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THE EFFECTS OF RELATIVE HUMIDITY ON THE STRUCTURAL RESPONSE OF SELECTED WOOD SAMPLES IN THE CROSS-GRAINED DIRECTION.

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ABSTRACT

Wood is common as a structural material throughout Art and Archaeological collections. While there is a considerable amount of information on the behavior of wood in the longitudinal direction, failure is often perpendicular to the grain direction. This study concentrated on the cross-grained mechanical behavior of several woods and their response to changes in relative humidity. The mechanical behavior of these woods coupled with the dimensional response to relative humidity can be used to assess the potential for damage to restrained wood objects as well as determine allowable museum environmental fluctuations.

INTRODUCTION

Wood is one of the most useful materials for structural applications in houses, small commercial buildings and many types of boats. As such there is a vast amount of information to be found in the literature regarding its physical, chemical, and structural properties. Wood as a structural material is used in very specific ways. For example, it is never expected to carry a tensile or bending load in the cross-grained (radial or tangential) directions. Structural applications rely exclusively on the strength, stiffness, and dimensional stability found in the direction parallel to the grain of the wood. The cross-grained directions of wood are only considered for low level compressive load applications. Consequently the majority of research on the structural properties of wood is conducted parallel to the grain direction with some of the research directed to the crushing properties and strength perpendicular to the grain. (1-3)

Wood as a integral material in cultural objects is found throughout the collections of galleries and museums the world over. It is certainly one of the most useful materials in the construction of paintings, furniture, sculpture, and the decorative arts. Guidelines to the use of woods in these objects are somewhat less rigorous than those found in structural applications. This results in tensile and bending loads often being applied in the cross-grained direction. In addition, the cross-grained lamination of wood as found in veneers, inlays, and plywoods, puts dimensional restraint on the wood and restricts nearly all movement which would otherwise result from moisture fluctuations. Wood panel paintings with locked cradles, or battens firmly attached to the reverse, leads to restricted dimensional movements from fluctuations in relative humidity (RH). The consequence of this restraint is the development of cross-grained tensile stresses with desiccation and compressive stresses with increases in humidity. The magnitude of the stresses that induce damage in the form of cracking (tensile response) or crushing and buckling (compressive response) is in question. Of equal importance is the magnitude of the RH variations that induce the damaging stresses. If it were possible to establish the RH fluctuation (and therefore the stresses) that first initiate damage in an object, then safety factors can be applied that preclude even incipient damage. At the same time, acceptable levels of RH fluctuations can be established for the continued stability of the wood bearing objects in the collection.

To determine the required information and develop environmental guidelines, a study of the dimensional and mechanical cross-grained properties of several woods was undertaken. This study, is intended to act as an initial effort to characterize the wood properties in question and to supplement the existing literature.

MECHANICS OF MATERIALS

Recent research (4) has determined that there is a clear connection between the externally loaded mechanical properties, the swelling behavior, and the environmentally induced forces and stresses in materials in general. In addition, it can be established that nearly all damage to material, whether in compression or tension occurs after the initiation of high shear deformations. Excessive shear causes permanent plastic deformation, void formation and ultimately cracking when tensile forces are involved. The same mechanism in compression is responsible for buckling and so called "compression set" in wood. In many materials, the point of onset of plastic deformation in an axial test, tensile or compressive, is called the yield point. Determining the yield point of a material is useful in that it determines the upper bound of recoverable deformations as well as the highest stress allowable beyond which, damage begins. This basic principle is used extensively by engineers in the design of steel structures where the maximum allowable stresses are based on the yield point of the steel being used.

Most of the wood samples in this program were tested largely in the tangential direction, though some of the samples had a radial component to it. For any given wood, the samples were cut from a single clear board. The sample dimensions were approximately 0.08" thick, 0.18" wide and 5" to 8" long depending on availability of the sample board.

Tensile tests were conducted using a variety of woods and at different levels of relative humidity. All of the woods were also tested while saturated with water to determine the difference between soaked wood and those tested at 100% RH. In general there was little difference. Figures 1-3 summarize test results for tulip poplar, white oak and spruce. These figures show the tensile tests and the test environments used. The starting points of the tests are spaced apart by the amount of swelling caused by the changes in the test environment. The tests themselves were conducted by inducing a small strain and waiting 30 seconds before recording the stress. This procedure eliminated variation effects due to the rate of loading even though this could still be considered a fairly rapid test.

The tulip poplar swells the most so the spacing is the greatest. The spruce swells only about half as much as the tulip poplar. The white oak swells only a little less than the tulip poplar. The tulip poplar and the white oak attain similar strengths (stress at breaking) at all of the environments while the spruce attains about half the strength of the other two woods. Of interest are the spruce samples which have a greater capacity to stretch during the tensile test than the other woods. The fact that this wood has a low moisture coefficient and a large capacity to deform makes it a rather durable material. Some of the other woods tested (walnut, red oak, pine, cherry, ash, and American mahogany) exhibited significant loss of ductility and premature brittle cracking in the low RH tests. Most of the woods become fracture sensitive under these low RH test environments. All of the woods strain hardened during the tests, meaning that the yield point increased during elongation. The yield point is the point of transition from the elastic (reversible) to the plastic (permanent deformation) zones of the material. This can be shown by periodic unloading of the wood during the tensile test. This is demonstrated in figure 4, where a sample of white oak was tested while saturated. The unload-reload slope is the same at all stages of the test but the transition from that slope to the plastic zone increases as the strain increases. That the unload-reload slope is not changing indicates that there is little actual damage to the structural properties of the wood. This is similar to many structural steels in that considerable plastic deformation must occur before actual damage is initiated. The line drawn to indicate the slope is E, the modulus of elasticity, and its magnitude, in pounds per square inch (PSI), is shown at the lower portion of the figure. As strain hardening advances, the wood is losing its plastic zone. The yield point has importance in that this is the point where in many materials some damage might begin. As such, locating this point can be useful in preventing damage either from external loading or from the stresses developed from environmental variations.

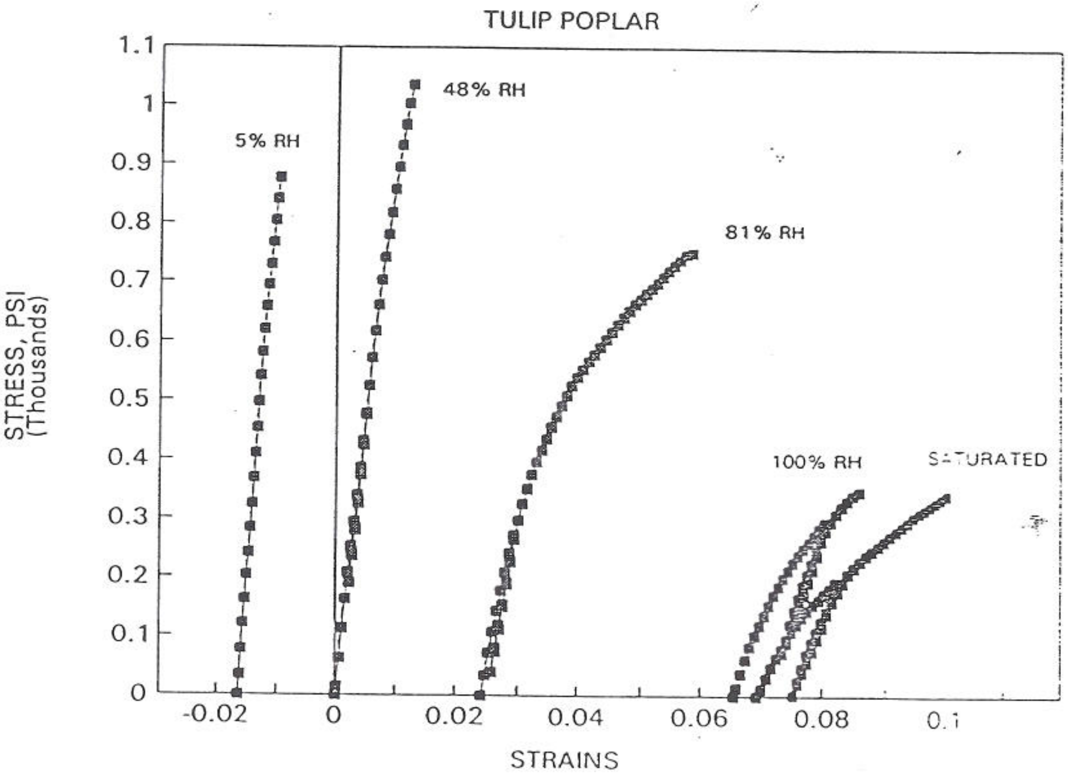

Figure 1. The tensile properties of tulip poplar conducted at five different moisture environments. The separation between plots is caused by the swelling or shrinking induced by the different moisture contents. The wood samples are in the tangential direction.

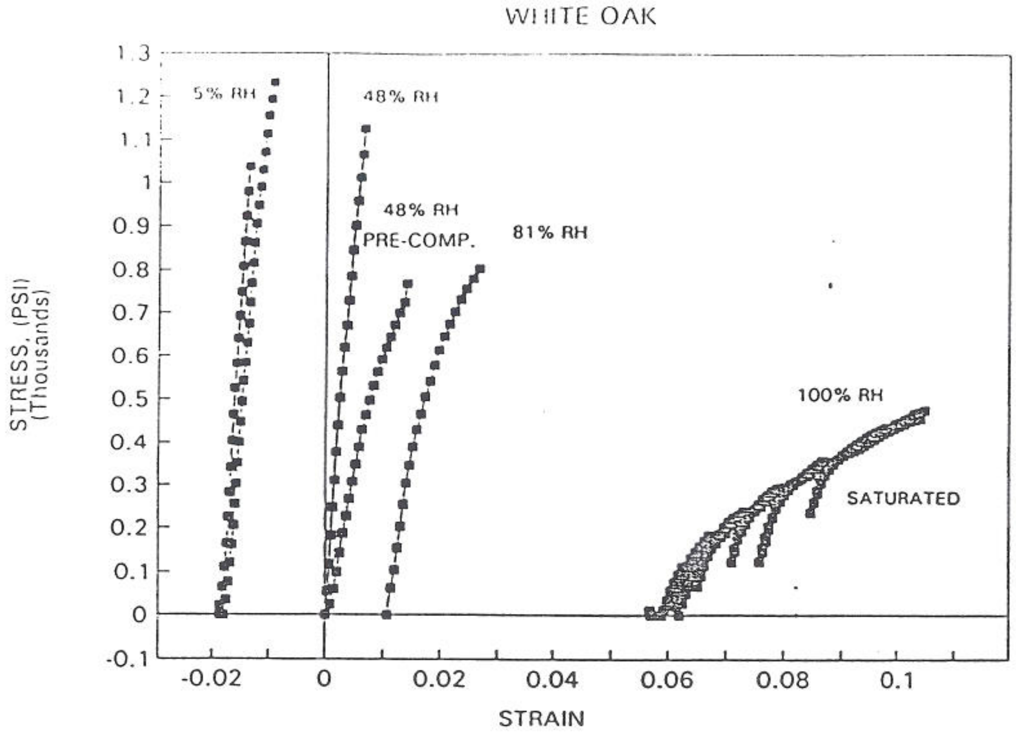

Figure 2. The tensile properties of white oak conducted at five different moisture environments. The separation between plots is caused by the swelling or shrinking induced by the different moisture contents. The wood samples are in the tangential direction.

