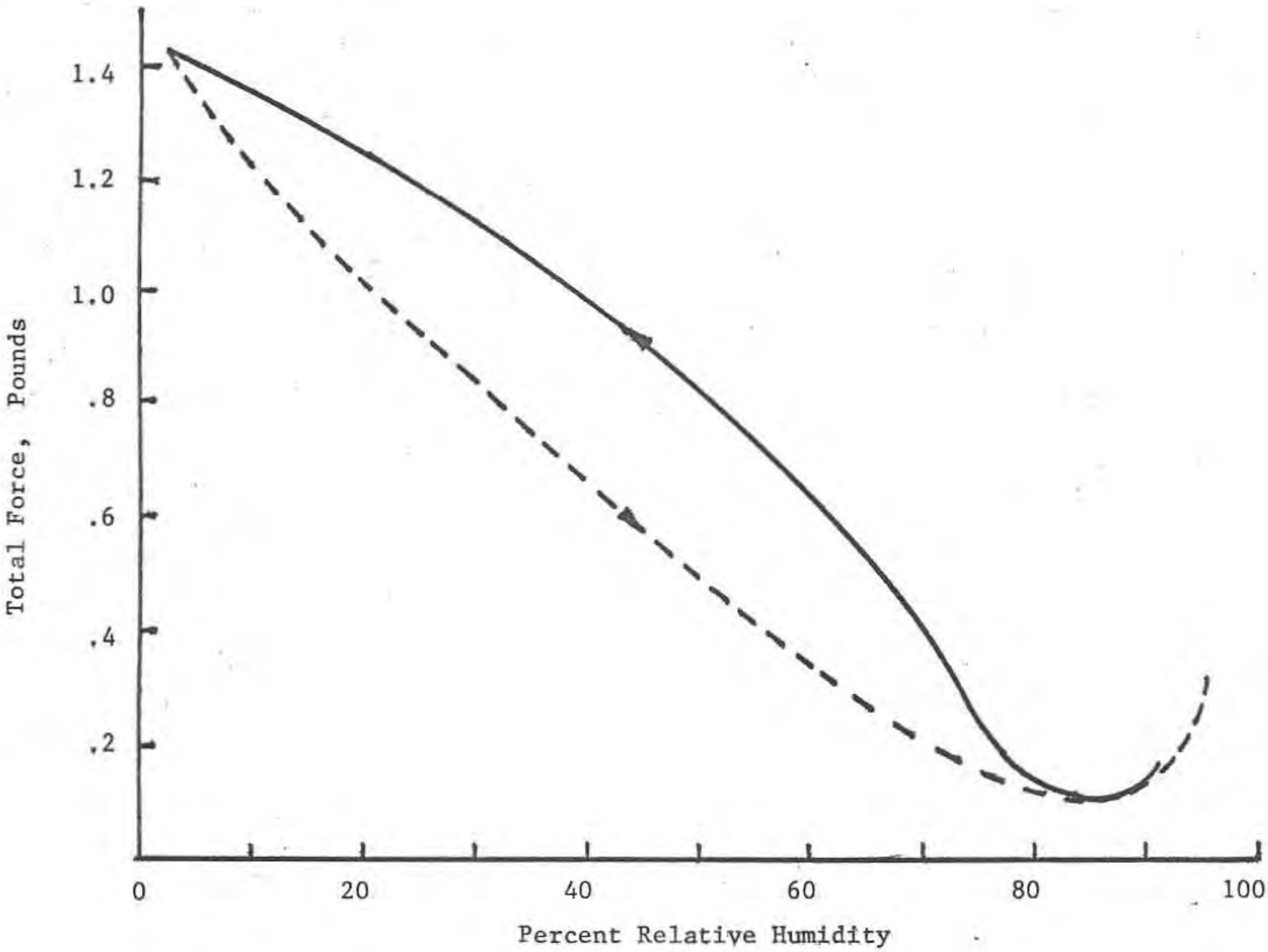


Figure 15. Restrained Specimen Force Development vs. Relative Humidity at 71° F. Composite of Forces in Figures 12 through 14.

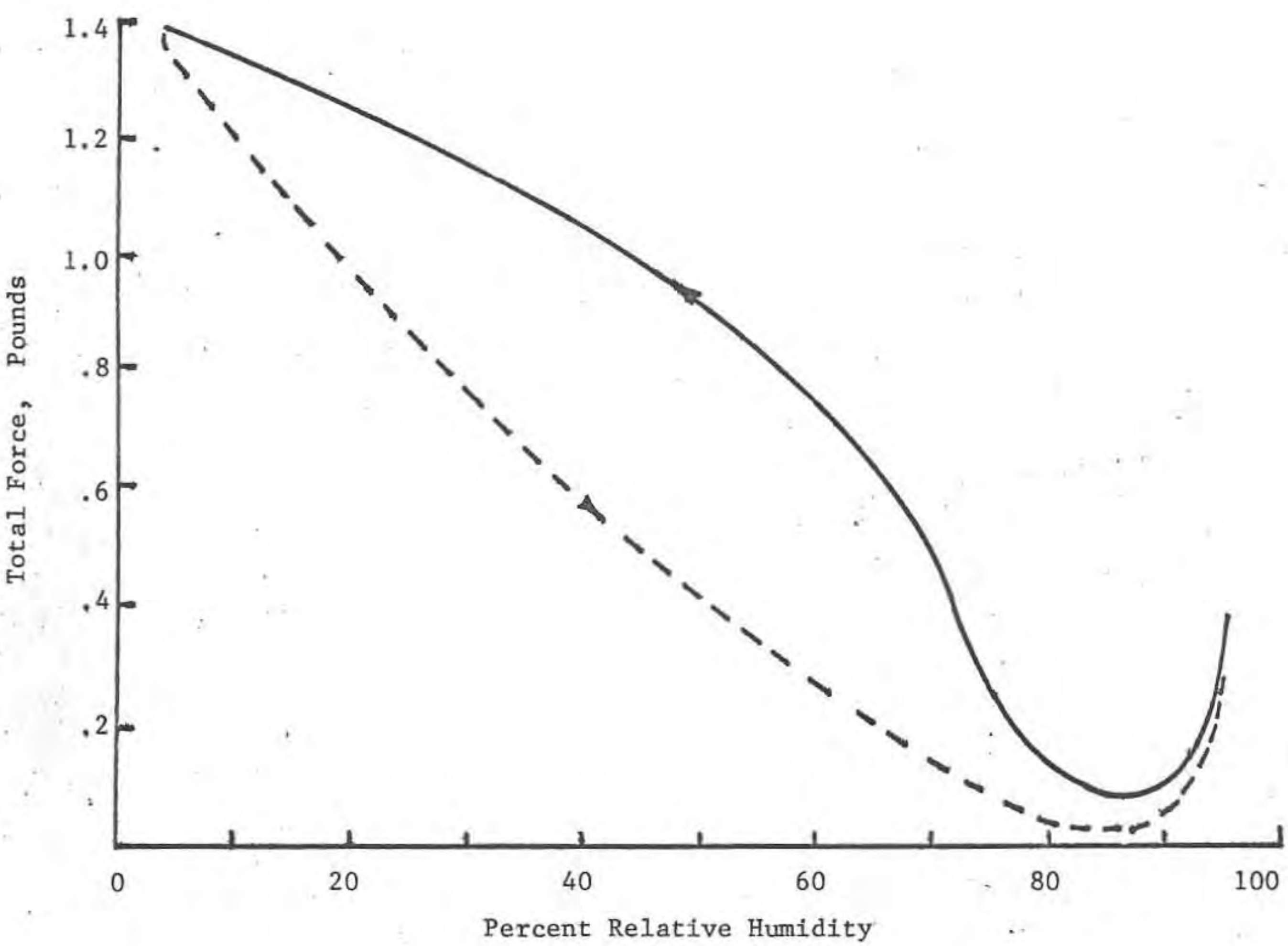


Figure 16. Restrained Specimen Force Development vs. Relative Humidity at 71° F for Warp Direction Sample from Painting by Duncan Smith, Dated 1912.

