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REPORT

on

THE DETERIORATION OF FABRIC SUPPORTED PAINT FILMS

PHASE I - RESEARCH REPORT

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Submitted to

NATIONAL MUSEUM ACT
SMITHSONIAN INSTITUTION
WASHINGTON, D.C. 20560

by

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PART II - A Review of the Behavior and Interaction of Fabric Supported Paintings

PREFACE

This report describes the work completed during the first phase of the research proposal initiated on July 1, 1976. The material is presented in two parts. Part I presents a review of work contained in the initial tasks as outlined in the original proposal to the Smithsonian Institution (1). Included in this section is a comprehensive bibliography and a list of needed research with respect to material properties.

The second part of the report contains a presentation of clinical test data and numerical results obtained from a finite element analysis covering the influence of a number of significant parameters on the behavior and response of fabric supported paint films.

The tasks established as guide lines for a systematic approach to the investigation (1) have provided direction and a starting point in developing a research method for the fundamental understanding of a subject that has remained elusive for nearly four centuries. In addition, by setting intermediate goals, an opportunity was provided to allow for changes in emphasis and direction in all related areas, which might be indicated by the results of the initial investigations. It was anticipated that this initial research would expose and identify contradictions between fundamental scientific theory and contemporary practices in conservation.

The project has progressed rapidly in certain areas while in others the lack of available data has presented temporary obstacles. In summary, Task 1 and 2 are essentially completed. However, the completion of these tasks emphasized the incredible lack of understanding of the physical properties of the materials involved in paintings and the overwhelming need for materials research in the field of painting conservation.

Until a thorough and pertinent materials testing program could be initiated, it was determined to continue work in those areas where the project could readily proceed. Therefore Task 3, Development of Required Test Procedures and Instrumentation, and Task 5, Materials Testing Program, were initiated. It also became apparent that some of the material presented in the original proposal should be re-evaluated in light of the enlarged body of relevant information disclosed by the continuing investigation. Considerable time was, therefore, devoted to reviewing work completed for the original proposal.

In summary, the following comments are presented:

(1) It is apparent that the methodology chosen, namely, the application of mechanics and computer technology, holds the key to the understanding

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(1) Original proposal - Colville/Mecklenburg (July, 1976)

of the deterioration of paint films on fabric supports.A general theory is developing which permits increasingly precise answers to the questions being asked. It is essential, however, that the questions asked be based on a detailed knowledge of the physical properties of the materials involved if the method is to provide more than qualitative answers.

(2) The deterioration of paintings is largely a physical phenomenon since most causes of damage are the result of fundamental physical actions. Biological and chemical changes in the materials involved are significant primarily in that they produce alteration of the physical properties of the materials. In view of the primary significance of physical phenomena it is surprising that the thrust of the only major research in the field of conservation today lies in the area of chemistry.* This present project, to our knowledge, is the only one to explore the causes of the deterioration of paintings in terms of physics and materials science.**

(3) Task 1, the literature search, has dramatized the need for the simultaneous development of an accurate research tool such as the finite element computer model and a comprehensive material testing program. Ironically, it is industry,which is responsible for most of the present information on the physical properties of fibers, yarns, fabric, sizes and paint films, which will benefit from the development of such a computer model designed to solve problems in the field of fine arts.

(4) The availability of a practicing conservator with a background in the physical sciences as co-investigator with the vocabulary for a concise and meaningful dialogue with both engineer and scientist has proven invaluable to this project. It has also emphasized the difficulties encountered when scientist and conservator attempt to combine efforts in the solution of a problem. The co-investigators spent considerable time reviewing contemporary scientific theory and the fundamental structure of paintings, and as a result the formulation of specific questions was possible.

(5) The education of conservators is of prime importance. One of the co-investigators recently presented a seminar in the areas explored by this research project to graduate students in conservation at Winterthur. The students inability to grasp basic concepts in mechancis due to the fact that only 1 in 10 nad an undergraduate background in the sciences is a matter of concern. Thus it is unfortunate that at a period in the history of conservation when so little is known and when there are no guidelines in conservation techniques based on scientific knowledge,that existing educational programs do not seek out and promote greater concentration in science. It is hoped that the field of conservation will promote even greater dialogue between conservator and scientist and that each will recognize their respective responsibility in achieving an overlap in understanding the basic problems involved in conservation.

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**Dr. Alex Ross, Director of Research, Spencer-Kellog, indicated agreement in correspondance, but explained that industry has little need to develop oil paint films with extremely long durability.

PART 1

A Summary of Completed Research

Task I - Literature Search

An exhaustive search of the Library of Congress, industrial associations, university and museum libraries has been performed in order to locate, examine and compile information related to the physical properties of the components of fabric supported paintings. While this search continues, emphasis is now on contemporary industrial research, including continuing communication with the paint coating, plastics and textile industries. The material reviewed to date includes over 600 American and foreign publications and a list of the most relevant is presented below.

As a result of this search, a number of observations may be made as follows:

(a) Textiles

The textile industry has conducted extensive testing on both natural and synthetic fabric fibers and yarns. Physical properties such as modulus of elasticity, strength, tenacity, and elongation have been evaluated for fibers in general. However, the wide variety of weaves, materials and finishes used as supports for paintings is such that additional testing is needed on a variety of support fabrics. Fabrics (textiles) are structures made from large numbers of fibers and must be considered in the strictest structural sense as simple materials with unique properties. The large variation in anisotropic behavior as a function of initial tensioning and the capacity for movement and variation in physical properties with moisture changes must be investigated.

The literature search has revealed certain unexpected facts. For example, flax fibers often have tensile strengths as high as that of high strength steel (50,000 psi to 150,000 psi) and this strength increases with increases in moisture. On the other hand paint film strength varies between 500 psi to 2,500 psi and decreases with moisture increases. These highly variable strengths for flax fibers and paint films can hardly be considerable "compatible." In addition moisture increases can cause up to a 50% increase in the cross-sectional area of a cotton or flax fiber while the fiber length remains essentially constant.

Use in tyres!

One of the most revealing comments that can be made on the present state of current painting conservation practices and understanding is that while the literature search has produced several hundred related references to the physical properties of textiles, only two of these references were included in the bibliographies of published conservation papers. In addition it is worth noting that although Mr. J. S. Hearle (England) and Mr. Ernest R. Kaswell (US) are extremely well qualified experts in the field of textiles, the co-principal investigator of this research was the first conservator of paintings to contact Mr. Kaswell with respect to gaining information on physical properties of textiles used as painting supports.

The investigation into textiles has also revealed the importance of the chemistry and biological properties of natural and synthetic fibers. This information is relevant since the cell structure and chemistry of both cotton and flax fibers play important roles in the physical behavior of these materials.

(b) Paint Films

The search for information on paint films has uncovered a considerably smaller volume of information. Nonetheless, the data discovered has provided a much clearer understanding of paint film behavior. Two authors in particular, Maurice Van Loo and Dr. Adolph C. Elm provide the most significant information to date. Although paint film behavior is complex, both Elm and Van Loo define the properties in such a way that the separation of necessary parameters is possible. Their work (along with that of Nathan Stolow) clearly implies that certain procedures in painting conservation need to be reviewed.

(c) Glue/Wood

One of the most significant activities made concurrently with the literature search was the review of work done previously by the co-investigators and included with the original proposal. Certain subtle, but important, inconsistencies were detected with respect to the behavior of fabrics due to moisture variations. It has been deduced that these variations were resolvable if the mechanical behavior of glue sizes in fabric rather than the behavior of fabric alone is considered. In addition, while wood stretchers were previously considered to be of lesser significance in the original proposal, it is now apparent that stretchers play an important role in the deteriortation of a painting. It seems incredible that in the search of conservation literature, the least information found related to these two most common material constituants of painting supports. Further discussion of these materials will appear in Part Two of this report.

In summary, it may be stated that while a tremendous amount of information is available from industry sources, considerable gaps still exist in the knowledge of material properties of the components of a fabric supported painting. These must be filled by appropriate testing. It may also be concluded that since many practices in conservation are inconsistant with the research findings of Van Loo and Elm, the basic principles of material science have not been seriously applied in the field of painting conservation and in fact, little understanding of basic concepts exists in practice.

Finally, it is believed that concise methods of identification of those materials used in the construction of a fabric supported painting should be readily available. Certain references dealing with material identification have been located. Most of these explore methods that are beyond the capability of a normal working conservation laboratory.

Perhaps, as a supplement to this project a concise bibliography as well as a list of methods of material identification should be prepared.

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Task II - Determination of Needed Research on Material Properties

The literature search has outlined clearly the gaps in existing information and an understanding of the kind of information required for the overall research project. For example, it is evident that the pigment chemistry has a dramatic affect on the drying rate of the paint film and is an important parameter in influencing paint film physical properties. While it is felt that the greater proportion of cracks fround in paint films are due to mechanical phenomenon, a study of the causes of other types of cracking will be useful in establishing and evaluating specific failure mechanisms. It can be further stated that the parameters affecting non-mechanical cracking include: the rate of volumetric change during drying; the rate of loss of solvent; the rate of strength development; and, the rate of polymerization and oxidation. In addition certain types of pigments, such as bitumen, for example, never become stable and it is concluded that the principle of surface energy affects their behavior significantly.

New paint films and fabrics need to be carefully examined, since deterioration of paint films begins almost immediately upon completion of a painting. In general, a considerable amount of information is needed on a wide variety of paint films with repect to physical properties such as stress,strain, and strength and the variation of these properties with time. Some of the most important work to be accomplished is in the area of animal glues and adhesives - animal glues as related to their behavior in existing paintings, and, modern adhesives as used in conservation. As stated previously, little information on the physical behavior of animal glues is available, particularly in their relationship to fabric behavior. Further, there is continuing controversy in the conservation field with respect to the strength requirements of adhesives applied during treatment. Early studies indicate that strength requirements are considerably lower if the fabric in-plane stress is reduced. Adhesives with low strength would be most desirable in terms of reversibility.

Below is a list of parameters which need to be studied in future testing of material behavior:

I Paint Film

A The general stress-strain relationship, including biaxial relationship, as affected by:
  1. moisture
  2. temperature
  3. oxidation and polymerization
  4. degree of stress and duration of stress
  5. chemistry of pigment
  6. distribution of pigment
  7. pigment particle shape
  8. % pigment to medium
  9. pigment particle size
  10. biological attack
  11. light

B The strength of film as affected by:
   1. moisture
   2. temperature
   3. oxidation and polymerization
   4. degree of stress and duration of stress
   5. chemistry of pigments
   6. distribution of pigment
   7. pigment particle size
   8. pigment particle shape
   9. % pigment to medium
   10. biological attack
   11. light

C Volumetric change due to:
   1. temperature
   2. oxidation and polymerization
   3. solvent action in new and old film
   4. moisture

D Specific gravity

E Distinction between cohesion and adhesion

II Textiles

A The general stress-strain relationship, including biaxial relationship, of fabric found in paintings as affected by:
   1. moisture
   2. temperature
   3. oxidation
   4. degree of stress and duration of stress
   5. abrasive action
   6. solvents
   7. biological attack
   8. adhesive impregnation
   9. light

[It is not unreasonable to consider investigating synthetic fabrics for use in conservation]

B The strength of fabrics as affected by
   1. moisture
   2. temperature
   3. oxidation
   4. degree of stress and duration of stress
   5. abrasive action
   6. solvent
   7. biological attack
   8. adhesive impregnation
   9. light

III Glues and adhesives found in paintings

A General stress-strain relationship of glue films as affected by:
1. moisture
2. temperature
3. oxidation
4. biological attack
5. degree of stress and stress duration
6. chemical degradation - solvents
7. particle additives

B Volumetric change due to:
1. moisture
2. temperature
3. oxidation
4. solvents

IV Adhesives used in conservation - most of which will be determined later in the study

Additional Tasks

Task II has necessarily been coupled with Tasks III and IV since certain criteria could not be established without some identification of significant material behavior. Thus, for example, Washington Conservation Studios conducted a series of tests to determine the effect of moisture on naturally-aged fabric-supported paint film.

One test of three specimens was particularly revealing. One specimen was held in controlled conditions; the second subjected to a 100% relative humidity at 75° F for three days; and the third completely saturated with water. Both of the latter specimens exhibited massive contraction of the support structure causing a form of cleavage of paint film often noted in paintings. Specimen No. 3 also showed a loss of solubles in the paint film upon drying, as it contracted to a greater degree than the supporting fabric. This simple test clearly indicates that the effect of moisture on paint film behavior is significant, although no data whatsoever is available in the literature concerning this effect. Further tests of the effect of moisture on paint films is needed. Previous testing of paint films has been complicated by the complex methods of suitably isolating a paint film from any substrate.

Procedures have been developed as a part of work conducted in Task III which will permit isolation of paint films without difficulty. It is necessary, however, to allow the films to dry properly for periods of between 2 months and 2 years prior to testing. The resulting specimen can be tested under varying environmental conditions using standard testing equipment. A series of test specimens were initially prepared in 1977 in order to study and develop the procedure for specimen production and will be available for testing in the late spring of 1978.

In order to provide clinical test results for verification of the mathematical model (to be developed in Task 4), it was necessary to establish coatings which would behave as paint films and could be applied to fabric supports. It is now possible to produce a non-shrinking coating which can be applied to a fabric and duplicate independent patterns of cracking found in paintings.

Both cupping and flaking have been reproduced quickly in these specimens. The clinical tests performed to date indicate that fabric motion due to moisture variations produce cupping in the paint film, and that this effect is not caused by shrinkage of the paint film itself.

Since it has become clear that behavior of fabrics in normal humidity variations is governed by the presence of a size, a detailed investigation of this mechanism is a priority. The specific mechanics of the behavior is not clearly understood. If one were dealing with fabric performance alone, it could be shown that the swelling of fibers due to moisture affect the "crimp" of the weave thereby altering fabric configuration. The size, when applied, does not normally penetrate throughout the fabric, but lies as a film between fabric and ground. Its response to moisture is the reverse of fabric and overrides fabric behavior.

It is also evident that when a certain level of moisture content is reached there is a switch in dominence from the glue to the fabric. That is, the size is no longer the governing factor and at this point the fabric response to moisture assumes control. The implications of this reversal of behavior are enormous and are discussed further in Part 2 of this report. The basic questions involved relate to the magnitude of the "moisture switch point" and the source of this extra moisture. It is possible that cool walls in a given environment lead to a cooling of the painting thereby lowering the painting temperature to the existing environment's "dew point." In such cases, water would condense on the surface of the painting. Another source of extra moisture might be due to periods of excessively high humidity.

It is also evident that stretchers play a significant role in the deterioration of paintings. There is a great deal of existing information on the response of wood to moisture and the examination of the dimensional changes in wood in response to moisture and the resulting effect on paint films should be a straight forward procedure.

An exhaustive investigation of material properties would be most beneficial to the field of conservation. However the scope of such a project would be beyond the scope of the current research. Testing of materials will be limited to only those major parameters which affect the physical performance of paintings. These will include general mechanical properties as affected by load magnitudes, temperature and moisture. Test procedures are clearly outlined by ASTM and other publications and results of the tests will be presented in later reports as the research is continued in the future.

PART II

A Review of the Behavior and Interaction of Fabric Supported Paintings.

1. Introduction

In this part of the report, basic concepts related to the behavior and interaction of fabric supported paintings, which have been determined as a result of the research described in the previous section, are presented.

A significant portion of this section of the report is also concerned with an outline of the finite element method of analysis along with a discussion of the application of this numerical technique to the analysis of fabric supported paintings.

The major emphasis, however, is concerned with presenting information on the causes and effects of various deformations of the constituent materials. This information includes results developed from a number of clinical tests and corresponding numerical data obtained from preliminary computer modeling. Included in the presentation of this information are discussions of the sources of motion which lead to the deterioration and damage of paint films.

2. Basic Concepts of the Behavior and Interaction of Fabric-Supported Paintings.

A basic concept in the understanding of the behavior and response of a typical fabric supported painting to external agents is that all components, i.e., fabric, stretcher, ground and paint film, contribute to the overall resistance to deformations of the composite. Acceptance of this major concept, makes possible for the first time a rational application of basic scientific principles to a study of the physical determination and distortion of paintings. Only in this way it is possible to examine differences in failure mechanisms of paintings, although the concepts of chemical or biological degradation of paintings must not be excluded from consideration. The implication of this basic approach is that extensive and specialized investigations need to be conducted on all components of a painting, and in particular paint films.

Historically, paint film has not been considered to contribute structurally to the overall response of the composite. Thus while certain tests such as hardness, abrasion resistance, and resistance to moisture are regularly performed by the coating industry little is known about physical properties such as modulus of elasticity, biaxial stress relations and the thermo-plastic coefficient of expansion. These latter factors are critical in understanding and evaluating the contribution of the paint film to the structural behavior of a painting. A second basic concept related to the behavior and response of a fabric-supported painting is the recognition that, excluding modifications such as varnish and restorations, deformations in the composite structural system, may be initiated independently in each of the three basic structural components; (1) fabric; (2) stretcher; and (3) paint film.

The extent to which these two basic concepts are applicable in a particular painting depends entirely on the interconnection between the elements. Thus for example if the laminate materials are rigidly conncected, such that there is no relative movement permitted along the laminate interfaces, full composite action results, and all materials will participate to their fullest in resisting any distortion induced in any or all of the materials. Thus for example, in this case, for a typical painting on a fabric support, any tendency for the fabric to distort will be resisted by the paint film. Due to this interaction, free deformation of the fabric is restrained and stresses are induced in both the fabric and paint film.

On the other extreme, if there is no interconnection between the paint film and fabric, so that relative movement between these components is not restrained, a movement in one of these elements will not cause a stress or distortion in the other. Finally if the interconnection is semi-rigid, meaning that resistance to relative movement is available on a limited scale, then a situation between the two extremes outlined above will result.

It is evident that in a typical painting on a fabric support, various portions of the system may have each of these three levels of interconnction. Thus for example if the bond between the paint film and fabric has been destroyed locally, the overall interaction response is complicated due to the nonuniformity of the interconnection between the materials. Thus the degree to which relative movement is prohibited is an important parameter in predicting the response of the structure to any induced deformation.

It is the hypothesis of this research that if an understanding of the causes and corresponding magnitudes of deformation in each of the three components listed above can be developed,that the finite element method of analysis can be used to provide the means of quantitatively evaluating these resulting effects on the composite structure. In this way studies can be undertaken using the mathematical model and guidelines established for the development and practice of rational conservation techniques.

3. Mathematical Modeling.

The stress analysis of complex continua has developed rapidly in recent years due to the advent of the high-speed electronic digital computer. Thus it is now possible to employ numerical discretization techniques to obtain approximate solutions to previously insoluble problems. The most powerful of these numerical techniques is the finite element method (FEM). Originally developed intuitively for structural analysis, the technique has been generalized using variational principles of mathematical physics and has been applied successfully to such fields as seepage, heatflow, hydrodynamics, soil and rock mechanics, and bioengineering. The procedure may also be used to analyze ~~on~~ paintings on fabric supports.

Although a detailed discussion of the finite element method is not presented here, the following is included in order to explain the basic approach of the procedure and to illustrate its application to the analysis of oil paintings.

The basic concept of the method is that every structure may be considered to be an assemblage of individual structural components or elements. This assemblage must consist of a finite number of elements, and these elements must be interconnected at a finite number of joints or nodal points. The approximation is, therefore, of a physical nature and a modified problem is substituted for the actual problem. There is, however, no approximation in the mathematical analysis of the modified structure. Provided that the solution of the modified problem is approximately equal to that of the actual problem this approach has tremendous potential. Substantial experience in solving a wide variety of complex problems has identified three general criteria which, if satisfied, will guarantee that the method yields a known bound of the correct answer and that if the number of elements is increased, the accuracy of the solution is increased.

In general, problems of mathematical physics may be specified in one of two ways:

(1) Differential equations governing the behavior of a typical infinitesimal region are given.

(2) A variational on extremum principle valid over the entire region of interest is postulated.

These two approaches are mathematically equivalent, and the finite element method is based on the second approach. The appropriate variational theorem relating to static problems of structural analysis is the well known theorem of minimum potential energy which may be derived from the principle of virtual work.

The steps involved in a finite element analysis may be summarized briefly as follows:

(1) Discretization of the Continuum (Structure).

In this step the body is subdivided into a system of component elements. A certain amount of judgement is required in the execution of this step. However, in many cases good results may be obtained with relatively crude divisions and this is, therefore, not a difficult or crucial step in the procedure.

(2) Selection of Element Displacement Model.

This is the crucial step in the analysis procedure, and the selection of an appropriate function to represent the displacement within each element determines to a considerable extent the validity, and accuracy of the final solution.

For simplicity, polynomial functions are usually selected and rules have been established for selecting the proper number of terms in order to guarantee accuracy of the solution.

(3) Determination of Element Stiffness.

Using the appropriate variational theorem, which in this case is the minmum potential energy theorem, the element stiffness can be determined. The basic parameters affecting element stiffness are the displacement model previously selected, the element geometry, and importantly the element material properties and strain-displacement relations. Appropriate strain-displacement relations for particular classes of problems, such as plane stress, plane strain, plate bending, axi-symmetric shells and solids of revolution, etc., may be obtained from mechanics. With respect to the analysis of oil paintings the stress - strain relationships of the constitutive materials are of paramount importance.

(4) Assembly of Governing Equations.

The equations governing the response of the discretized structure may be assembled by appropriate merging of the element stiffnesses and forces applied to the structure using a standard procedure known as the direct stiffness method. This step in the analysis procedure is well standardized and application to oil paintings does not introduce any complexities to the process.

(5) Solve for Unknown Displacements.

Once the governing equations have been generated, standard procedures for solving large systems of equations may be used to evaluate the displacements of the structural system. Depending on whether or not the material stress - strain relations are linear or nonlinear the solution process may require an iterative solution procedure which must be continued until a convergent solution is obtained.

(6) Compute Element Stresses.

From the element displacements, elements strains, and subsequently element stresses may be obtained without difficulty.

The basic advantages of the FEM outlined above is that the method can consider without major difficulty complex variations in the following four significant factors.

(1) Structure geometry

(2) Support conditions

(3) Loadings or stimuli

(4) Material properties

Thus irregular shaped structures with complex supports subjected to variable external loadings can be readily analyzed in a typical FEM computer program. In addition structures composed of elements with highly variable material properties can also be included without excessive computational difficulties.

4. Application of the Finite Element Method to the Analysis of Fabric-Supported Oil Paintings.

A fabric-supported oil painting may be considered as a thin, multilayered flexible membrane, subjected to an initial tension stress field.

Basically three general problems exist in developing a suitable model capable of accurately predicting the response of this structural system to various motions induced by any number of stimuli. These may be itemized as follows:

(1) Technical problems associated with developing a layered element capable of considering the contributions to stiffness from the paint film and ground, fabric, and stretcher.

(2) Determination of the appropriate constitutive material relations for each of the materials composing the overall structure.

(3) Evaluation of the interaction between the interface of the paint film and fabric.

These three problems are interrelated in that the complexity of the first is dependent to a large extent on the results of the latter two. In general, it is safe to state that the state of the art of the FEM is such that the use of this procedure and the validity of numerical results is hampered in most applications primarily by a lack of data and understanding of the properties of the materials composing the system being analyzed. Thus, it is necessary that the material properties of the fabric, paint film and ground, and stretcher be developed in sufficient detail before valid results from an appropriate model can be developed. The complexity of these relations will dictate the complexity of the resulting numerical procedure. With respect to the paint film alone, the stress - strain relation and tensile strength are of particular importance. This relationship has been shown by Elm' to vary with age of the paint film. Initially the paint film is fairly plastic and becomes more nearly elastic with a corresponding increase in stiffness for a period of around 32 weeks. As the paint film dries and "ages", the stiffness increases at a decreasing rate so that the stiffness increase does not vary linearly with time. Also the rate of loading has an appreciable effect on the tension strength of the paint film at any age, with a decrease in strength resulting from an increased rate of deformation. The effects of moisture and temperatures are of great importance on the behavior of paint films.

Paint film failure and mechanical cracking is not limited to old paintings. Thus many relatively new paintings of about 20-25 years show marked mechanical cracking and flaking. One possible reason for this relatively rapid failure may be related to the decrease in fabric stiffness with time which contrasts to the paint film stiffness increase with time. Thus initially when all of the initial tensioning force is transmitted to the fabric, no stress is induced in the fresh paint film.

However, as the paint film dries and hardens a composite system is formed

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(1) Ehn, A. C., Some Mechanical Properties of Paint Films, Federation of Societies for Paint Technology, Official Digest, #346, 1953.

and subsequent changes in fabric stress and fabric movement will transmit stresses to the paint film. This is particularly significant since it appears that dry paint films have greater stiffnesses but lower strengths than the supporting fabrics. Significant stresses will, therefore, be developed in the paint films and in order to release this stress, either tension cracking or compression buckling will occur.

In spite of these complexities, there is no doubt that the development of a FEM model through appropriate application of the specific parameters of paintings does provide a means of quantifying and defining the mechanisms of deterioration of oil paintings. A computer program that is capable of accurately predicting the effect of various stimuli on stresses and distortions in paint films is not currently available.

However, while little has been done to date on the physical properties of paint films, the existing information can be used to clarify some of the behavior of paint films during restoration and refute contemporary concepts. Thus a computer program which assumes linearly elastic material properties for the constituent materials and which is applicable to continua in a state of plane stress has been used to provide an insight into the response of the more complex multilayered inelastic media.

This program has been used specifically to study the effects of the deformation of the fabric and stretcher on the stress distribution in the fabric, paint film and ground.

