APPLIED MECHANICS OF MATERIALS IN CONSERVATION RESEARCH

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ABSTRACT

Much of the damage found in cultural and artistic objects is not chemical in nature but results from mechanical responses to stimuli such as changes in temperature, relative humidity, impact, and vibration. Analytical tools of engineering mechanics are available that allow us both to diagnose existing problems as well as to predict the effects of future potential hazardous conditions for many objects. A systematic approach of applying engineering principles to cultural objects requires two fundamental steps: 1, determining the mechanical properties of the constitutive material found in objects, and 2, developing analytical procedures that determine the overall effect of the individual material responses to various stimuli on the object as a whole. The individual material properties are typically defined as the yield and ultimate strengths, the elastic modulus, and the strains to yield and failure.

For the vast proportion of cultural objects, the materials are organic, and their mechanical properties are dramatically altered by environmental factors such as changes in temperature and relative humidity.

One of the most successful analytical techniques is Finite Element Analysis (FEA) using the digital computer. This method will allow one to numerically model an object, to mathematically induce environmental changes as well as determine the mechanical effects of these changes on the object modeled.

INTRODUCTION

There are four basic conditions that represent potential hazards to the structural integrity of cultural and artistic works. These conditions include exposure of an object to: 1, changes in relative humidity (RH); 2, temperature variations; 3, vibration, and 4, shock. Of the four conditions, the effects of RH on objects have received the most attention. Additionally, changes in temperature have been traditionally viewed as a parameter that affects RH and not necessarily as a potential hazard independent of RH considerations. Research into vibration and shock has never been conducted to the degree that would allow a clear description of the adverse effects of this type of stimuli on cultural objects.

Control of temperature and relative humidity

Current museum practice is that objects should be maintained in an environment of constant temperature at 20° C and a RH of 50%. This recommendation is, in fact, expressing the need to keep the moisture content of the object constant, thereby keeping it dimensionally stable (1,2,3,4,5). These values seem to work well within buildings for paintings on canvas as well as those painted on wood panels, and in general for those objects composed of hygroscopic materials. What is not clearly defined is the acceptable range of deviation from the recommended values that objects might safely endure. This consideration is important,

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since many historic sites housing cultural objects either cannot afford costly air conditioning systems or, their installation would destroy the historic building housing the collection. The latter condition results from water migration through the building walls in the winter seasons and the subsequent freeze-thaw damage. Additionally, objects are removed from museums and galleries, and they are transported around the world for temporary exhibitions. Under these circumstances environmental control is very difficult.

Consequently researchers have spent considerable time in designing and evaluating packing crates that attempt to maintain a constant internal temperature and RH when subjected to adverse external environments (6,7,8,9,10,11). They have shown that this is not a trivial problem. Depending on the volume of air in the crate and the amount of absorbent materials (wood, etc.) used in its construction, the internal environment of this confined space can either decrease or increase in RH with changes in temperature. The balance of crate construction materials to air volume is critical to the stabilization of the transported object. Additionally, maintaining a constant RH while allowing changes in temperature does not necessarily stabilize the object, since temperature changes affect the moisture content of objects even at constant RH. Short of mechanical means, the best one can hope for is a crate that moderates and delays changes (both temperature and RH) in the interior environment that would result from changes in the outside environment.

Control of vibration and shock

Vibration, inherent in the various modes of transport, is a potential source of damage if cultural materials are prone to damage by fatigue (12,13). Additionally, the natural or resonant vibration of a given object may be dramatically amplified, if it is matched by the frequency of the transportation mode (14,15). Under these conditions, objects could sustain damage. Vibration, as it pertains to art transport, presents one of the least understood problems and as one researcher states,

> "It seems inevitable that a canvas will vibrate during transport and it is not easy to see a method of preventing this in the packing system without immobilizing the canvas. At the moment, as with shock, we have no way of relating vibration to damage. These results suggest that this may be an area for further research."(16)

There have been efforts by various conservators (17,18) to measure the levels of shock and vibration produced in most of the typical modes of transportation; however the most reliable information is provided by the Department of Transportation (19) and the Forest Products Laboratory (20). Some attempts have been made to measure the degree of vibration and impact attenuation provided in several packing case designs (21,22). Almost no data are available correlating damage of the paintings to vibration or shock levels.

It is easy to recognize the difficulty of recommending protective measures in packing when one does not know the effects of vibration, or the magnitude of shock, that causes damage to the object. At best, one can assume an extremely conservative maximum allowable shock and vibration levels and attempt to design packing cases that provide maximum protection.

RESEARCH CONSIDERATIONS

Excluding damage from mold growth resulting from damp conditions, it may be generally stated that the form of failure typically observed in objects subjected to adverse environments is stress related cracking and flaking of paint as well as splitting of the wood-support panels. For example, desiccation usually results in shrinkage when hygroscopic materials are unrestrained. Restraining them, such as in a stretched painting, will result in dramatic stress development. On the other hand, while excessive vibration and shock could result in the cracking of materials as has occurred in wood panel paintings, vibration induced failure has yet to be documented in a sound, uncracked canvas painting. Whatever the source of the damage, it is useful to recognize that nearly all of the damage takes this "mechanical" or stress related form.