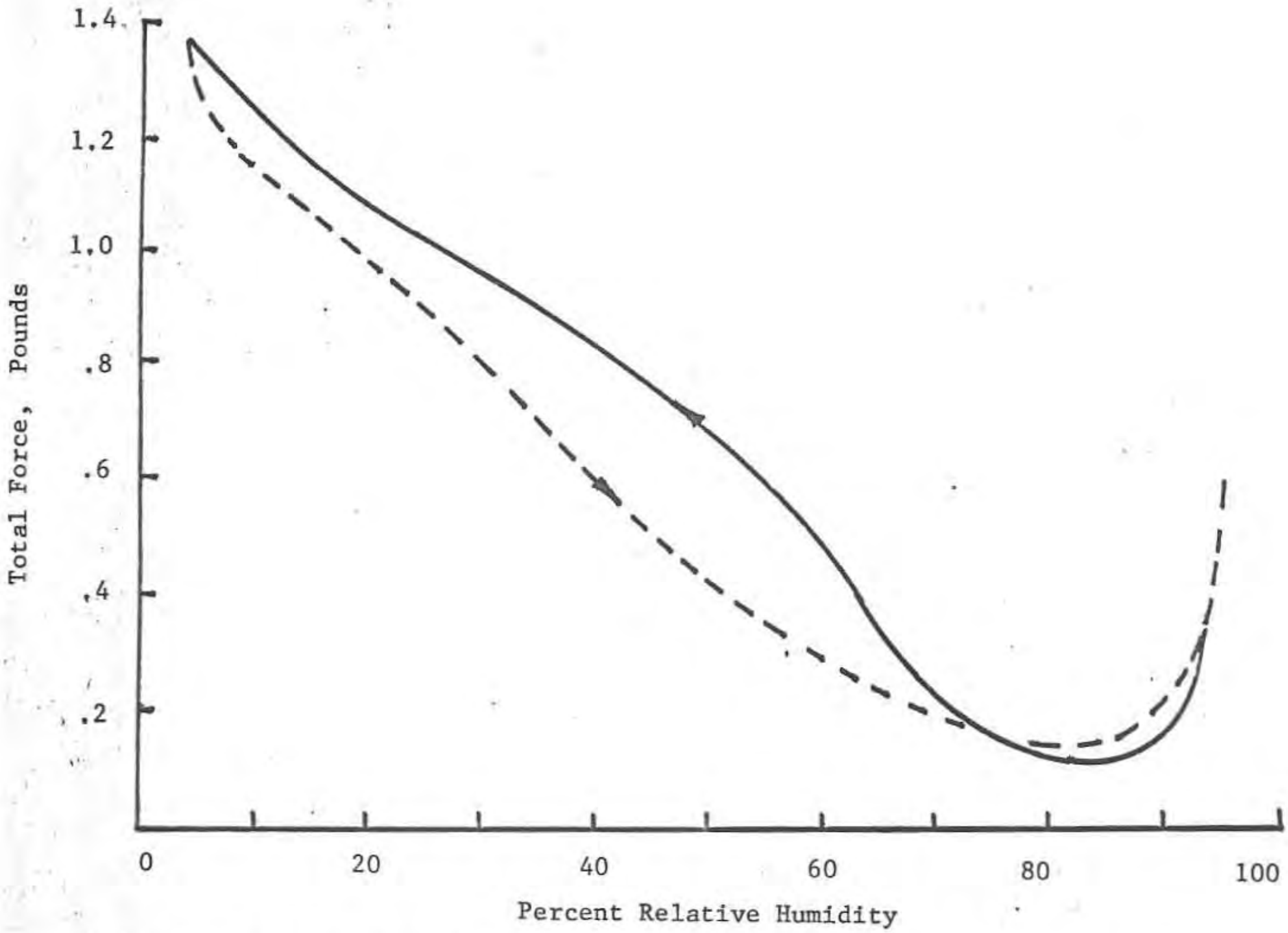


Figure 17. Restrained Specimen Force Development vs. Relative Humidity at 71° F for Weft (Fill) Direction Sample from Painting by Duncan Smith, Dated 1912.

the forces are remarkably alike in all these, indicating that the theoretical composite plot reflects the general behavior of both the warp and weft directions of specimens from an actual painting.

Most important is that the force can now be identified as originating in specific layers as a function of RH. From zero to 80% RH the single most important source of force is the glue layer; the paint layer is the next, and lastly, the fabric. Since these forces are directly proportional to the thicknesses of the respective layers, thicker paint and glue layers would develop even higher forces. Even more significant is that the fabric is responsible for a decreasing proportion of the total force in a painting as the RH decreases. In fact, at 50% RH the fabric of the hypothetical composite is supporting only 13% of the total force and at 10% RH the fabric is supporting only 10% of the force. In other words, the glue is really the support of the painting having a glue size layer and the paint film is the second contributing support. The only time a painting in the humidity range below 80% is fully supported by the fabric is after a crack through the paint, ground and glue layers has formed. After crack formation, the fabric simply acts as a "safety net" holding the pieces of the painting together. Under very high RH conditions, from about 85% to 100% RH for the restrained painting, the fabric is responsible for nearly all of the force in the given examples and only under these circumstances it is actually "supporting" the painting.

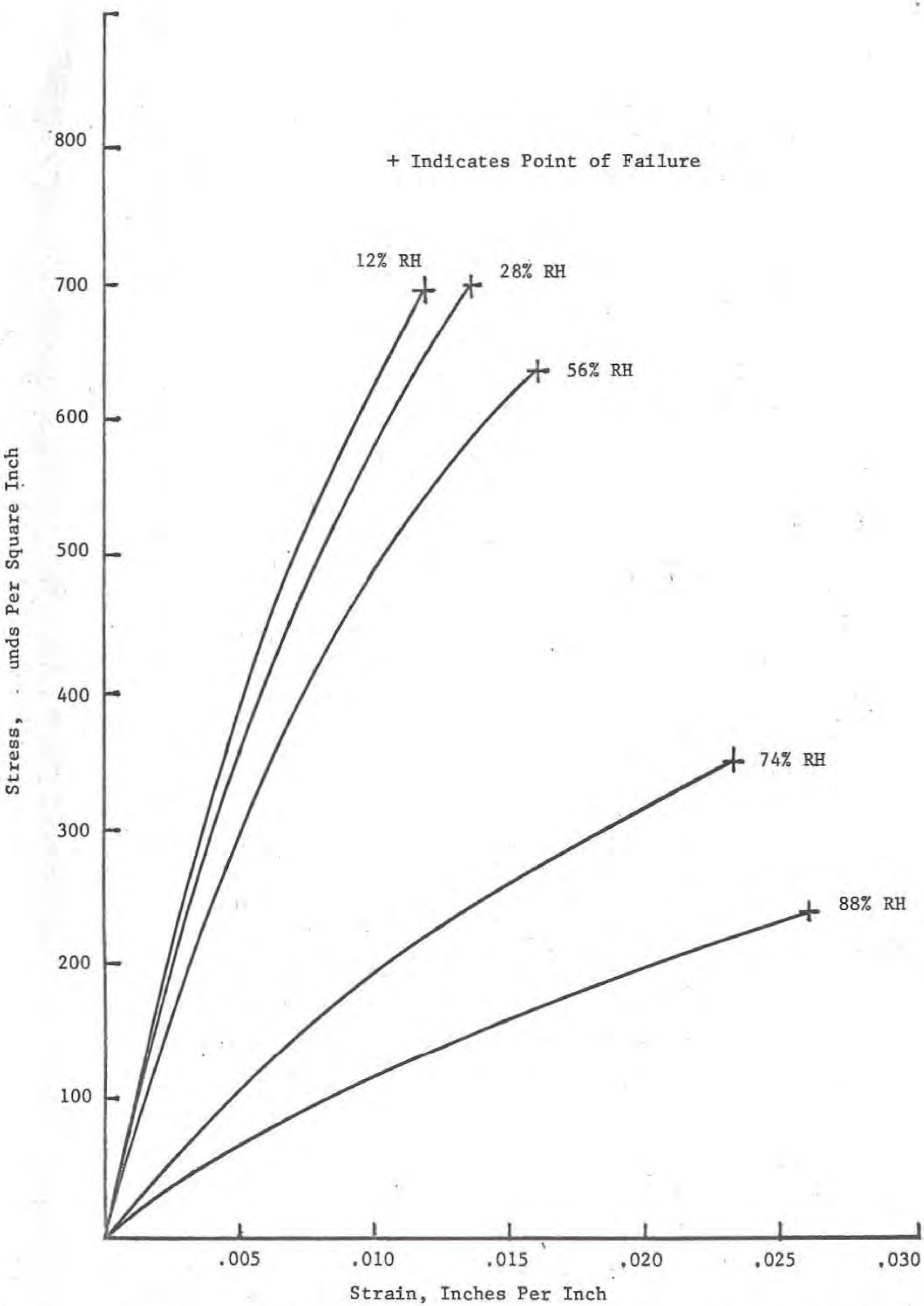
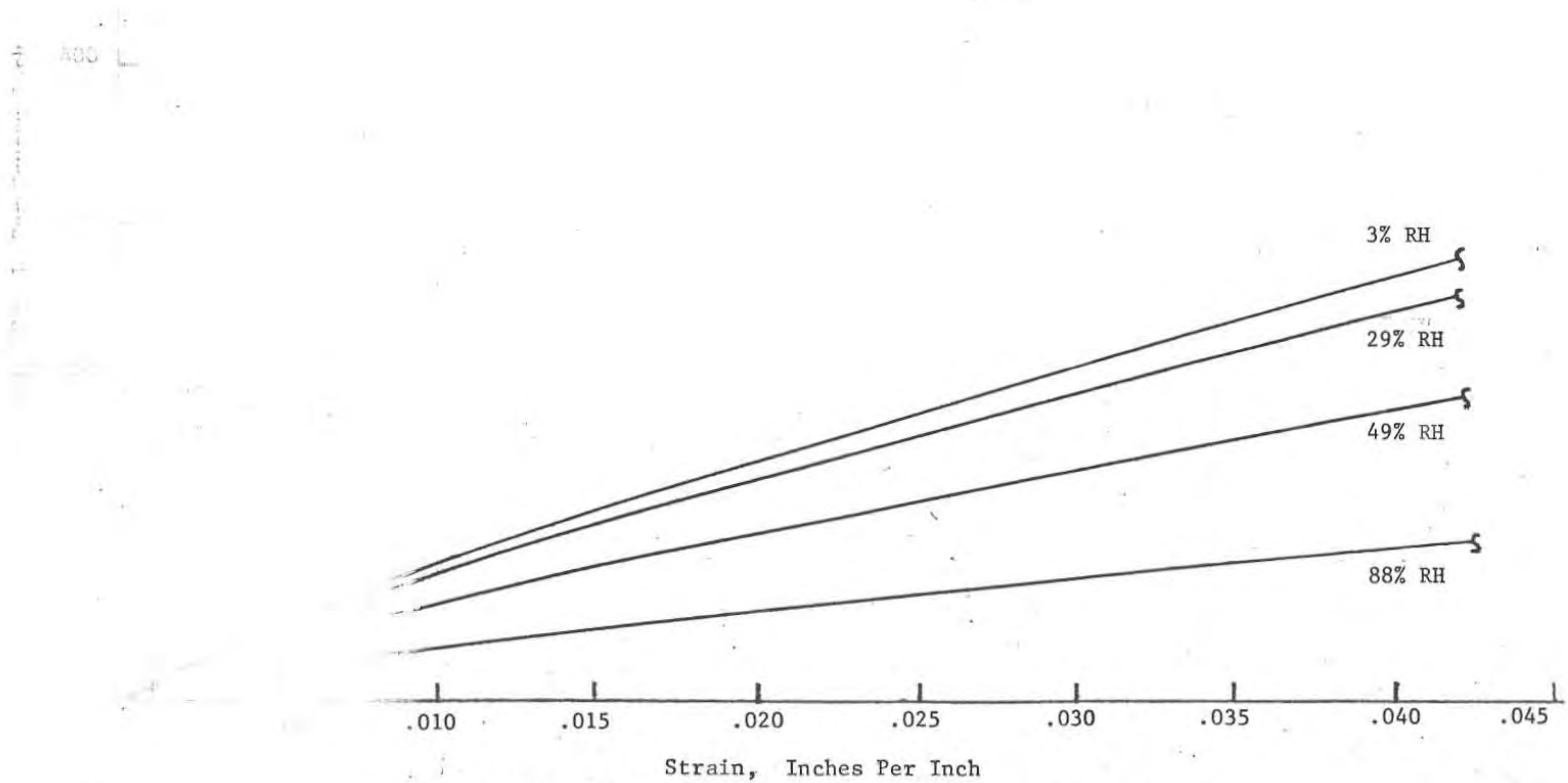