5. Initial Fabric Tensioning.

(a) Introduction.

Although a woven fabric support is an orthotropic continuum having different material properties in the weft and warp directions, it is sufficient for the purposes of this discussion to assume isotropy. Ideally a properly stretched isotropic canvas (Figure 1) is in a state of equal biaxial tension, i.e., the tension stress in the fabric is the same in all directions. However, since the fabric is seldom attached continuously to the supporting frame, there are localized areas of release between the support points which modify the stress distribution somewhat. Figure 1 illustrates the final deformed configuration around the perimeter of the fabric. The effect of these local distortions on the distribution of stress depends on the spacing of the support points, however, it is assumed herein that initial tensioning of the fabric creates an equal biaxial stress state.

(b) Clinical Tests.

To confirm the existence of this stress state during stretching, a series of lines were drawn on a stretched fabric.(1) Some of the lines were drawn over a single thread, and some were drawn diagonally across the thread intersections (Photos 1-A and 1-B). These lines appear as the darker lines in the photographs. Since the thread lines were reasonably straight and parallel to their respective edges, a uniform biaxial stress state in the linen was reasonably assured.

A second series of uniformly spaced intersecting lines were drawn (appearing as light lines in the photographs), ignoring slight variations in the thread alignment. Finally, a piece of plexiglas was placed over the stretched fabric and the lines retraced onto the plexiglas. The lined plexiglas sheet provided a reference with which subsequent deviations of the lines on the canvas could be compared.

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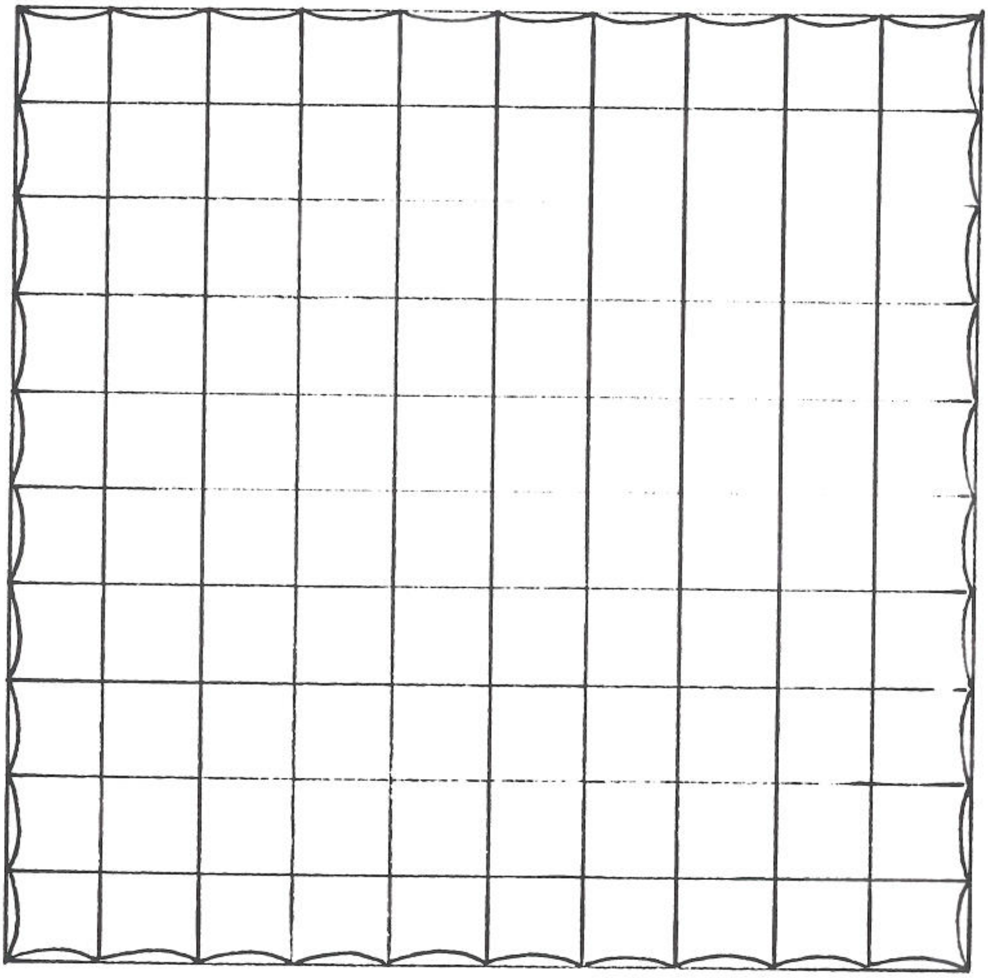
(1) Unsized, basket weave, double threads, warp and weft, 100% linen, 10 oz. 62 x 52, #248 Gernay-Delbecque, Waregem, Belgium.



INITIAL TENSIONING

Figure 1

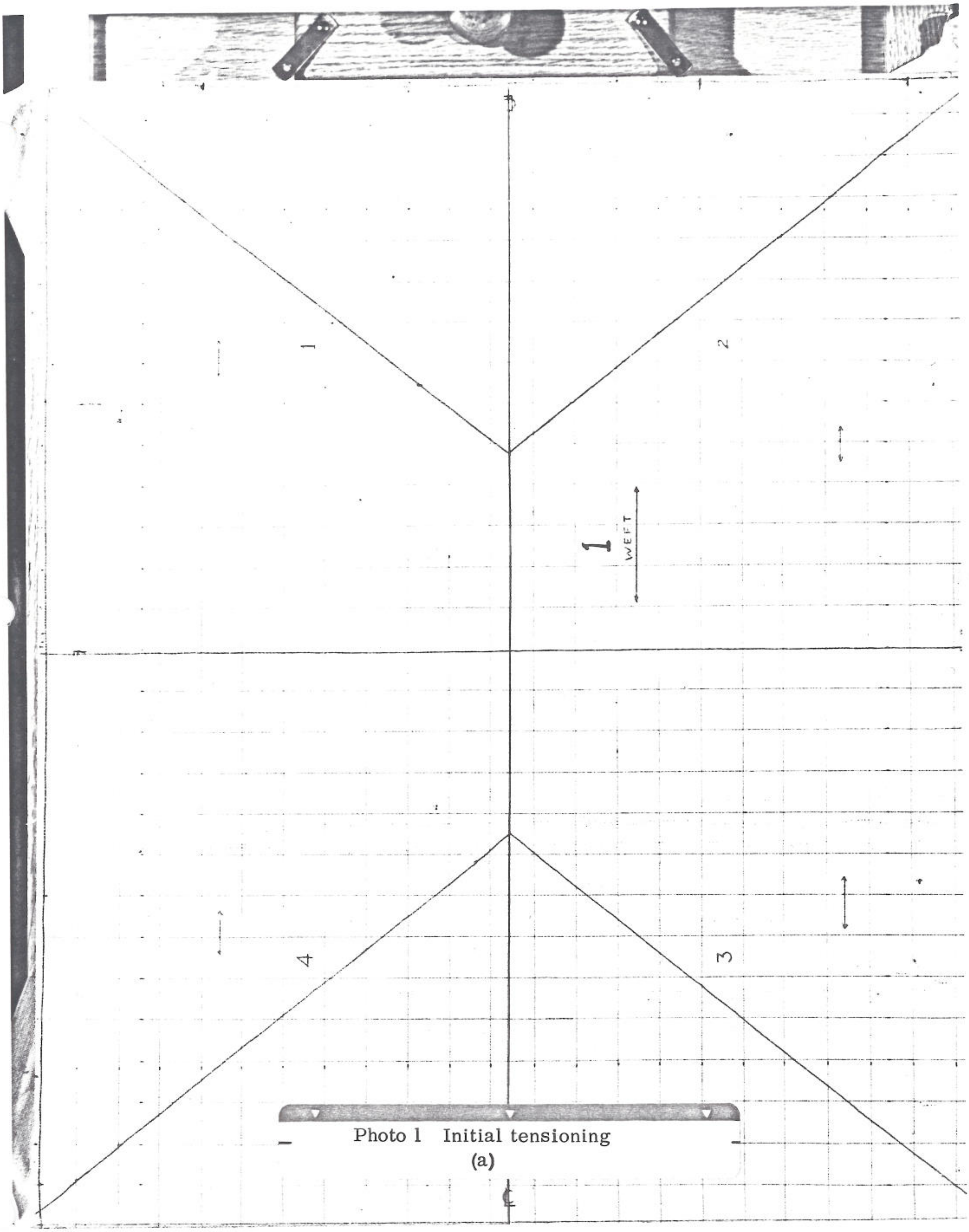


Photo 1 Initial tensioning
(a)

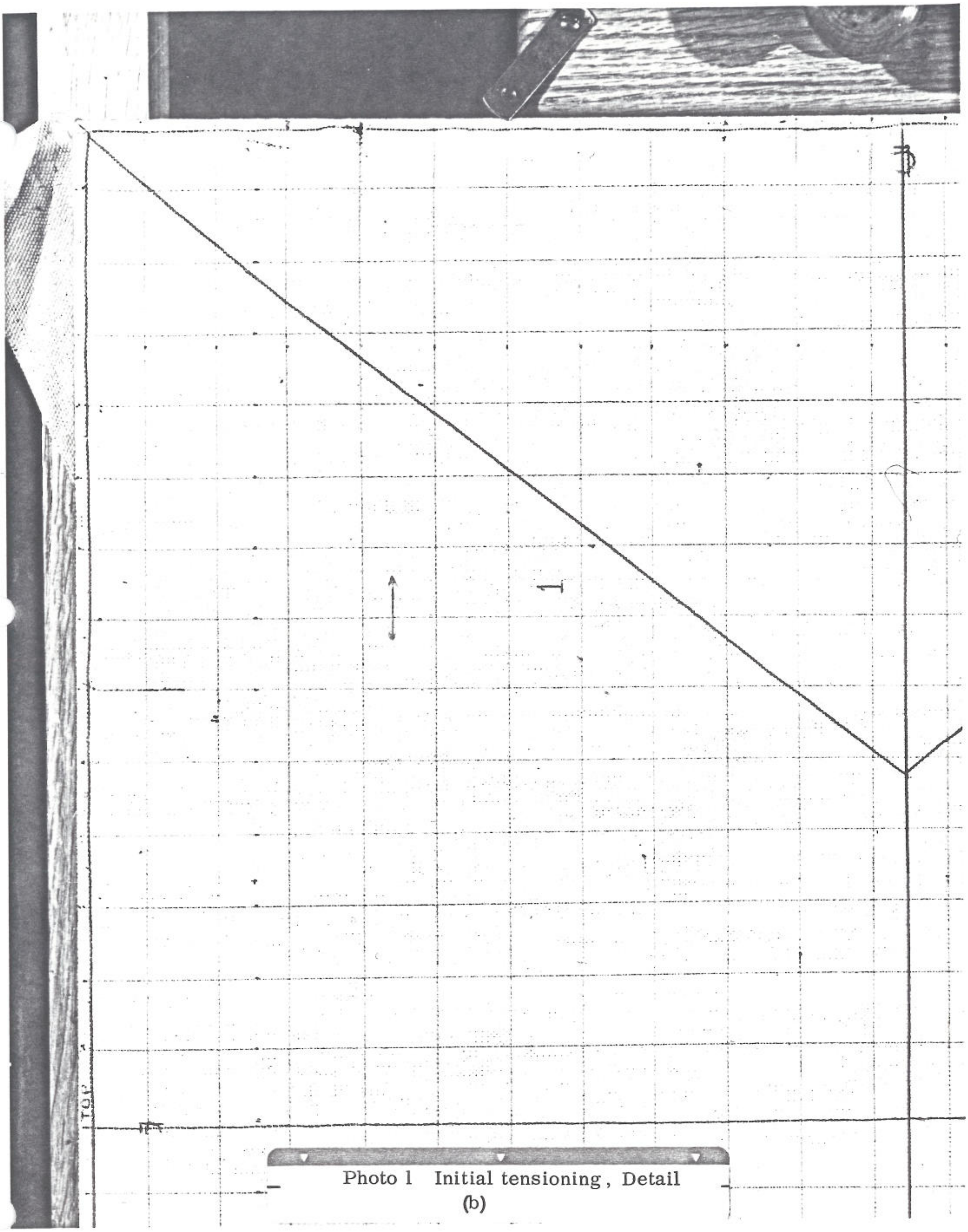


Photo 1   Initial tensioning, Detail (b)

6. Effects of Humidity Variations on Fabric Behavior.

(a) Introduction.

An important consideration affecting the behavior of a fabric supported oil painting is an understanding of the mechanism which induces dimensional changes in a fabric due to humidity variations. It has been found that cellulose which is the main constituent of cotton and flax fiber structure undergoes dramatic changes under the influence of moisture fluctuations. Increases in moisture content can cause up to a 50% increase in the cross-sectional area of a cotton or flax fiber while the fiber length remains essentially unchanged. In addition increases in humidity can increase the strength of flax fibers to as much as 50,000 to 150,000 psi although this strength increase is accompanied by a reduction in stiffness (resistance to deformation).

For an unsized linen or cotton fabric the effect of fiber swelling on the woven fabric has been described by Kaswell.(1) However, most fabrics used as painting supports have been sized with some form of animal glue. Cornelius(2) has demonstrated through some rather simple but informative tests that the response of the size to moisture changes induced by humidity variations overrides the effect of fiber swelling.

The responses of both wood and fabric to humidity variations were studied by Cornelius and the results of his fabric tests are summarized below:

- Sized fabrics and unsized fabrics react in opposite ways to humidity.
- When a fabric expands during the damp part of the humidity cycle, it shrinks to a greater degree in the opposite side of the cycle. This means that if a fabric is allowed to expand and contract freely with humidity fluctuations, the net result is an increasingly smaller (shorter) fabric with each cycle.
- While the warp and weft directions of both sized and unsized fabric behave in a similar manner, the magnitudes of the warp and weft distortions are different (for unstretched and unrestrained fabrics).
- If a sized fabric is grounded, the differences in warp and weft distortions are reduced, and the fabric behaves more as an isotropic material.

As a result of this research it may be stated that:

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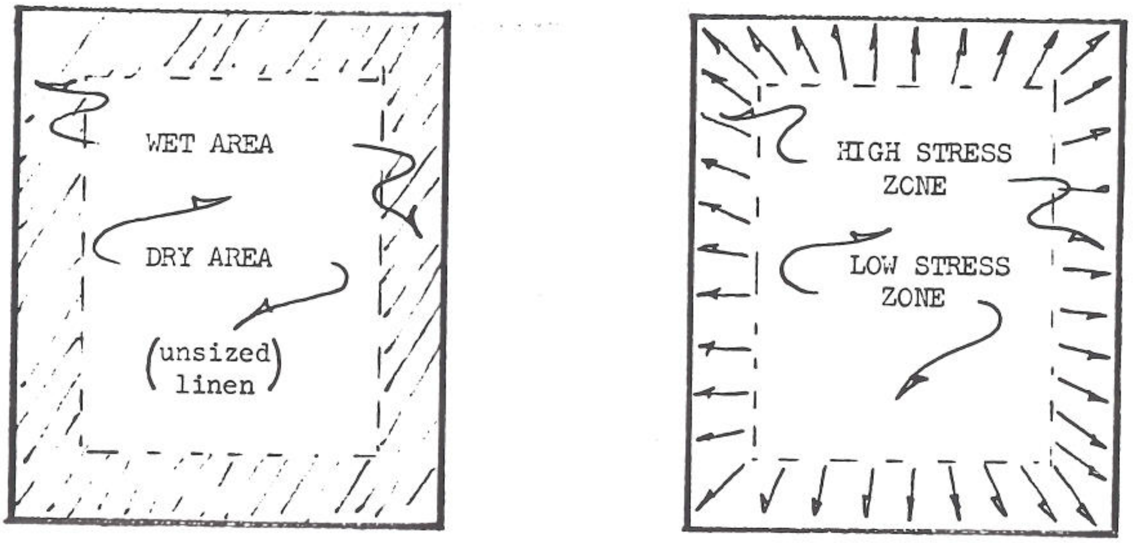
(1) Kaswell, Ernest, R., Wellington Sears Handbook of Industrial Textiles, Wellington Sears Co., Inc., N.Y., 1963.

(2) Cornelius, F. duPont, "Movement of Wood and Canvas for Paintings in Response to High and Low RH Cycles", Studies in Conservation, 12(1967), 76-79.

- Sized fabrics respond to moisture changes oppositely to unsized fabrics.
- During humidity oscillations, a fabric reduces in length.
- Stretched fabrics tend to dry differentially.

(b) Clinical Tests.

Test 1 - To observe the effect of fabric shrinkage, the stretched fabric shown in Photos 1-A and 1-B was saturated to insure an even moisture content. The fabric became very tight, dramatically increasing overall tension. The lined plexiglas sheet was placed over the wetted fabric and no deviation of the grid lines was observed. (See Photo 2). The fabric was then allowed to air dry. The fabric dried differentially and when dry in the center, a band of fabric about 3" wide and about 1/8"from the expansion bolt stretcher bars, which restricted the circulation of air, was still wet. This occurrence of nonuniform drying created an interesting deformation response. When the fabric was dry (in the central portion of the unsized linen) the fibers became somewhat relaxed, whereas the wet fibers near the stretcher bars remained under considerable tension (Fig. 2-A). This differential stress field caused the relaxed central fibers to be drawn towards the edges of the stretcher (Fig. 2-B). When the edges finally did dry, the entire fabric had relaxed and the overall tension was less than prior to wetting the canvas. In addition a permanent set had been induced into the fibers and as shown in Fig. 3 the grid lines had been displaced with the maximum distortion being perpendicular to the warp direction.



PARTIALLY DRY FABRIC

(A)

GENERAL STRESS CONDITION

(B)

Figure 2

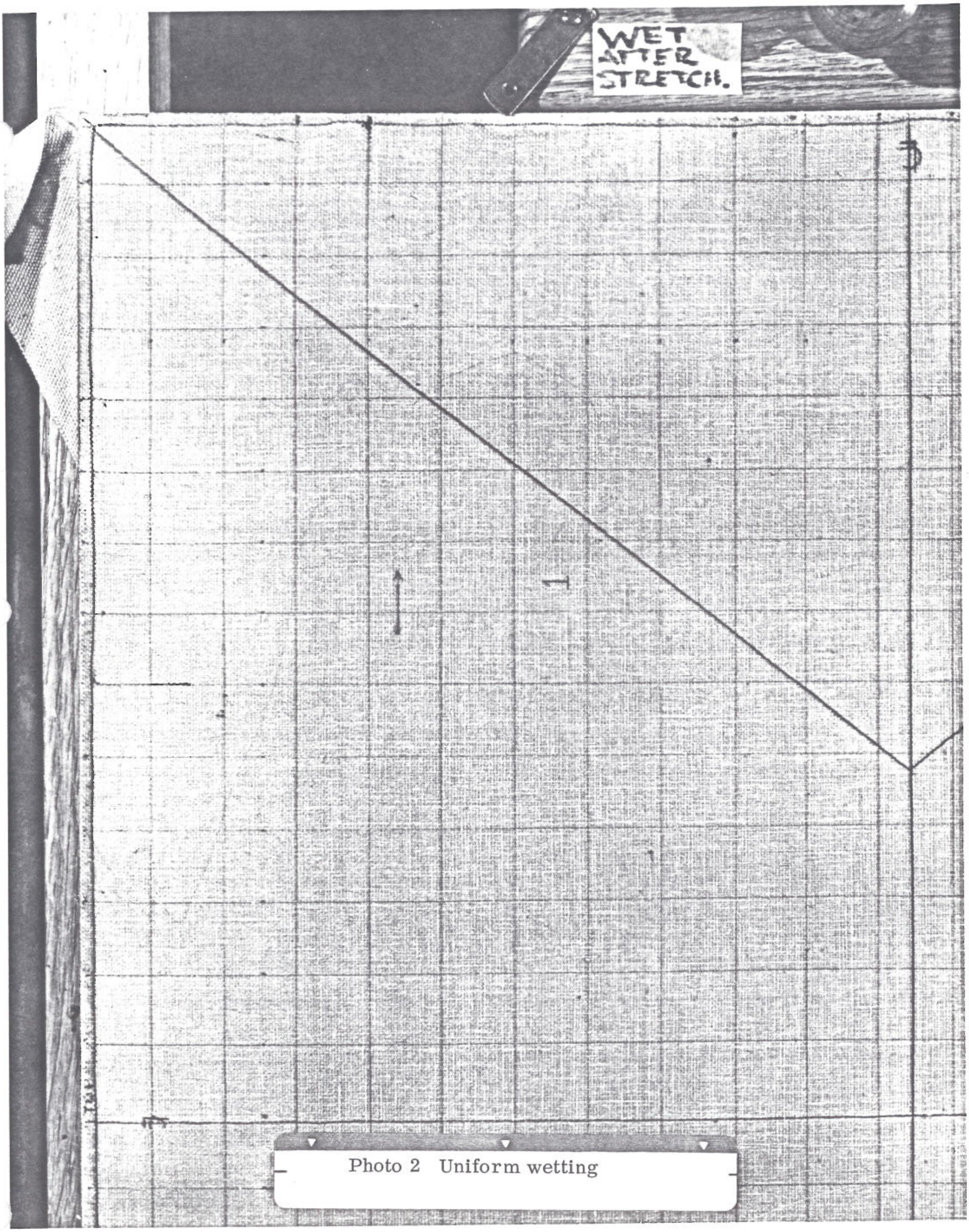


Photo 2 Uniform wetting

Test 2 - In order to study the effect of differential increases in moisture content, water was applied to a stretched linen in those regions away from the areas covered by the stretched bars. The resulting fabric deformation is illustrated in Figs. 4 and 5 and Photo 3 can be seen to be a reversal of the response due to differential drying. There was a marked difference between the warp and weft directions although it is believed that grounding would have reduced this difference somewhat.