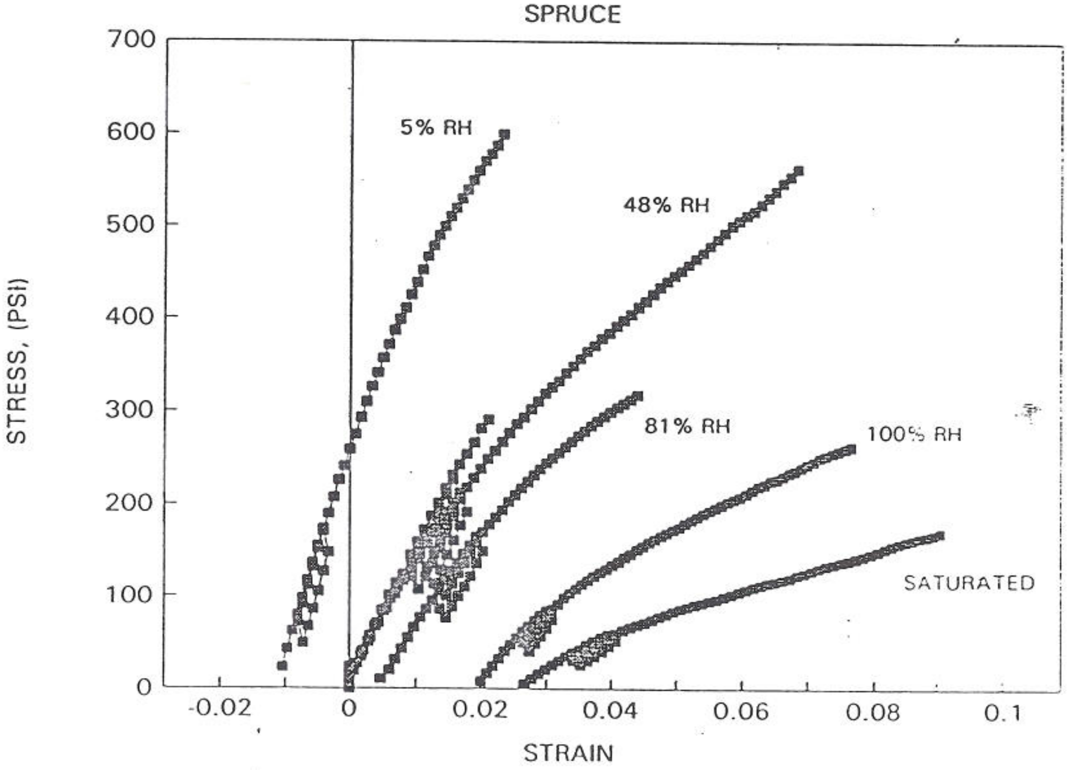

Figure 3. The tensile properties of spruce conducted at five different moisture environments. The separation between plots is caused by the swelling or shrinking induced by the different moisture contents. The wood samples are in the tangential direction.

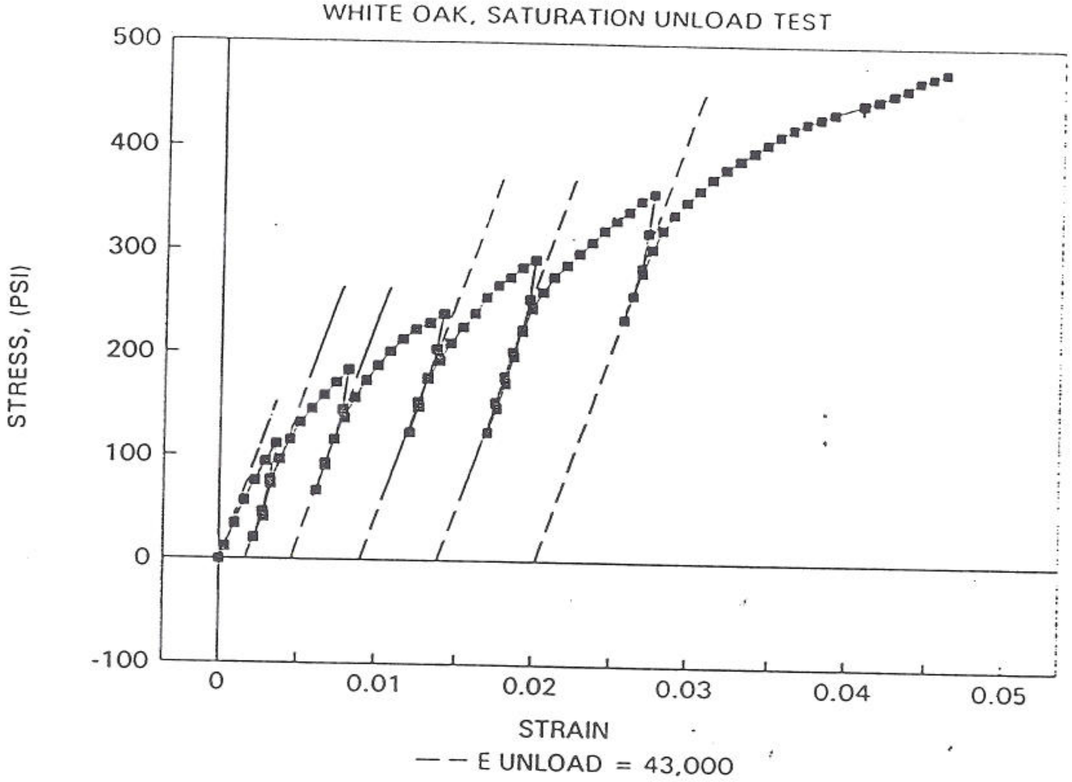

Figure 4. An unload compliance tensile test of a sample of white oak in the tangential direction at 100% RH. The unload slope is the same indicating that the wood is strain hardening.

THE INITIAL YIELD POINT AND THE EXTERNALLY APPLIED LOAD

Careful examination of the individual tests reveal that the initial transition points from the elastic to plastic zones of the woods fall in a fairly narrow range from between 0.002 to about 0.006. This is determined by the deviation from linear behavior in the tensile tests. Figures 5-9 show the deviation from linear behavior for tulip poplar for tests conducted at 5%, 48%, 81%, 100% RH and while fully saturated. The initial yield points for these previously untested wood samples at these environments are approximately 0.0045 at 5% RH, 0.002 at 48% RH, 0.003 at 81% RH, 0.0025 at 100% RH and 0.003 at saturation. The strains to breaking for the sample tested, 0.012 at 48% and 0.007 at 5% are quite low, especially when compared to tests conducted at higher RH. When many of the woods were desiccated and tested, their ductility was reduced in that they became stiffer and retained smaller plastic regions. This behavior is a clear indication that there will be a tendency to exhibit brittle fracture if restrained and desiccated to very low humidity levels and should be viewed as a precaution against allowing restrained wood objects to become dry. Dry environments routinely occur in heated spaces in the wintertime where additional humidification is not provided. Those environments can easily reach as low as 10% RH in the colder regions of the United States and most of Canada.

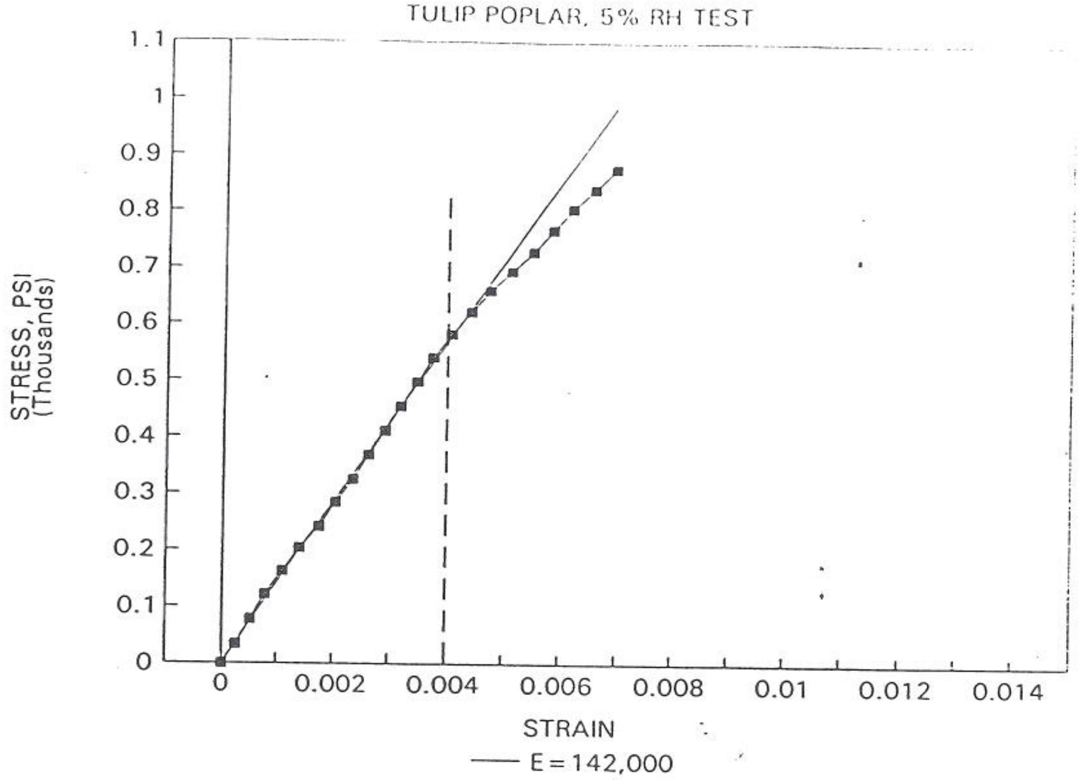

Figure 5. A tensile test of a sample of tulip poplar conducted in an environment of 5% RH. This sample is yielding at a strain of approximately 0.004.