Figure 6 c. Effect of Relative Humidity on Stress-Strain Properties of Artificial Vermillion (Azo) in Safflower Oil, 36 Months Old, at 70° F



...f Relative Humidity on Stress-Strain Properties of Burnt Umber
...d Oil, 36 Months Old, at 70° F

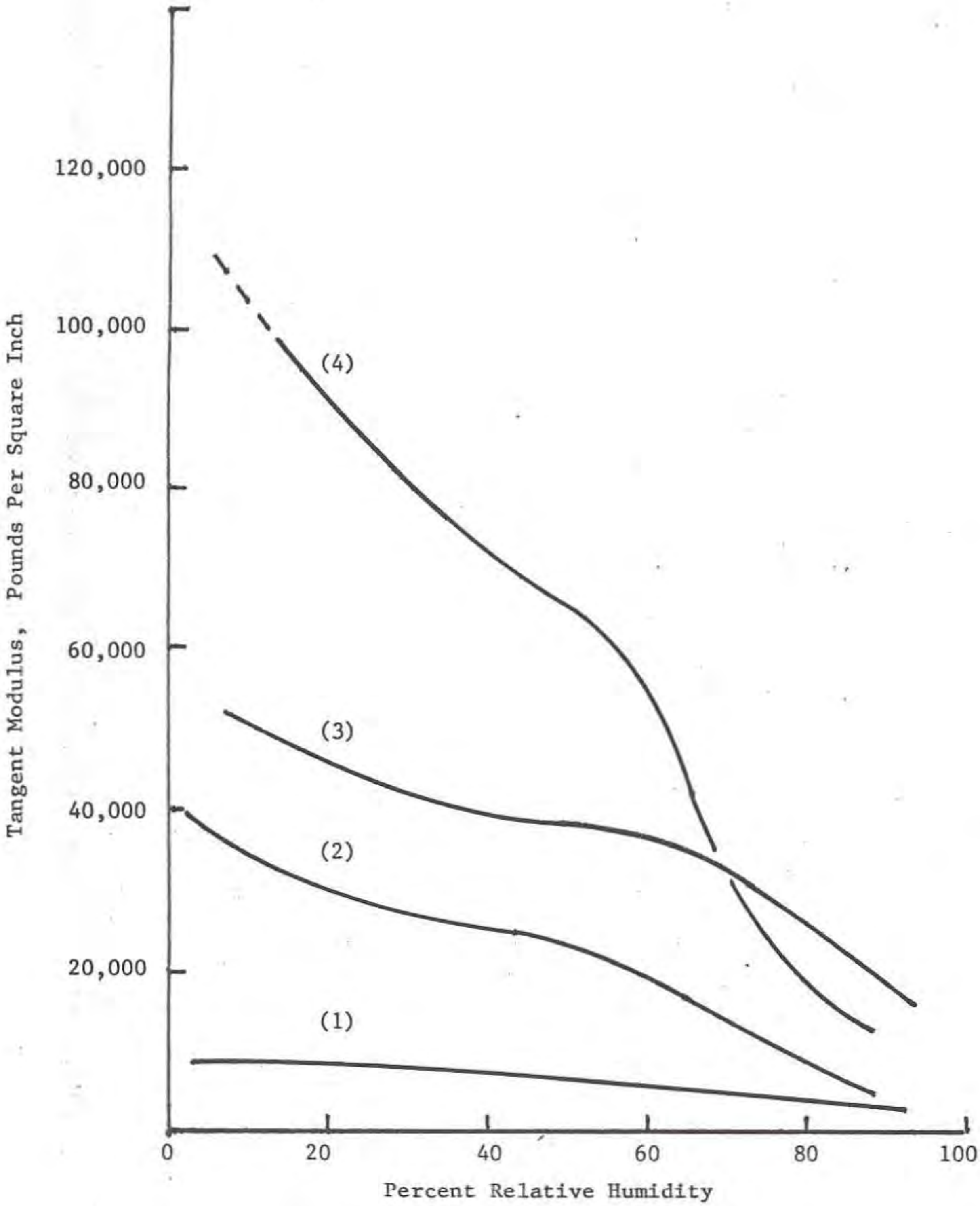


Figure 7. Effect of Relative Humidity on the Tangent Modulus of Four Paint Samples

(1) Burnt Umber in Linseed Oil
(2) Flake White in Linseed Oil
(3) Titanium Dioxide in Linseed Oil
(4) Artificial Vermillion (Azo) in Safflower Oil

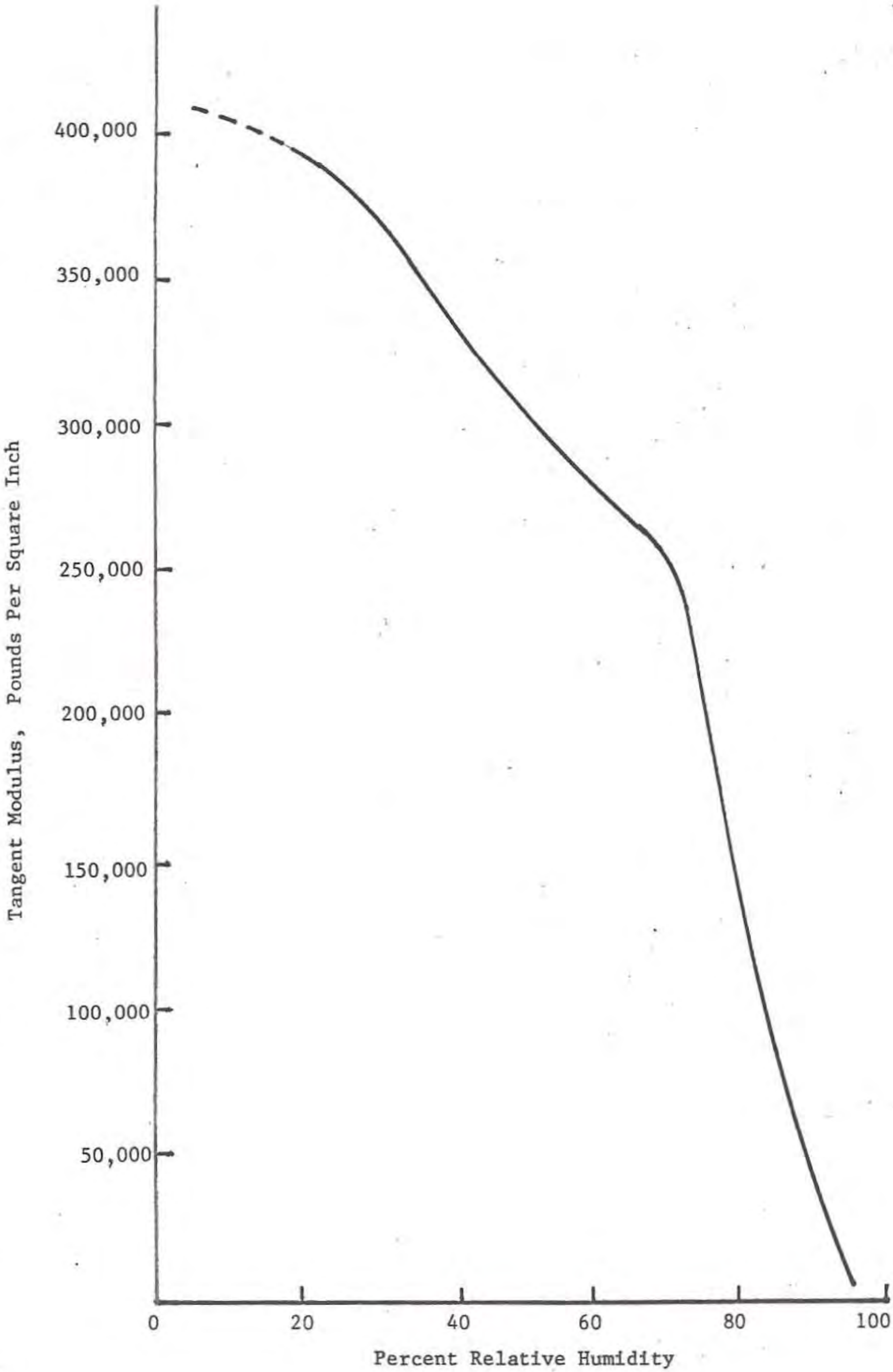


Figure 9. Effect of Relative Humidity on the Tangent Modulus of Rabbit Skin Glue

V. Axial Behavior

The difficulty in describing the structural behavior of a painting is that intuition about materials can betray understanding. Obviously a "stretched" material is in "tension", i.e., positive strain, positive stress. But layers of a painting can literally contract in negative strain and still be in tension (positive stress). The positive and negative values must be correctly interpreted. Force (stress) and displacement (strain) are different properties which vary in magnitude, not only from layer to layer, but also from one area of a painting to another.

Taking the simplest examples first, we can begin to systematically examine the behavior of a painting. The simplest behavior might be called the "axial behavior", or the structural behavior in a single planar direction as a function of the layers present.

A one-inch wide strip isolated from an uncracked painting, extending from one stretcher bar to the parallel bar, could be illustrated as in fig. 18a. Upon expanding the stretcher, the strip of painting also would expand as shown in fig. 18b. That all layers of the painting expand (fabric, glue size, ground and paint) is important, and structurally speaking, all layers are strained. But strain can originate in any of the layers, so we must identify the sources of strain other than that from stretcher expansion.