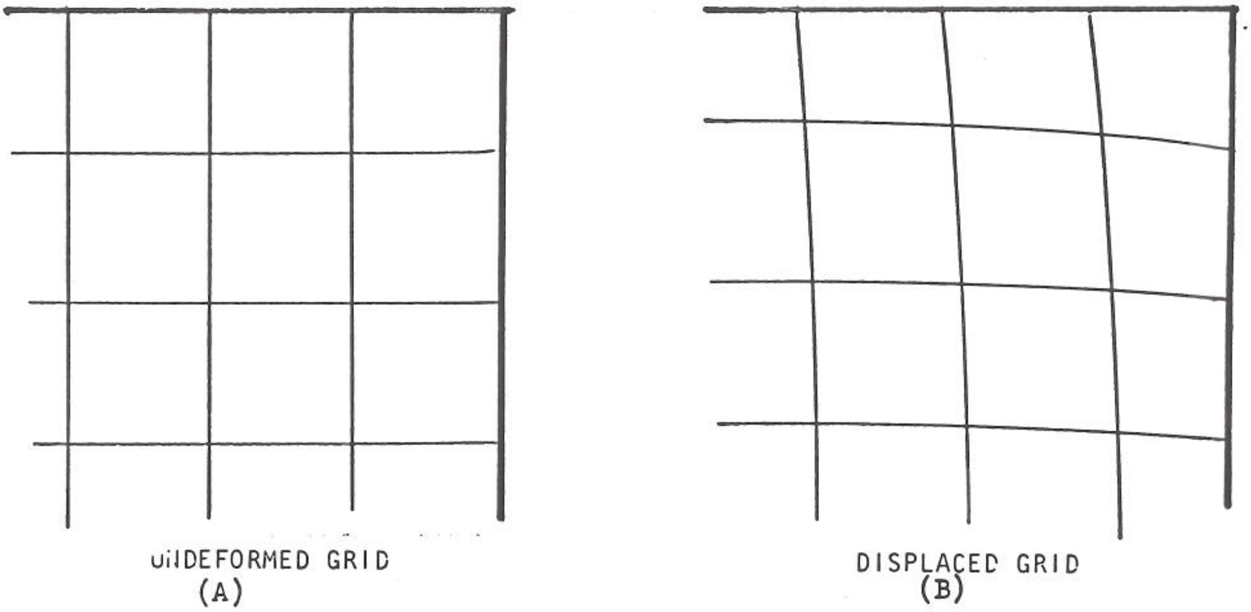
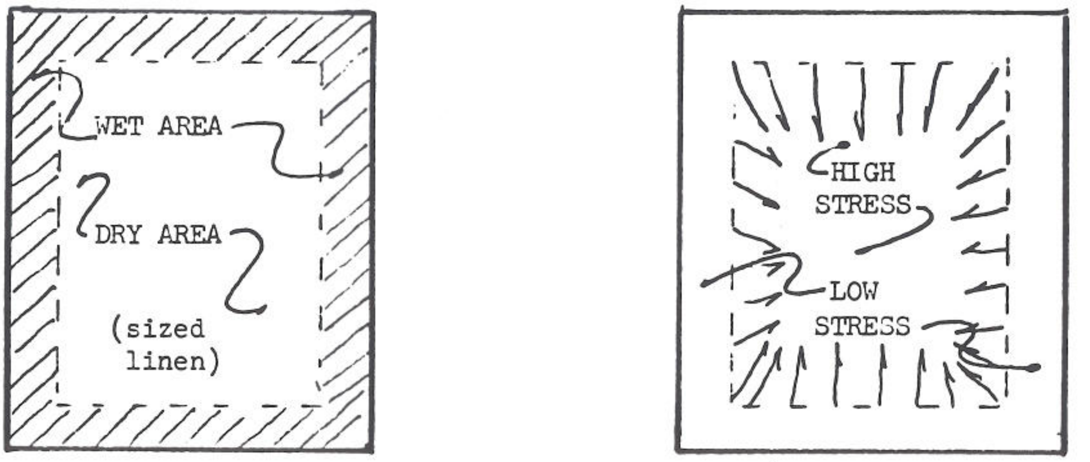


Figure 3



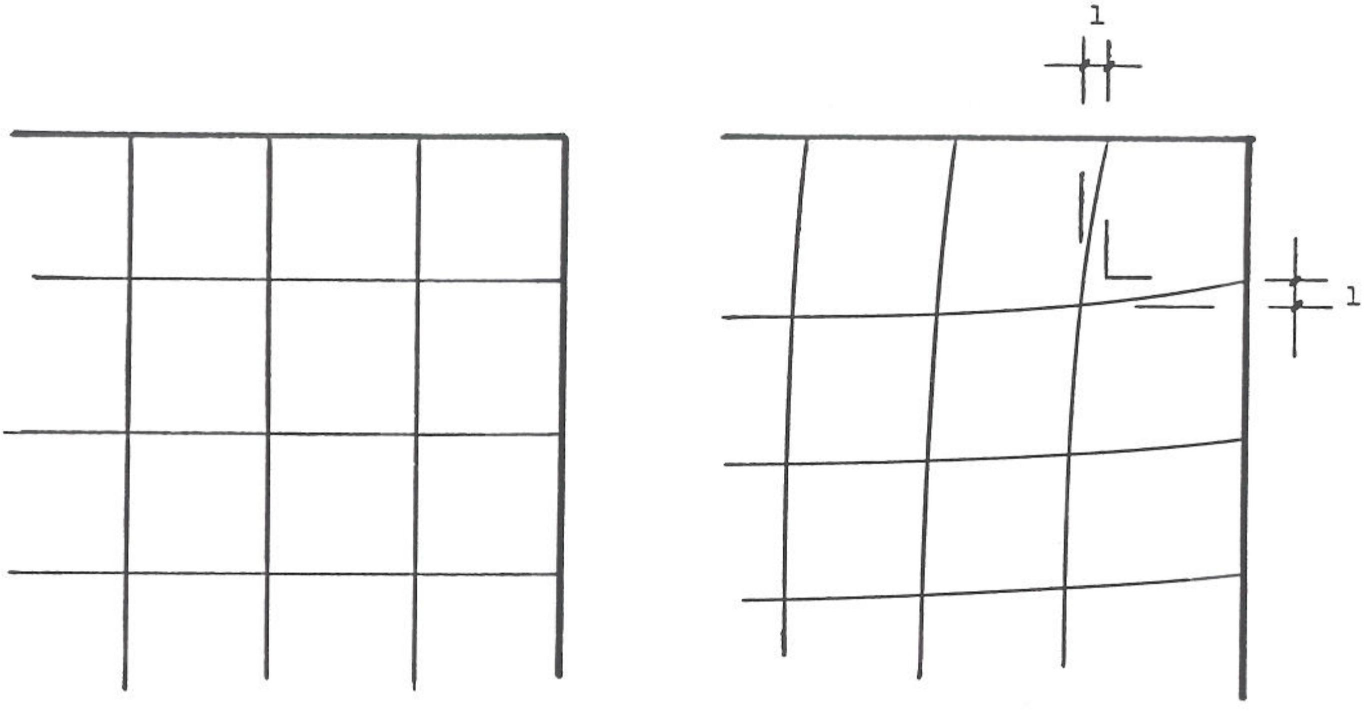
PARTIALLY DRY FABRIC

(A)

GENERAL STRESS CONDITION

(B)

Figure 4



FIRST DRYING CYCLE

(A)

(B)

Figure 5

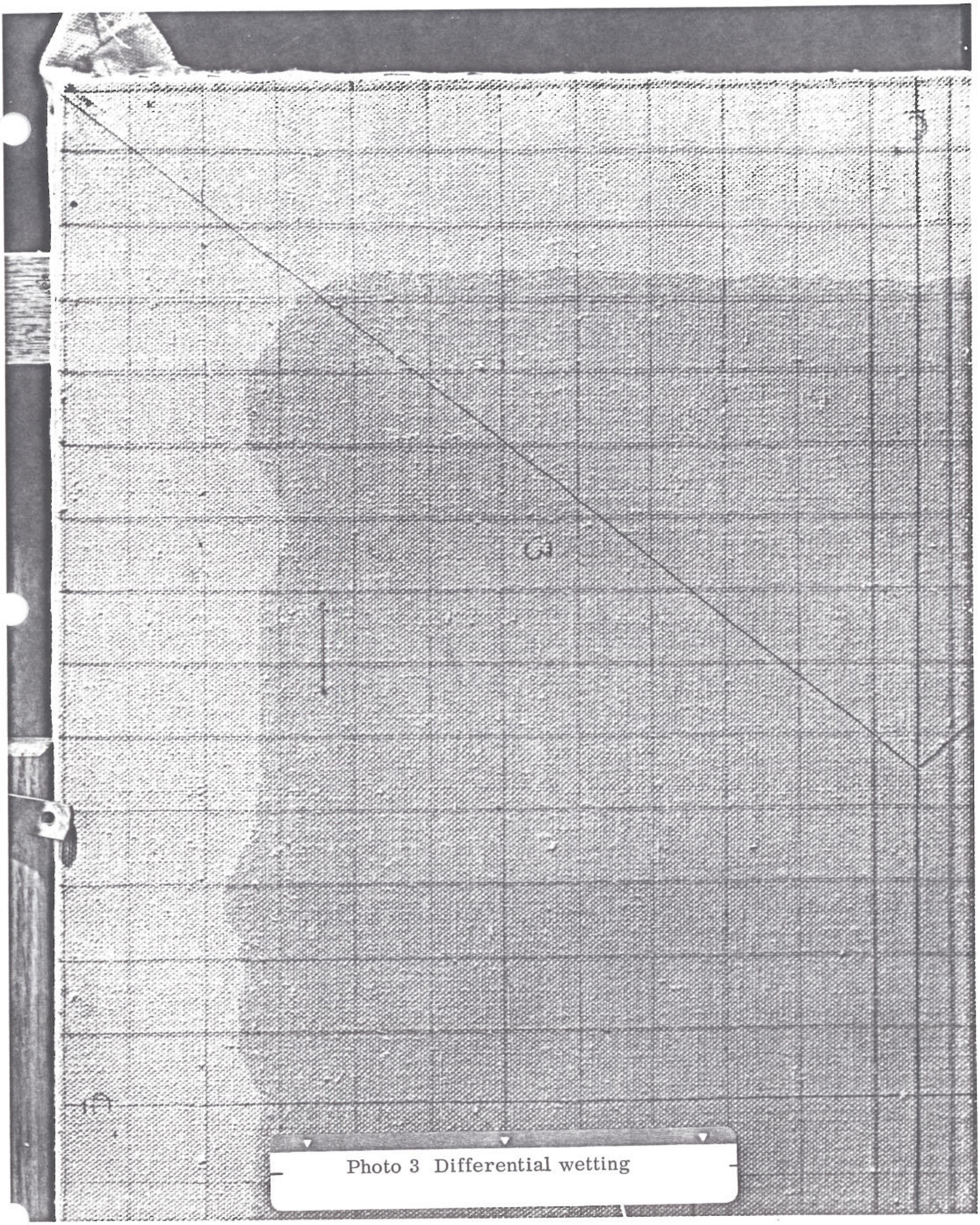


Photo 3 Differential wetting

Test 3 - Since the primary purpose of studying the consequences of differential fabric drying is the effect on paint films, a drying test was conducted on a stretched fabric coated with a non shrinking gesso film made with Whiting and Piccolyte S-115 resin dissolved in Toluene. After allowing the gesso film to dry for 24 hours, moisture was applied to the back side of the fabric in the area removed from the stretcher bars. In approximately 30 minutes a series of cracks developed in the film as shown in Photo (4). As may be seen the cracking was also accompanied by a marked cupping of the paint film, indicating that fabric motion is at least one source of cupping behavior.

Photo 4 Corner crack Development

(c) Numerical Tests.

To obtain stress results with any analysis technique the general relationship between stress and strain must be established. For a material stressed uniaxially (in only one direction), the ratio of stress, σ , to strain, ε , is called the modulus of elasticity, E. For a linearly elastic material the value of E is a constant.

Although at present sufficient material data does not exist in a form necessary for quantitative numerical results on differential moisture changes in a stretched fabric, qualitative results may be obtained by considering the apparant changes in the fabric material properties. Therefore, since the grid lines did not move when moisture was introduced into the unsized uniformly stretched fabric, there was no apparent change in strain. There was, however, an apparent increase in stress - strain relationship and the apparent change in stress, Figure 6 shows that fabric shrinkage can be represented as an apparent change in the modulus of elasticity, E.

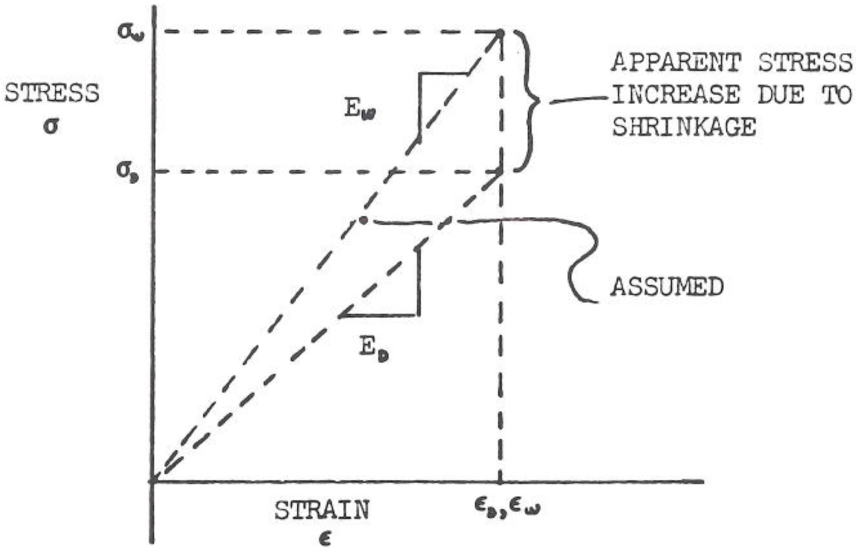


Figure 6

Thus the introduction of moisture in varying degrees to a fabric may be simulated by modifying the elastic material properties, permitting discussion of fabric behavior in a more concise form. In a sized linen then, the presence of additional moisture can be said to decrease the apparent E,while in an unsized linen the addition of moisture increases the apparent E. (This must be qualified since both sized and unsized fabrics will behave similarly if moisture content increases beyond normal humidity content values.)

If moisture is introduced into a stretched fabric differentially it follows that the continuum may be represented as a structure with differential material properties, and a systematic study of this effect can be performed.

Using the concept of the apparent change in material properties, it is possible to recreate the results of differential shrinkage with the present computer program. The model duplicated the observed deformations of the grid lines and generated the relative stress distribution over the surface of the model. Figures 7-A-D provide an insight into the results of differential movement due to moisture variations.

(d) Discussion of Test Results.

The most significant result from the numerical tests concerns the elongation of the fabric at the corners. As shown in Fig. 8-D the maximum principal stress directions and fabric elongation are in a direction which essentially bisects the right angle at the corner of the fabric. This elongation would induce high tensile stresses in a supported paint film which would tend to induce cracks at right angles to the principal stress directions.

This pattern of cracking predicted by the analysis is identical to that exhibited in Test 3 and illustrated in Photo 4. Thus even the approximate analysis assuming linear behavior gave an accurate indication of the expected cracking.

It should be noted that the effect of stretcher movement was not considered in either the experimental tests or the model analysis. The effect of dimensional changes in the stretcher will be discussed in the next section.

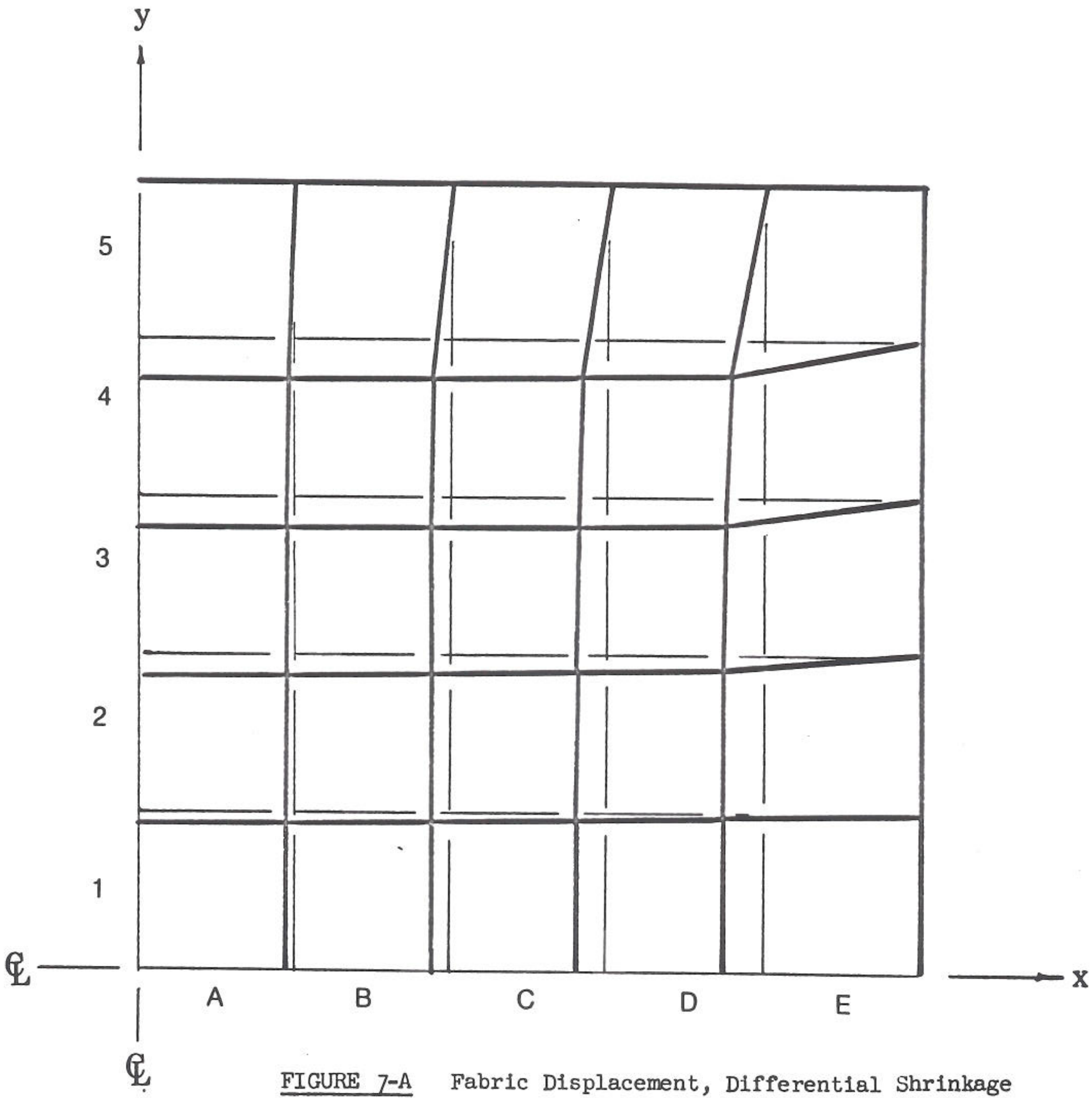


FIGURE 7-A Fabric Displacement, Differential Shrinkage
FEM Model Output

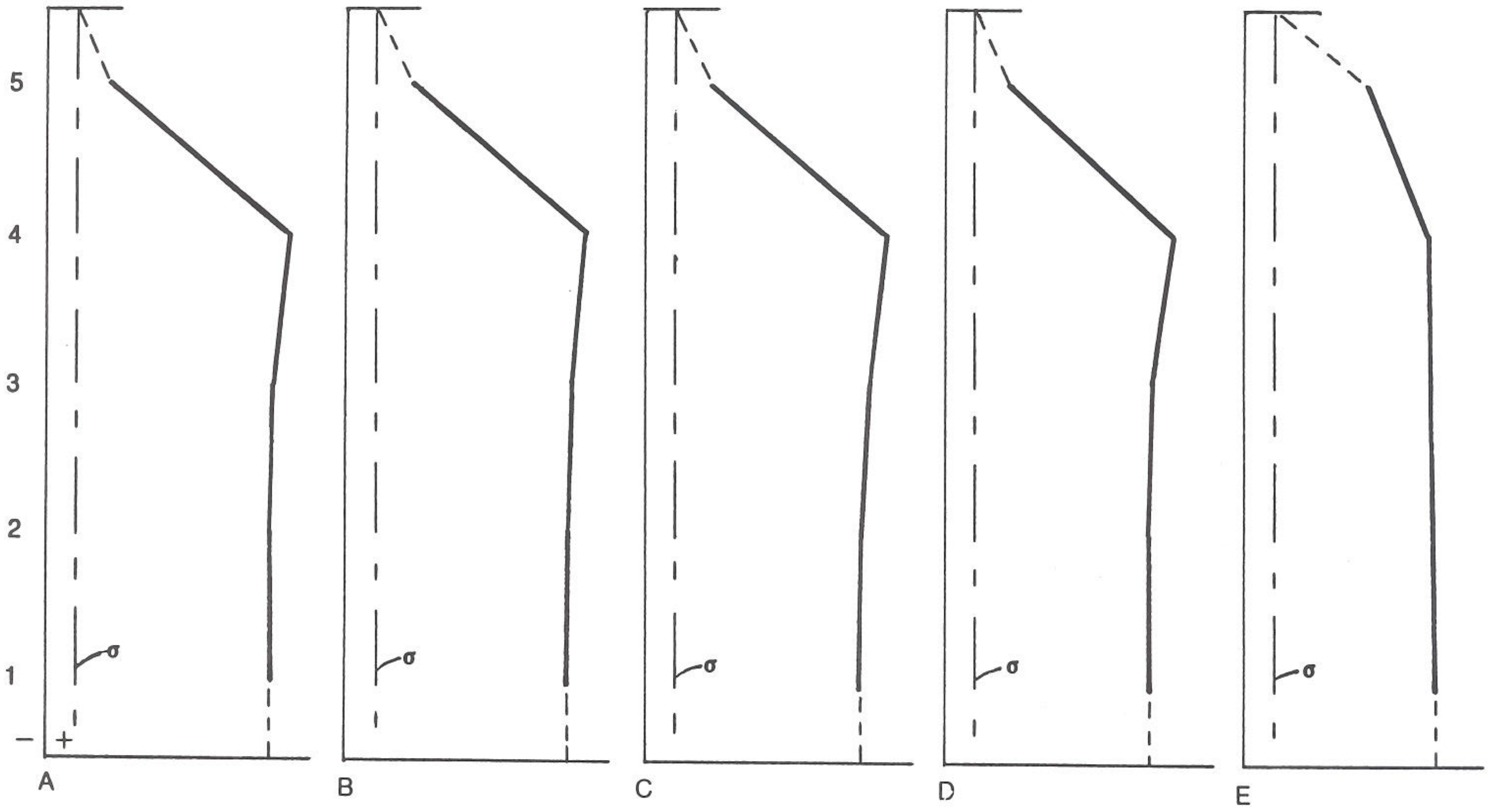


FIGURE 7-B X-Direction Normal Stress, Differential Shrinkage FEM Model Output. σ Is Initial Uniform Stretching Tension