The mechanical properties of materials are those which define the strength and stiffness (or inversely flexibility), that is, determining the materials ability to deform when subjected to forces. Once these material properties are well determined, one may conduct an analysis of the structure composed of these materials. In such an analysis, it is possible to establish how a structure might fail under different types of applied forces. Structural analysis may take the form of subjecting an actual structure to its expected loading conditions and observing when and how failure occurs. Often, smaller models of the structure may be constructed and tested, providing the same information at a much reduced cost. There is also the case where testing an actual object to failure is not possible. Cultural objects clearly fall under this category. Under these circumstances, an alternative or "non destructive" form of analysis must be used. One such approach uses the computer to mathematically "construct" a numerical "model" of the object to be tested. This method, called Finite Element Analysis (FEA), allows an extremely accurate stress field analysis of a structure using the computer (23,24,25). This approach mathematically constructs the object using discreet or finite elements. These elements include the mechanical properties of the material used in constructing the actual object. If correctly modeled the accuracy of the analytical solution depends on the number of elements used. The more elements, the more accurate the solution. Even though paintings are complex in that they consist of numerous layers of different materials, most modern FEA software is capable of providing a reasonable stress analysis.

In the case of paintings, (and most cultural objects) complete information about the mechanical properties of the materials encountered is not available. Thus, it is an objective of the research at the Conservation Analytical Laboratory (CAL) to establish the necessary material baseline information.

CURRENT RESEARCH EFFORTS

The scope and magnitude of this program require that considerable resources are available in order to be able to develop the necessary information needed to provide environmental and transport recommendations in a reasonable amount of time. Consequently, the Canadian Conservation Institute (CCI), Ottawa, Ontario, the National Gallery of Art (NGA), Washington, D.C., CAL have joined in a cooperative effort to conduct the necessary research to complete this study. CAL has been assigned the responsibility of determining the necessary mechanical properties of the relevant materials and developing the numerical modelling techniques. CCI is responsible for the experimental verification of the analytical results provided by CAL. This includes the dynamic testing of full scale "test" paintings and other objects as well as evaluating crate designs. Currently, the equipment necessary for vibration and impact testing is installed and operating. Preliminary tests on sample paintings constructed for analytical model verification have been conducted with the initial computer predictions being verified. NGA is primarily responsible for the verification of the environmental performance of crate designs. Currently NGA has an large environmental chamber that is capable of reproducing the ranges of both temperature and RH expected under transport conditions. Work is presently being conducted which determines the dimensional response of actual panel paintings subjected to RH and temperature fluctuations. This work will assist in further computer modeling as well as determining the time rate of the effects of environmental changes.

THE MECHANICAL PROPERTIES OF MATERIALS

Data on the mechanical properties of painting materials are limited with respect to oil paints, hide glues and gesso. The paint industry, investigates the properties of paints, but is primarily interested in the resistance to weathering. Some measurements on the mechanical properties were made on oil films in order to determine the effects of various ratios of pigment to oil medium (26,27,28). It is not surprising the that so little information is available on the mechanical properties of paint, since only recently was it shown that paint actually contributes a significant degree of support to a fabric supported oil paint (29). Recent work on environmental effects on the properties of the materials found in oil paintings has determined that for wood, paints, hide glues etc, in addition to swelling and shrinking with changes in RH, the mechanical properties alter dramatically (30,31). Both effects play substantial roles in RH related damage to paintings.

Unsupported oil paint films, cast in 1979, are currently available for mechanical testing and developing a base of necessary data to use in numerical modelling. CAL has mechanically tested small samples cut from the 11 year old paints. Acquiring sufficiently large specimens from actual old paintings has not been possible. CCI has developed equipment to test micro samples. Those tests show very good correlation with tests run on much larger samples with CAL's equipment (32) .

A large body of information is available on the mechanical properties of wood. It has been such a historically important structural material, that data on the effects of moisture and temperature has been gathered (33).

A considerable body of information on the mechanical properties of textiles is available (34). The primary difficulty with this information is the form presented. Stress as applied in engineering situations is the force applied divided by the cross sectional area of the material tested. Textiles present a difficulty in measuring the cross section of the fibers which are actually the load bearing components of textiles. The textile industry has developed a completely different approach to quantifying the stiffness and strength of textiles which is not easily compatible with the current engineering analysis. A new method has been developed to to establish the mean fiber stress while the textile is subjected to forces. This format is compatible with all of the other materials in a typical painting and readily allows one to determine the structural role of the fabric support.

The mechanical properties of materials represent the fundamental information used in the design, analysis and construction of any structure. Information, such as the yield strength, ultimate strength, and the modulus of elasticity are determined. This information is based on measurements using a tensile (or compression) test where the material is subjected to a slowly increasing force and both the applied force and the material deformation are recorded on a plot. This plot usually takes the form of a stress-strain plot where:

$$\sigma = F/A \text{ and } \epsilon = \delta/L \qquad \text{(Eq.1)}$$

and: σ is the stress in the test specimen
F is the applied force
A is the cross sectional area of the test specimen
ϵ is the strain in the test specimen
δ is the change in length of the test specimen
L is the original length of the test specimen.