Interlayer interactions become significant when strain in the painting occurs differentially, that is to say, non-uniformly. Suppose that after expanding the stretcher as in fig. 18b moisture were applied to the right

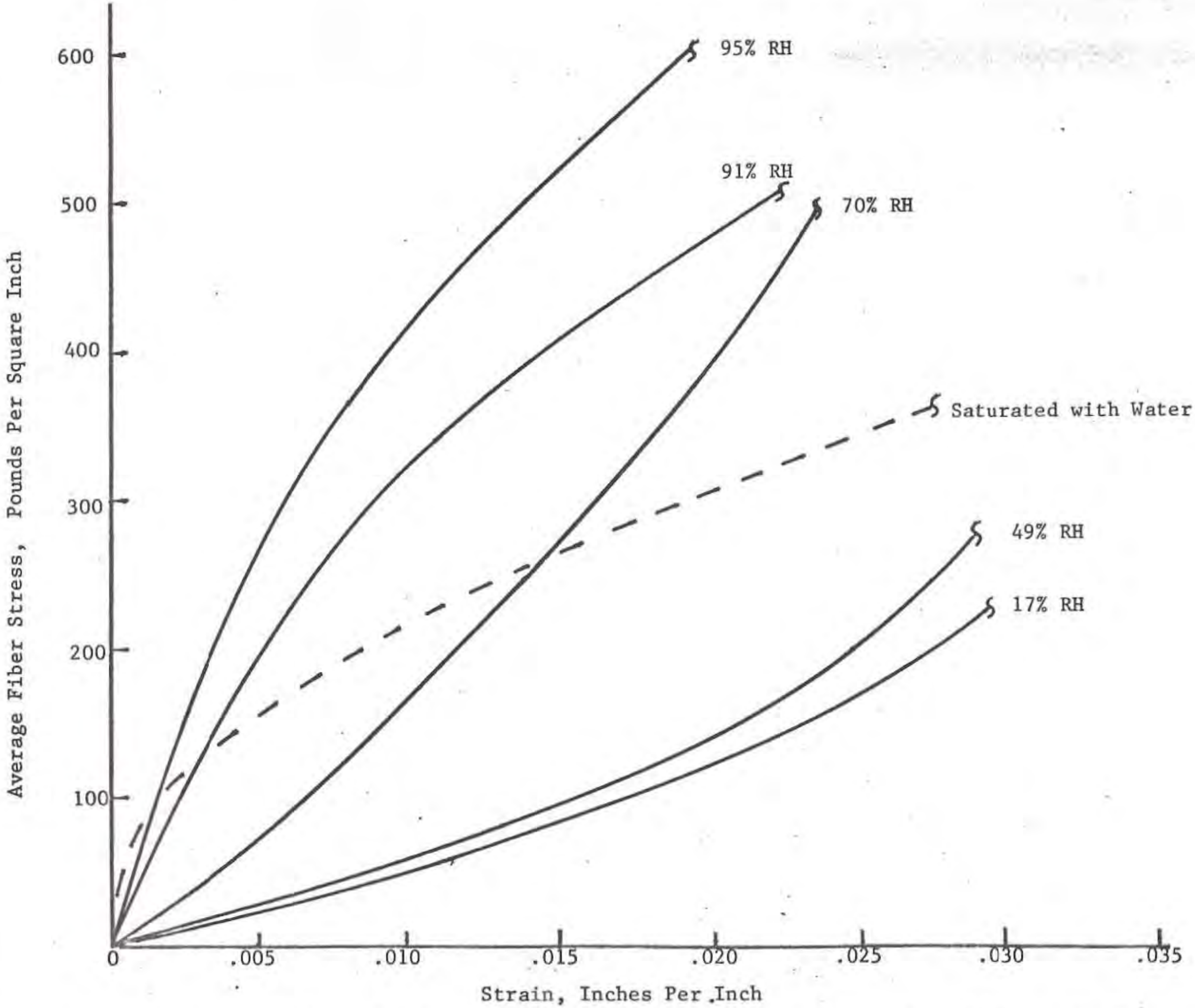


Figure 10 a. Effect of Relative Humidity on Stress-Strain Properties of Linen in Warp Direction, Medium Weight, 32 Yarns Per Inch (#8800 Ulster), at 71° F

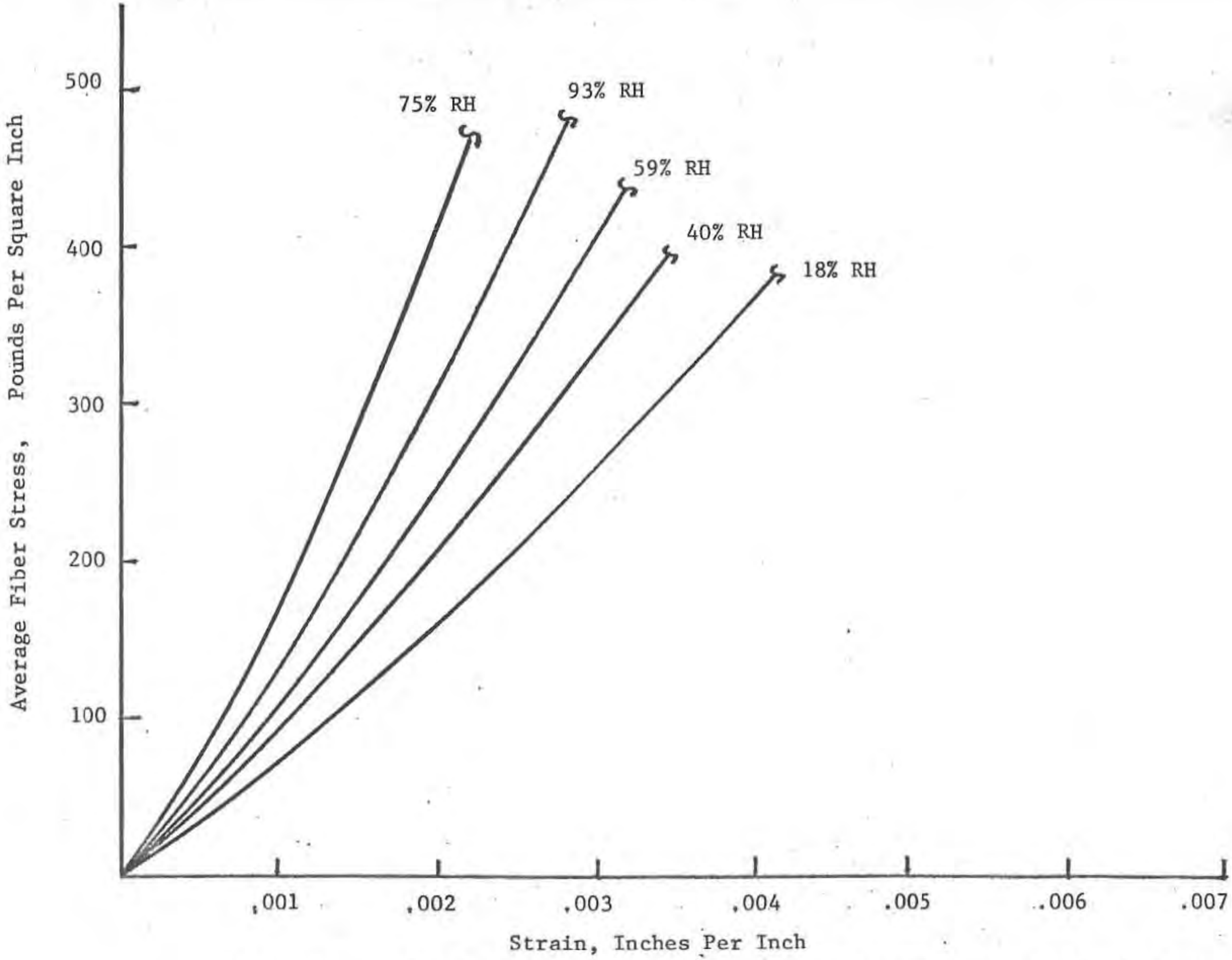


Figure 10 b, Effect of Relative Humidity on Stress-Strain Properties of Linen in Weft (Fill) Direction, Medium Weight, 30 Yarns Per Inch (#8800 Ulster), at 71° F half of the painting. In this case (fig. 19b), point A moves to the right to point A', and if the motion were severe enough the contraction of the fabric on the wetted side would compress and cleave the paint off the painting (fig. 19c). This could happen since water softened the glue size, deteriorating the bond of the ground to the fabric. Evidence of this mechanism often appears where water has condensed and collected behind the lower stretcher bar of a hanging painting. The fabric beneath the cleaved paint is directly responsible for the local damage. If the shrinkage of the fabric were severe enough, tensile cracking of the paint on the left side would occur due to expansion, and again all layers of the painting would be strained. Note that the overall dimensions of the painting were not changed; the moisture content of the painting was uneven and an in-plane displacement occurred. This behavior illustrates the point that while a stretcher can maintain the outside dimensions of a painting, it can do nothing to stop in-plane displacement. The stretcher would restrain massive contraction if the painting were uniformly wetted or if it were subjected to very high humidity. This restraint would correspond to the considerable increase in fabric tension due to very high humidity shown earlier in this discussion. Of concern is the question, does an environment of high humidity, or of any particular humidity, guarantee uniform moisture content of a painting? The answer is "no".