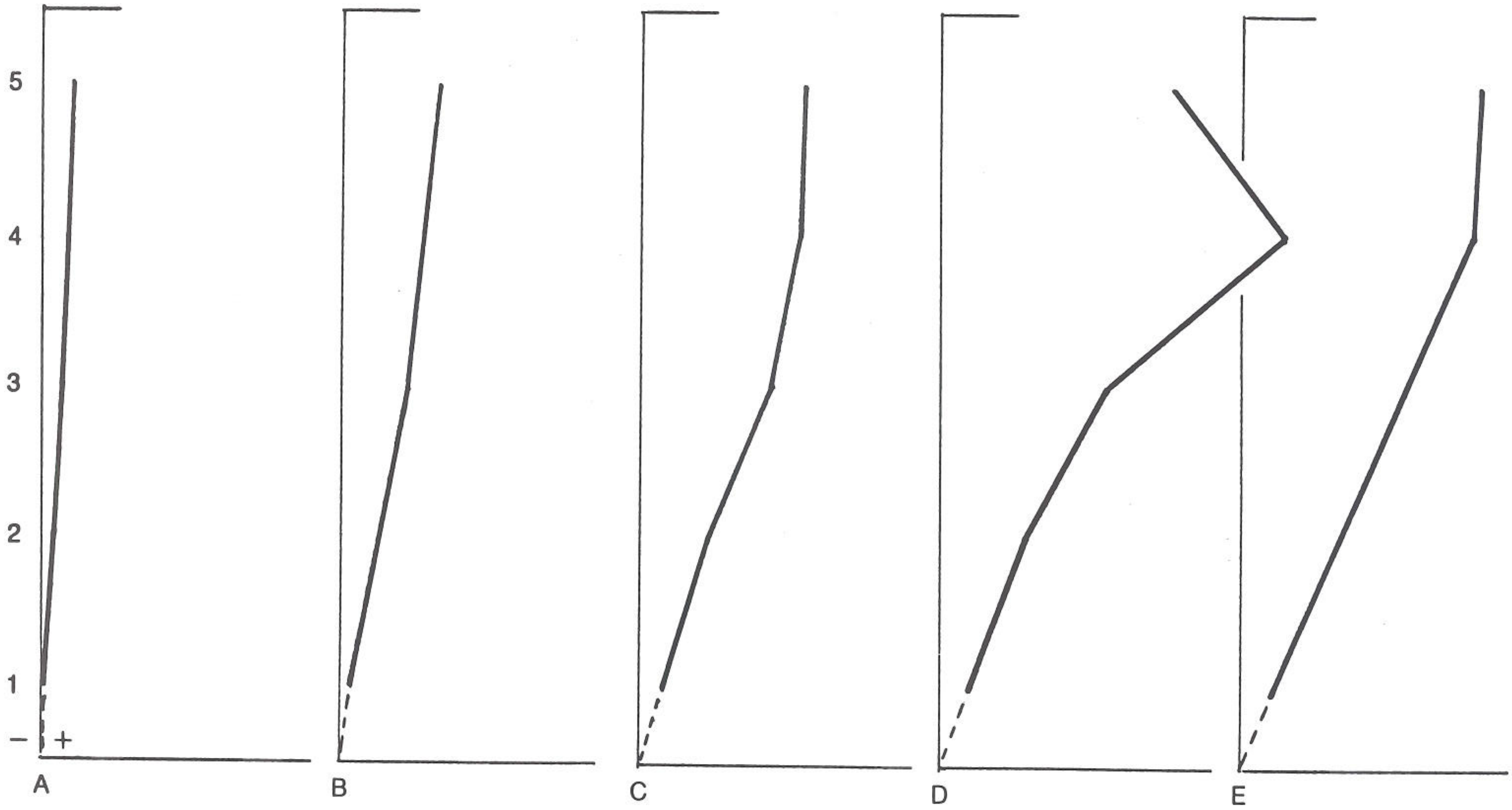


FIGURE 7-C X-Y Shear Stress, Differential Shrinkage FEM Model Output

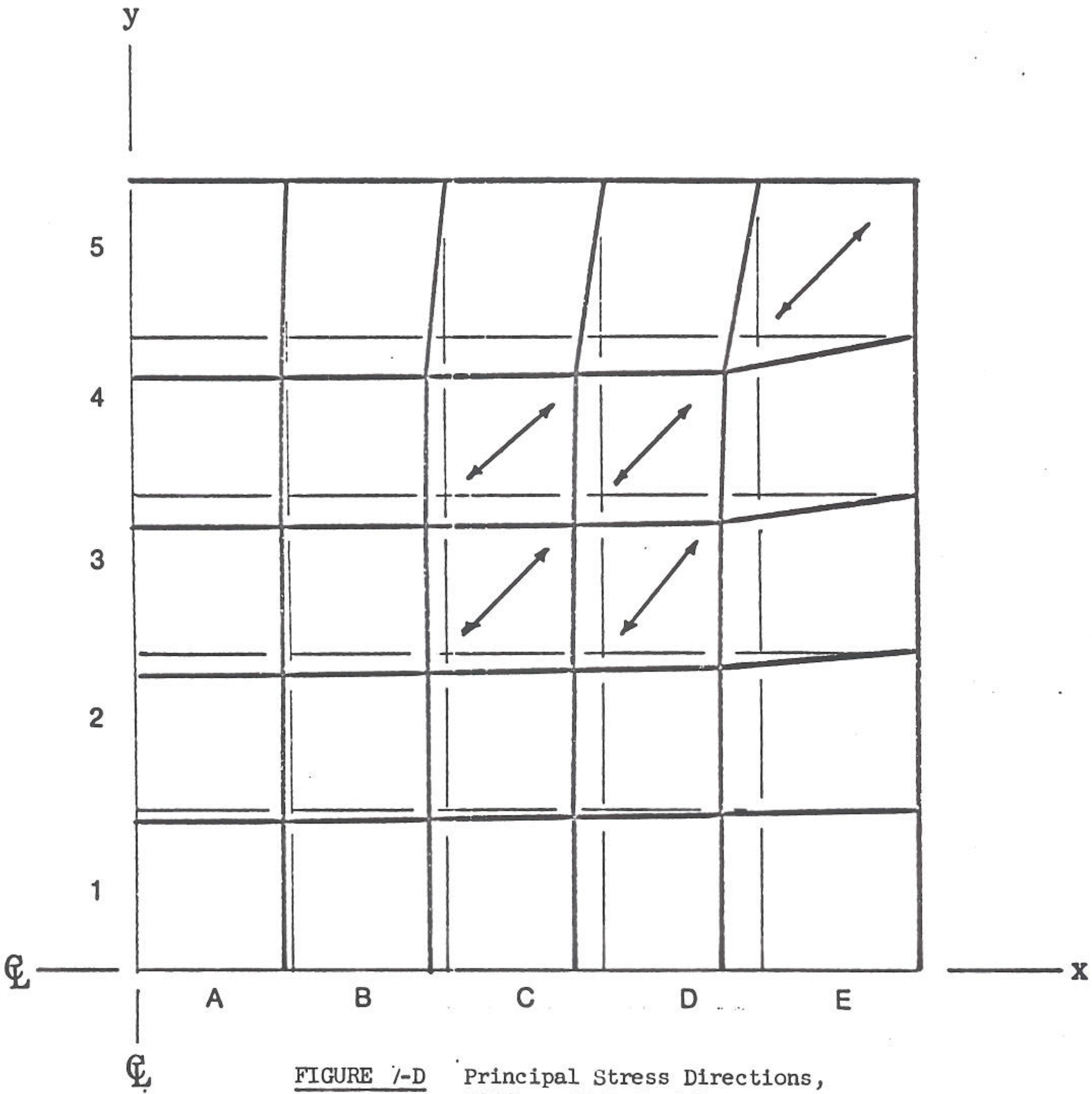


FIGURE 7-D Principal Stress Directions,
Differential Shrinkage
FEM Model Output

7. Stretcher Movement.

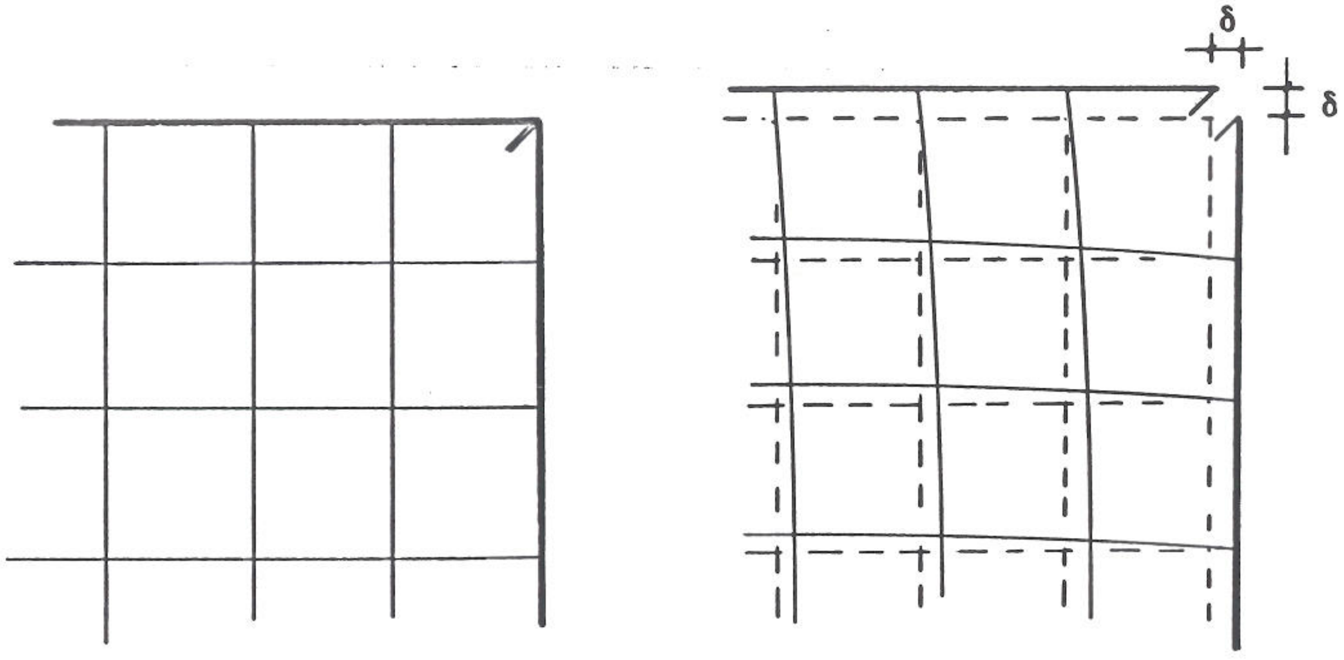
(a) Introduction.

As noted previously a uniform tension stress field may be obtained by proper stretching of a linen fabric. When a painting relaxes from this state, i.e., when the original tension stresses are released during a humid period, the painting is "keyed-out" to restore "uniform tension". A few simple tests were conducted to determine the behavior of a fabric during the expansion of a stretcher.

(b) Clinical Tests

Test 1 - As before a fabric was evenly stretched, and a series of grid lines were drawn to establish a control reference. An expansion bolt type stretcher was used in this case, and the bolts were opened.

Along with an overall increase in the tension of the fabric, considerable distortion in the grid lines was observed. (Figure 8).



Prior To Expansion
(A)

After Expansion
(B)

Figure 8

The reason for this distortion is that the edges of the fabric are restrained and not able to move freely as the stretcher bars are opened. This occurs in paintings which have been either tacked or stapled to the stretcher bar. If the edges could slide along the stretcher bar during the stretching operation, more uniform stress distribution would result.

Test 2 - In a painting that has been keyed-out, the development of stresses in the paint film attached to the fabric are related to those of the fabric. If stress can be computed throughout the area of the fabric, then there is a direct qualitative correspondence of the fabric stresses to the paint film stress provided the paint film is reasonably uniform and uncracked.

If the paint film has been previously cracked, the painting as a structure is quite different from an uncracked painting, and the stress distribution throughout both the fabric support and the paint film is markedly modified. This is reasonable since the paint film contributes to the structural stiffness of the painting.

In order to study the effect of keying-out a previously cracked painting a test was performed using the same gesso coated fabric as described previously in Section 6b, Test 3. The corners were expanded using expansion bolts and a second set of cracks were developed in the paint film, this time radiating from the corners of the "painting". Cupping again accompanied the cracking as shown in Photo (5).

(c) Numerical Tests.

To understand the stress distribution caused by expansion of the stretcher the problem was modeled with the computer program. The results shown in Figure 9-A indicate that the model duplicates the effect remarkably well, with the boundaries between each finite element representing the lined grid. The distortions were nearly identical to those of the expanded fabric. What is most revealing is the distribution of stress throughout the model. The results indicate a large variation between the highest normal stress and the lowest normal stress. Even greater variations, however, were noted between the highest shear stress and the lowest shear stress. Plots of the normal stress distribution and the shear stress distribution are given in Figure 9-B, 9-C. Principal stresses at the corner are shown in Figure 9-D.

(d) Discussion of Results.

It is of interest to comment here on certain existing paintings. Both clinical observations and the FEM model indicate distortion in the surface of a painting. It is not unusual for a 60-inch painting to be expanded 1/4" at each stretcher bar during its history. Many paintings of the "hard edge color field" type are very large and have precise geometries. These paintings will surely be keyed-out in the future and this distortion will show. A Gene Davis strip painting, for example, will display this distortion quite readily.

The effects of keying-out a painting and moisture gain in a wood stretcher are identical. The kind of expansion mechanism used at the corners affects the total dimensional change. Keyed stretchers feel the effect of wood swelling across the entire width of the stretcher, while expansion bolts reduce the effect since the restraint mechanism is located nearer the center of the stretcher bar.

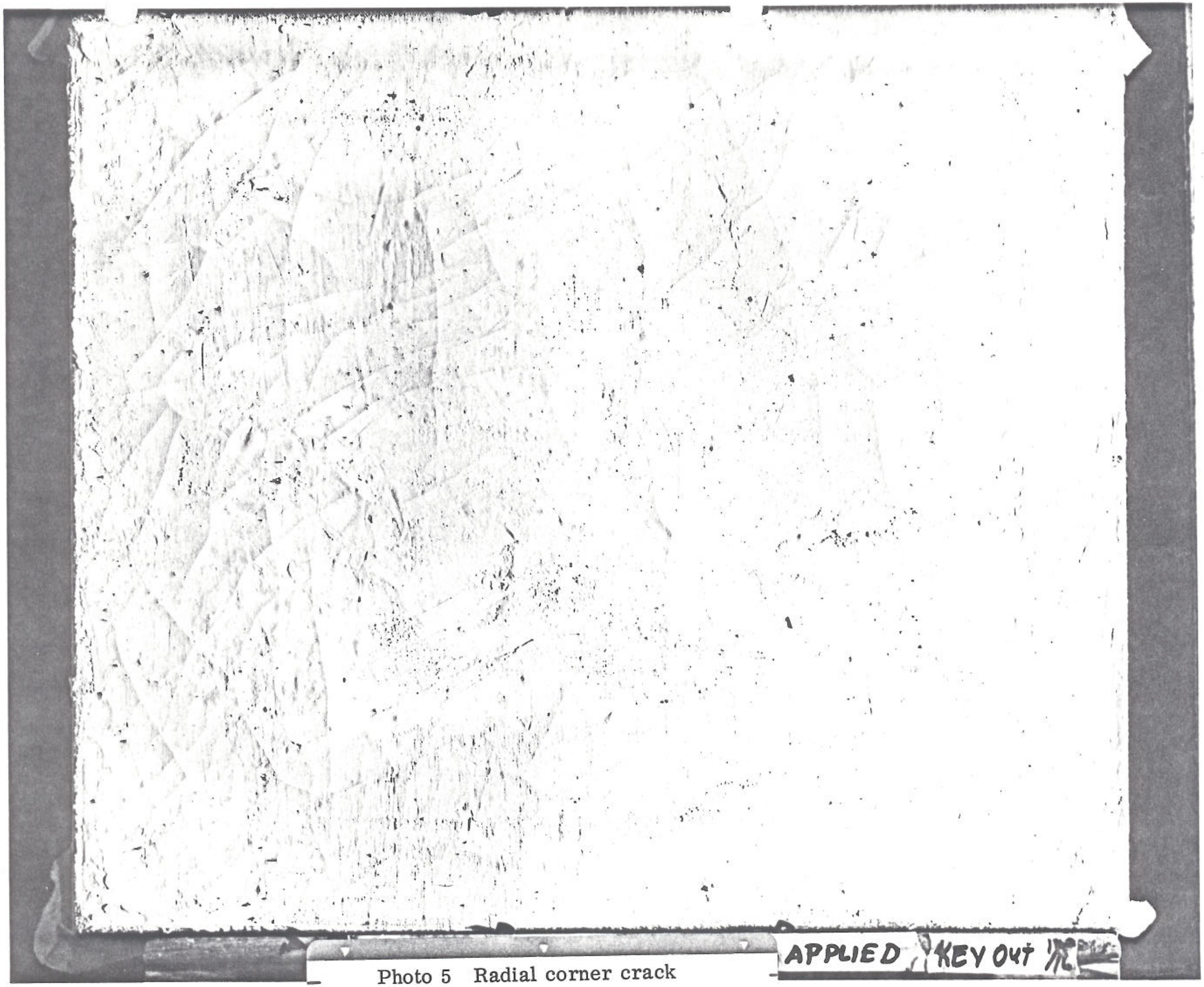


Photo 5 Radial corner crack development

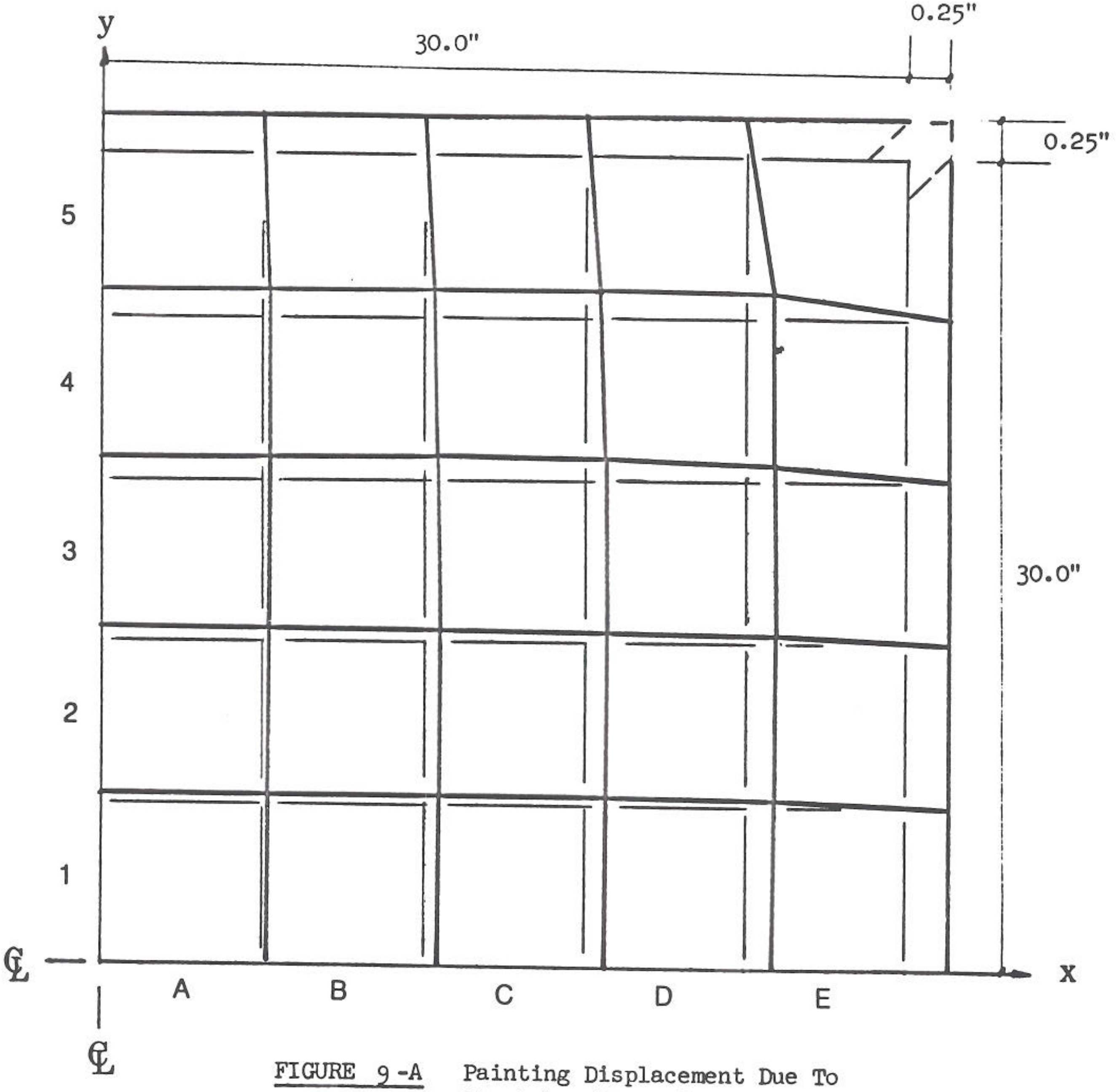


FIGURE 9-A Painting Displacement Due To Stretcher Expansion FEM Model Output

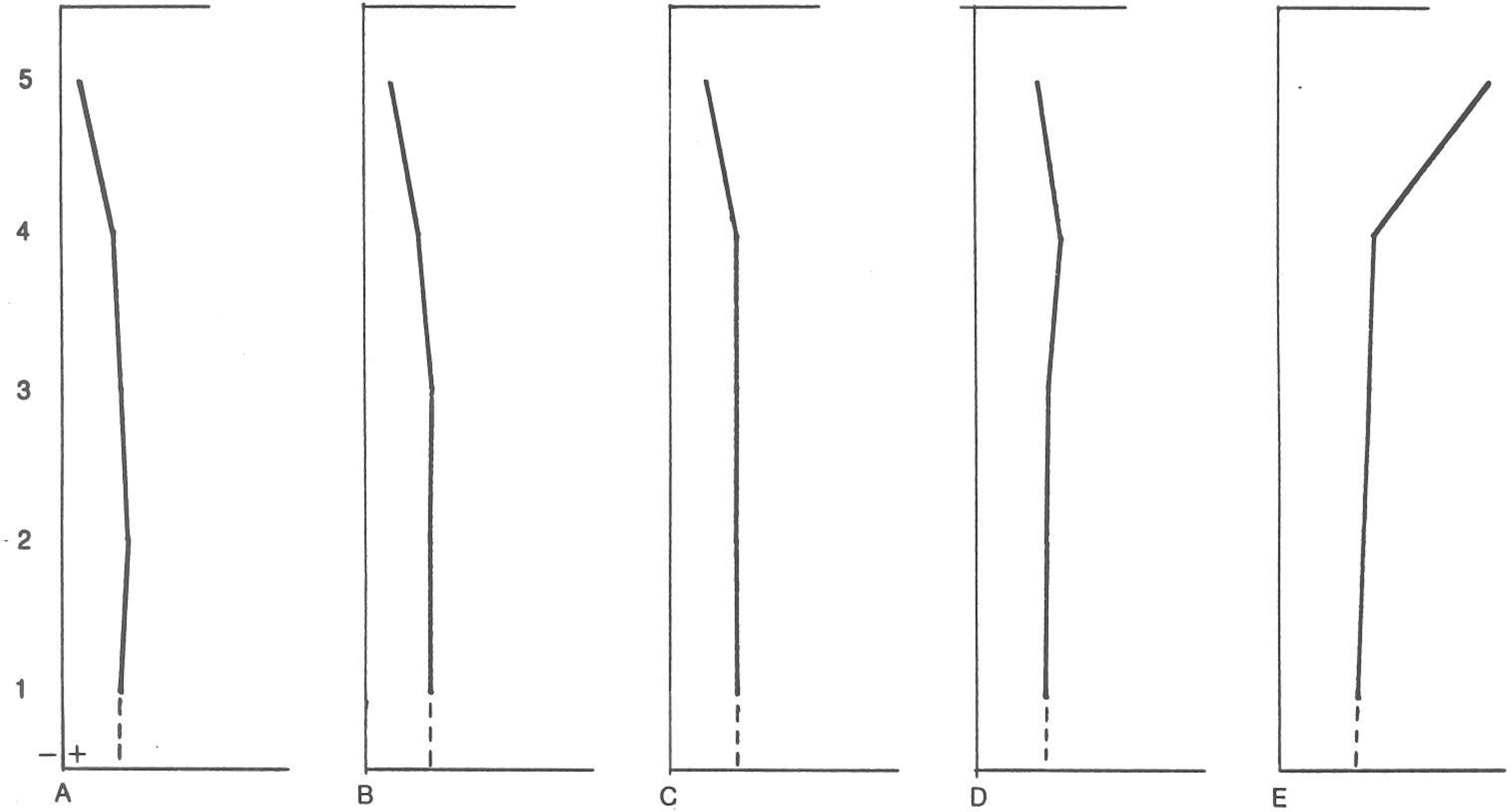


FIGURE 9 -B X-Direction Normal Stress Due To Stretcher Expansion FEM Model Output

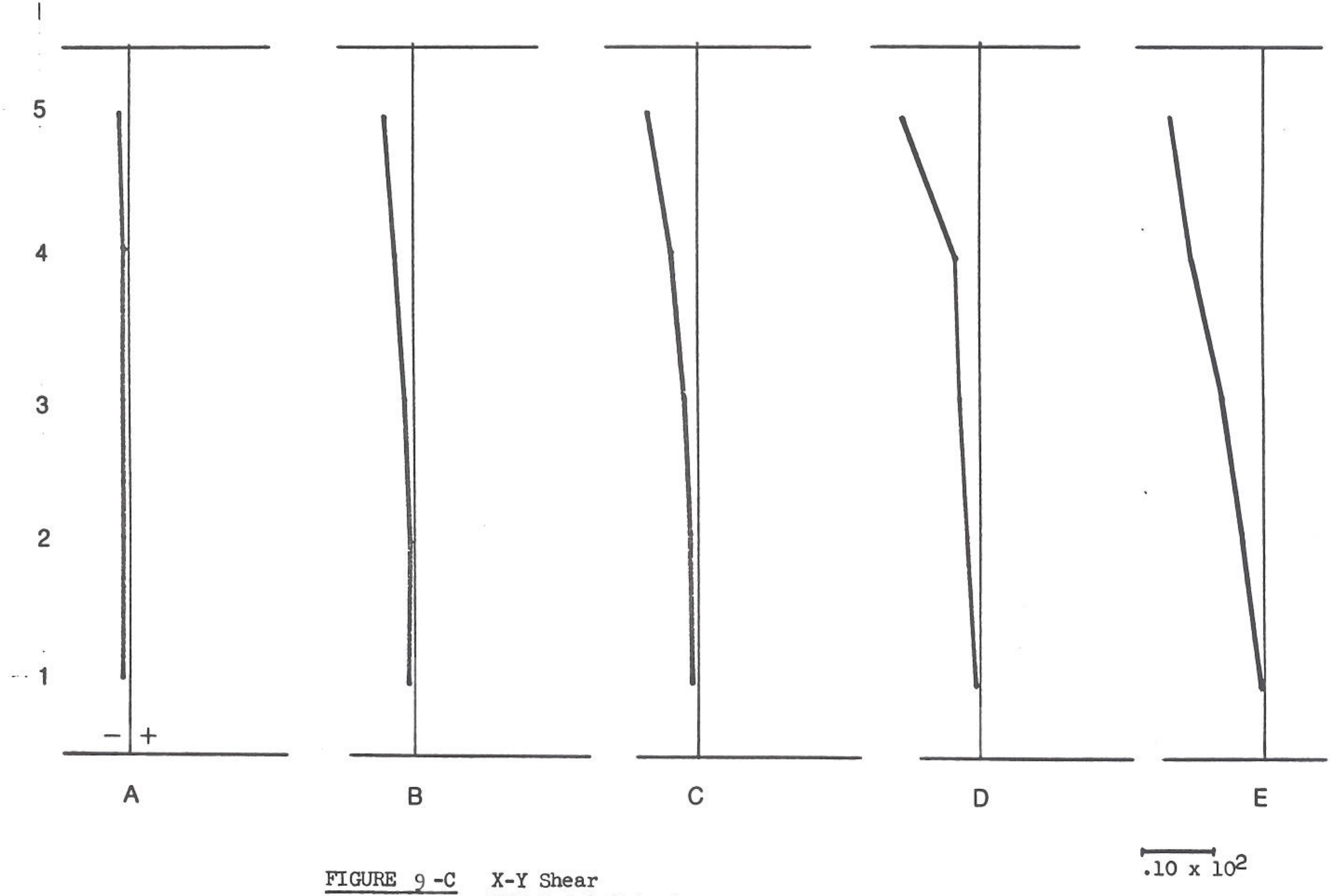
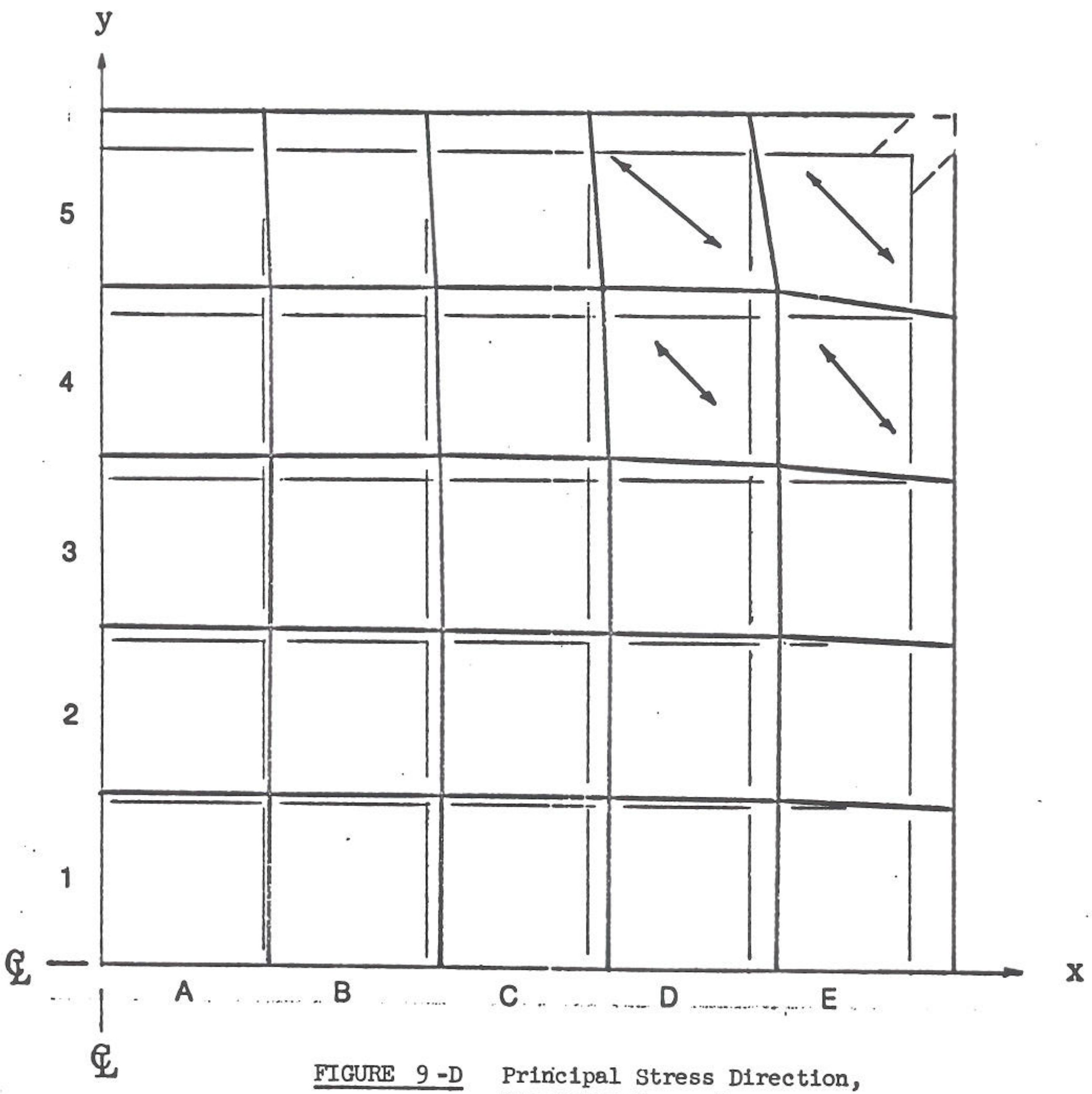