Some illustrations will serve to show how the mechanical properties of artist materials are highly dependent on environmental factors such as RH, temperature and the rate of the applied load.

The equilibrium stress-strain plot of an 11 year old Naples' yellow oil paint made largely with lead carbonate, a colorant and linseed oil is shown in Fig. 1. In this test, the paint samples

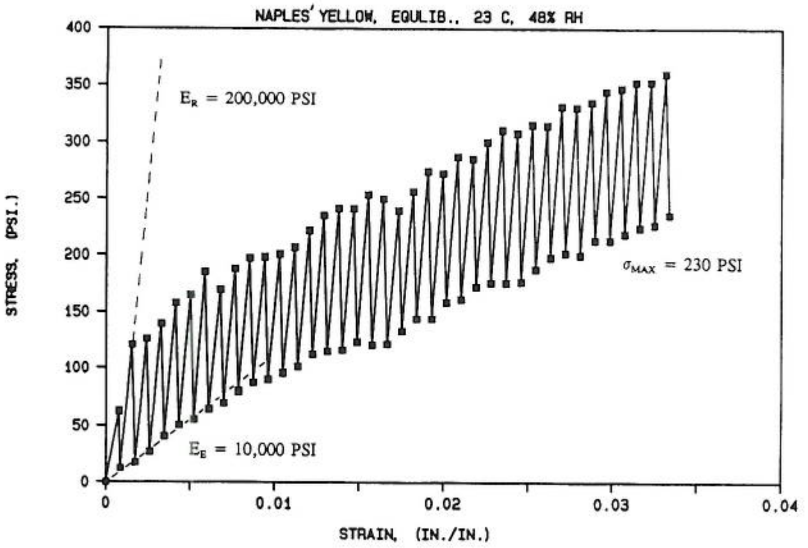

Figure 1. Equilibrated stress-strain plot for Naples' yellow linseed oil paint. Dashed lines show the equilibrium and rapid loading slopes.

were subjected to small, rapid loading increments after which the displacements were fixed and the specimen was allowed to "stress relax" over a period of time. For oil paints, the relaxation period was between 4 and 8 days depending on the type of paint and the surrounding environment. This procedure was repeated until the specimen failed. This test sometimes took more than three months and was conducted at 23°C and 48% RH. The locus of points after relaxation describes a tensile test of the paint at quasi equilibrium with the environment. This approach was undertaken in order to observe the behavior in mechanical properties of these materials when subjected to long term environmental changes. Fig. 1 also shows the rapid loading and "equilibrium" slopes of the test paint. These are indicated with dashed lines and labeled E_S and E_E. This is the first indication of the differences caused by different loading rates. The slopes, $E = \sigma/\epsilon$, or the modulus of elasticity for each condition, differ significantly where E_R is approximately 200,000 psi and E_E is only about 10,000 psi. The data have considerable implications for the behavior of a structure subjected to environmental and dynamic conditions. Since E is a measure of the "stiffness" of materials, the paint under dynamic conditions is much stiffer than under equilibrium conditions.

A more complete picture of dynamic properties is illustrated in Fig. 2 where a previously untested paint film is rapidly loaded starting at the origin . The locus of the stress relaxed points from Figure 1 is also included. At the end of this test are plotted the results of the same test specimen subsequently

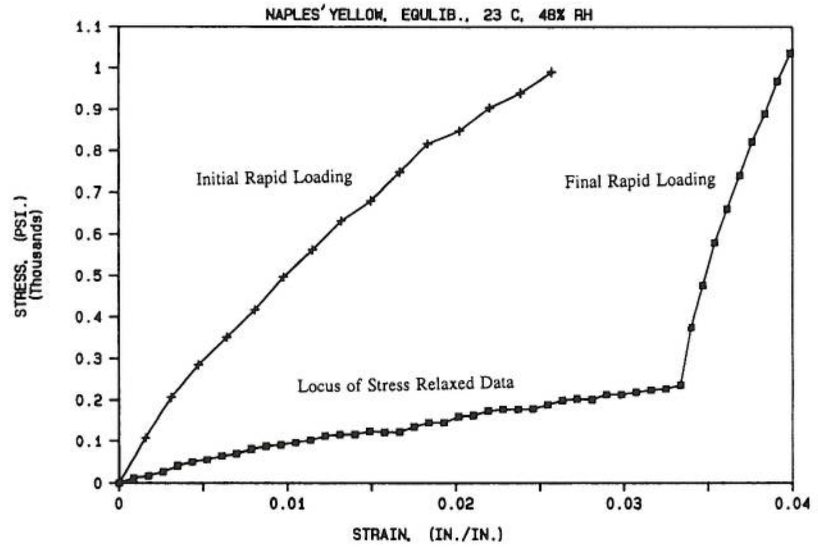

Figure 2. The comparison of the equilibrated stress-strain plot with the rapid loading tests of Naples' yellow paint. Note the reserve dynamic strength of the paint as shown in the final rapid loading of the equilibrated test data.

subjected to rapid loading. A dramatic difference in the strength of the paint results from the different test modes. Rapid loading strengths are about four times higher than the equilibrium strength. The slope of the rapid test at the end of the equilibrium test is considerably higher than that of the previously untested paint, suggesting "strain hardening" has occurred during the equilibrium test. More important is of the dynamic reserve strength in a paint film previously subjected to slow, long term testing.