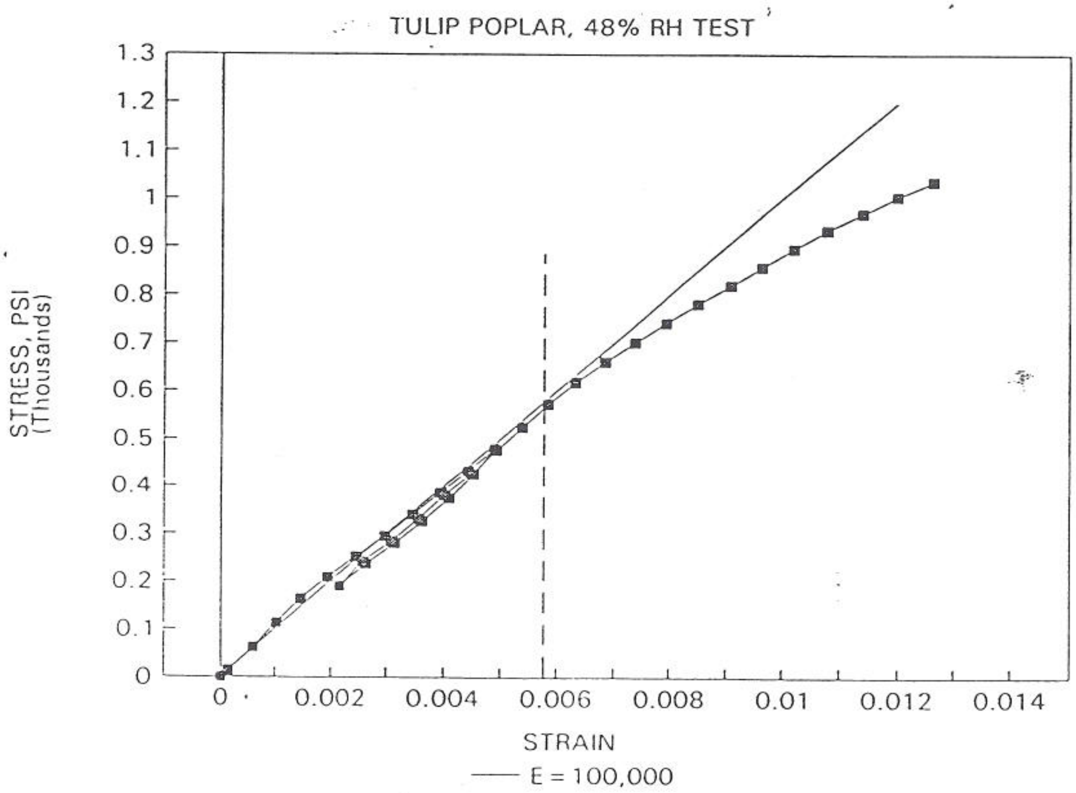

Figure 6. A tensile test of a sample of tulip poplar conducted in an environment of 48% RH. This sample is yielding at a strain of approximately 0.006.

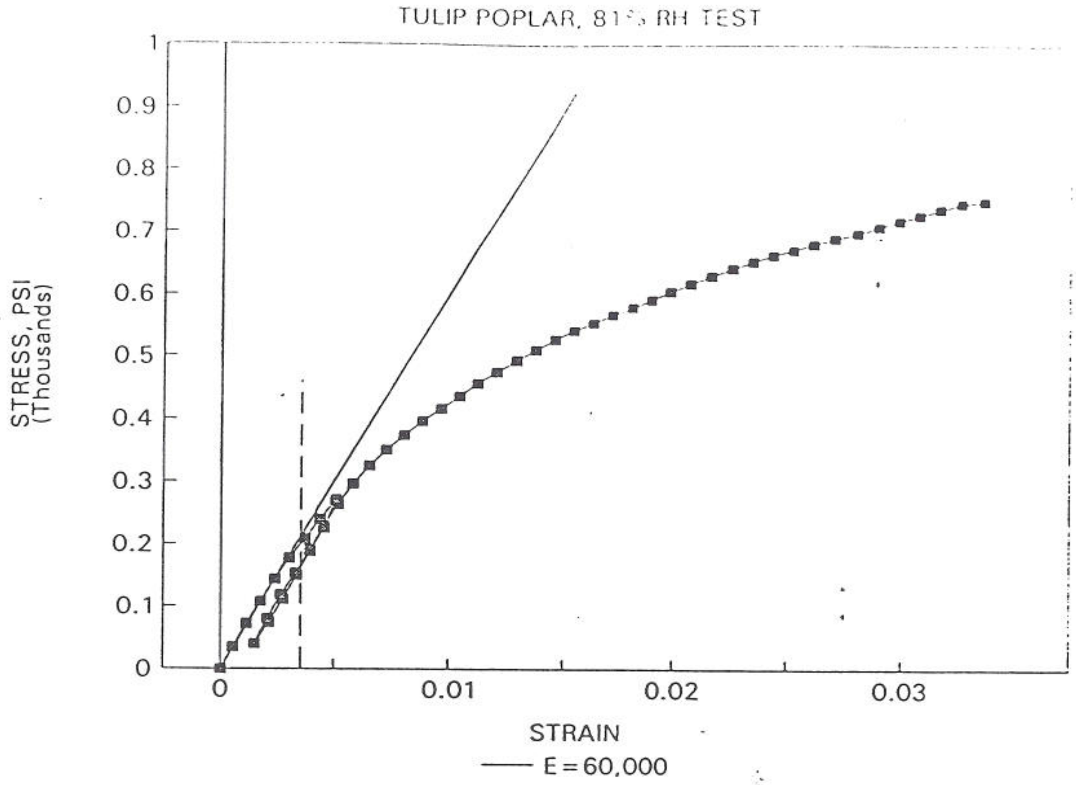

Figure 7. A tensile test of a sample of tulip poplar conducted in an environment of 81% RH. This sample is yielding at a strain of approximately 0.004.

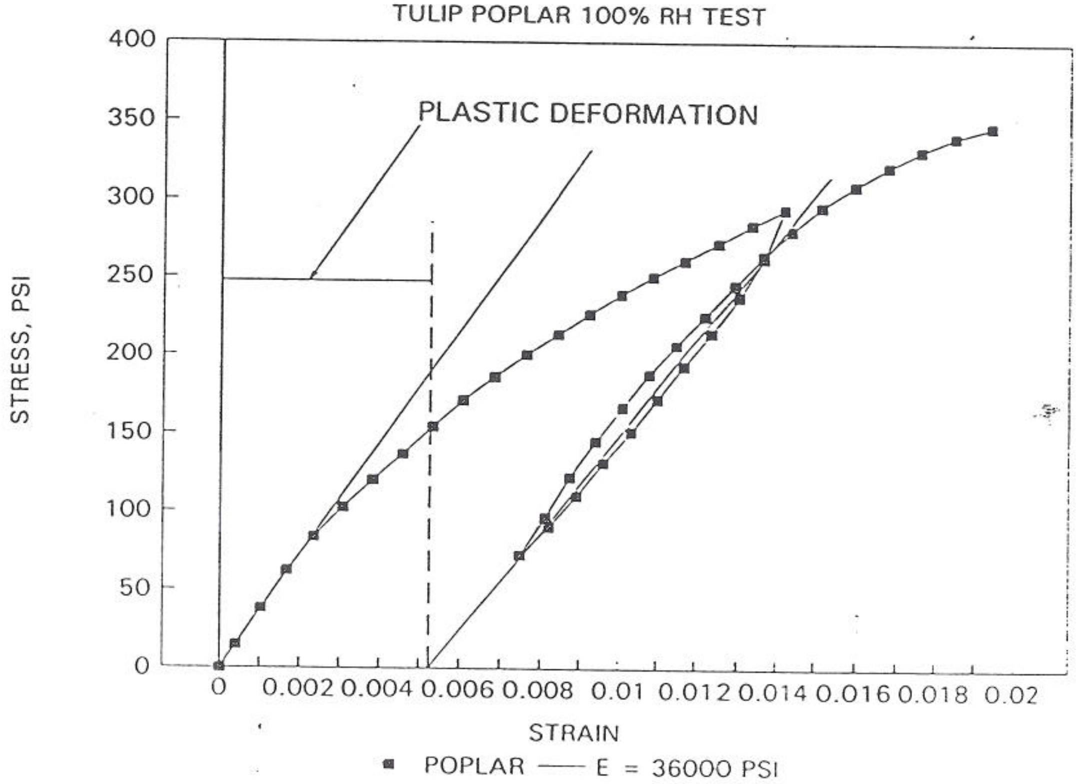

Figure 8. A tensile test of a sample of tulip poplar conducted in an environment of 100% RH. This sample is yielding at a strain of approximately 0.0025. The unload compliance illustrated the amount of plastic deformation occurring in the wood during this test.

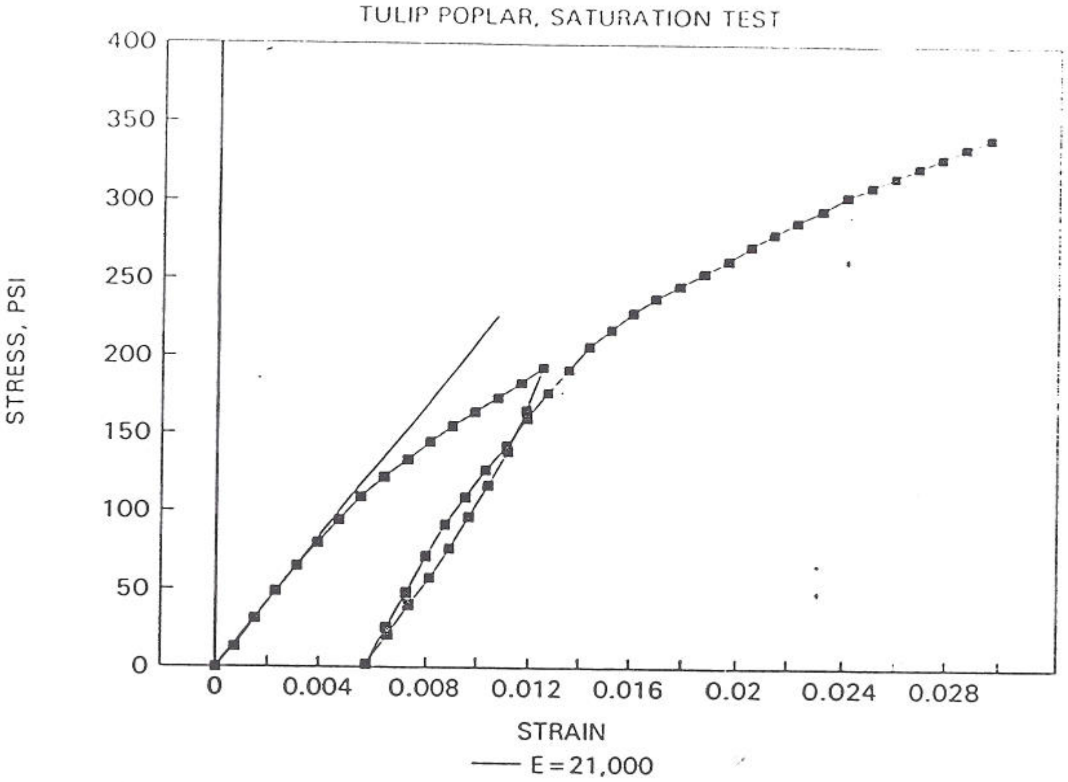

Figure 9. A tensile test of a sample of tulip poplar conducted while saturated with water. This sample is yielding at a strain of approximately 0.003. The unload compliance illustrated the amount of plastic deformation occurring in the wood during this test.