FIGURE 9-C X-Y Shear
FEM Model Output



<u>FIGURE 9-D</u> Principal Stress Direction,
Stretcher Expansion
Computed from FEM Model Output

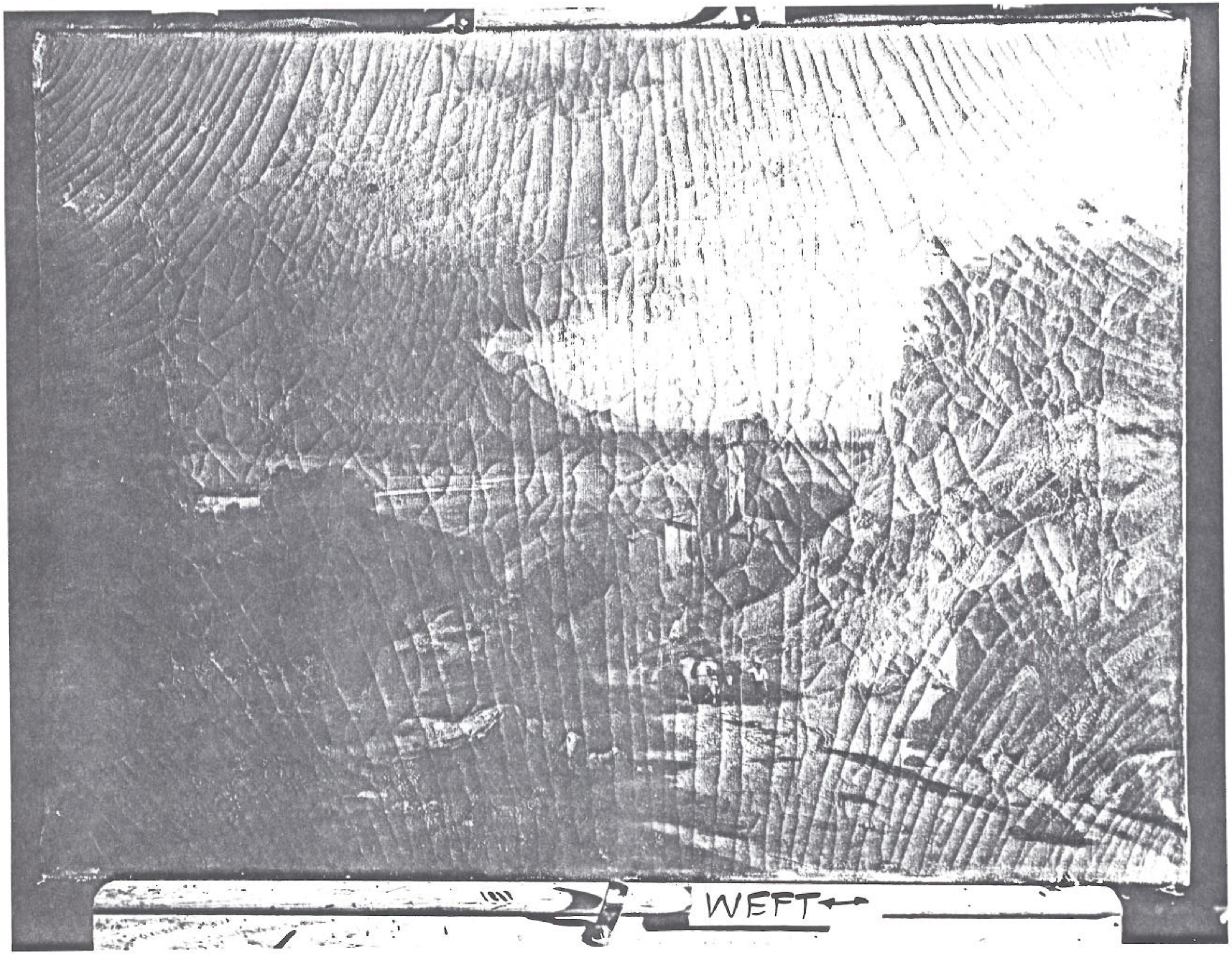


Photo 6 Painting on strainer
showing corner cracking

Photo 7 Corner drapes

In Photo (4) the corner cracks have a curvature that is opposite to that found in painting Photo (6). If, however, the fabric were sized and, accompanying moisture deflections, the wood stretcher were to shrink again due to moisture loss, the combined effect of these two actions would be to probably duplicate the cracking found in paintings.

Also, shrinkage of the stretcher promotes a decrease in the maximum principle stress at the corner while the contraction of the size tends to increase the maximum stresses. (See Fig. 7-D). The resulting movement results in a corner condition known as drape, which is illustrated in Photo (7).

If a painting were lined on a relatively inert fabric where motion due to moisture variations is inhibited, the effect of shrinkage of the stretcher would create a new condition. Keck states:

> "In regard to painting on either canvas or wood supports, many of the current practices in the treatment of defects caused by mechanical stress are not based on an understanding of the forces involved. Consequently some of the treatment performed today will only tend either to aggravate the stresses which they are attempting to overcome, or inadvertently to create new ones."

In this case the painting was linen lined with a wax adhesive. The resultant buckling of the painting (Photo (8)) was a result of loss of moisture in the wood, expansion bolt stretcher. The corner buckling was again the initial form of deformation when the large principal stress was relieved. The change in the painting dimension (30" x 25") was only about 1/16" from an initial uniformly stressed condition. In the same environment (dry) causing such buckling, sized unlined paintings remain reasonably taut. The conclusion is that the motion of both fabric and wood operating simultaneously confuse observations into the apparant stable condition of the paintings.

Also the development of nonlinear stress due to stretcher expansion clearly indicates that present keying-out techniques need to be reevaluated.

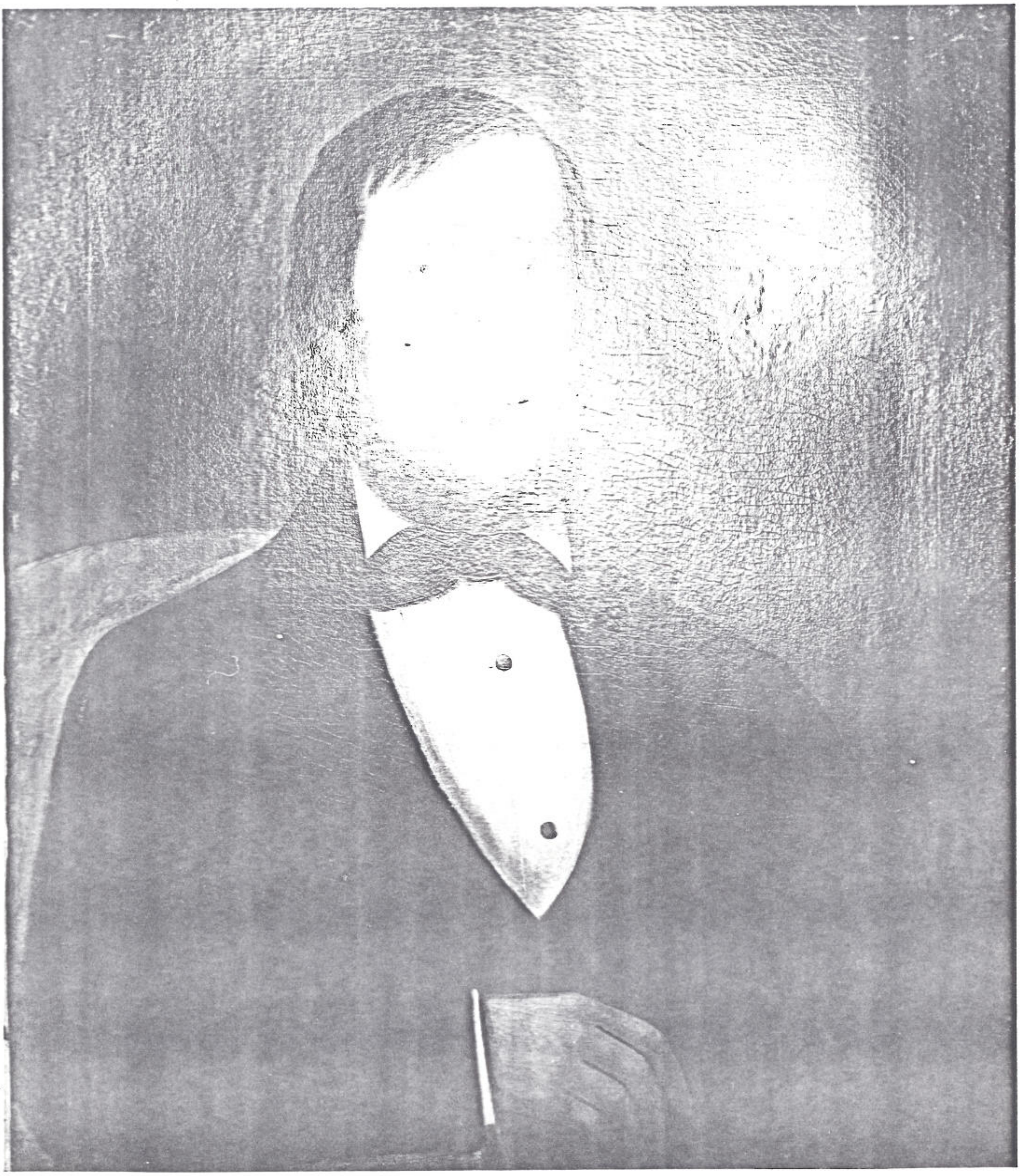


Photo 8 Corner buckling due to stretcher shrinkage

8. Structural Interaction of Paint Film and Support Fabric.

(a) Introduction.

In Section 6, it was shown that a stretched fabric develops a differential stress field under nonuniform variations in moisture.

It is important to understand, however, that the behavior of a fabric support is not necessarily the same as the behavior of a paint film attached to that fabric support. In fact, the stress distribution developed in a painting support fabric is often quite different from the stress distribution developed in the paint film due to the fabric motion. The development of stress in paint film is closely related to displacement of the support fabric.

The paint film will resist and reduce the motion which the support fabric tends to undergo and in the following discussion the structural contribution of the paint film will be considered. The main purpose of this discussion is to present the basic mechanisms of interaction between fabric and paint film and thus in order to simplify this presentation a single unsized fabric section will be used. Therefore, a single unsized fabric section which has been tensioned between two supports is illustrated in Fig. 10. The initial tension stress is σ_i and the corresponding initial tension strain is ε_i.

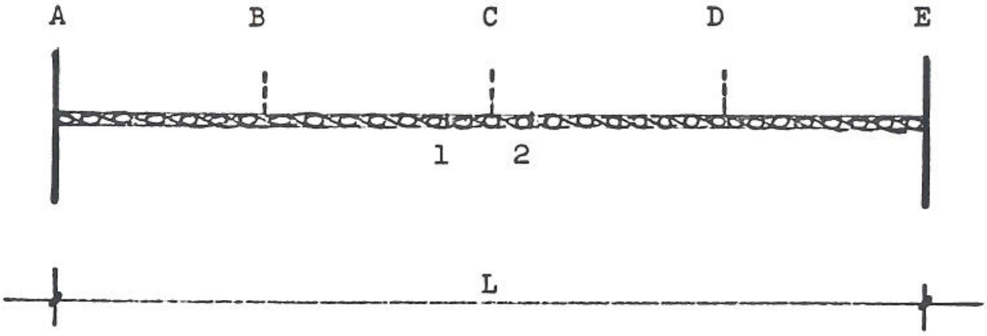


Figure 10

In demonstrating the effect of fabric displacement on paint film stresses the concept of an apparent E is again useful.

If the section were uniformly wetted, tension stress would increase even though Points B, C, and D would not move. In Figure 11 the increased stress is shown as in increase in σ_i to σ_ω.

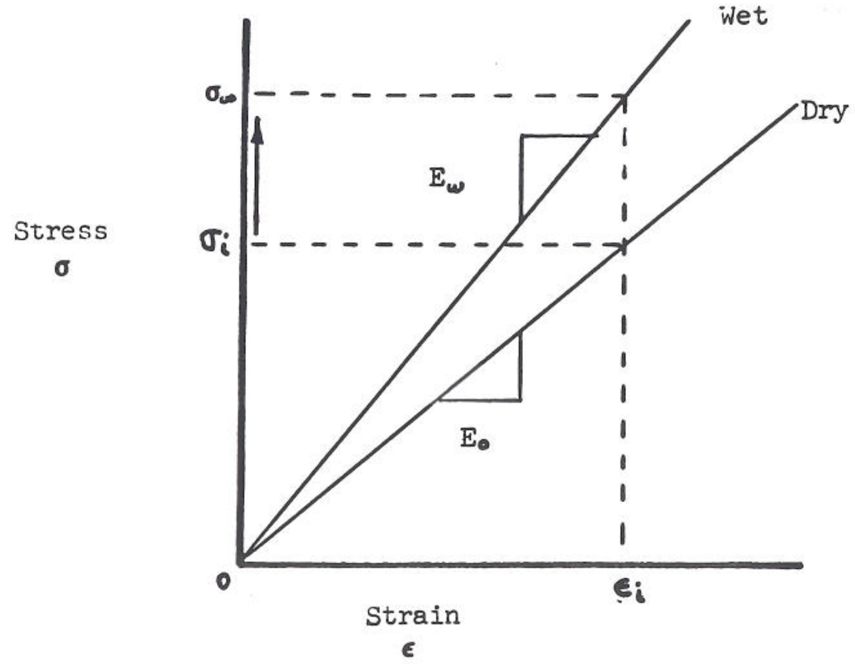


Figure 11

If only that portion of the dry fabric from Section A to C is wetted, then it would seem that the stress in Section A-C would be greater than the stress in Section C-E. However, this is not possible since the laws of statics require that for equilibrium the forces acting on a section must be equal and opposite.

A detailed look at Section 1-2 (Fig. 10) shown below in Fig. 12 requires that for equilibrium that the stress in both the wet and dry fabric sections must be the same.

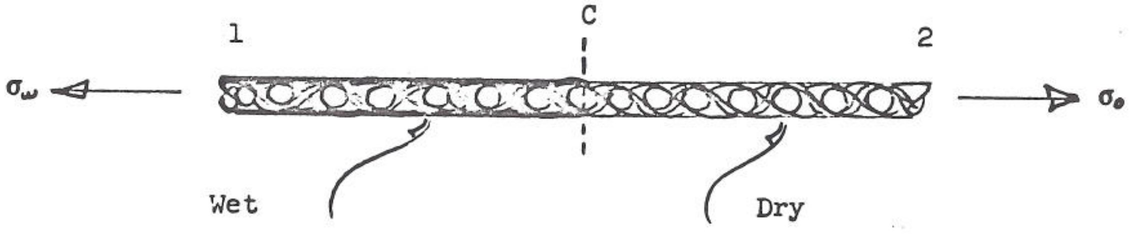


Figure 12

This condition requires a change in strain in the fabric, and the resulting strain and stress changes are illustrated in Fig. (13).

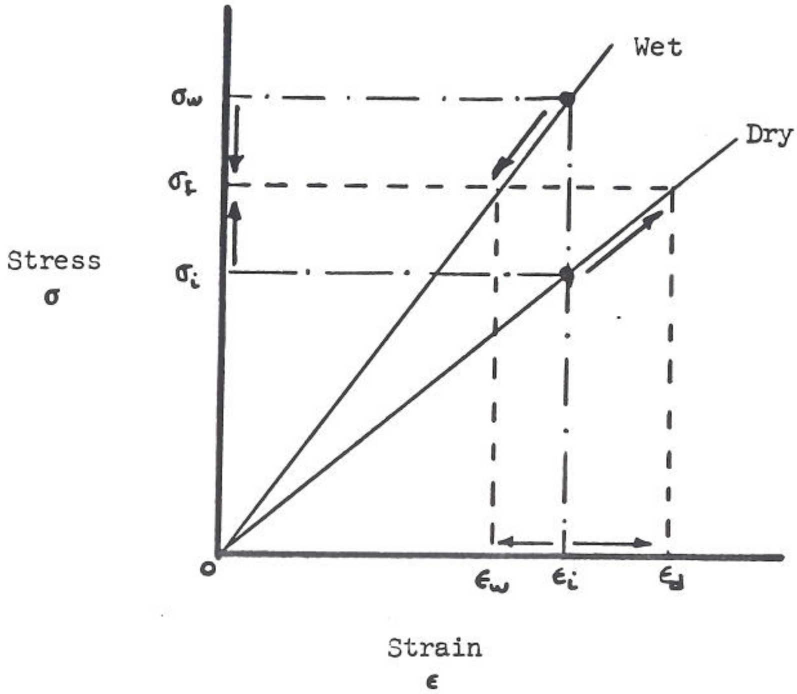


Figure 13

Note that the strain in the wet fabric must reduce from ε_i to ε_ω while the dry fabric strain increases from ε_i to ε_d. These changes in strain are necessary so that in both the wet and dry sections, the final stress is δ_f. Thus equilibrium of the stresses is produced by deformation of the fabric.

Thus as the strain in Section ABC decreases and the strain in Section CDE increases, Point C has moved left to point C' (Fig. 14).

Note also that Points B and D are moved to B' and D'.

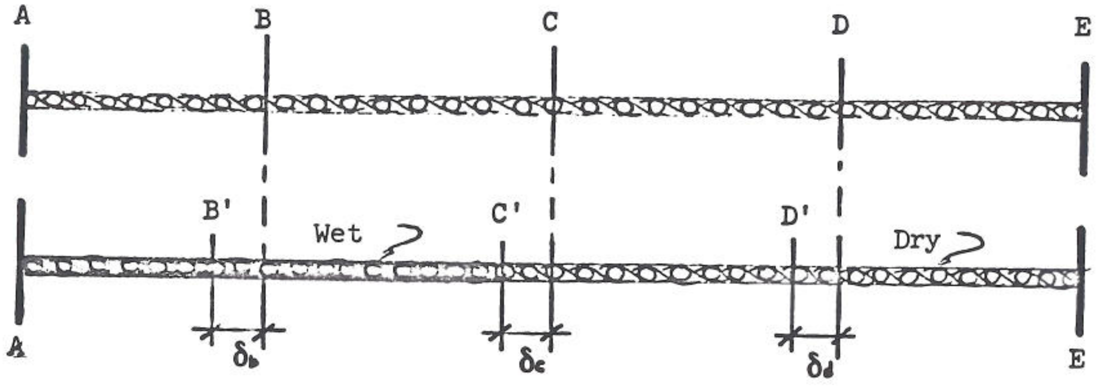


Figure 14

Consider the effect of this movement on an initially unstressed paint film which had been recently applied to the fabric prior to the nonuniform wetting. Between points A and C' the film would be under compression and between points C' and E, tension stresses would be developed. In its early history the paint film has a very low stiffness and, therefore, provides little resistance to the differential movement of the supporting fabric. Thus the fabric motion simply causes deformations in the relatively soft film. Since, however, it has been shown in Section 6 that a permanent deformation will be induced into the fabric as a result of differential drying, the drying paint film has been biased in the sense that stresses developed in the film due to drying contractions of the film are magnified by the permanent deformation of the fabric. The most critical area of the paint film will, therefore, be in the corners of the painting where high stresses have been shown in Section 6 to exist in the fabric. In these areas, paint film cracking as a result of drying of the film will form in patterns that follow the stress patterns in the fabric.

It is worth noting that cupping of the paint film rarely accompanies this cracking. In the compressed section of the fabric the soft paint film will simply be deformed.

However, if considerable drying of the paint film has occurred prior to the fabric movement such that drying cracks have occurred in the paint film or if mechanical cracks have formed in a previous expansion, the compression induced in the film due to differential fabric drying could lead to buckling of the film. This condition occurs often on the lower edges of a painting as shown in Photo (9) and illustrated in Fig. 15.

Photo 9 Cleavage at lower part of painting

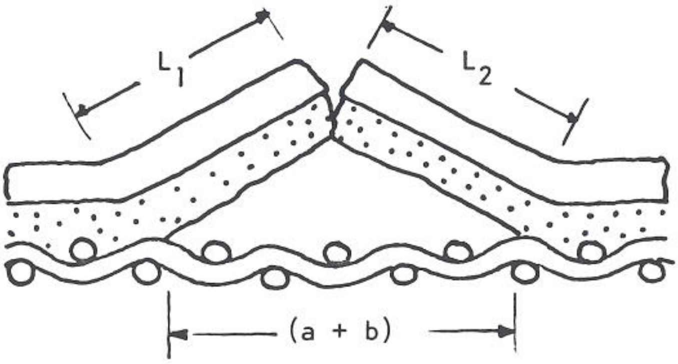


Figure 15

Also in the majority of cases illustrated in Fig. 15, the distance $(L_1 + L_2)$ is in excess of the distance (a + b). This is observed by conservators attempting to replace the buckled paint film. The reason for this situation is that after cleavage occurs the restraining effect of the paint film on the fabric is destroyed and the fabric is free to contract without resistance.

In some cases the paint film compression is not severe enough to cause buckling and the film is merely distorted in the region of previously formed cracks as shown in Photo (10) and Fig. 16.

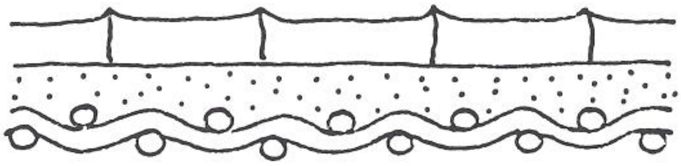


Figure 16

While this distortion is not really cupping it can accompany cupping which had previously formed due to an earlier disturbance.

(b) Numerical Tests

The finite element computer program was used to examine in detail a small segment of the paint film surface between cracks. A detailed section through a typical painting showing the support fabric, ground and paint film is shown in Fig. 17.

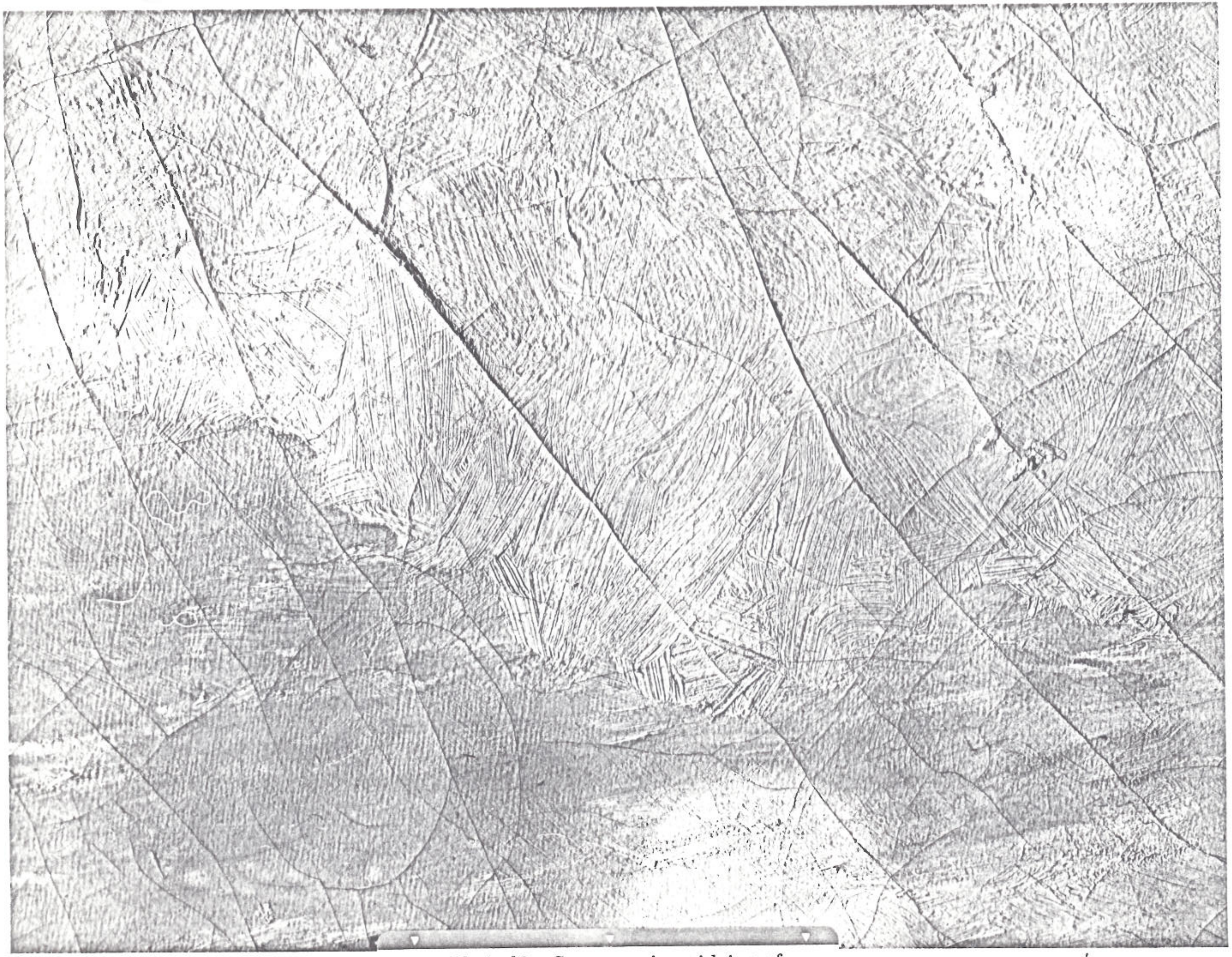


Photo 10 Compression ridging of paint film

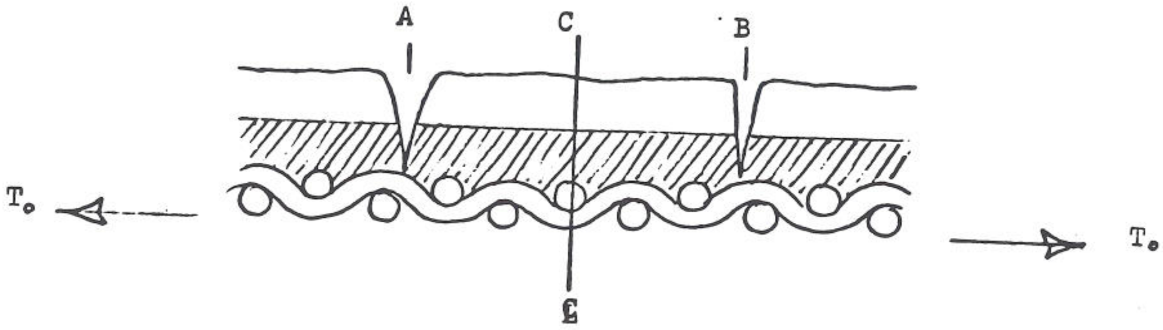


Figure 17

In particular an analysis was made of the composite structure between Section C-C and the crack located at B, as shown below.