Equilibrium tests were conducted in two different environments, 23°C, 48% and 5% RH to study the effects of RH on the mechanical properties of paint films (Fig. 3). The equilibrium slopes of the plots increase with a decrease in RH, (from 10,000psi to about 50,000 psi) but the rapid loading slopes seem to be relatively unaffected as indicated by the dashed lines. The breaking strength (maximum stress) of the material increases with a loss of RH, and the strain to failure decreases with desiccation. In other words, while this paint gets stronger as it dries out, it loses flexibility and becomes brittle.

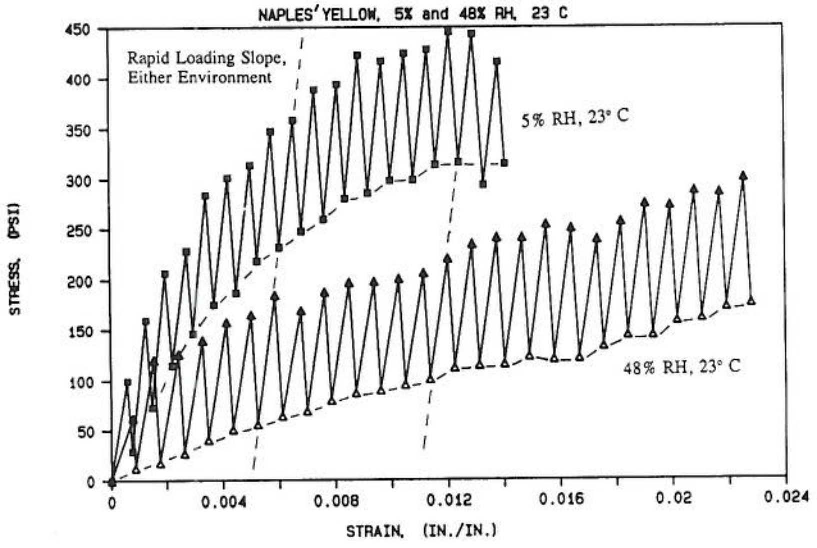

Figure 3. The comparison of equilibrated stress-strain plots of Naples' yellow conducted in two different environments. The dashed lines show that there is little difference in the rapid loading slopes while the equilibrated slopes and strengths are considerably different.

Is worth inserting a comment concerning temperature effects at this point. Testing the Naples' yellow oil paint at -2°C and 5% RH increases the equilibrium modulus to 150,000 psi and the rapid modulus to over 800,000 psi. These are substantial increases over the results previously shown. These mechanical properties, however, are typical of some oil paints. The specific properties of these materials depends heavily on their age and the kind of pigment used in the paint. Many pigments have a rapid drying effect on the oil medium. This behavior is demonstrated in Fig. 4, where the Naples' yellow has a high lead content, which acts as a socalled "dryer", and the sienna is an earth pigment which has no drying affect. The Naples' yellow, therefore, has considerably more strength and stiffness than the sienna.

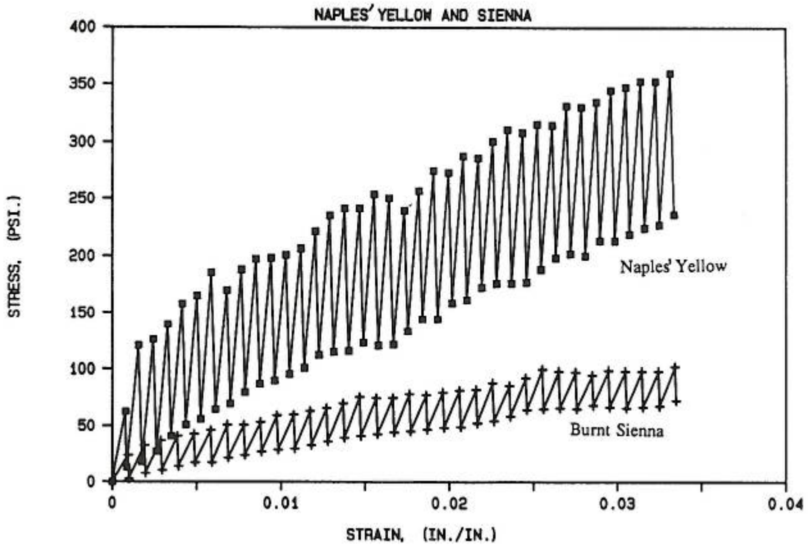

Figure 4. the comparison of the equilibrated stress-strain plots of two different paints in the same environment of 48% RH and 23° C.

Another material typically found in paintings is hide glue which is responsive to RH and to the rate at which the load is applied. In Fig. 5, samples of rabbit skin glue were subjected to rapid loading increments at three RH levels after which the strains were fixed, and the specimen is allowed to "stress relax". A glue layer in paintings subjected to long slow changes in RH would exhibit these properties. On the other hand the slopes of the rapid loading increments are quite similar in the different RH environments. This suggests that the dynamic properties of the glue seem to be relatively unaffected by these changes humidity. This information is important when analyzing paintings subjected to vibration and shock where materials are loaded extremely rapidly.