Fabric "shrinkage" at very high humidity causing cleavage in one part of a painting and simultaneous cracking in another part is a frequently observed phenomenon. What is not so obvious is that the glue size can cause

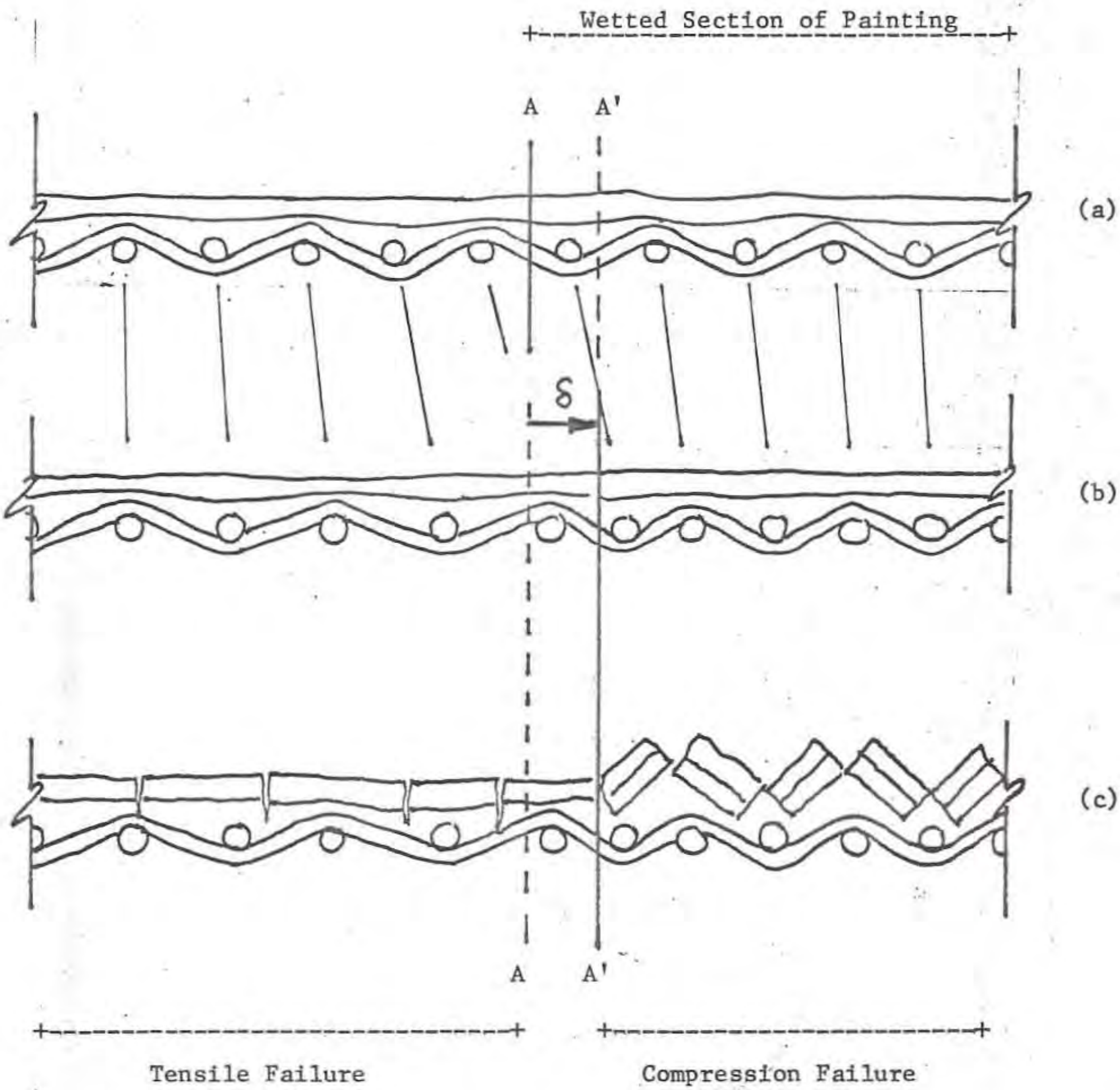


Figure 19. In-plane Displacement Due to Uneven Moisture Content.

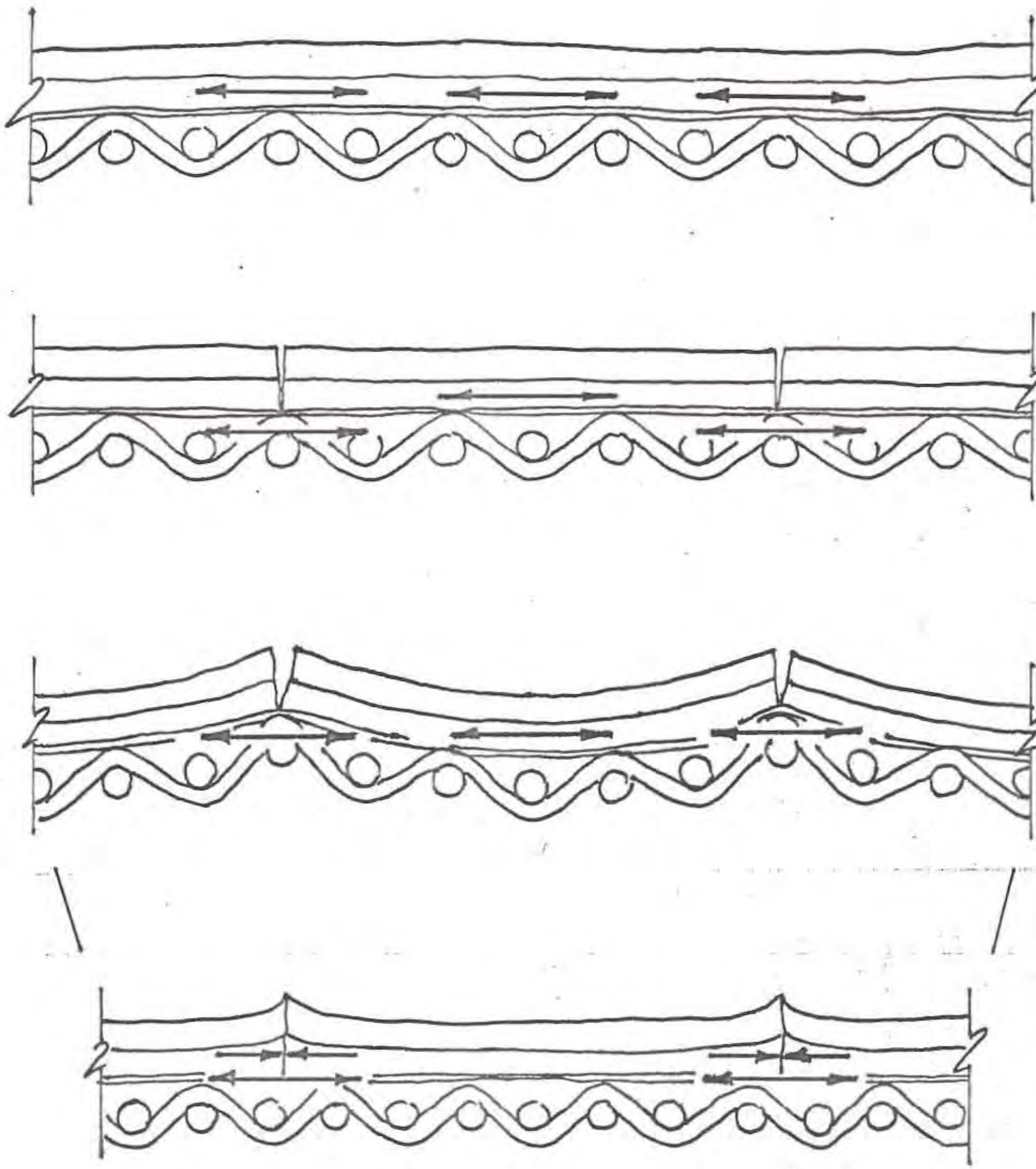
(a) Initial Condition Prior to Displacement
(b) Displacement upon Wetting Right Section
(c) Damage Resulting from Displacement

similar paint compression and cleavage at the other end of the humidity spectrum, at severe dessication.

Now consider a sequence of possible steps that could occur in a painting at low humidity. Start with the fixed strip of painting at 50% RH. If the length of this specimen is held constant and the specimen is dessicated evenly, then the stress in the paint, the glue and the fabric increases, but each to a different magnitude. If the paint film were old enough and the painting were given an initial "tension" at 50% RH, then the increase in stress in the paint film due to dessication (fig. 18b) could be sufficient to crack the painting. The paint film could be described as having been "prestressed" at 50% RH so that lowering the RH was sufficient to crack the paint. In this case neither the glue nor the fabric contributed actively to the paint film failure. Again, while the stretcher could fix the outside dimensions of the painting, it could not stop this internal stress development.

Crack formation modifies the geometry of the painting as a structure. Prior to cracking the total force acting on the painting is the algebraic sum of the forces acting on each layer. The force in each layer is simply the stress in the layer times its cross-sectional area. Once a crack forms in the paint film and ground, partial stress release occurs in the cracked layers and the total force in the painting decreases slightly (cracking is a stress release mechanism). More important though is the relocation of the forces in the painting and its consequences. At the crack, the <u>geometric center of total force</u> of the painting is located just below the middle of the glue layer. But between the cracks, the center of force still lies above the middle of the glue layer and a series of offset force lines appears (fig. 20b). In order to regain full axial alignment of the geometric center of force, displacement occurs and the painting "cups" (fig. 20c). Remember that the outside dimensions of the painting have not changed since the original "pre-tension" at 50% RH; only the change to low RH is required for this cracking, displacement and cupping. If the painting had been stretched even more tightly at 50% RH, the cracks could have formed at that time with the same resultant cupping. The important point here is that stretching a painting "conditions" it for humidity related failure. The tighter it is stretched, the more prone the painting is to damage due to dessication; the less initial tension, the less prone it is to cracking at low RH. Lowering the initial stress in a paint film contributes to longevity of the painting.

The concept of axial displacement of forces has other interesting implications. An obvious one is of course the change caused by a patch on the reverse of a painting. Eventually the patch shows up as a distortion on the front of the painting. The patch lowers the center of force of the painting in that area, and the "lifting" of the patch is simply the realignment of forces throughout the painting. Another example is a painting which has a very thick but very uneven design layer. Originally the painting is basically flat, yet ultimately a mirror image of the painting appears on the reverse (fig. 21a,b). This demonstrates the active structural participation of a thick paint layer. It is definitely supporting a great deal of the painting.