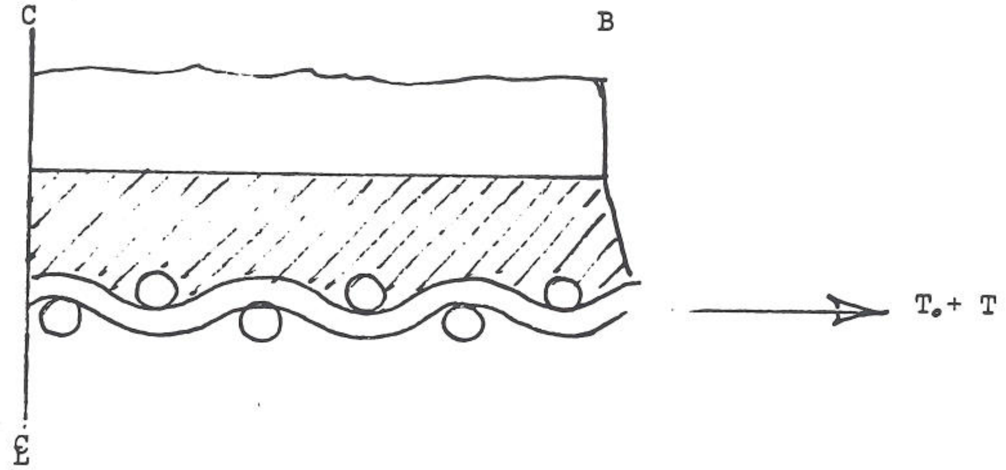


Figure 18

The idealization of the actual structure shown in Fig. 18 is given in Fig. 19. In this idealization, Row 1 represents the fabric, Rows 2 and 3 represent the ground, and Rows 4 and 5 represent the paint film.

Included in the analysis were three different elastic moduli of elasticity, the highest being in the dried paint film, the second highest representing the ground and the interface between ground and fabric, and the lowest being that of the fabric. Although the material properties used are not entirely accurate, since little quantitative information is available on the physical properties of old paint films, the qualitative results can be used to identify sources and regions of high stress concentration and possible failure.

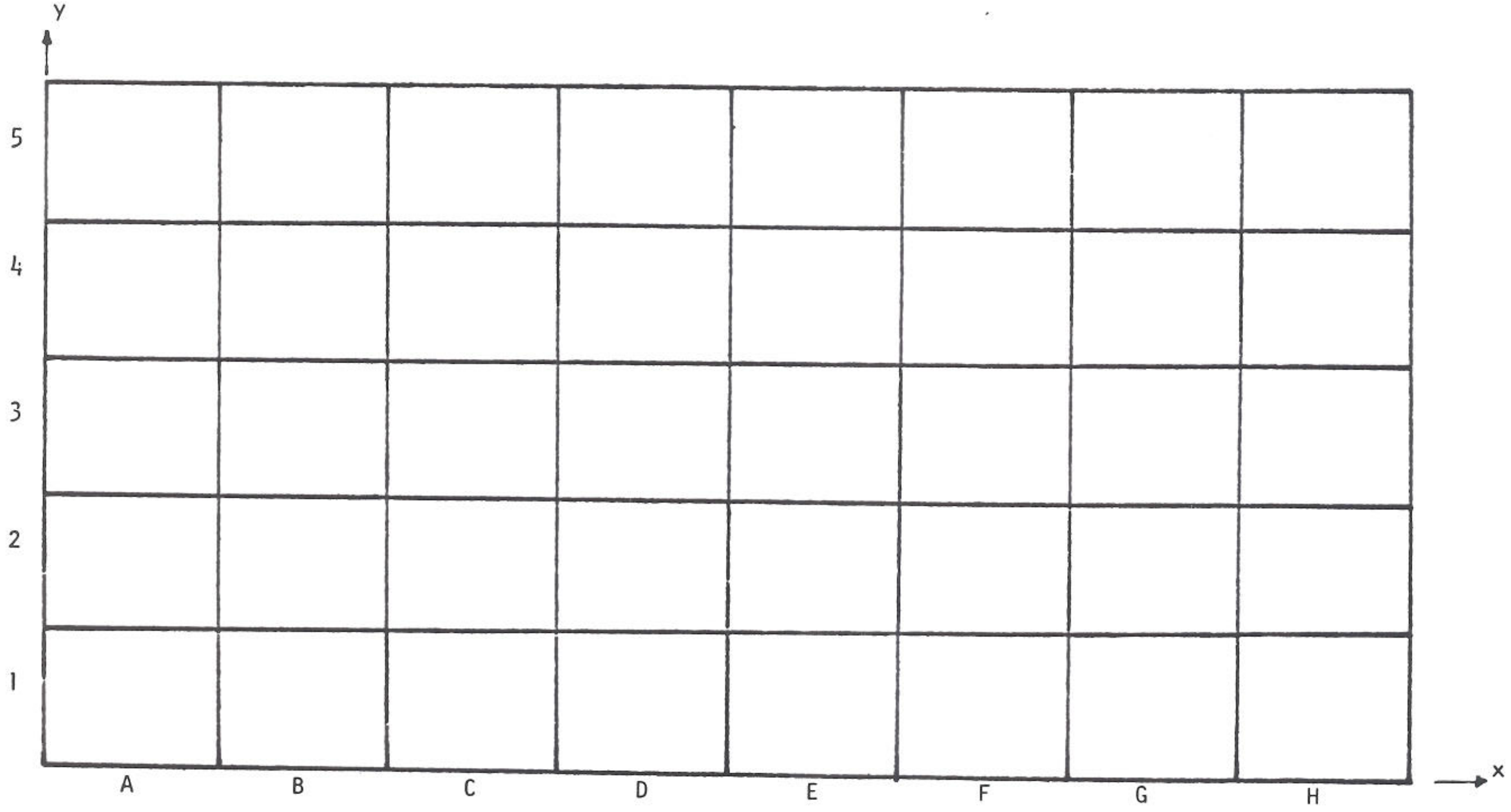


Figure 19. Finite Element Grid

Because of the dimensions of the model the paint film can be considered to be a thick film, in comparison to the fabric thickness.

The model shown in Fig. 19 was assumed to be supported along the line C-C and forces were applied as shown, representing tension stress changes in the fabric due to differential drying, etc.

In discussing the numerical results of the analysis, the overall deformation of the composite system is of interest. This responce is shown in Fig. 20-A which indicates a curvature in the laminate of paint, ground, and fabric commonly referred to as cupping.

Also the shear stress distribution is important since shear stress has long been associated with bond failure at the ground-fabric interface. The shear stress distribution is highest at the crack edge and decreases towards the central portion of the model.

However, shear stress alone is not solely responsible for high bond stresses and failures. Bond failure, or "flaking," results from the composite effect of the x and y normal stress and the shear stresses. These stresses combine to create principal stresses which really are the cause of failures at the ground/fabric interface.

Figures 20-A-E show respectively the model deformation, the x and y normal stresses, the x-y shear stresses, and the resultant computer principal stresses at certain specific areas. The plot of the section deformation is fairlystraightforward; conservators have observed this cupping effect for centuries. However, the display of stress distribution which included the effect of the structural contribution of the paint film is interesting.

First to be observed is the high magnitude of both x and y normal stress and x-y shear stress in the same areas (1G, 2G, 1H, 2H) (Figure 20-B, C,D). These are the areas where bond failure begins.

In this particular model run, areas 5A-F of Figure 20-B are under compression stress. These stresses suggest the potential for crushing the upper layer of paint, perhaps a potential source of interlayer cleavage.

It was stated previously that the model was based on a purely elastic basis. In considering the effect of the stresses on a plastic material, it can be readily seen that variations in the stress/displacement information would occur.

If the load applied is of a long duration and/or increased in magnitude, the increased deformation of the painting is quite measureable. This is because plastic materials are time-responding to load. That is, as the load is applied over a long dry winter cycle, for instance, the increased stress is acting annually over a period of months. While it is uncertain what magnitude these stresses can develop, it is probably much higher than previously suspected. Also, if the painting were to relax and then be keyed-out, the stresses would

Creep

FIGURE 20 -A Section Displacement, Fabric Tension FEM Model Output

δ_x = .03841

δ_y =.04273

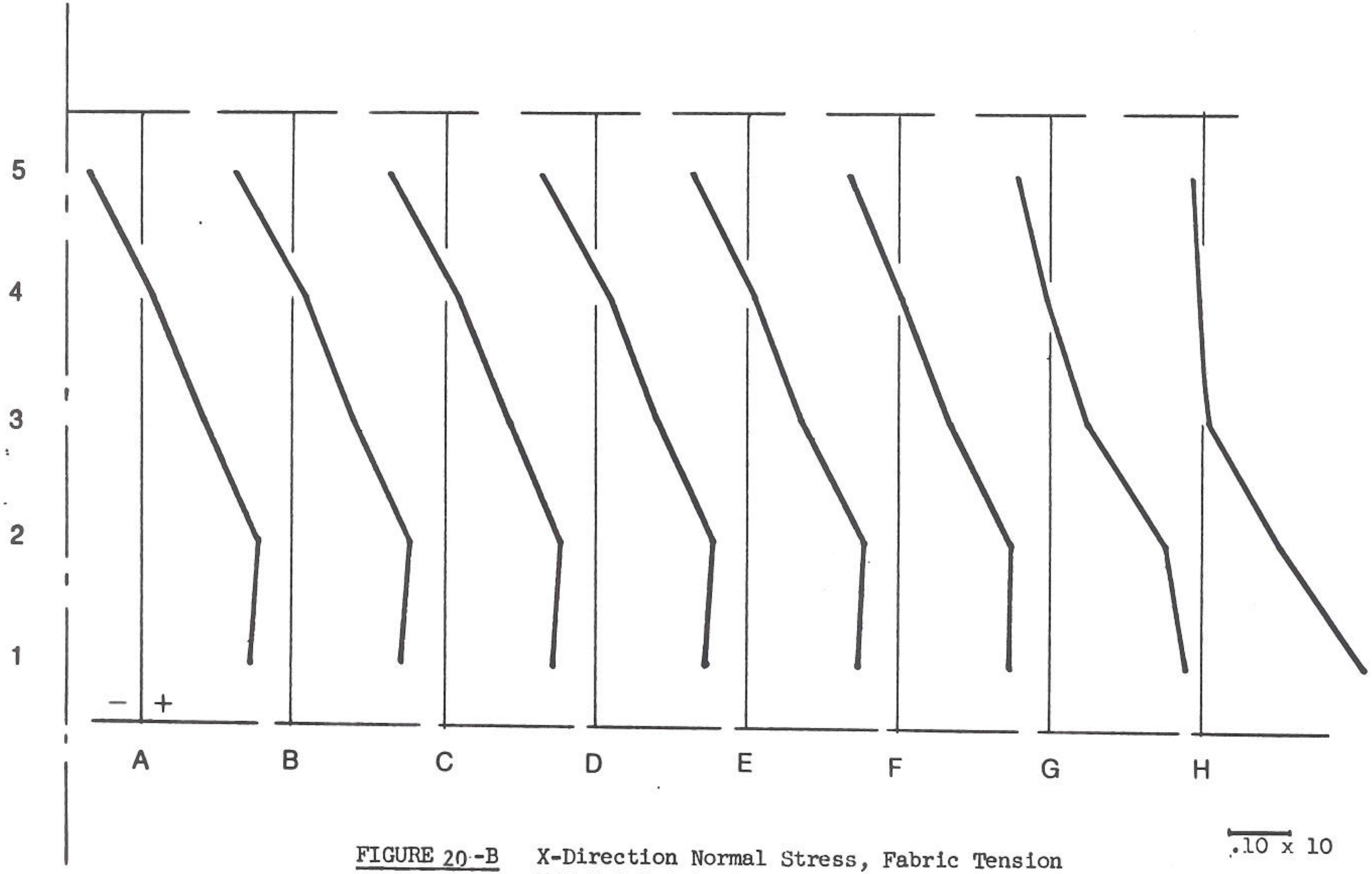


FIGURE 20-B X-Direction Normal Stress, Fabric Tension FEM Model Output

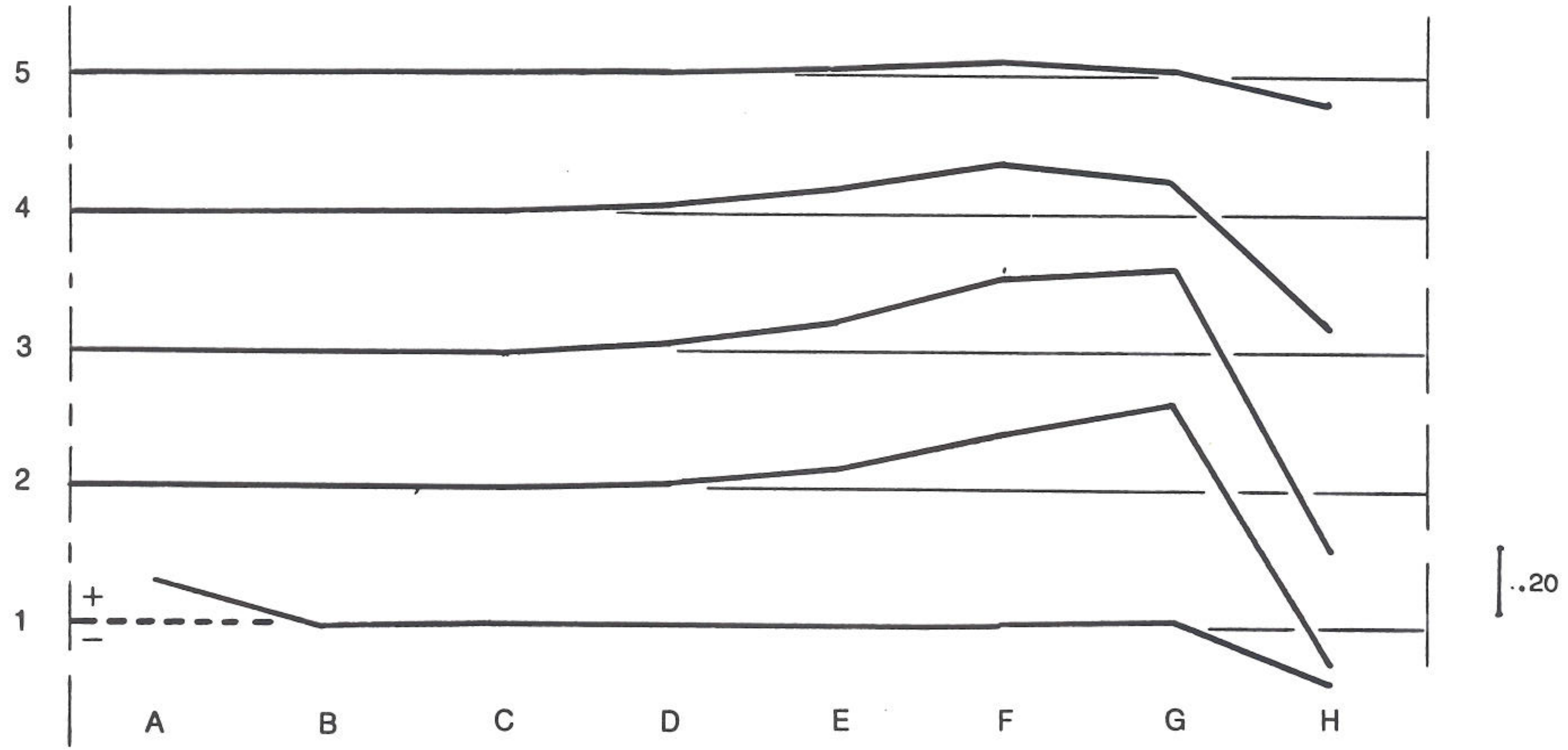


FIGURE 20-C Y-Direction Normal Stress, Fabric Tension FEM Model Output

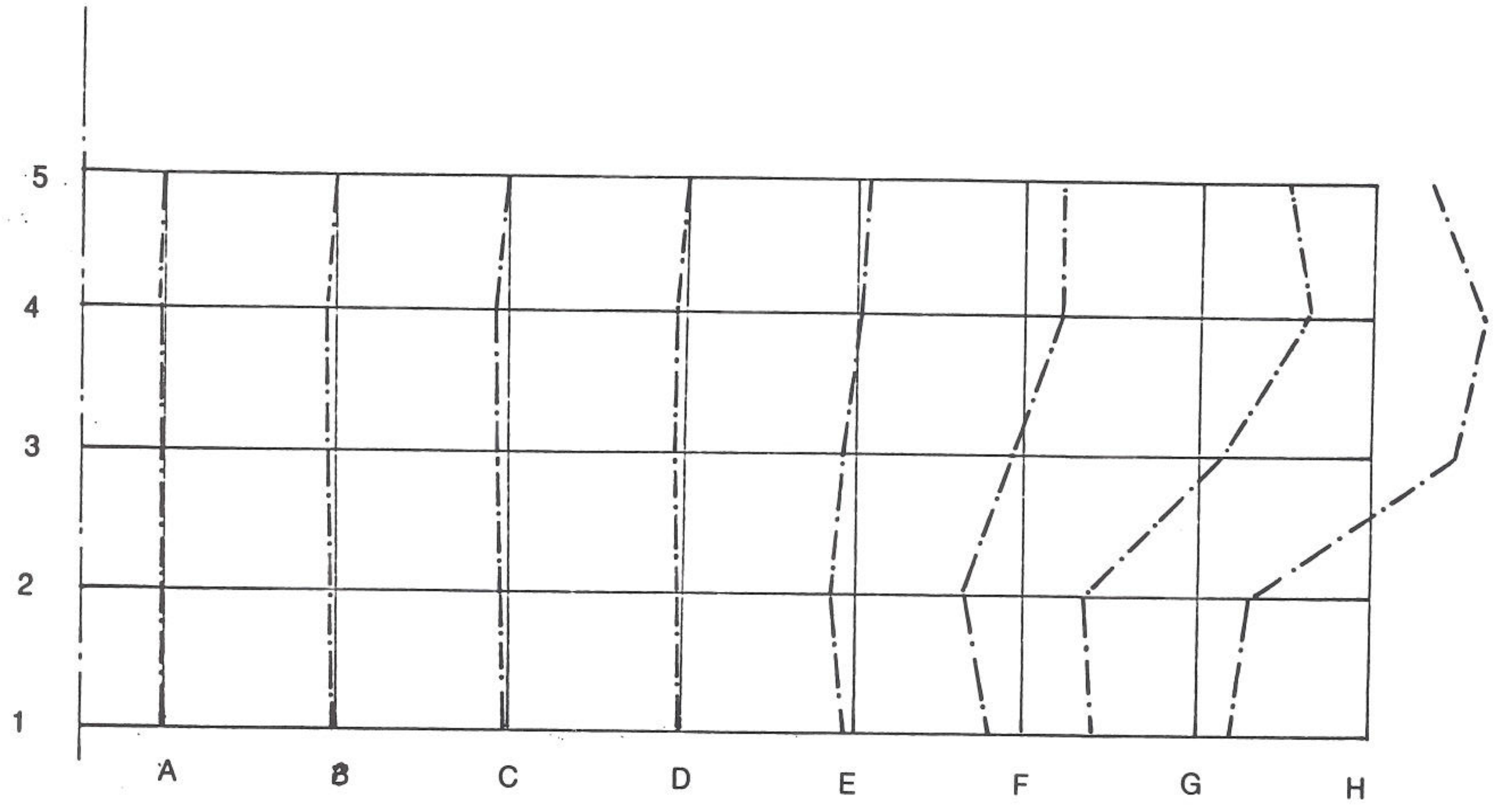
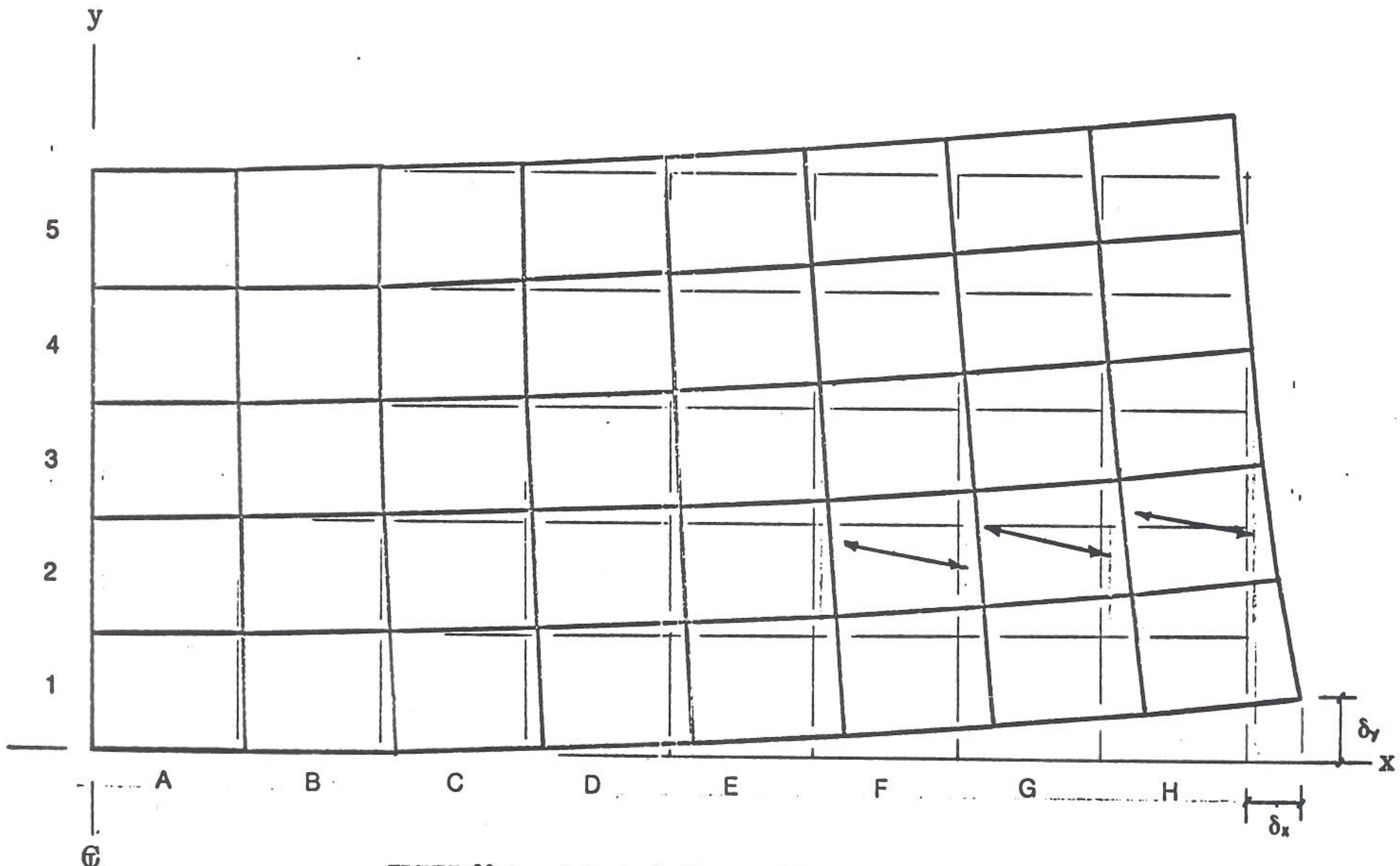


FIGURE 20-D X-Y Shear Stress, Fabric Tension
FEM Model Output



<u>FIGURE 20-E</u> Principal Stress, Fabric Tension
FEM Model Output

remain even longer. Any number of events can occur which continue the stress of the fabric support. Also important here is that the relaxation of a fabric support does not reverse the process, since no equivalent (vs. tension) compression force can be developed in a fabric. The fabric force is always tensile and displacement behavior is the reason for other forms of failure.