Table 1 below lists the yield and breaking strains of several other woods tested in the same environments as above. It is clear after examining these strains that the initial yield points are confined to a narrow range over the entire moisture content spectrum as well as within the wood group. The breaking strains vary considerably more. What is significant is the loss of ductility or elongation to break at the lower humidities. Cracking is most likely to occur at these environments.

Environmentally induced stresses can produce plastic deformation so that determining the magnitude of the related RH or temperature change can be extremely useful in setting allowable museum environments. An example of an environmentally induced plastic deformation is "compression set." This occurs when a wood is restrained and subjected to a change from a moderate to fairly high humidity. The result is that the wood is permanently compressed to a length less than before the set. Upon redrying, the wood is restrained at the shortened length and the stresses due to desiccation are initiated from the highest RH attained and not the more moderate starting RH. If the desiccation is severe enough, the wood will crack. Another condition that can exist when restrained and humidified is compression buckling. This is often seen in panel paintings having cradles attached to the reverse. These paintings have the appearance of a large "washboard." By restricting the fluctuations in RH that induce plastic deformation in wood, it is possible to prevent cracking and buckling. It now remains to establish those RH fluctuations, acting on a restrained wood, that cause plastic deformation at different points of the environment.

Table I. Yield Strains and (Breaking Strains) for Various Woods

WOOD	5% RH	48% RH	81% RH	100% RH	SATURATED
Ash	.0025 (.006)	.002 (.01)	.002 (.016)	.007 (.021)	.005 (.035)
Amer. Mahog.	.005 (.012)	.004 (.016)	.004 (.028)	.005 (.04)	.005 (.046)
Cherry	.004 (.009)	.004 (.012)	.003 (.022)	.004 (.036)	.003 (.05)
Maple	.006 (.014)	.005 (.012)	.0025 (.022)	.005 (.044)	.003 (.05)
Pine	.005 (.008)	.004 (.017)	.005 (.035)	.006 (.035)	.004 (.028)
Red Oak	.007 (.012)	.003 (.008)	.004 (.016)	.003 (.033)	.005 (.038)
Spruce	.005 (.04)	.004 (.07)	.006 (.04)	.005 (.055)	.005 (.06)
White Oak	.004 (.008)	.003 (.0065)	.004 (.016)	.0025 (.018)	.003 (.045)
Walnut	.002 (.0075)	.0035 (.008)	.002 (.016)	.004 (.028)	.0035 (.028)
Tulip Poplar	.0045 (.007)	.006 (.012)	.004 (.034)	.0025 (.019)	.003 (.028)

DIMENSIONAL PROPERTIES AND THE RESTRAINED STRESS DEVELOPMENT

In the directions perpendicular to the grain, woods swell considerably more over the RH spectrum then parallel to the grain. They even act differently in the radial and tangential directions, with the tangential direction swelling the most. The longitudinal direction swells so little, about 40 or more times less, that it can often be assumed to be nearly stable. Much of the literature treats the swelling of wood as a function of moisture content. In addition, swelling is often described using a constant swelling coefficient over a limited range of moisture content. For the discussions in this paper, it is more convenient to refer it to RH and, as will be shown, the swelling coefficient varies widely over the entire RH spectrum.

For example, figure 10 shows a plot of the strain (percent elongation divided by 100) versus RH for tulip poplar. This figure shows tulip poplar swelling 8.5% between 5% RH and 100% RH. The swelling coefficient of tulip poplar is shown in figure 11. The coefficient is the instantaneous slope of the isotherm fit shown in figure 10 and is not a constant anywhere. Nearly all the woods tested have coefficients with similar shapes as the tulip poplar but they differ in magnitude. American mahogany and spruce had the lowest swelling coefficients while walnut and tulip poplar had some of the highest. In general the denser woods have considerable swelling coefficients.

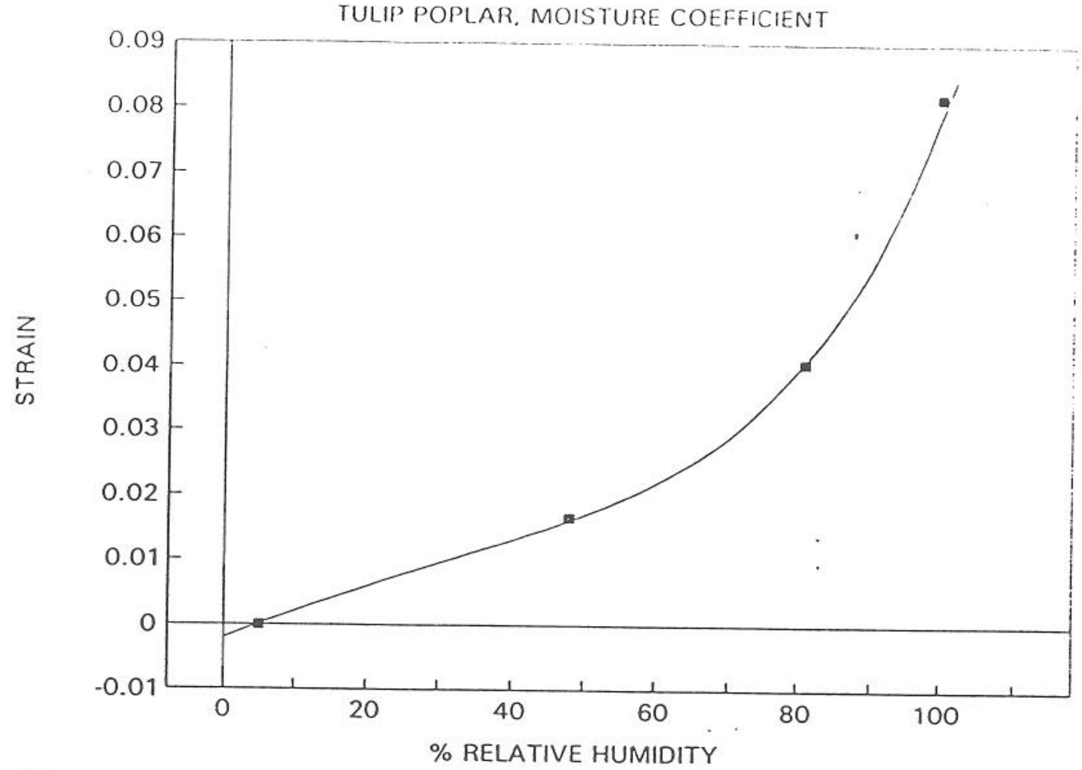

Figure 10. The equilibrium moisture isotherm in terms of RH for tulip poplar at 23° C. The woods swells a total of about 8.5%. The continuous line passing through the data points is a polynomial fit.

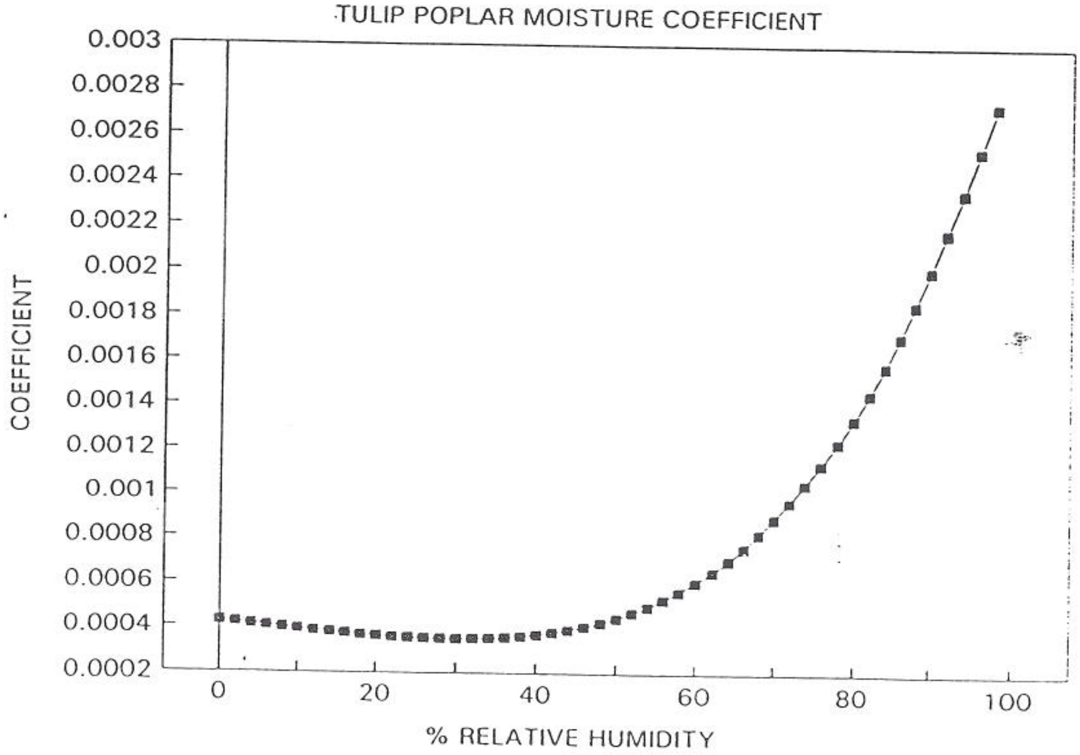

Figure 11. The moisture coefficient of expansion for tulip poplar. The plot shows that the coefficient is clearly not a constant.