The other conditions which were tested concerned organic materials that absorb moisture from the environment and swell with moisture uptake, and conversely shrink with loss of moisture. For materials, such as the paints, glues and fabrics in a stretched painting, the stretchers represent a restraint to shrinkage when desiccation occurs. Under these circumstances, high tensile stresses develop in the various layers of the painting, normally leading to the cracking and flaking of the painting. These

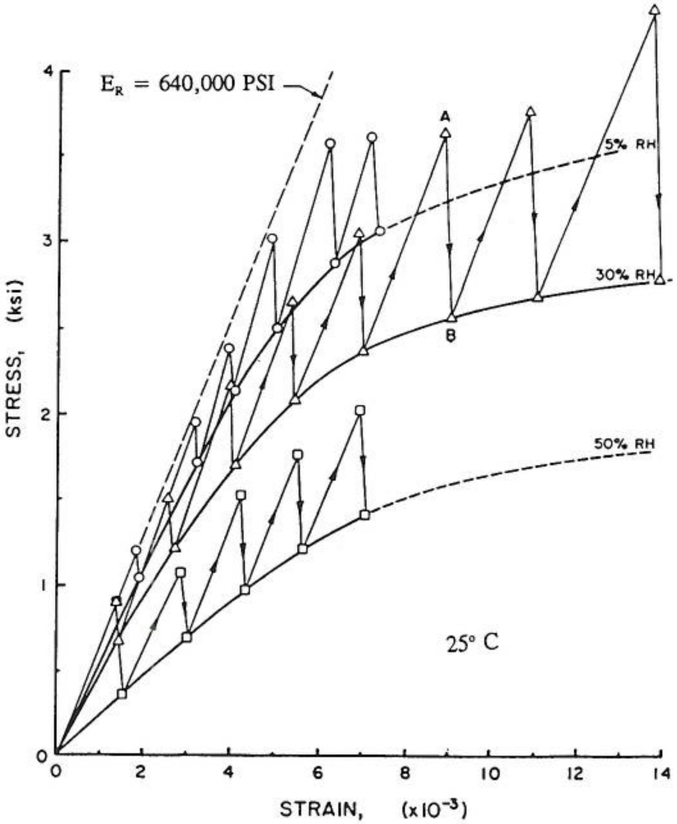

Figure 5. Equilibrated stress-strain plots for rabbit skin glue run at three different RH levels and at 25° C. This material is considerably stiffer and stronger at than oil paints in these environments.

stresses are illustrated by specimens of rabbit skin glue which were restrained stress-free, at different relative humidities and then desiccated (Fig. 6). The stress levels at maximum desiccation are nearly as high as those shown in the equilibrium stress-strain curves in Fig. 5. In fact, there is a specific relationship that exists between the stress levels attained by the stress-strain curves and the stress levels attained by the restrained desiccation (31).

Paintings subjected to vibration and shock develop their own characteristic stress field patterns and should the stresses exceed the measured breaking strength of the paint layer (as measured in the rapid loading tensile test), cracks will develop in the painting. Both the form and magnitude of the stress fields can be predetermined by the numerical analysis method using the

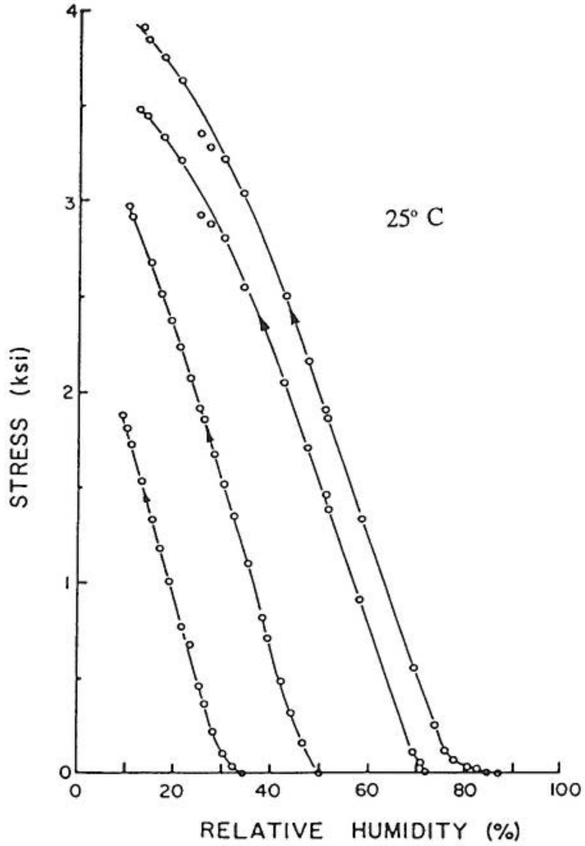

Figure 6. Stress development in restrained rabbit skin glue subjected to desiccation. The stress levels are quite high and can cause considerable damage to objects with the glue and subjected to large drops in RH.

computer. This allows one to determine the magnitude of dynamic stimuli that is safe for painting transport.

NUMERICAL ANALYSIS USING FINITE ELEMENT METHODS AND THE DIGITAL COMPUTER.