In Figure 20-E the direction of the principal stresses are indicated. Their orientation indicates that cracking failure occurs as a pulling of material at the fabric/ground interface. This type of failure tends to leave crumbled particles of material behind, explaining in part the residual debris accumulated in the areas of such failure. This debris prevents the paint film from returning to an inplane position. It is also likely that varnish and other resinous material would lock these particles of ground in place, making it almost impossible to remove them.

As a result of the above information, the problem was reanalyzed to observe what happens when bond failure actively occurs and the same forces are applied to the failed section. Below is a sketch of the model as it would appear on a painting.

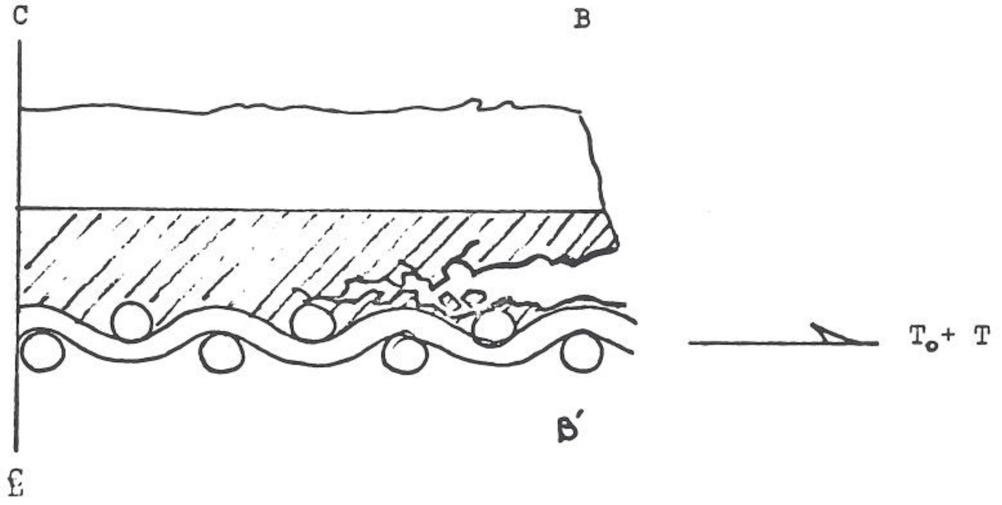


Figure 21

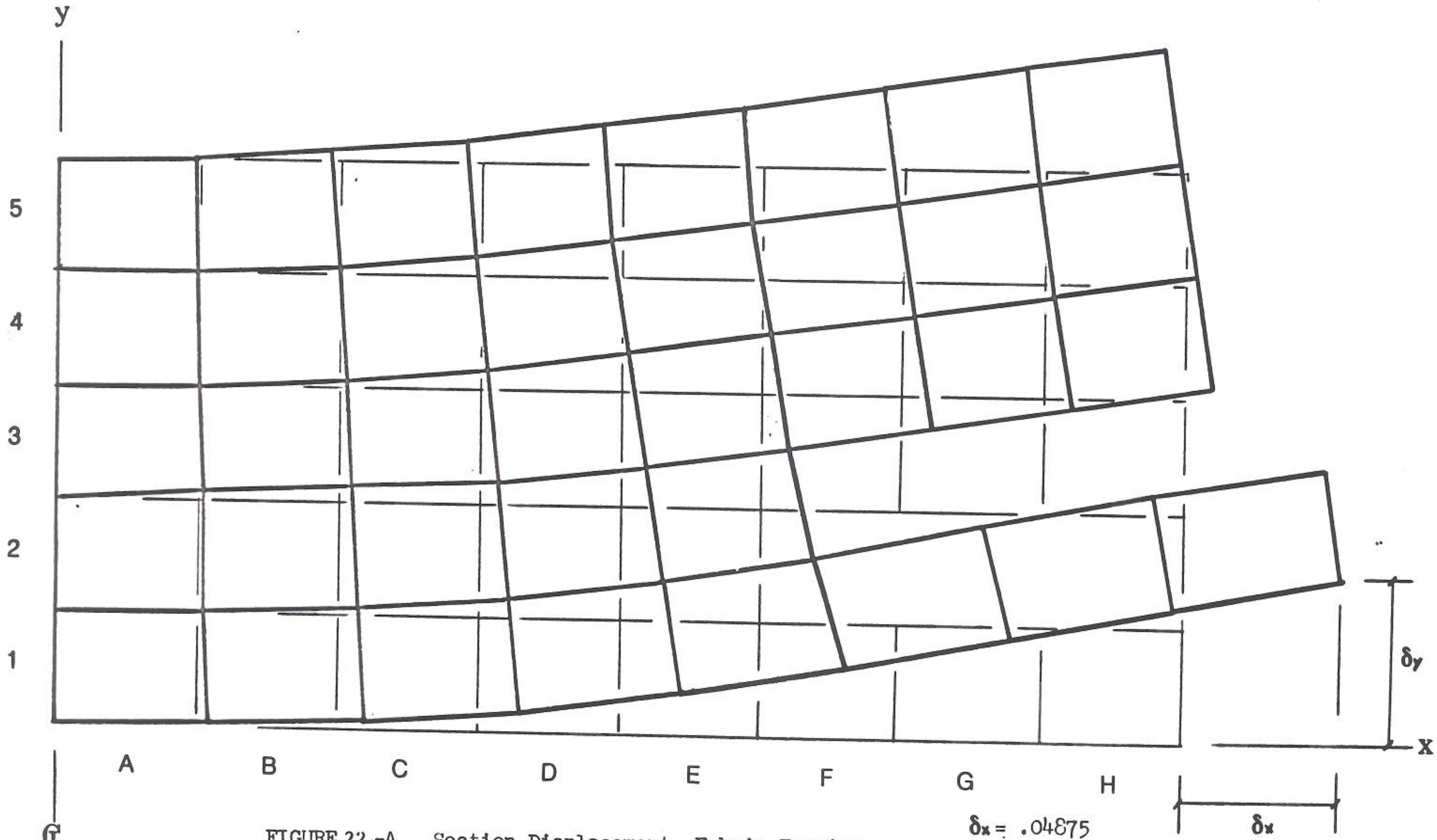


FIGURE 22-A Section Displacement, Fabric Tension Bond Failure at Ground/Fabric Interface FEM Model Output

$\delta_x = .04875$

$\delta_y = .04742$

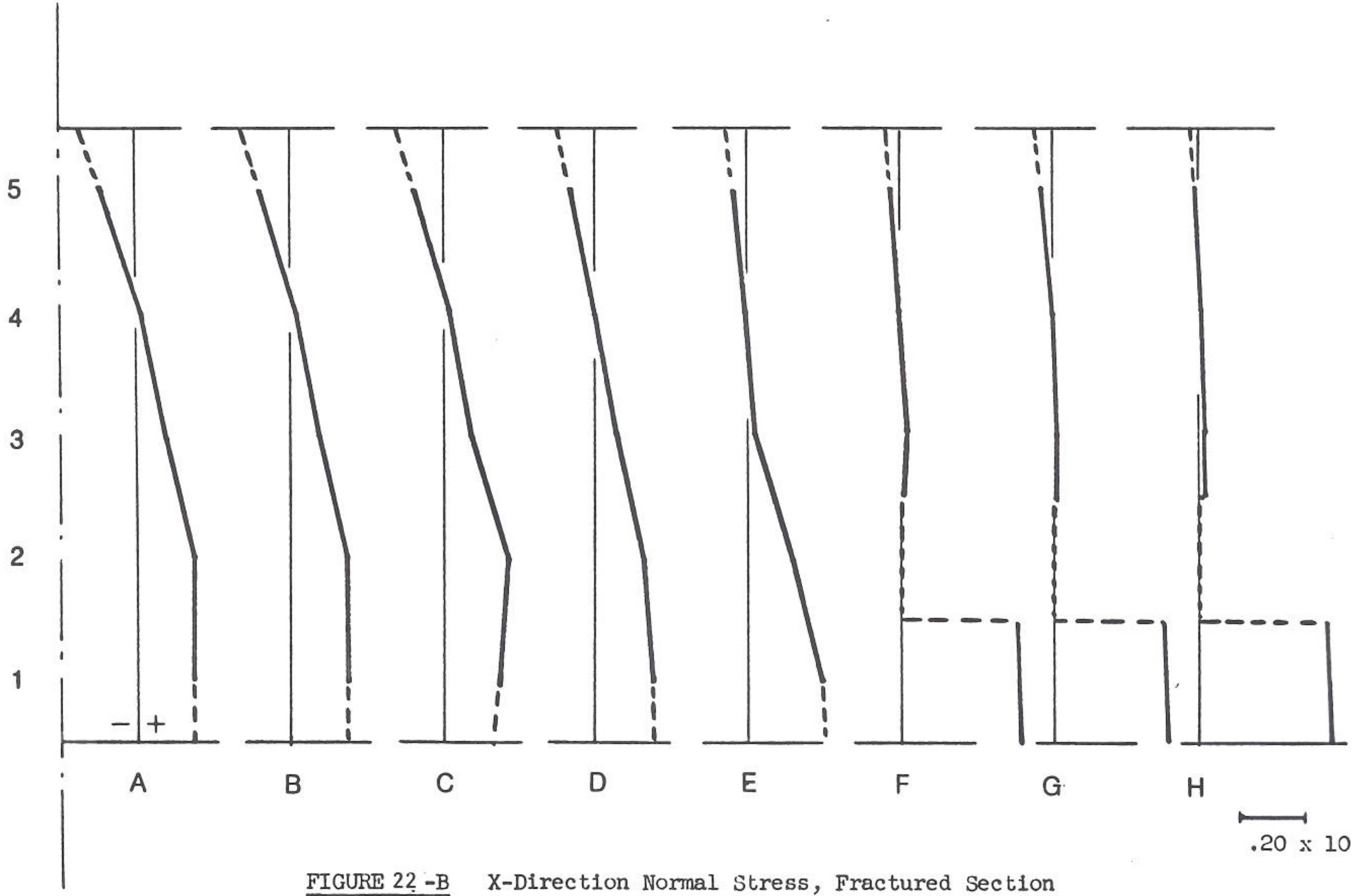


FIGURE 22-B X-Direction Normal Stress, Fractured Section FEM Model Output

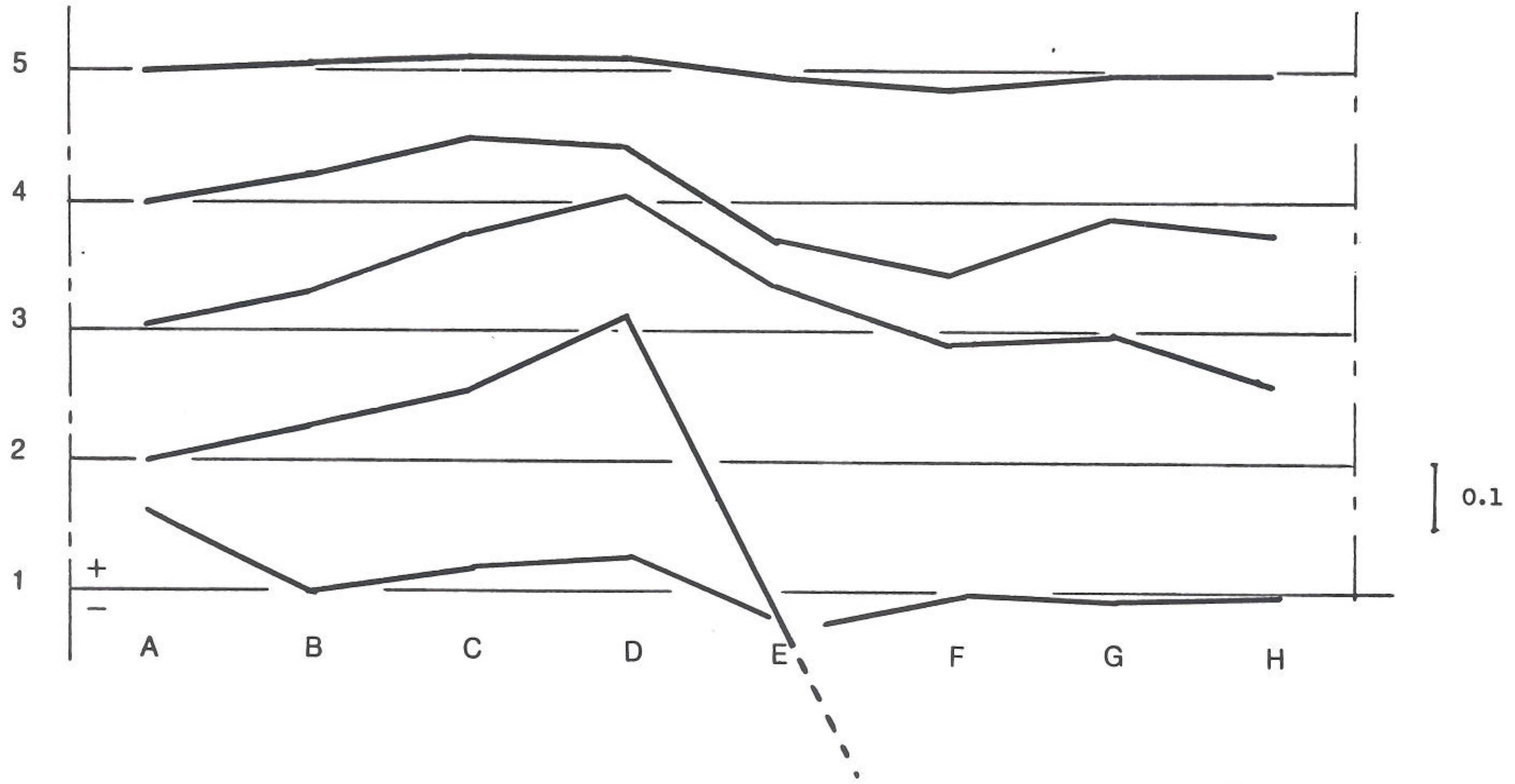


FIGURE 22-C Y-Direction Normal Stress, Fractured Section FEM Model Output

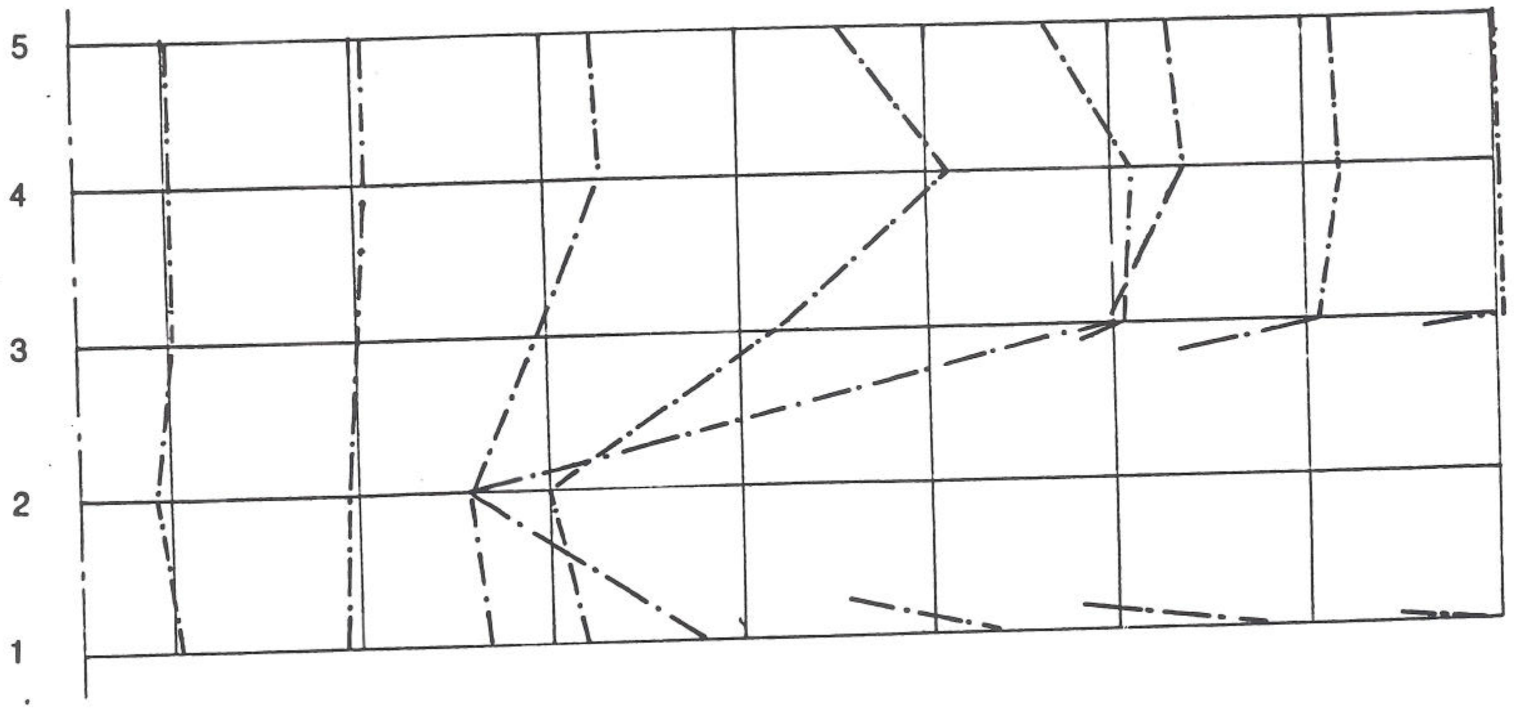


FIGURE 22-D X-Y Shear Stress, Fractured Section
FEM Model Output

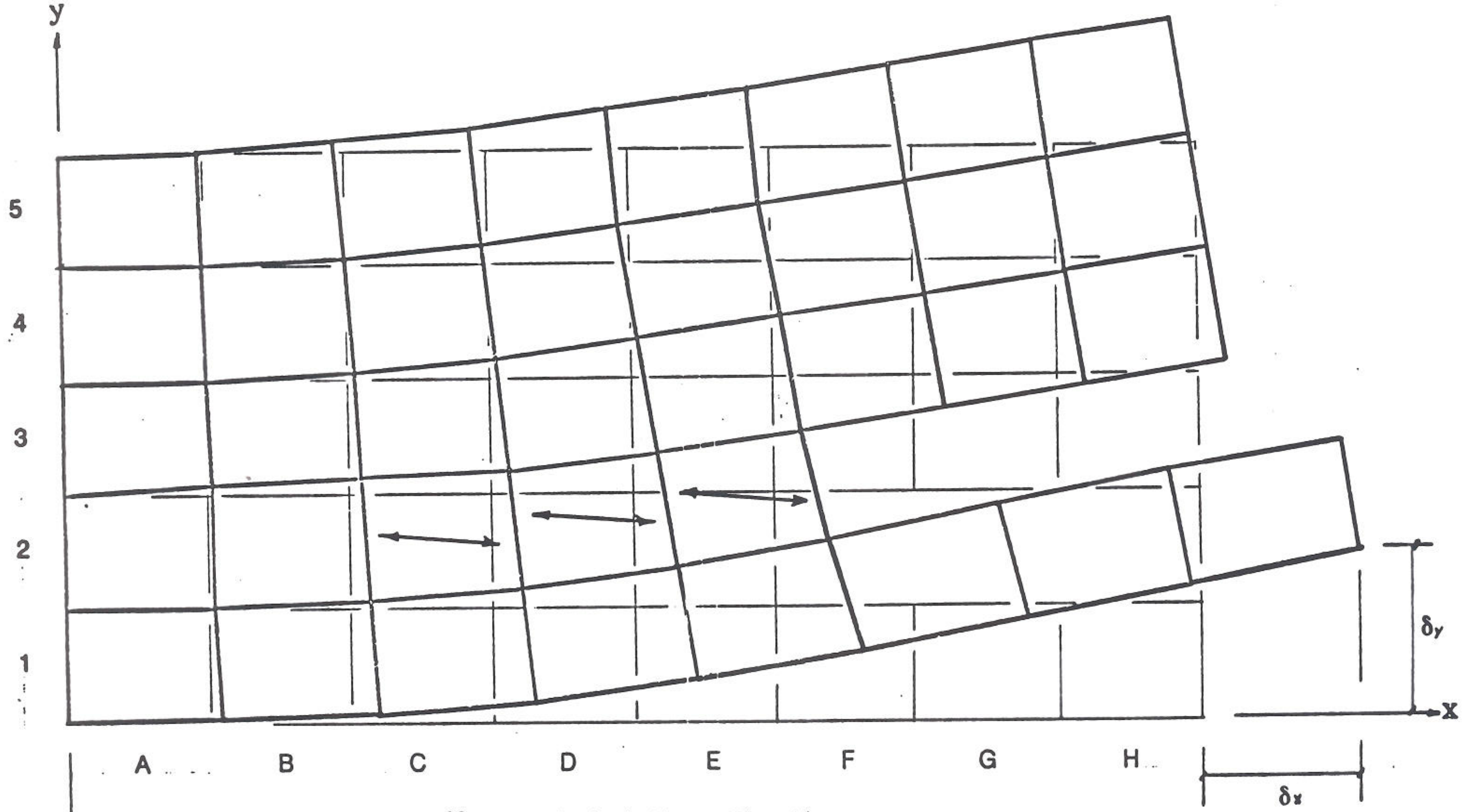


FIGURE 22-E Principal Stress Directions Computed From FEM Model Output

The results are shown in Figure 22-A-E. The graphic representation of the information received from the computer is most meaningful when the unfractured section is compared with the fractured. First, there is a general decrease in the curvature of cupping. Second, the increased elongation of the fabric support further opens the crack at B-B'. When looking at the stress distribution it is significant to recognize that while the stresses have decreased to zero at the area of the bond fracture, at the areas immediately adjacent to the crack (1E, 2E, 3E) both x-direction stress and x-y shear stress are increased. Also, worth noting is that the stresses developed here are higher than at any point on the unfractured painting section. This means of course that as bond failure proceeds inward (to the left) there is an increased tendency for further bond failure.

A variation of the same model was used to analyze a section of a paint film fractured at a point other than the edge. In this case the fracture was simulated at the central area of the section and again at the ground/fabric interface. Figure 23 illustrates this condition. The results are as shown in Figure 24-A-E.

This condition represents the greatest degree of curvature. However, the development of stress never reaches the magnitude in the two previous examples. There is no "spiked" concentration at specific areas and this condition more closely resembles that of the unfractured section.