Tulip poplar, when restrained and desiccated from a high to a low RH will develop significant stress as shown in figure 12. In fact when desiccating from approximately 60% to 6% RH, the tangential sample develops around 400 pounds per square inch (PSI) stress while the sample tested in the longitudinal direction reached only 70 PSI. This difference in stress development is largely, but not solely, due to the considerable difference in the swelling coefficients of the two different sample directions. The restrained desiccation test can be used to determine both the equilibrium modulus (see other paper) as well as to determine if plastic deformation occurs in the sample.

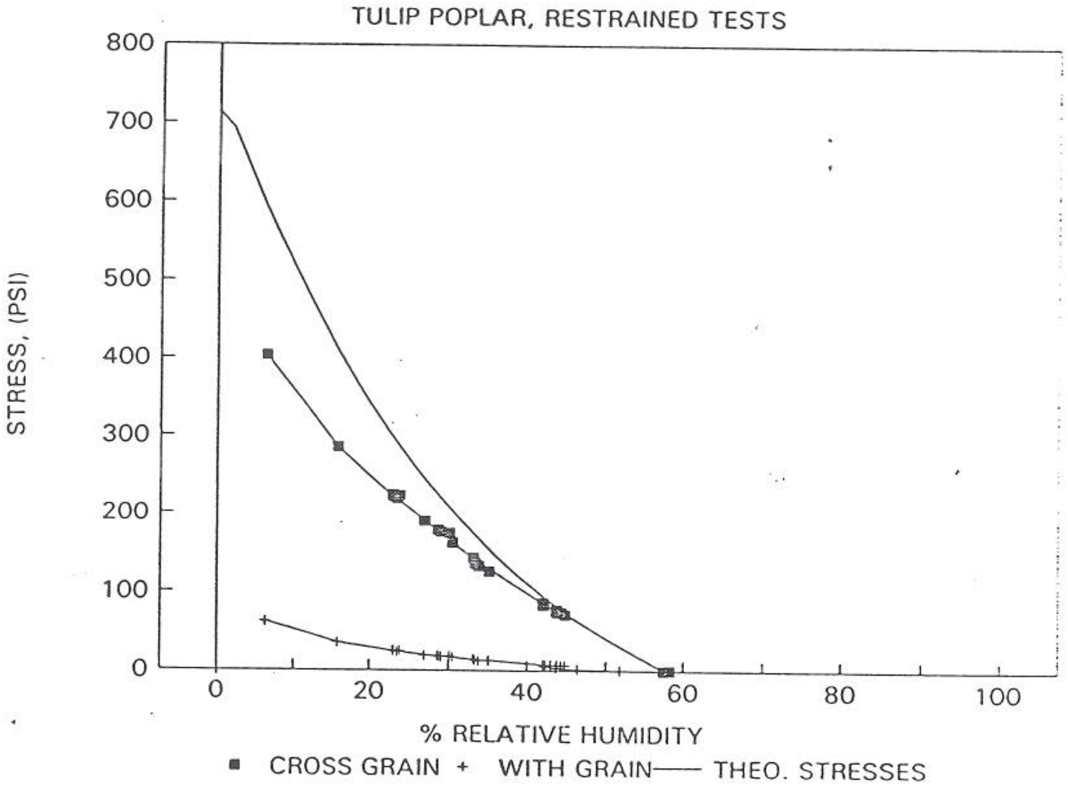

Figure 12. Restrained desiccation stress development versus RH for tangential and parallel to grain samples of tulip poplar. The stresses in the tangential direction sample are nearly 7 times as high as in the with the grain sample.

In figure 13, the calculated and theoretical potential strains are plotted for the same sample of tulip poplar as discussed in figure 12. The theoretical strains are calculated directly by integrating from the high (starting RH) to the low RH (ending RH) points using the equation:

$$\epsilon = -\left(\int \alpha dRH\right)/\left(1+\int \alpha dRH\right) \qquad (1.)$$

where: ϵ is the strain resulting from a fully restrained and desiccated specimen,

α is the functional expression for the moisture coefficient of expansion of the material in question,

dRH is the incremental change in RH.

In figure 13, this equation was adjusted to correct for the compliance or "give" of the load cell which measures the stresses and strains of an actual specimen. The effect was to reduce the strain development by the amount shown in figure 14. When the test specimen reaches an environment of 6% RH, there is a deviation of the strains of approximately 0.0047 indicated as the plastic deformation in figure 13. This permanent set, was a direct result of the tensile stresses resulting from restrained desiccation. The point of deviation of the measured data from the theoretical strain is a value of about 0.003 which is a comparable value to the initial yield strains as measured by the mechanical test. In this test it is possible to see that the specimen started yielding when the RH dropped from 60% to about 52%, an 8% decrease. This figure illustrates the concept that restrained wood specimens can experience plastic deformations and gives an estimate of the variation of RH needed to induce that permanent set. But this specimen was not fully restrained because of the load cell compliance and if it were fully restrained, a much more severe condition, the allowable RH decrease to attain a strain of 0.003 would be only 5% as shown in figure 14. Full restraint is in fact the most severe condition that can exist for most objects found in museums. A simpler, more conservative estimate is possible using the moisture coefficient of expansion directly.

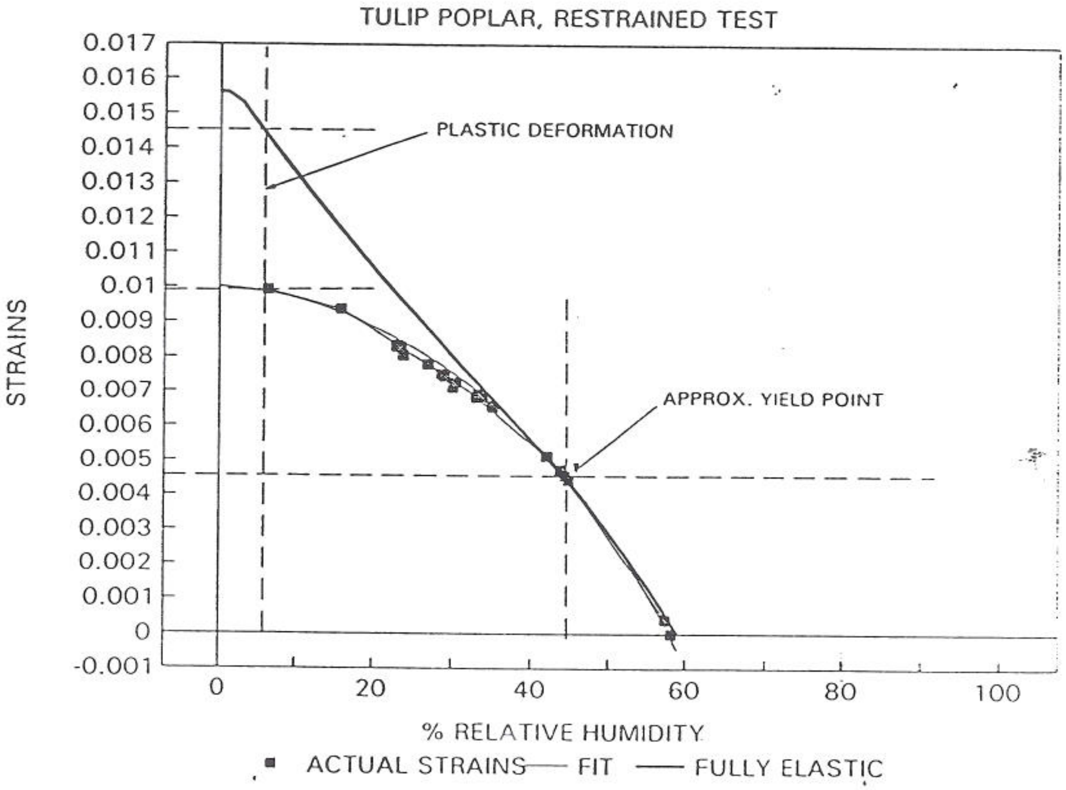

Figure 13. Restrained desiccation strains versus RH for tangential sample of tulip poplar. The deviation of the data points from the fully elastic strains (bold line) indicates the point of yielding for this test.

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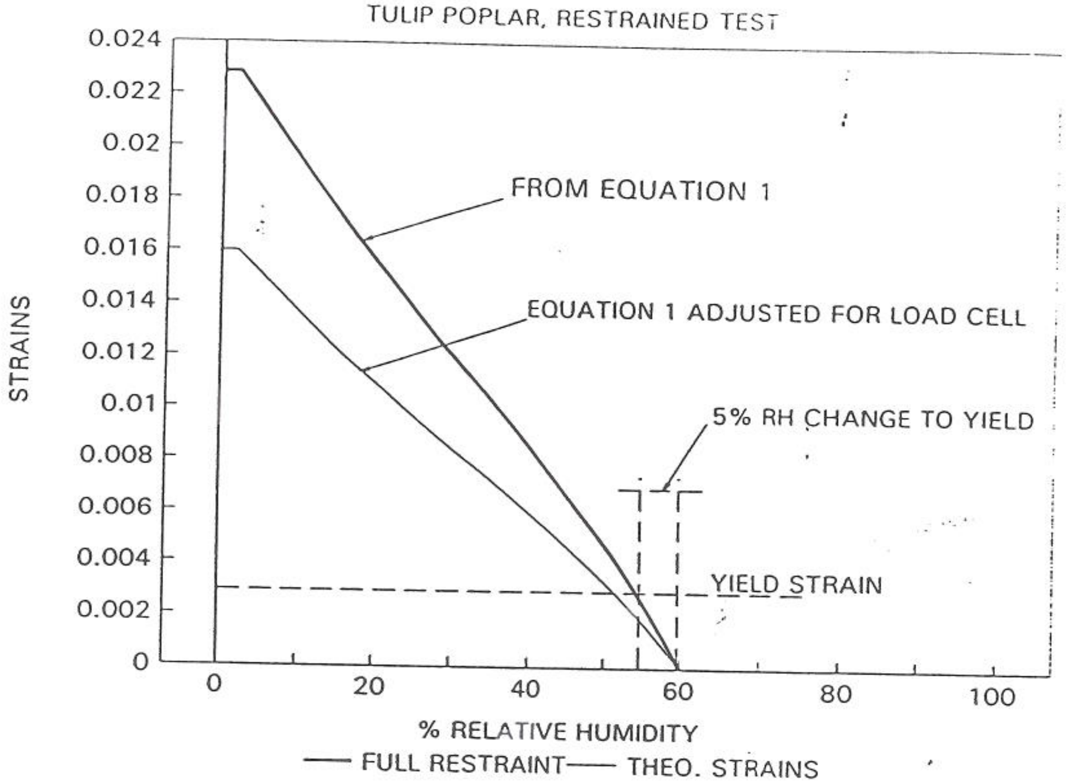

Figure 14. Maximum potential strains versus RH for released and fully restrained tulip poplar. This diagram indicates the approach used to determine the allowable RH fluctuations for a fully restrained material with a yield strain of 0.003.