Stress field analysis is complicated for cultural objects constructed with several different materials, most of which are hygroscopic. However, stress analysis is necessary to determine the magnitude and location of the stresses that are induced in an object as a result of changes in temperature, RH and those resulting from shock and vibration. The type of failure as well as the magnitude of acceptable environmental changes, level of acceptable vibration and severity of impact can be determined. Currently, computer programs are available for numerically modelling objects to determine these stress fields. FEA programs have been used to determine stress fields in fabric supported paintings resulting from environmental and dynamic stimuli.

FEA was developed initially by the aircraft industry for the design and analysis of complex aircraft parts, which were required to sustain both severe static and dynamic loadings yet at the same time be as light as possible. As a consequence, the geometry of the parts became quite complex, preventing an economic way to either design or test them. FEA provided a method to quickly arrive at an optimum design as well as give clear indications as to the expected structural performance of these components. Subsequent advancements allowed more complex geometries as well as entire structures to be analyzed. FEA has been adapted to problems in conservation using desk top computers. The approach to FEA can be summarized as follows: (23)

1. Divide the structure on to a finite number of subregions (or elements) of simple geometry (triangles, rectangles, etc.)
2. Select key points on the elements to serve as nodes, where conditions of equilibrium and compatibility are to be enforced.
3. Assume displacement functions within each element, so that the displacements at each point within the element are dependent on nodal displacements.
4. Satisfy strain-displacement (theory of elasticity) and stress-strain (constitutive) relationships within each element.
5. Determine stiffness and equivalent nodal loads for a typical element, using work or energy principles. This is the determination of the so-called element stiffness matrix.
6. Develop equilibrium equations for the nodes of the subdivided model in terms of the element stiffness contributions, Thus assembling the structural stiffness matrix, the displacement vector and the force vector.
7. Solve these equilibrium equations for the nodal displacements. This can be done for a wide variety of applied forces and restraints (boundary conditions).
8. Using the calculated nodal displacements, solve for the element stresses.
9. Determine the support reactions, if necessary.

FEA as a diagnostic tool.

The patterns of cracks that are observed in paintings could be the result of one or more adverse conditions. It is significant that the crack patterns themselves hold clues as the conditions that caused them. Since cracks occur in a direction perpendicular to the maximum principal stress, when the strength of the material is exceeded, we can determine the stress field that is associated with such crack patterns, and thus provide considerable insight into the conditions that existed when the cracking of the painting occurred. for example, Fig. 7 shows a photograph of a 19th landscape painting, oil on canvas, which is stretched on its original strainer (a strainer is a stretcher that is fixed at the corners and cannot be expanded). It is helpful that we know this is the original strainer, since it is possible to eliminate corner expansion (keying out) of the painting as a source of the cracking. Convex cracks propagate from the corners and continue to the center of the picture where the cracks are primarily perpendicular to the long direction of the painting. Additionally, the crack pattern is symmetric about both the long

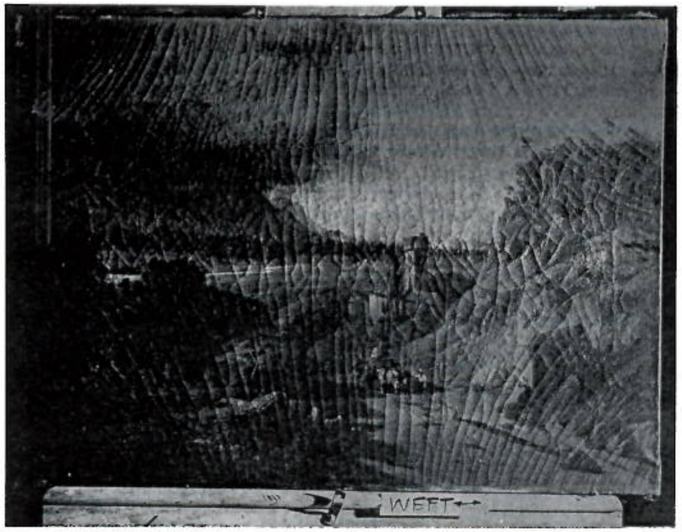

Figure 7. A 19th century oil painting showing a crack pattern typically found in many North American paintings. It can be shown that the glue size layer is the primarily cause of this type of cracking.

and short axes of the painting, and each quadrant is a mirror image of adjacent quadrants. The different colors or pigments found in the quadrants have no influence of the formation and propagation of the cracks.

Because of this double symmetry, it is only necessary to model one quadrant of the painting, allowing one to conserve computer storage space as well as arrive at a solution in a shorter time. The results of FEA show the maximum principal stresses and directions displayed in vector form (Fig.8). Cracks occur perpendicular to these vectors, and the each associated crack is superimposed over the stress vector. A remarkable correlation is seen of the crack pattern in the actual painting with that in the computer model. This pattern was correlated to a specific environmental condition, namely that the crack pattern was the result of desiccation over a considerable time. The duration was sufficient to allow for the desiccation of the wood in the strainer as well as the painting itself, since the pattern cannot exist without the shrinkage and narrowing of the strainer bars. Although the paint layer contributed to this condition, the glue-size layer was the material that was primarily responsible for the destruction of this painting (29). This result accounts for the lack of influence of the different pigments in the painting. The fabric support of this painting played no active role in the crack formation, nor was it capable of preventing it. This painting could have been analyzed with a model "lining", thereby allowing one to evaluate the effects of such a treatment.