(a)

(b)

(c)

(d)

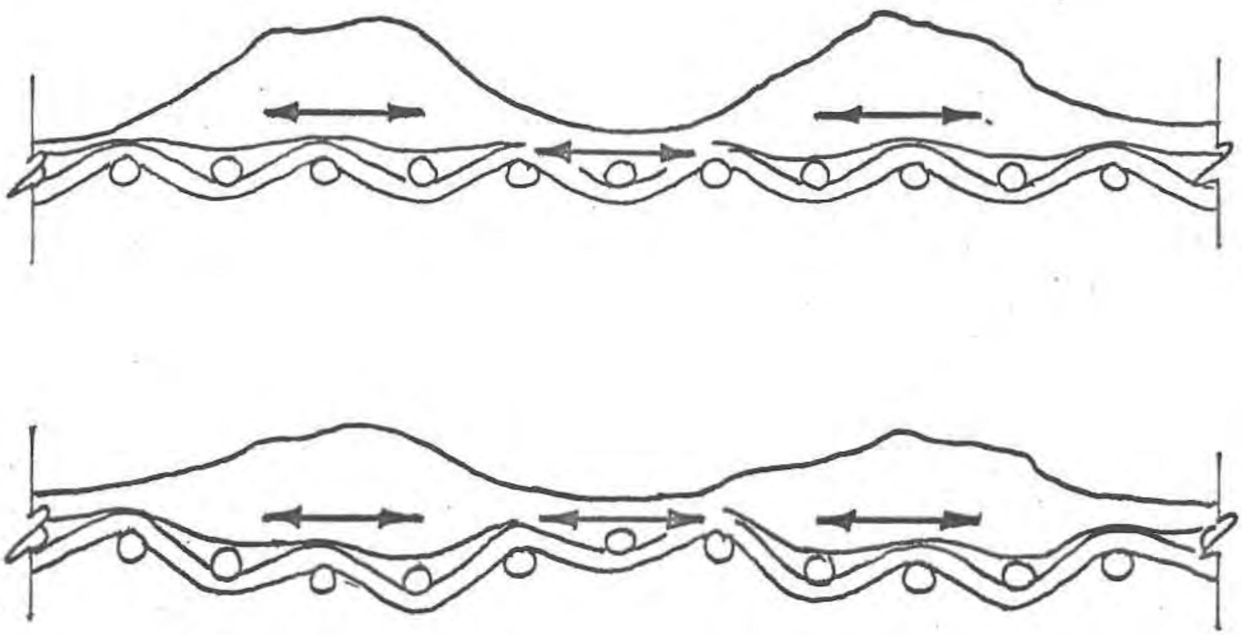
Figure 20. Locations of Geometric Center of Force in a Painting

(a) Prior to Cracking of Ground and Paint Film

(b) Force Relocation Immediately after Cracking of Ground and Paint Film

(c) Force Realignment Displacing All Layers Out of Picture Plane, "Cupping"

(d) Force Locations in Unrestrained Painting in Low RH: Glue in Tension; Ground and Paint Layers in Compression.



(a)

(b)

Figure 21. Locations of Geometric Center of Force in a Painting with Heavy but Uneven Design Layer

(a) Immediately after Application of Force

(b) Distortion Resulting after Sustained Force Realignment

Suppose now that a painting has cracked for one of the reasons above and is no longer restrained. This could happen if the painting were left in low humidity long enough to permit the stretcher to contract or if a tacking edge fails. The painting seemingly relaxes. However, now observable is that while the paint film is relieved of all tensile stress, the glue size is not. The paint film alone restrains the full stress-relieving contraction of the glue layer, and the paint is now forced into compression and a form of "ridging" can occur (fig. 20d). Usually no general cleavage occurs since the bond of the fabric to the ground is at its strongest, unlike cleavage at high RH discussed earlier; but, interlayer cleavage is most likely to happen at this time when the paint film is in compression and the glue size is in tension. This interlayer cleavage happens simply because the dimensional contraction of the glue is so much greater than that of the paint layer. The fabric does not inhibit this behavior since it is incapable of developing compression stress.

This behavior suggests that at some point all layers are initialized or are at minimum stress. This point actually lies at about 85% RH (figs. 16, 17). Above 85% RH any residual stress and strain from the period of low RH in the ground, paint and glue layers are reduced to zero due to swelling of these layers. Every time a painting is allowed to enter this high humidity zone the fabric begins to increase its role in supporting the painting, and all glue and paint layers "initialize" to a near zero stress level so that any previously stress-induced deformations of the design layer are "set". From approximately this point, 85% RH, dimensional changes in the various layers can be measured. For example, unrestrained paint (white lead) at 85% RH will shrink about 0.3% if subjected to 10% RH;

glue, however, will shrink 2.4% with a change from 85% RH to 10% RH. This is a substantial difference.

Clearly, the balance of forces in a painting is delicate. If a painting is stretched too tightly, tensile cracking of the design layer is risked, and the painting is conditioned for further low humidity stress development. On the other hand, if it is too loose, compression cleavage of the paint at high humidity or compression ridging at low humidity are strong possibilities. Finding the exact balance is not a simple task.

VI. Biaxial Behavior

In this discussion the assumption has been made that with some exceptions the outside dimensions of a painting remain fixed. However, when wood stretchers are used the dimensions remain fixed only if the painting is held at constant humidity and temperature. Such maintenance is not always found. The general behavior of the stretcher can be simply stated by saying that stretcher contraction at low humidity lowers the stress development in a painting and stretcher expansion at high humidity increases the stress. The influence of the stretcher can be imagined as counter-clockwise rotation of the graphs in figs. 16 and 17, lowering the left sides and raising the right sides. Though not readily apparent but of utmost importance is that this effect can only be assumed at certain points on the painting because the stretcher does not release stress uniformly under low RH conditions. This is because: 1) changes in the wood are greater across the grain than along the grain direction; 2) the painting is tacked to the stretcher bar and is unable to release stress in the direction parallel to and near each stretcher bar.

To stretch a painting "evenly" and to increase stress uniformly in all directions, the edges must follow paths by which a "rectangle" drawn on the surface of the "painting" will enlarge without a net change in shape or proportion. When attempting to carefully stretch a linen so that the yarns are not distorted but remain parallel to the edges of the stretcher, the diagonal path required for each point along the edge becomes apparent. When a stretcher is "keyed out", however, the points along the edges follow the horizontal and vertical paths of the stretcher bars (fig. 22). Expanding the stretcher thus enlarges the rectangle and simultaneously distorts it to a diamond shape, as seen in fig. 23 where the solid lines represent the expanded but distorted grid, and the dotted lines represent the initial, pre-stretched position. As a result of the distortion of the painting, a principal stress orientation occurs and cracks will form at the corners about 45° from the stretcher bars and usually they will be parallel to one another. Fig. 23 is the graphic display from a finite element analysis computer program which shows the principle stress orientation. The expansion of a stretcher due to high humidity is nearly identical to keying out the stretcher with the minor exception that the stretcher bar does expand slightly along the grain direction in high humidity. Why and when the cracking occurs is important to understand. Cracking occurs because expansion of the stretcher strains all layers of the painting and therefore stresses all layers, including the paint. At low humidity the paint film is most brittle, cannot withstand expansion and is most likely to crack. At high humidity, on the other hand, the glue, ground and paint layers are much more flexible and are more likely to withstand expansion. Why does the need to expand paintings seem to arise at low humidity? Simply because this is when the stretcher shrinks and corner "draws" and "drapes" appear in the painting. An expanding stretcher increases tensile stress in the direction indicated in fig. 23. The contracting stretcher relieves that stress and if contraction is great enough the painting literally goes into compression and buckles at the corners, after which the painting is keyed out.

Fig 23

Another, even more serious problem can develop at low humidity. At low RH stress in the paint and glue layers can increase so tremendously (figs. 16 and 17) that the stretcher contraction cannot release this stress completely or uniformly and another stress pattern develops. This is illustrated in fig. 24, a graphic display of computer output. A series of crack "waves" develops, radiating from the corner of the painting. This is the result both of stress increase in all layers of the painting at low humidity and of stretcher contraction. The less the stretcher contracts, the less pronounced the wave crack curvature. Corner drape occurs simultaneously with wave cracks. If the stretcher did not contract during this low humidity period then no drape would result; nor would partial stress release in the various layers occur, and cracking would be random and more extensive.

In addition to these results of low humidity failure mechanisms, wave cracks and drapes, the center of the painting usually is cracked perpendicularly to its long direction (fig. 25). Although this effect has been associated with differences between the weave directions of the fabric,

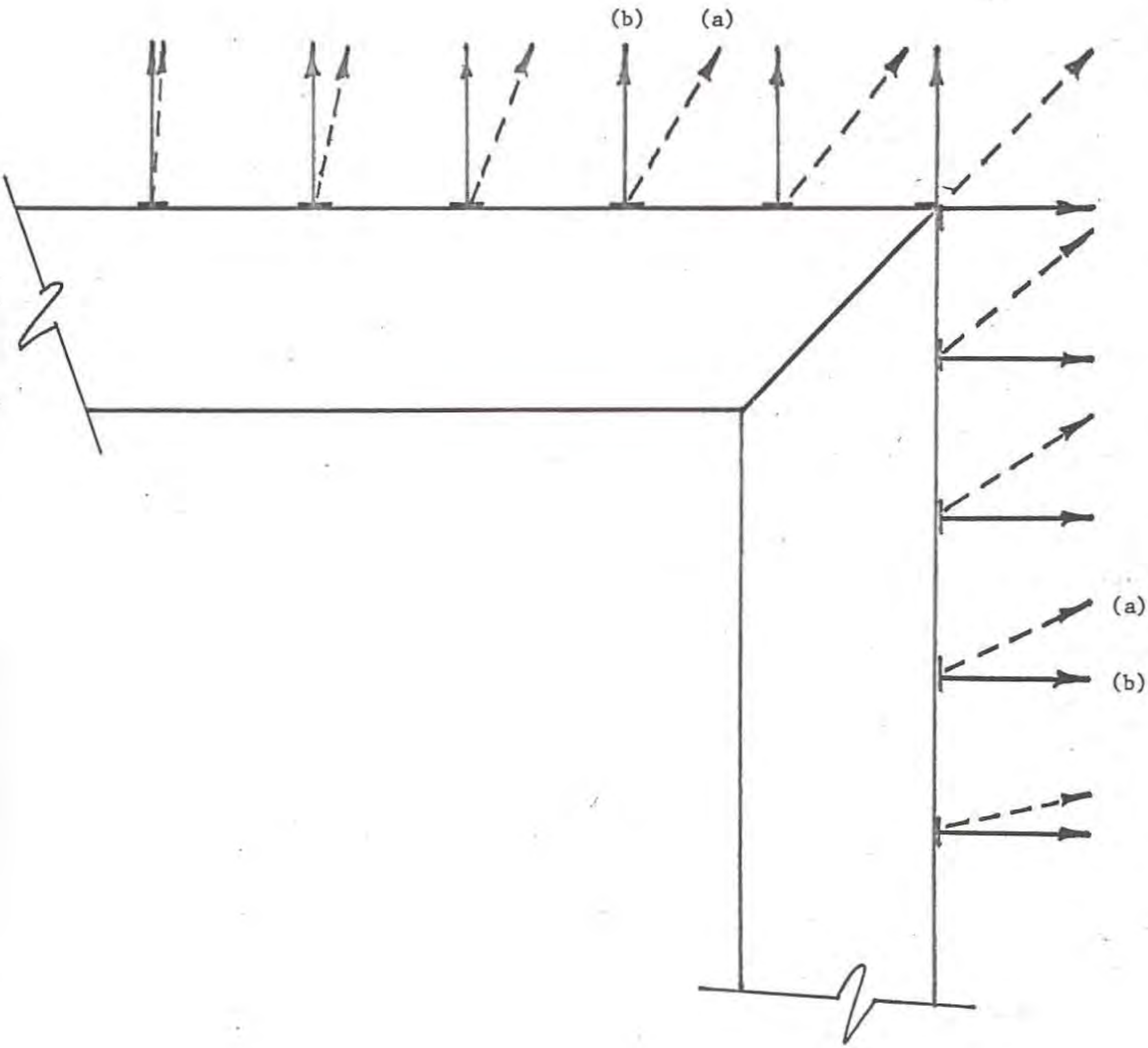


Figure 22, Movement of Edges during Stretcher Expansion

(a) Broken Vectors = Path Required for Uniform Expansion and Uniform Stress Development in a Painting