A CONSERVATIVE APPROACH TO SETTING ALLOWABLE RH FLUCTUATIONS

Assuming that the construction of an object using wood causes some portion of it to be fully restrained from dimensional response, a simple assessment of its structural environmental response can be made. The assumption of full restraint, is extremely conservative since no object exists in that condition. In general, loose or poorly fitting joints and existing cracks allow some dimensional response of all materials, regardless of the orientation in the object. Partial penetration of moisture into wood creates one of the more severe stress conditions but even this takes time. It took three days for the small wood samples used in this test program to come to equilibrium with the environment.

One further consideration is that most materials, including wood, behave similarly in both tension and compression if the strains are not excessive. Normally woods fail at lower strengths due to cell buckling rather than fracture as seen in tension.

If one assumes full restraint and nominal yield strains, then a conservative value for the allowable RH fluctuation, $RH_{allow.}$, is easily calculated. This is done by dividing the allowable strain, ϵ_{yield}, by the coefficient of expansion, α, or:

$$RH_{allow.} = \epsilon_{yield}/\alpha \qquad (2.)$$

The units for the coefficient of expansion is strain per RH, so when inverted and multiplied by strain, the final units are RH. This equation works for both tension and compression, so the strain value chosen can be positive or negative in value. The allowable RH fluctuation is then given as plus and minus. If one makes this calculation over the entire RH spectrum, the result will be a plot such as shown in figure 15. Here allowable RH fluctuation (plus or minus) is plotted versus ambient RH for a piece of tulip poplar in the nearly radial direction.

The way to interpret this plot is to pick a level of RH and read the intersecting value on the vertical scale. For example at 50% RH the allowable RH fluctuation for a new, radial direction, fully restrained piece of tulip poplar is plus or minus 5% before a strain of 0.003 is attained. The wood is fully within the elastic region for both tension and compression and no permanent or plastic deformation occurs. Notice however, that at 35% RH, the allowable fluctuation is about plus or minus 8% RH. That is, this wood is more forgiving in a drier environment. All materials exhibit these peaks but they are not all at the same RH level. Figures 16-24 show the allowable fluctuations for nine other woods tested.

Many of the woods tested, walnut, ash, maple, red oak, American mahogany, and spruce show are quite durable in the sense that the allowable fluctuations are high even when assigning a minimum allowable strain value. Tulip poplar, white oak, cherry, and pine are the least durable under these conditions.

The allowable fluctuations for all of the woods are based on the lowest allowable strains and full restraint. In reality, all woods found in cultural objects are strain hardened to some extent simply because it is certain that they were exposed to some extreme environment under at least a partial restraint. In that case the allowable strains assigned for this discussion are really quite conservative.

There are some other points to make, all of the data show that the woods have a minimum allowable RH fluctuation at high ambient RH levels. The figures show that if the RH levels get high enough the wood cannot be desiccated without plastic deformation occurring. For most of the woods severe desiccation will cause plastic deformation upon the reinfusion with moisture. For restrained wood, the RH extremes appear to act as states from which they cannot escape without permanent deformation.

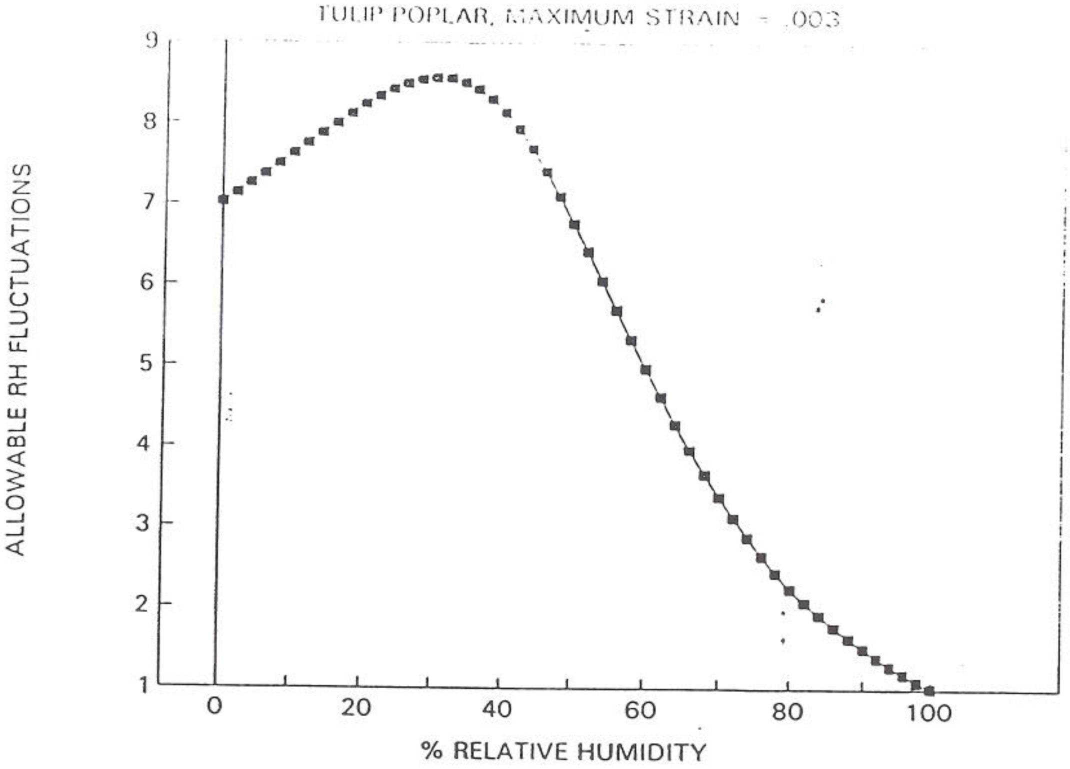

Figure 15. Allowable RH fluctuations versus ambient RH for fully restrained tulip poplar in the tangential direction.

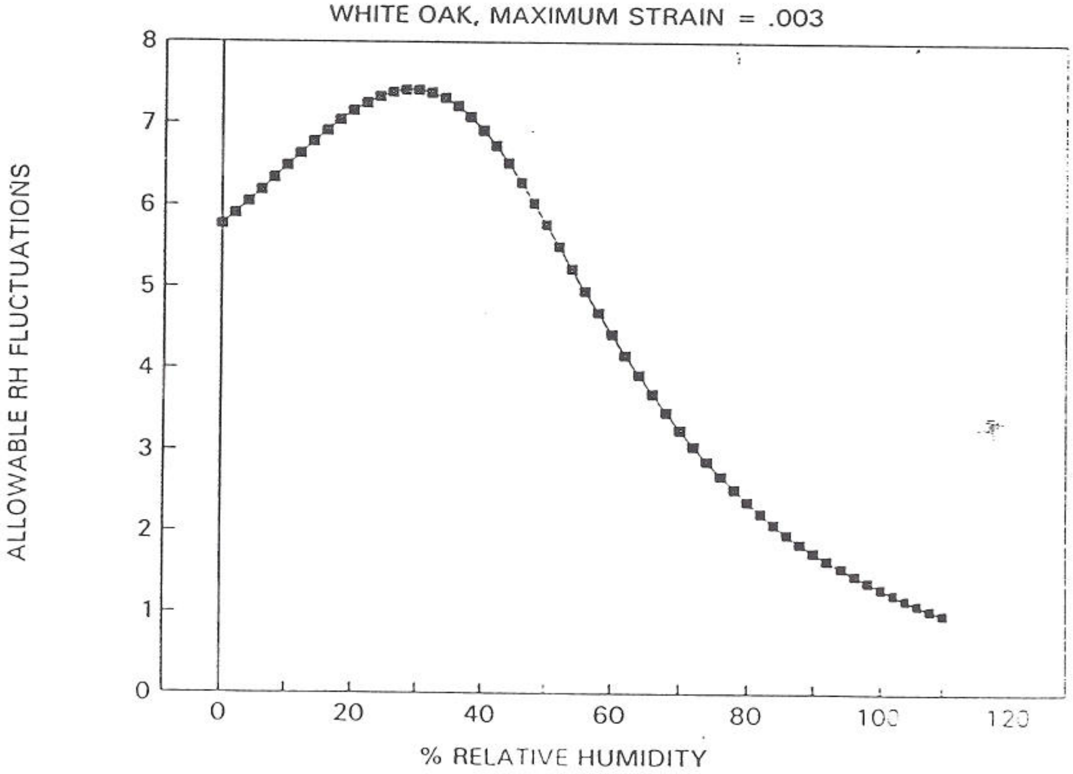

Figure 16. Allowable RH fluctuations versus ambient RH for fully restrained white oak in the tangential direction.

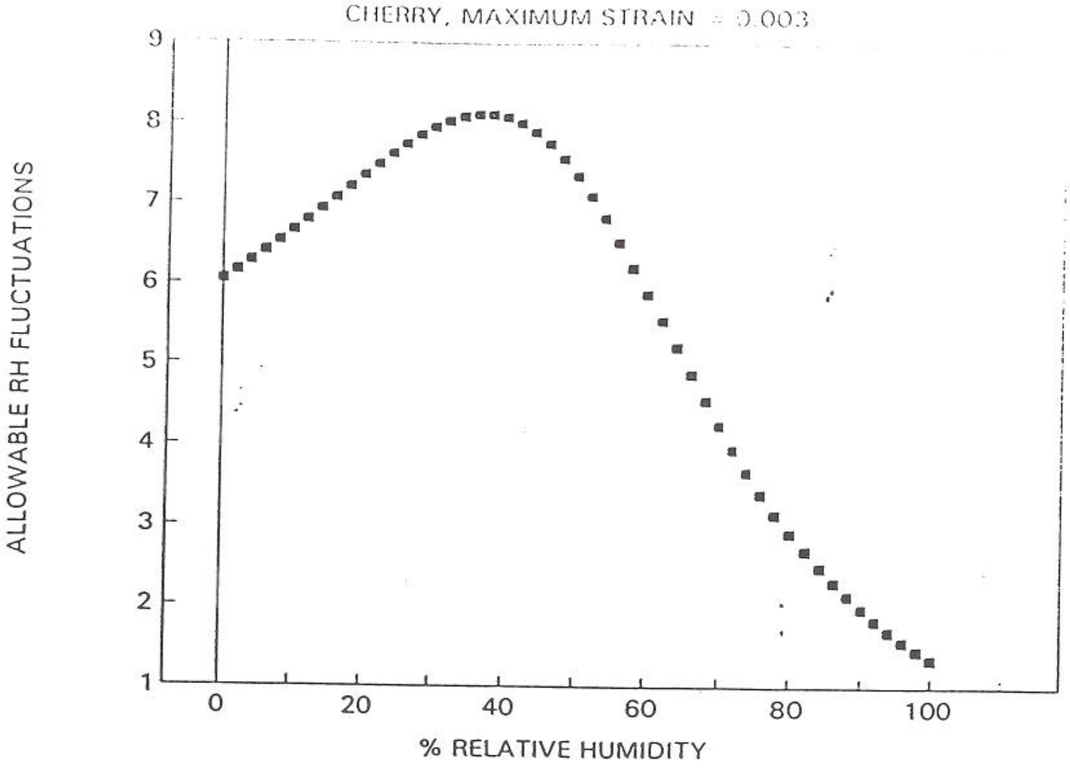

Figure 17. Allowable RH fluctuations versus ambient RH for fully restrained cherry in the tangential direction.