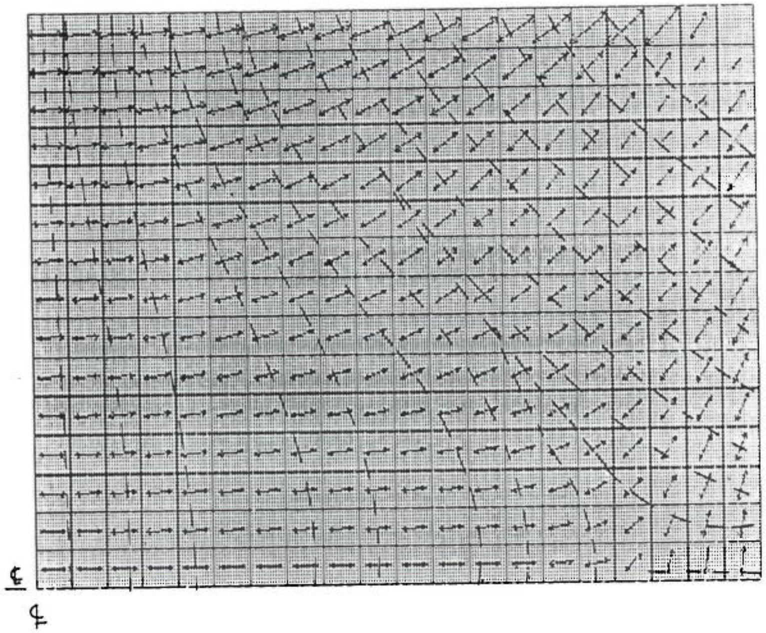

Figure 8. A computer generated stress field using the FEA program, ANSYS. The dashed lines superimposed over the stress vectors represent the theoretical crack pattern. This pattern was a result of increasing the modulus of the paint and glue layers while allowing cross grain contraction of the strainer bars as would occur in the desiccation of a painting.

FEA as a predictive tool.

If a fabric supported painting is subjected to vibration, the paint layer, ground, glue size and canvas together vibrate out of the plane of the stretcher. The severity of that vibration is a function of a considerable number of factors, including the mass of the painting, the frequency of the vibration and the tension of the painting. As with any structure, paintings have more than one natural resonant frequency, but the ones that are of the concern are the primary frequencies, i.e., the first and second modes where the out-of-plane displacements are most severe. Additionally, in packing crates the higher frequencies are much more easily attenuated. At the primary or lowest frequency, the maximum displacement coincides with the maximum acceleration. At the node there is no velocity to the painting, and a simple equation of motion can be written where: $F = ma$; where:

F = inertial force felt by the painting,
m = mass of the painting and
a = instantaneous acceleration at the maximum displacement.

The acceleration is given in terms of earth's gravitational constant g, or G, where G = a/g. Using these concepts, one can load a painting with an equivalent force, F, perpendicular to surface of the painting when it is subjected to some acceleration, G. This loading produces a displacement and induces both planar (diaphragm) and bending stresses in the painting. If stresses are sufficiently high that cracks form, then comparing to that modeled will allow one to determine whether vibration induced cracks are present.

Using the FEA program ADINA, a 30"x40" painting model was subjected to a 30 G acceleration. Again because of symmetry only a quadrant of the painting was modeled. Fig. 9 presents the computed displacement field of the model where squares defined by the grid lines are the elements. The shape of the displacement is that of a vibrating painting in the primary mode. The elements used in this analysis are called "shell elements" and will calculate both the bending and diaphragm stresses. The important calculation was the maximum principal stresses. Fig. 10 plots the maximum principal stress vectors from the computer model, where the longer the vector the greater the stress. The maximum principal tensile stress calculated by this model was 450 pounds per square inch (PSI) and occurrs at the center of the model painting. These stresses occur at the surface of the painting, when the displacement occurs away from the reverse of the painting. As with Fig. 8, a theoretical crack pattern is superimposed onto the stress field. This crack pattern, however, is not seen on actual paintings. These stresses calculated are lower than the maximum breaking stresses from dynamic tensile tests. This analysis strongly suggests that vibration may not be a serious problem for stretched canvas paintings.