(b) Solid Vectors - Path Taken during Stretcher Expansion

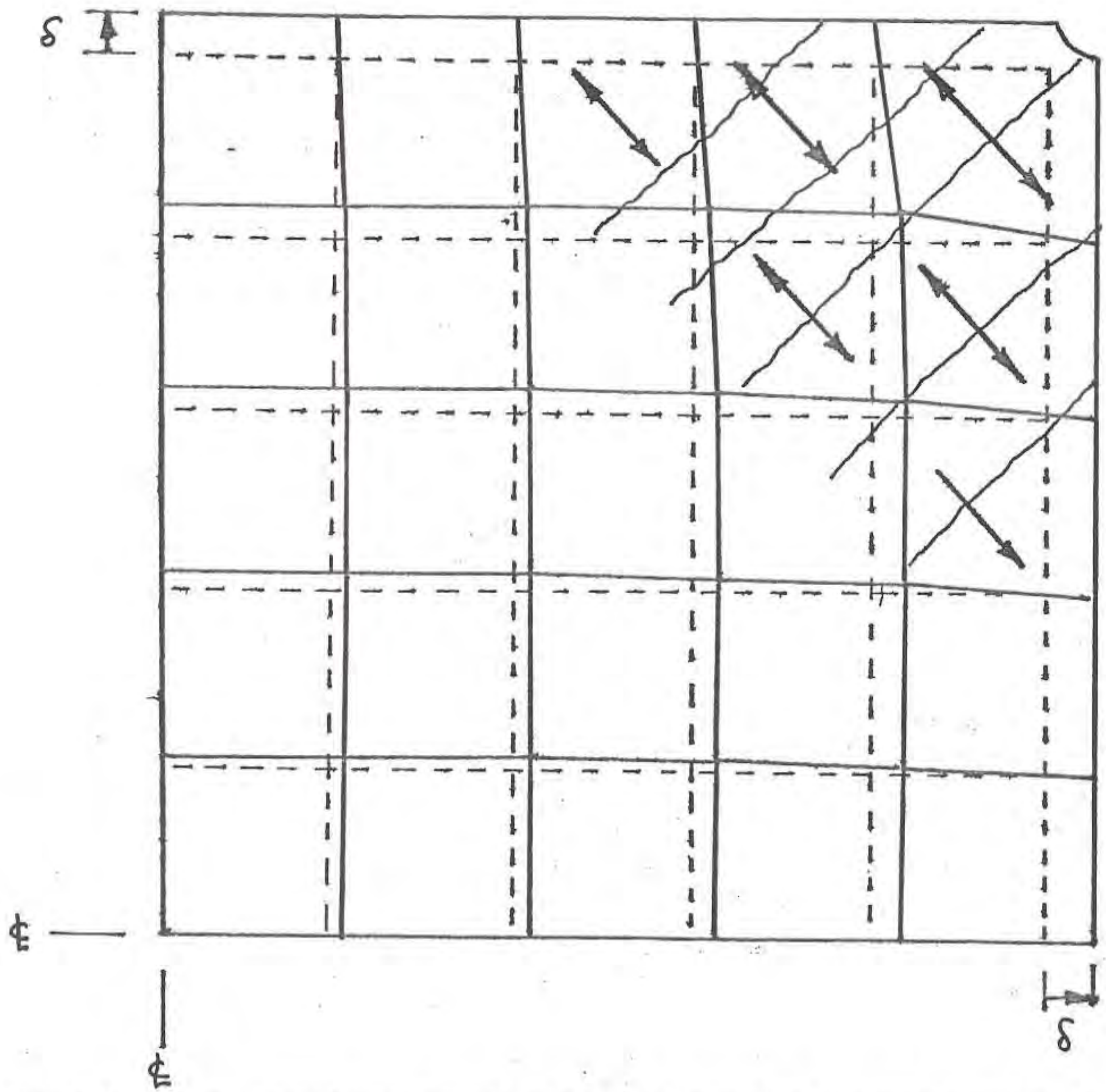


Figure 23. In-plane Distortion, Stress Development and Crack Formation Due to Expansion of Stretcher (Computer Output)
From J. Colville, M.F. Mecklenburg, <u>Report on the Deterioration of Fabric Supported Paintings</u> (Submitted to National Museum Act, Smithsonian Institution, Washington, D.C., 1978).

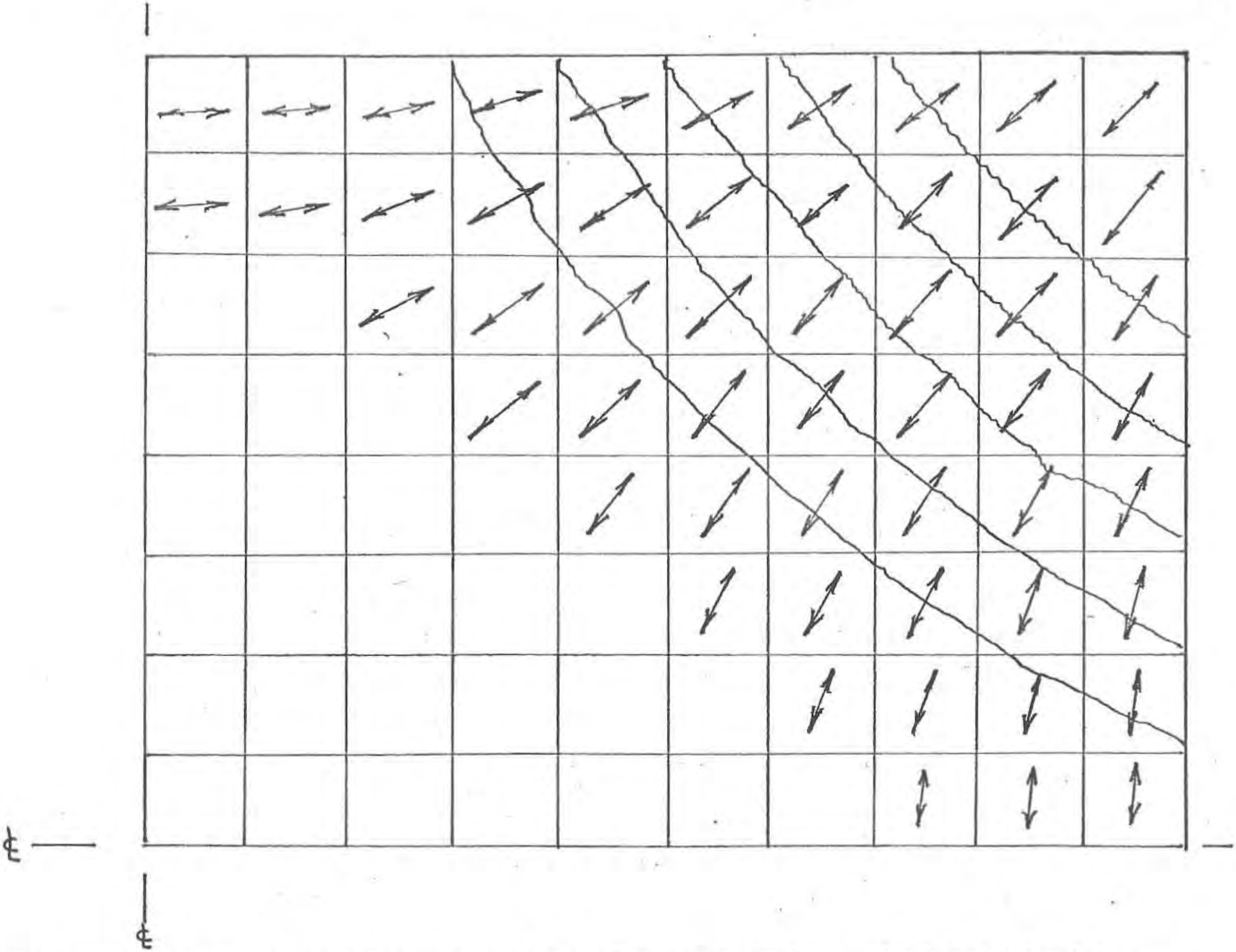


Figure 24. Residual Stress Distribution and Crack Formation at the Corner of a Painting Resulting from Dessication of Glue Size, Ground and Paint Layers Accompanied by Stretcher Shrinkage.

another explanation now appears more valid because, first, the general fabric behavior does not appear to differ much from warp to weft at any humidity; and second, the fabric is responsible for very little of the total force in a painting at low RH.

To understand the formation of these central area cracks, assume that a painting is subjected to low humidity resulting in high stress development in the paint, ground and glue layers. If the stretcher did not contract the stress could be assumed uniform, and if cracks were to form they would be random throughout the painting.