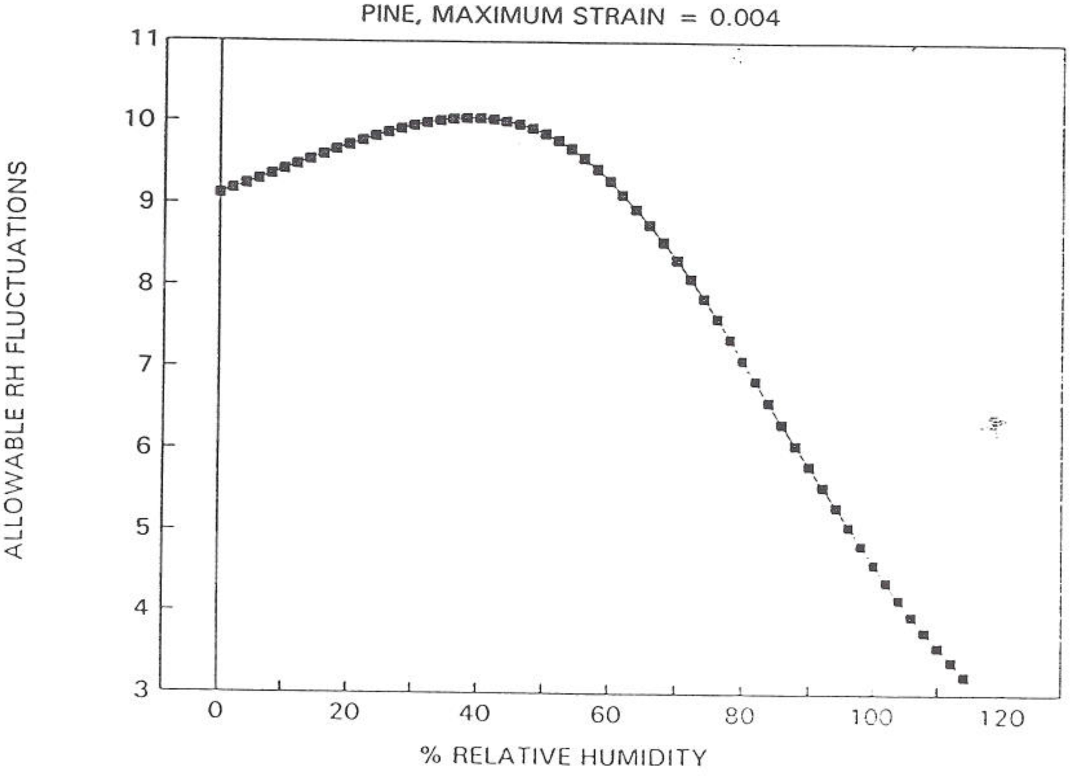

Figure 18. Allowable RH fluctuations versus ambient RH for fully restrained pine in the tangential direction.

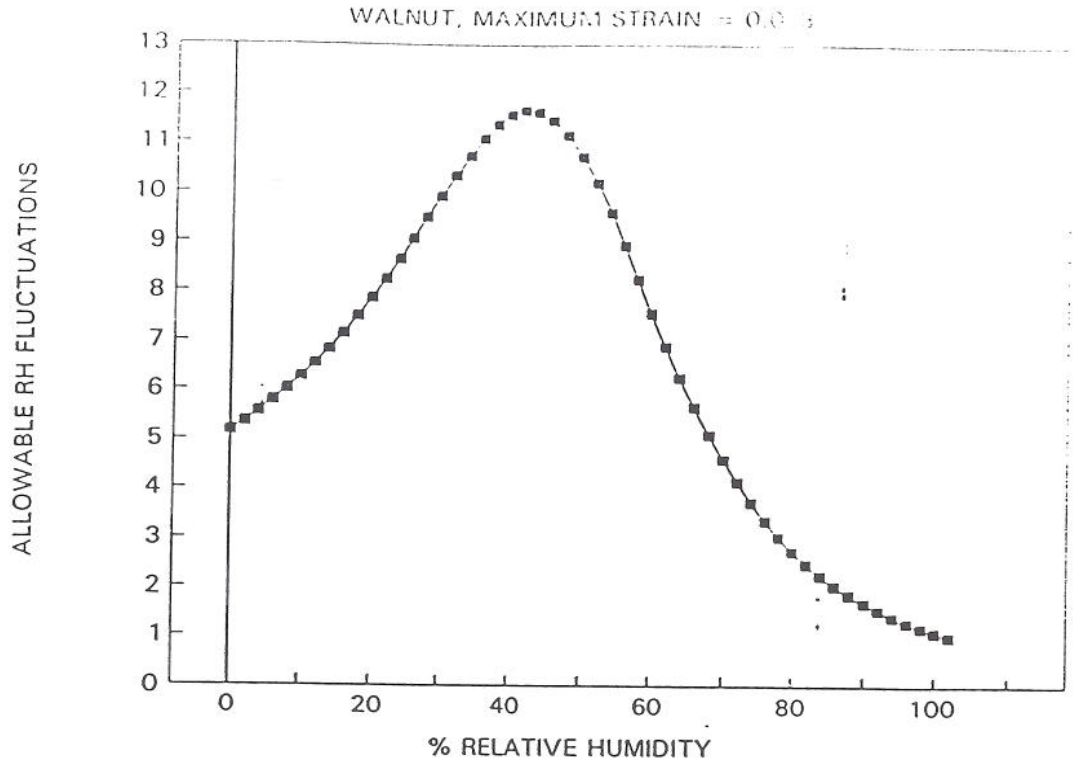

Figure 19. Allowable RH fluctuations versus ambient RH for fully restrained walnut in the tangential direction.

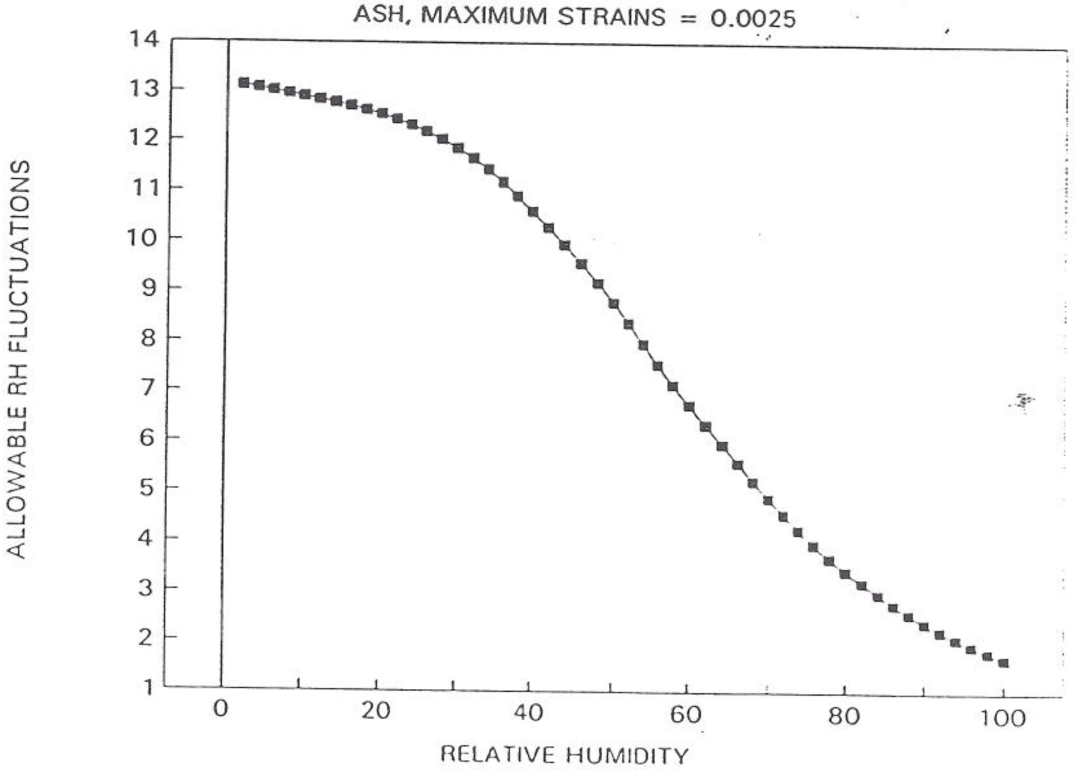

Figure 20. Allowable RH fluctuations versus ambient RH for fully restrained ash in the tangential direction.