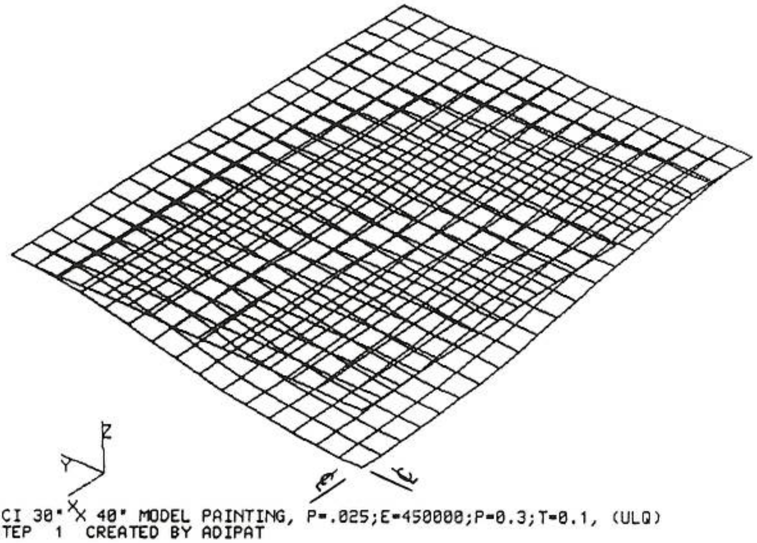

Figure 9. Computer generated displacements of one quadrant of a 30"x40" fabric supported oil painting. The model was .1 in thick with a normalized modulus of 450,000 psi and subjected to out of plane (z-direction) forces of 30 G's.

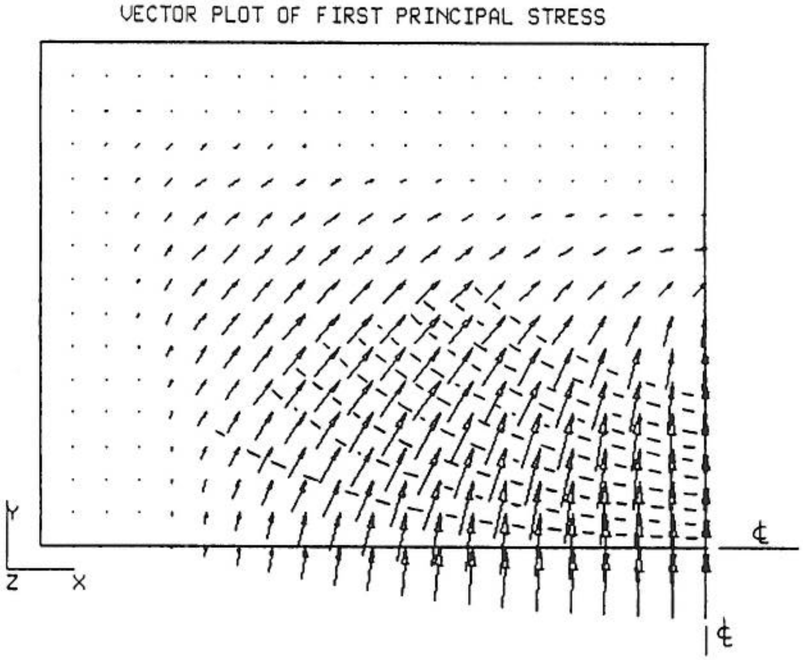

Figure 10. The computer generated stress field and superimposed theoretical crack pattern in the 30"x 40" painting shown in figure 9.

To confirm this finding, a 25"x25" painting was similarly modeled. Again, the crack pattern was not similiar to those found on paintings. The computed stresses did not exceed 300 PSI. The conclusion was that a 30 G vibration at the primary frequency was insufficient to crack a typical painting. At CCI a painting, measuring 24"x24", was constructed with a commercial ground and coated with a brittle gesso layer having an ultimate strength of 600 PSI and a elastic modulus of 400,000 PSI. This painting represented a weaker and more brittle one than that modeled on the computer. The test painting was subjected to it's 17-hertz primary frequency vibration for two hours and showed severe displacements. No cracks appeared, and it was not possible to induce cracking at any of the other natural frequencies. This represents a substantial advancement in our ability predict what levels of stimuli are going to cause failure.

Other observations were made during the CCI testing. A vibrating painting moves a large volume of air adjacent to its surfaces which provides a considerable resistance to motion or a "damping" factor. This damping established an upper limit to the displacements observed in the test painting. From this observation the amplification factor could be calculated (14) of about 6. Thus, the painting only feels G forces that are 6 times greater than from a vibration source such as a truck. If one considers the maximum G forces for sustained vibration measured in any mode of transportation will not exceed 1 G,(19), then the maximum G forces the test painting could experience during uncrated transport is only 6 G's. This further adds to the argument that sustained vibration may not be a serious problem in painting transport, but it is also necessary to tests other size paintings and paintings incorporating preexisting damage.

CONCLUSIONS

The problem of determining the adverse effects of the transport of cultural objects can be effectively addressed by the engineering discipline of mechanics, since all of the damage takes the form of cracking, splitting and flaking. Irrespective of the source of the damage (adverse environment, vibration or shock), failure is a result of excessive stress. A systematic approach to resolving the problem requires that the mechanical properties of the related materials are determined. The information on mechanical properties is then used in the structural analysis of the object. The most appropriate type of analysis is conducted using numerical modeling on the digital computer. The computer models are necessary since it is simply not possible to subject actual paintings or a sufficient number of test paintings to the experimental conditions required to cause damage. Once these tasks are accomplished, experimental verification using a limited sample can be accomplished. The model can then become the basic tool for examining the allowable tolerances of objects subjected to both adverse environments as well as dynamic stimuli from transport. Paintings were studied first, due to the relatively uncomplicated geometry and work on the mechanical properties of the materials of paintings is sufficiently advanced to allow for a moderately detailed feasibility study. With time, detail investigations of more complicated objects such as furniture and sculpture can proceed.

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