Now assume that the period of time to achieve dessication is long and that the stretcher does contract. Stretcher bars are normally of the same stock on all sides so that the amount of contraction is the same in both directions. If the amount of contraction of the stretcher bar is δ (deformation), then the release of stress in the central section of the painting can be computed in both the vertical (short) and horizontal (long) directions. Since stress is related to strain, a strain release means a stress release. To compute the strain release in the horiziiontal or long direction, use $\epsilon_{LR} = \delta/L_L$; in the vertical or short direction use $\epsilon_{SR} = \delta/L_S$. Because L_L is much greater then L_S the strain release in the short direction is much greater than the strain release in the long direction; and a much greater stress is released in the short direction than in the long direction. Therefore, the residual or unrelieved stress in the long direction is sufficient to crack the painting while residual stress in the short direction is not.

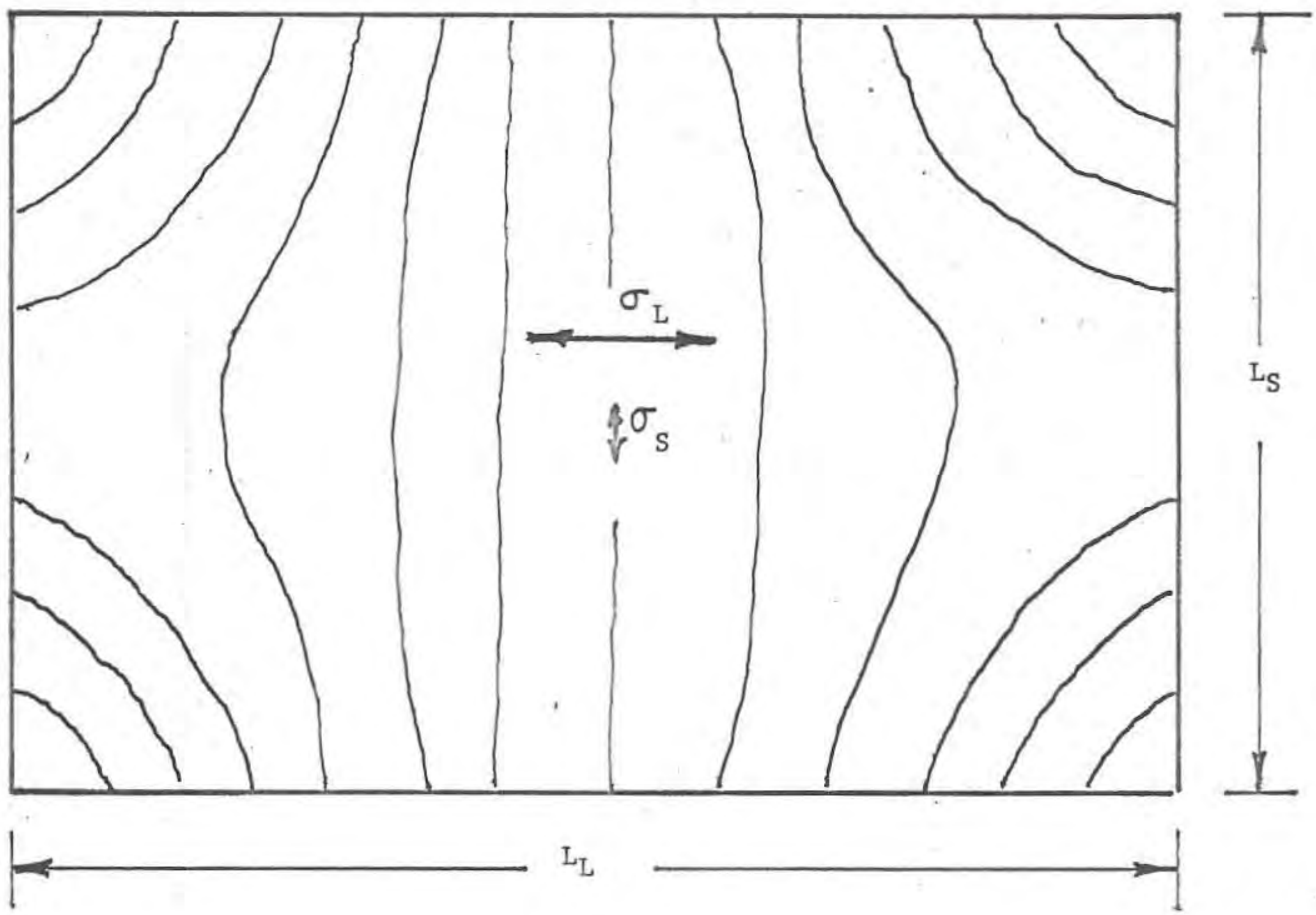


Figure 25. Residual Stress Distribution and Crack Formation Resulting from Dessication of the Entire Paining.

Vectors Show Directions and Relative Magnitudes of Residual Stress in Central Zone of Painting.

VII. Conclusion

This discussion of some highlights of the mechanical behavior of the fabric supported painting certainly must be considered only as an introduction to a field requiring much broader investigation. For example, among aspects yet to be discussed are the thermal properties of the materials.

But some conclusions can be drawn even at this stage of the study. Previously the structural role of the linen fabric support has been completely over-estimated at humidities under 85%. The structural participation of the paint itself, on the other hand, was almost entirely neglected in traditional discussions of painting behavior. The structural role of the glue size had been most definitely under-estimated.

A concept of great importance to understand is that if a painting is stretched, then all layers are stressed and "pretensioned" for further stress development resulting from dessication. While a painting can be restrained at the edges, this does nothing to stop in-plane displacement or damage due to humidity extremes. Although a wood stretcher does contract and relieve some stress at low humidity, it does so unevenly, causing general stress patterns to appear. The situation would be worse if a stretcher were not to contract at all, for then no stress would be released.

This study surely demonstrates the potential devastation resulting from exposure to the extreme ends of the humidity scale. Holding an environment at a constant temperature and RH certainly appears to reduce damage to fabric supported paintings, but the assumption should not be made that humidity oscillation is the cause for damage because a constant environment also obviates extreme dessication and extremely high humidity.

There is some evidence that the most extreme oscillations in humidity, from below 20% RH to above 85% RH, cause continually increasing dessicated stress development in the rabbit skin glue. This must be explored in detail.

Other evidence shows that a narrow band of oscillation in RH might be quite acceptable if these oscillations occur within relatively short periods of time, probably less than eight hours. The reason for this is the very slow rate of moisture loss from paint. A film of paint only 0.01 inch thick might take at least 24 hours to lose 90% of its moisture if dessicated from 85% RH. And this rather long period of time was required in a controlled situation where the air was constantly agitated by high velocity air fans to facilitate moisture loss from all exposed surfaces of the paint specimen.

The rate of moisture loss from the glue size and cellulose is much faster, but is considerably buffered by the paint film in an actual painting. A completely closed backing board of a hygroscopic material will act to buffer the painting further. More study of the rate of moisture loss would be exceedingly valuable. If such studies were to reveal that the stringent control of museum environments for fabric supported paintings might be relaxed a bit, then substantial savings in energy costs soon would be realized. Comparison between rates of moisture loss and the lengths of time works of art spend in different environments while traveling would provide valuable packing and shipping guidelines.

Along with controlled environments certain measures in conservation should be reassessed. An obvious concept is that if a painting can be supported stress-free then the probability of further cracking, cupping, and hence flaking, is over. But this is unrealistic because to let a painting expand and contract in order to relieve the humidity related stress development, the layers would have to change dimensions at different rates; since they are bonded together this is impossible. On the other hand, stretching a painting can pre-condition it to increased stress development. Clearly a compromise must be reached. A long-held assumption has been that lining a painting to linen would support the painting further. Now recognizable is that if a painting is linen-lined with a hide glue adhesive, then the glue adhesive does far more to support the painting than the linen. In the northeastern United States and most of Canada, the use of hide glue as a lining adhesive is ill-advised, for interior spaces during the winter season routinely reach relative humidities below 15%. At low RH, the in-plane contraction of such an adhesive is unacceptable, particularly since it is usually applied more thickly as a lining adhesive than when used as the size layer, and the linen lining fabric, like the original support fabric, does little to restrain in-plane displacement.

In summary, to support a painting, the material chosen must: 1) be capable of developing and maintaining a large percentage of the total force of a stretched painting; 2) be able to restrain in-plane displacement as developed by dessicated glue and paint films; 3) restrain out-of-plane distortion such as cupping and buckling. Other factors to be considered when choosing the support include: 1) the modulus of the lining material when a high modulus is preferable; 2) the total thickness of the lining material, since thickness gives more structural stiffness and can be achieved with multiple layers of the material; 3) the total dimensions of the painting, as well as the thickness of the paint.

At one extreme of supports is the inert, solid panel which carries nearly 100% of the forces in a painting. Several people have offered other promising alternatives.[10] Further study of the structural behavior of paintings will more clearly define the mechanical requirements for a lining support as well as for the lining adhesive. If the proper support is chosen, then the options available in choosing the adhesive might be broadened considerably.

While the research has come a certain distance, it has much further to go for utmost precision and refinement in understanding. Methods are now available for analyzing both the materials of paintings and the structure itself without experimenting on the objects themselves. Two significant points already clear are that the stress development within a painting will never be completely eliminated and that avoiding the extremes of relative humidity cannot be over-emphsized.

ENDNOTES

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GLOSSARY

Brittle - A material is said to be brittle if it breaks without yielding.

Creep - Continuing deformation without an increase in applied force.

Elastic - A material is said to be elastic if it returns to its original dimensions after having been deformed by an applied force and the force has been removed.

Mechanics - The study of the effects of force on bodies. In this paper it is limited to static systems.

Modulus - The ratio of stress to strain; this ratio is the slope of the stress-strain curve.

Orthotropic - Exhibits similar material behaviors at 90° directions, in this paper, the direction of the weave (warp and weft).

Plastic - A material is said to be plastic if after having been deformed by an applied force it does not return to its original dimensions.

Strain - Change in length per unit length, i.e., inches per inch.

Breaking Strain - Strain magnitude at which a material fails either in tension or compression.

Stress - Force per unit area, i.e., pounds per square inch.

Breaking Stress - Stress magnitude at which a material fails either in tension or compression.

Tangent Modulus - Slope of the stress-strain curve tangent to the curve at the origin of the coordinates.

Yielding - A material is said to yield when its behavior changes from elastic to plastic.