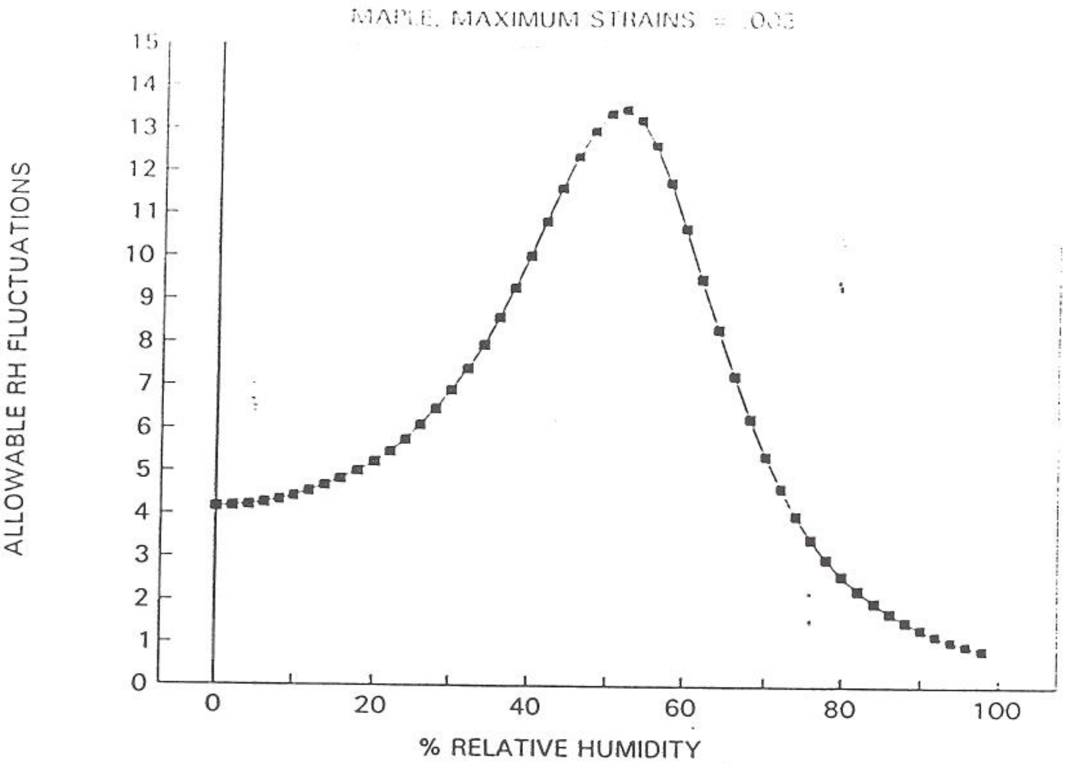

Figure 21. Allowable RH fluctuations versus ambient RH for fully restrained maple in the tangential direction.

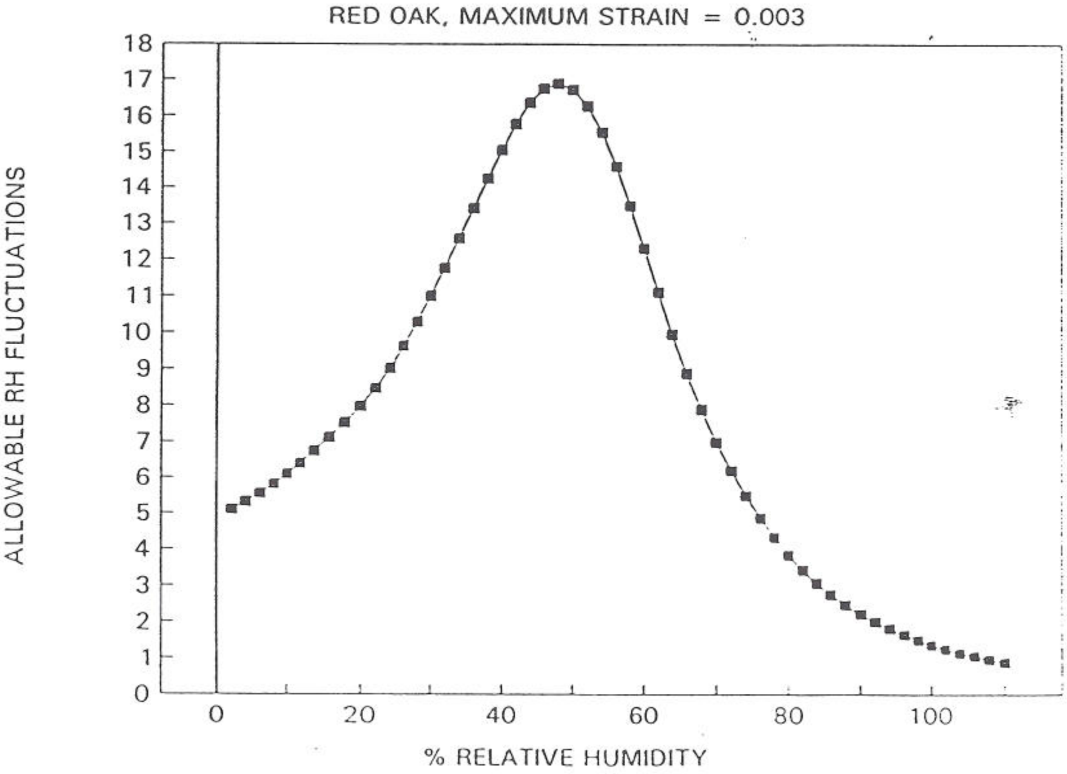

Figure 22. Allowable RH fluctuations versus ambient RH for fully restrained red oak in the tangential direction.

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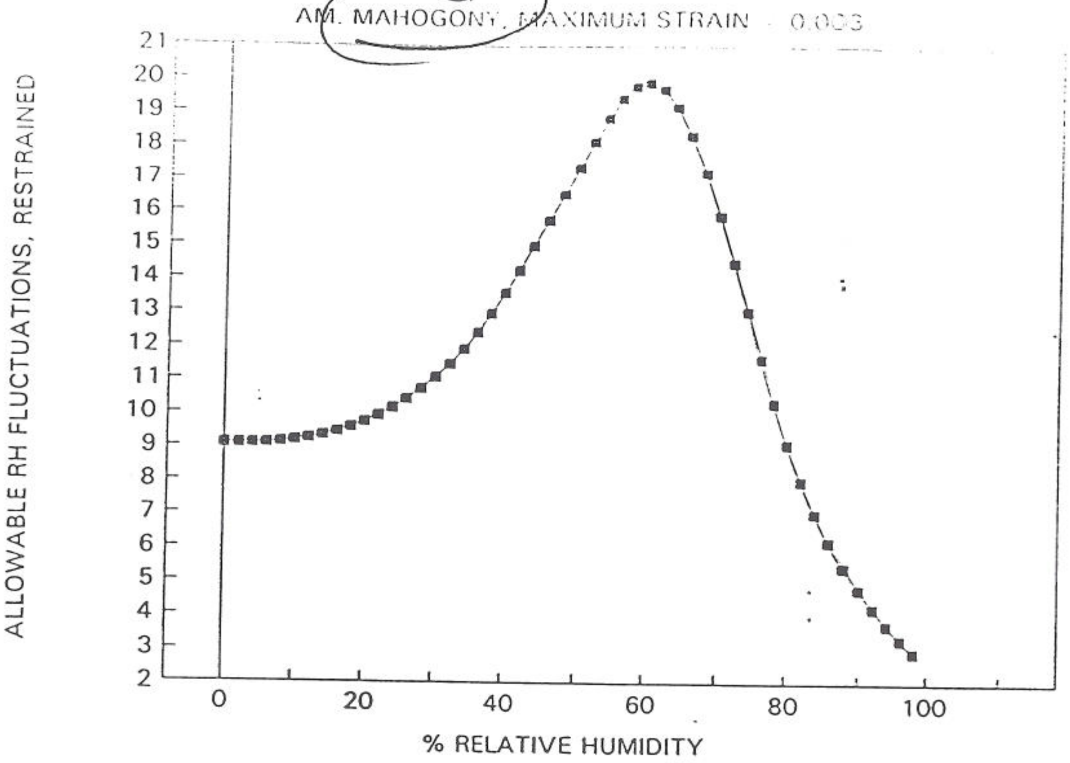

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Figure 23. Allowable RH fluctuations versus ambient RH for fully restrained American mahogany in the tangential direction.

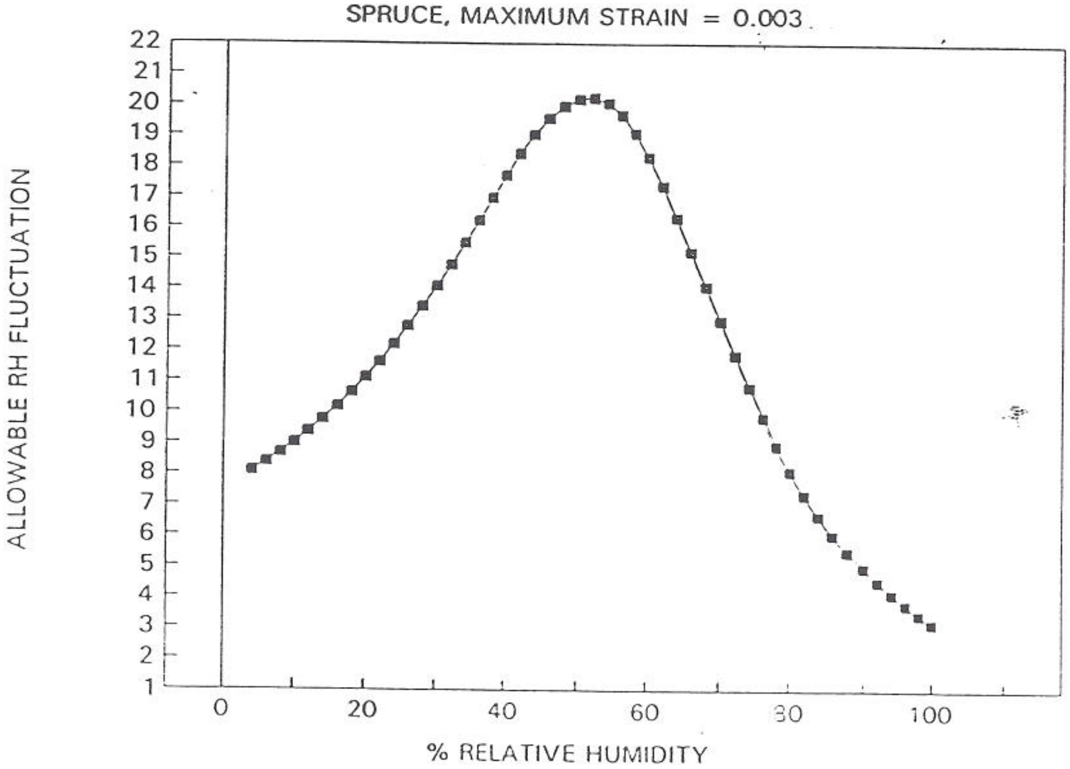

Figure 24. Allowable RH fluctuations versus ambient RH for fully restrained spruce in the tangential direction.

CONCLUSIONS

The dimensional properties of 10 representative woods were determined in the cross-grained direction to obtain information about damage brought about by environmental changes. The data show a variation in swelling for each wood, with some woods swelling more than others as would be expected. This dimensional information coupled with the yield point of the woods determined from stress-strain plots have allowed the determination of RH ranges within which a restrained wood object can remain in an elastic region. The maximum allowable fluctuation was found to vary for each of the 10 woods tested. For all restrained woods, changes in RH from either very wet or very dry environments can produce plastic changes in the structure. Such changes are clearly to be avoided. Under usual museum conditions most wood objects will easily remain in the elastic region if fluctuations are kept within the 40-60% RH range.

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