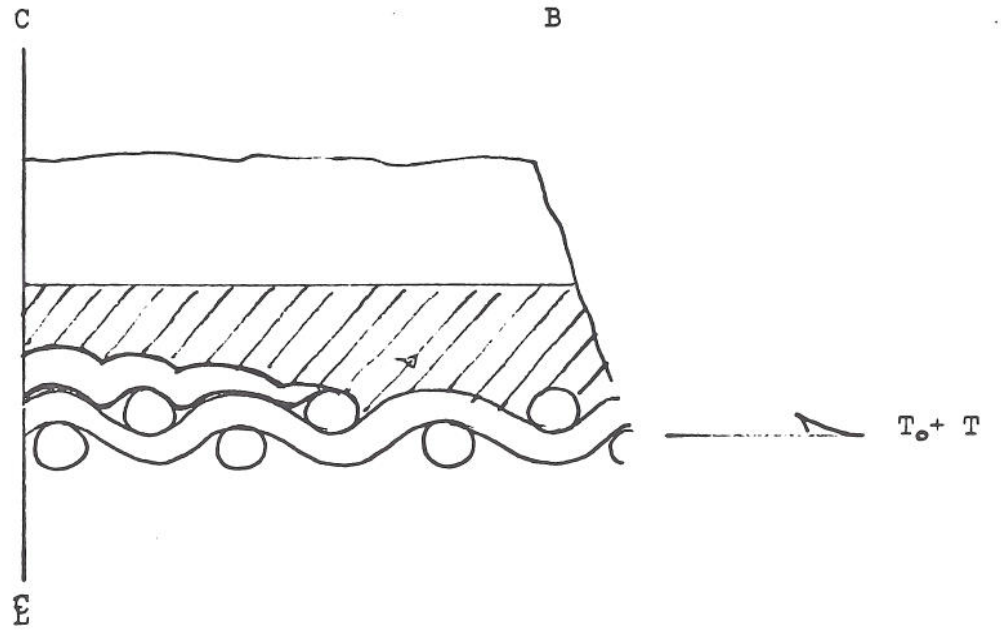


Figure 23

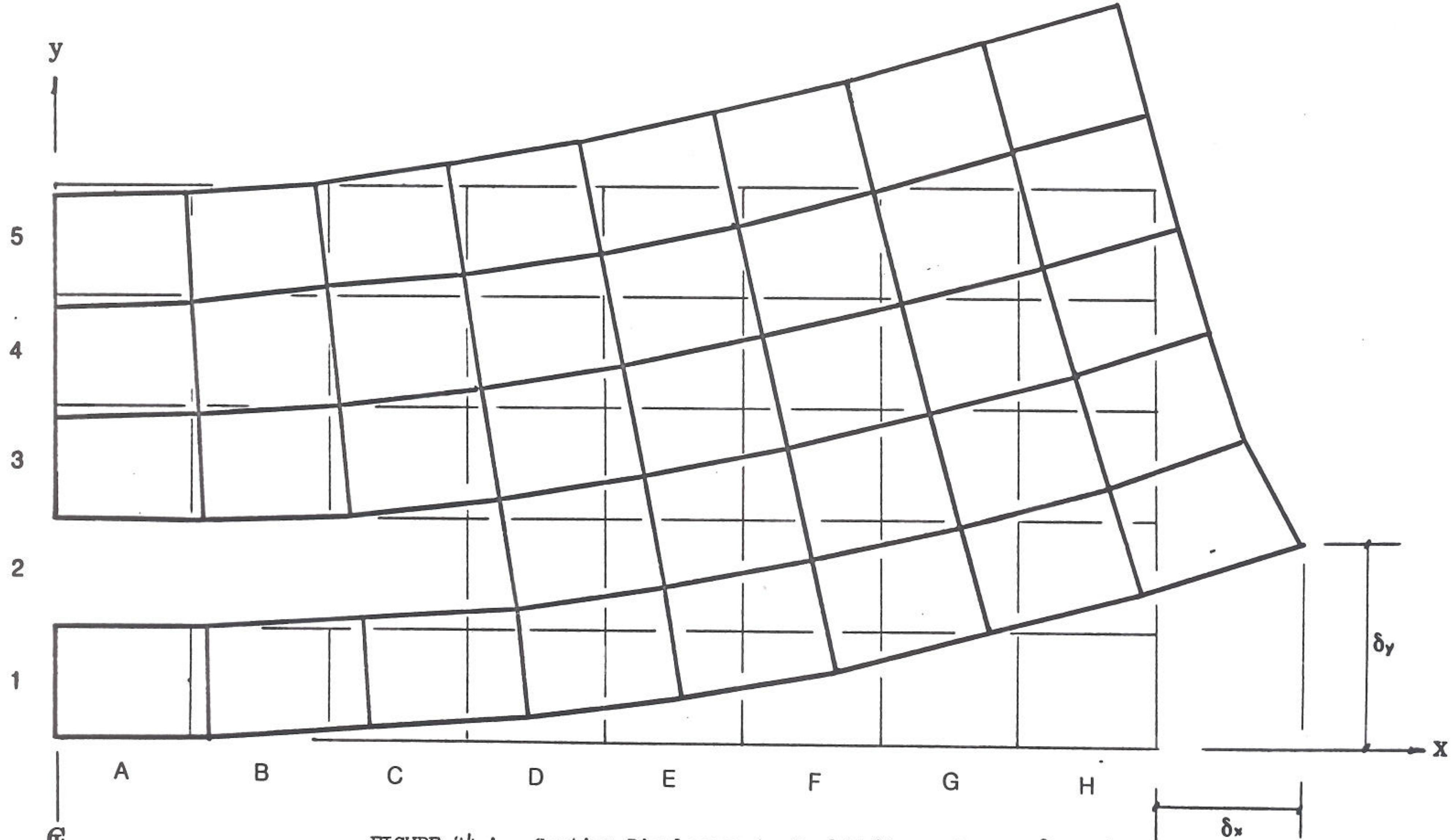


FIGURE 24-A Section Displacement, Bond Failure at Ground/Fabric Interface, Central Zone FEM Model Output

δ_x= ,04707

δ_y= .05245

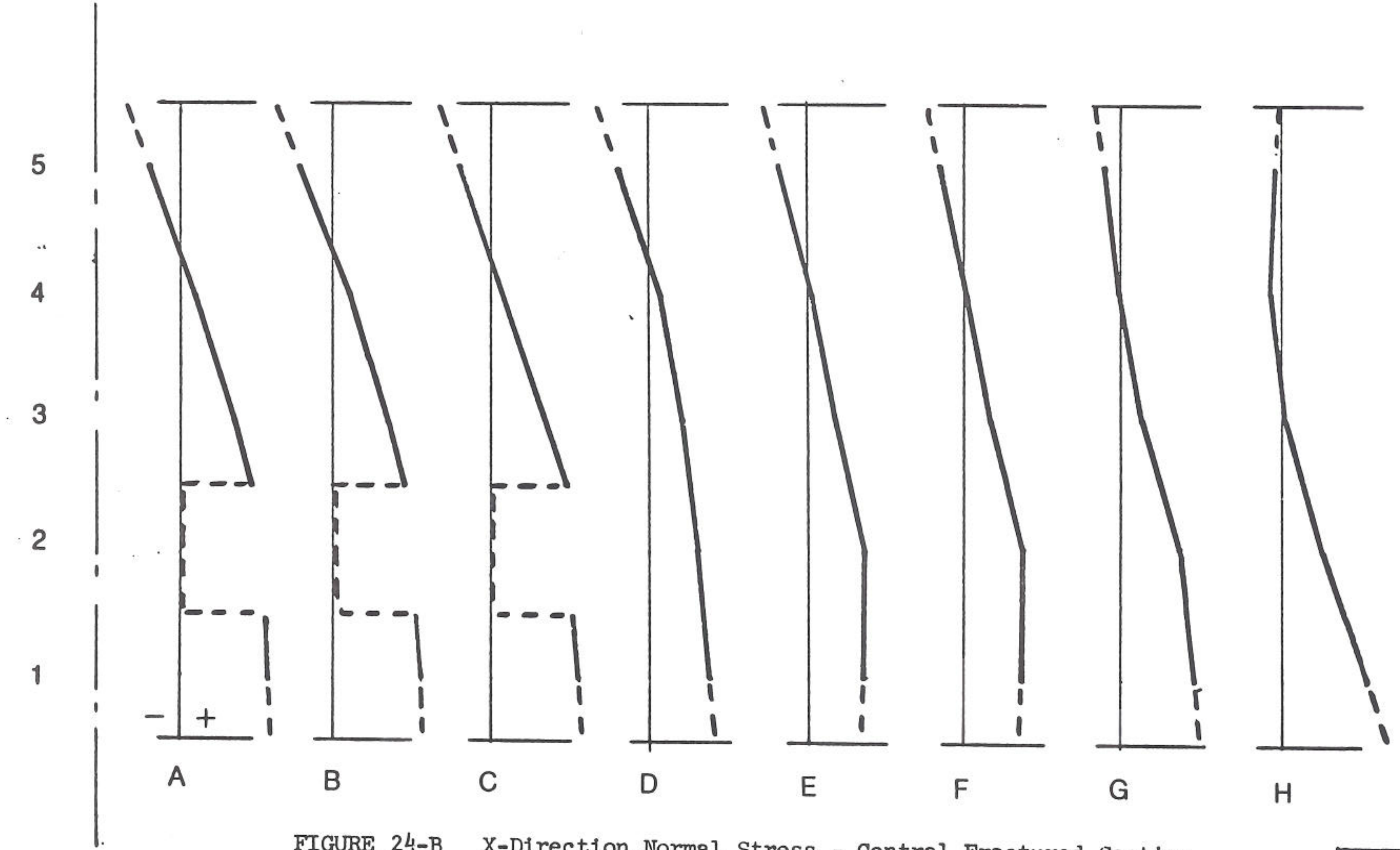


FIGURE 24-B X-Direction Normal Stress - Central Fractured Section
FEM Model Output

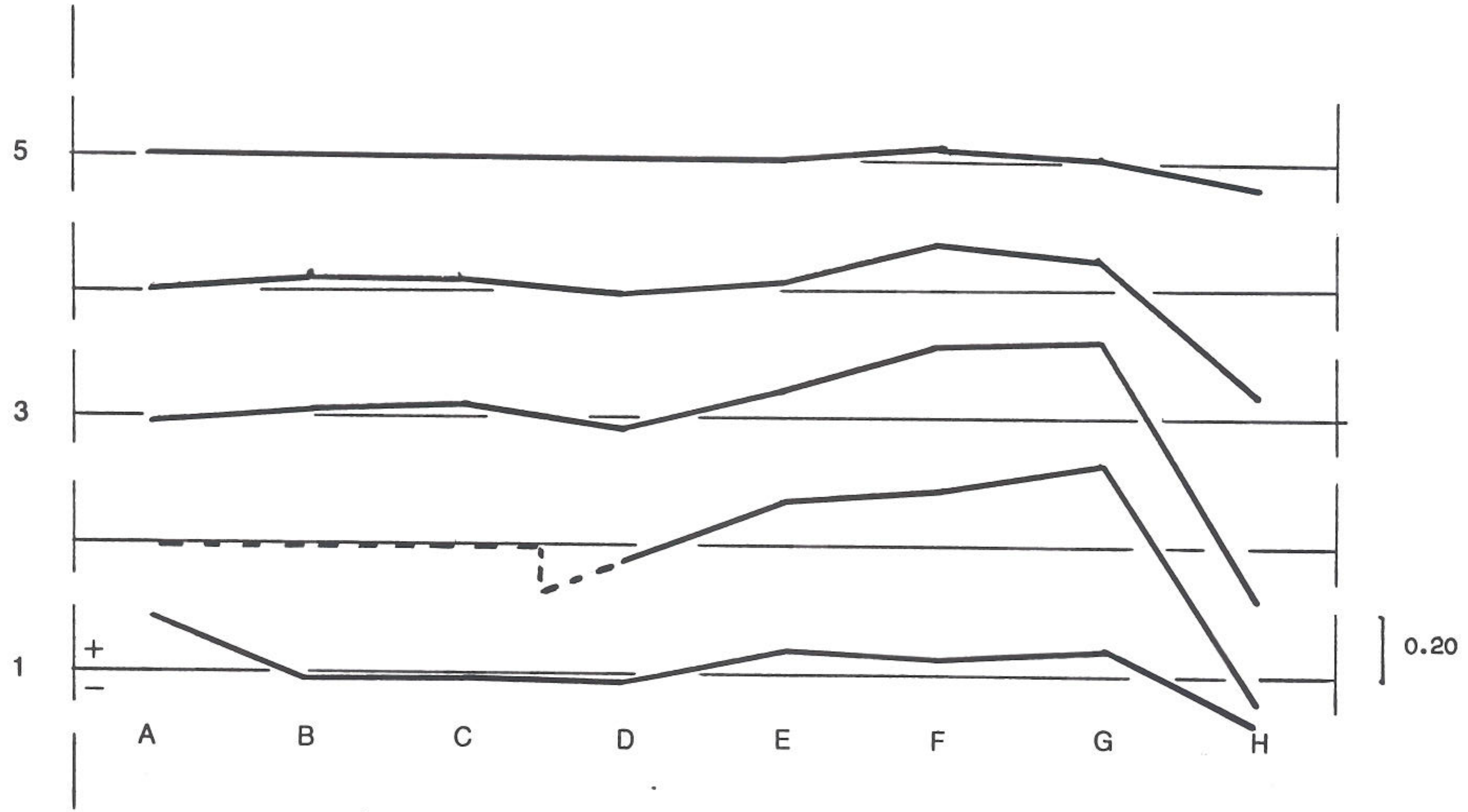


FIGURE 24-C Y-Direction Normal Stress - Central Fractured Section
FEM Model Output

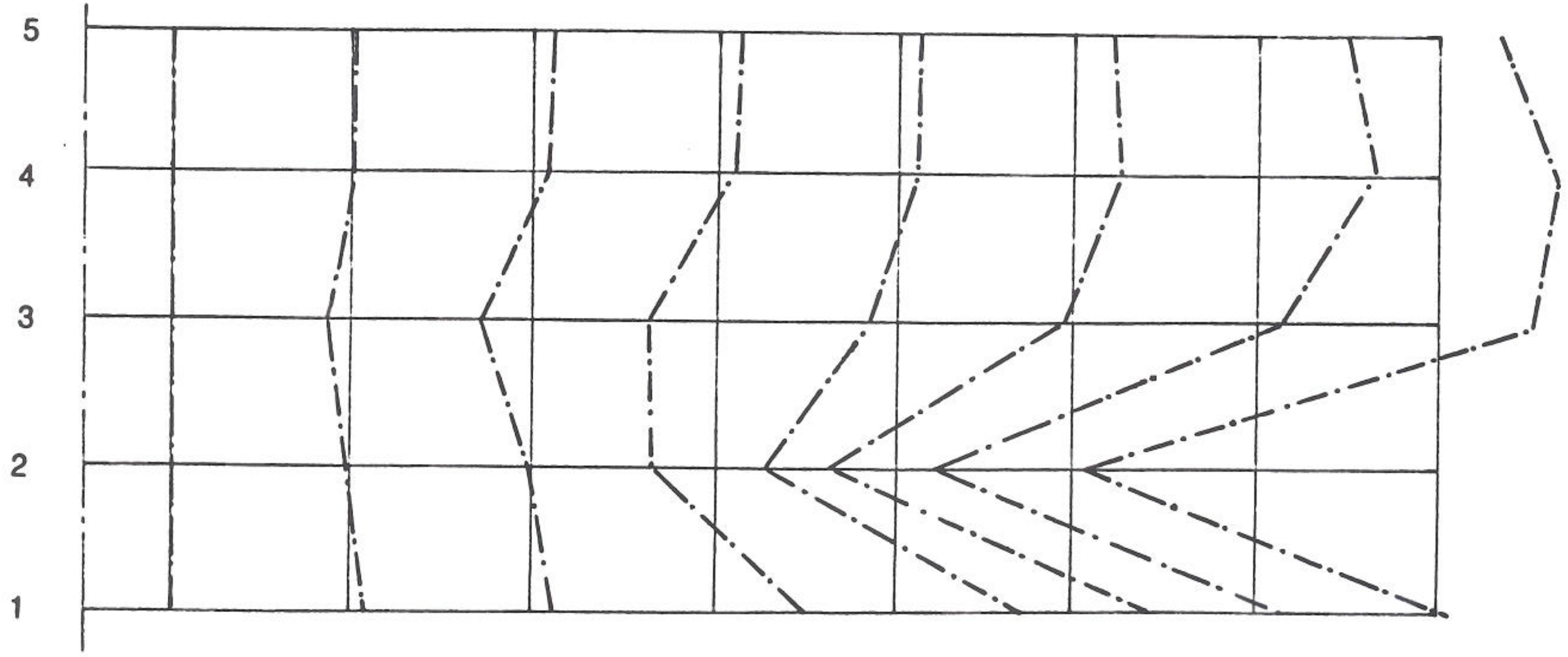


FIGURE 24-D X-Y Shear Stress - Central Fractured Sectic
FEM Model Output

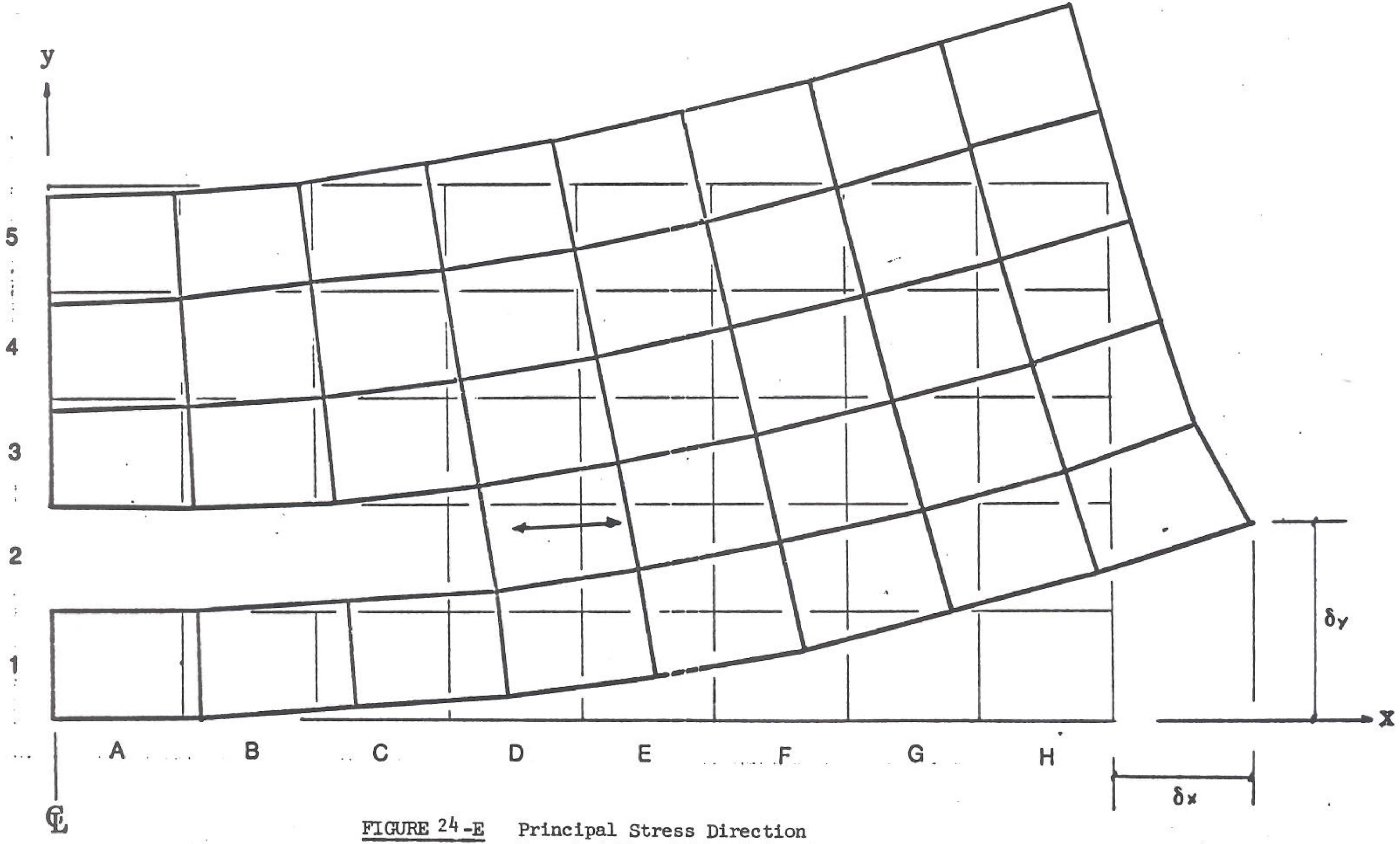


FIGURE 24-E Principal Stress Direction Computed From FEM Model Output

9. Tacking Edge Effect.

(a) Introduction.

In the previous sections the discontinuous attachment of a fabric to a stretcher was not considered. It was recognized that there is an effect, although the degree of this influence had not yet been explored. In this section a small segment of a tacking edge is examined in some detail using the finite element procedure. Figure 25 shows the location of the modeled section.

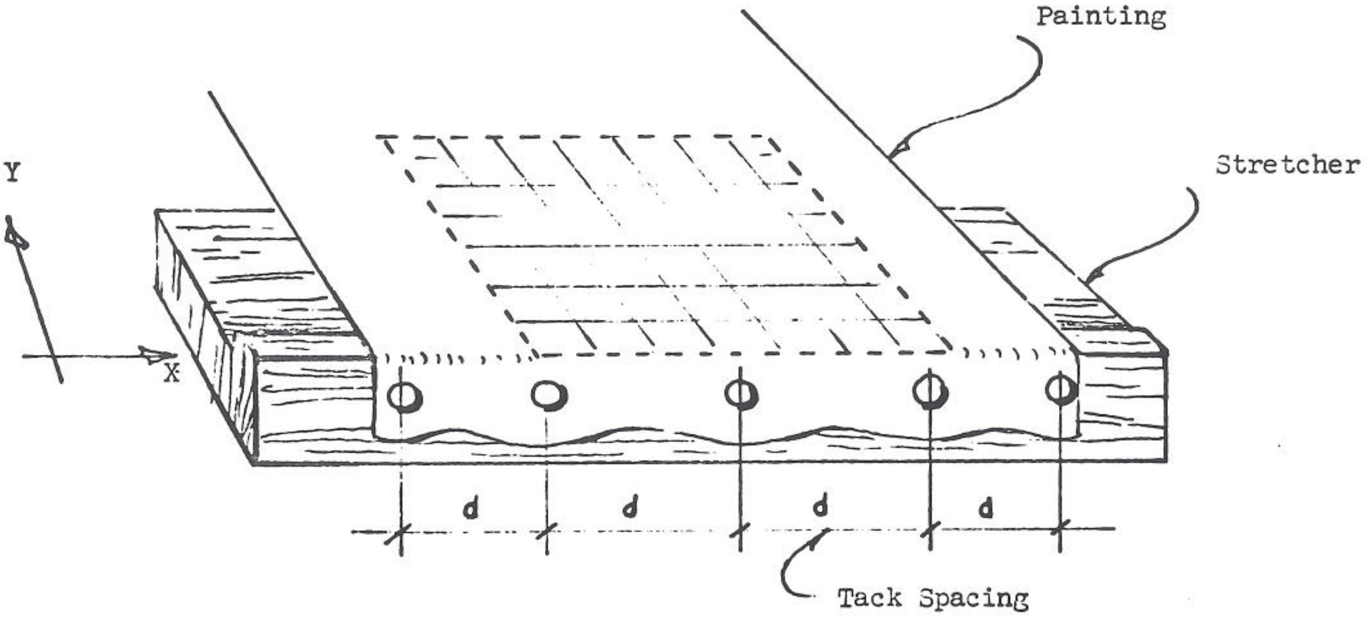


Figure 25

(b) Numerical Tests.

The painting section was modeled as if the painting were under tension due to either stretching, differential fabric motion or expansion of the stretcher.

Figures 26 graphically display the computer results, including normal and shearing stresses. The greatest deformation of the painting occurs at the tack location.

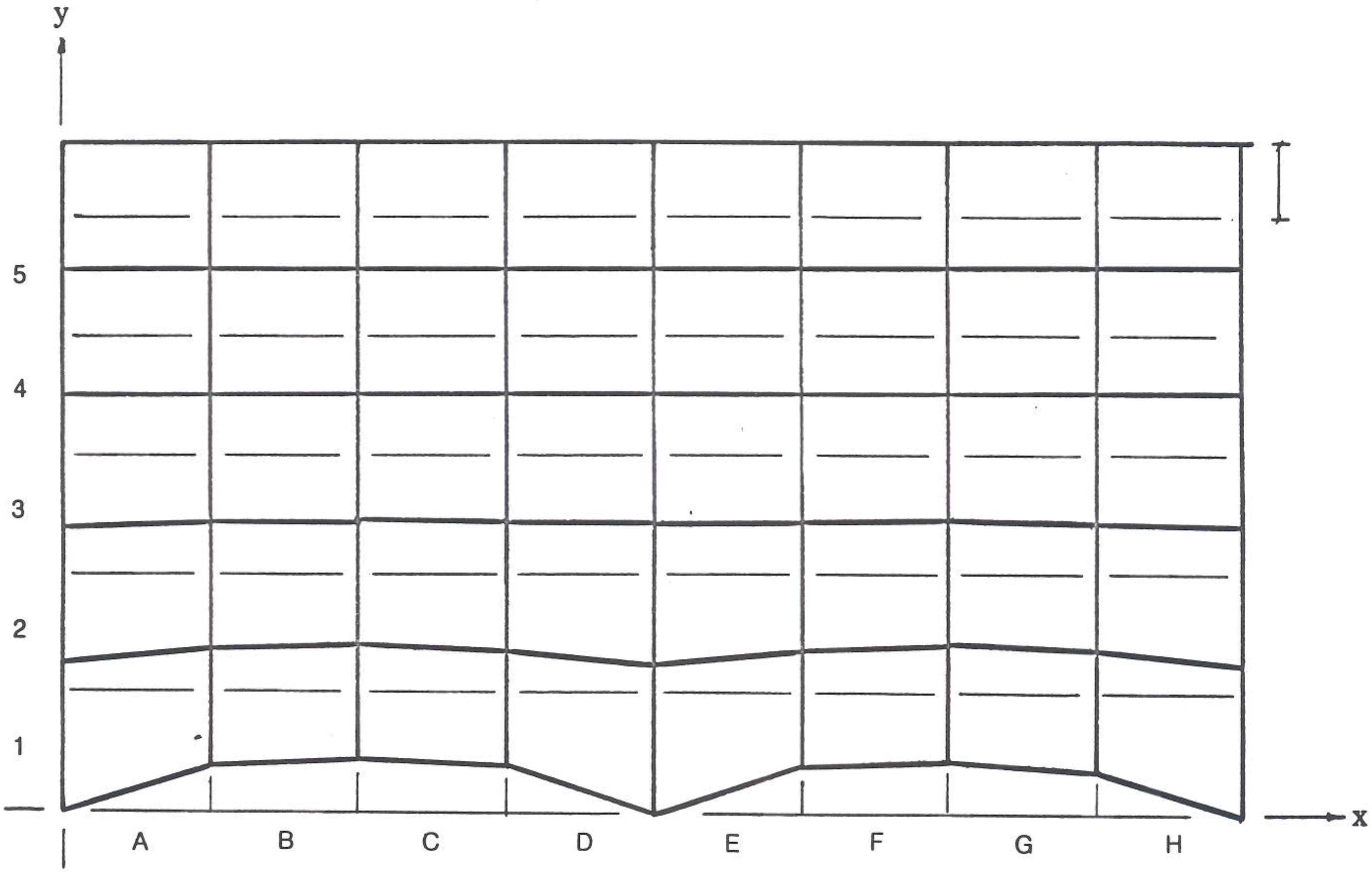


FIGURE 26 -A Painting Displacement, Tacking Edge Effect
FEM Model Output

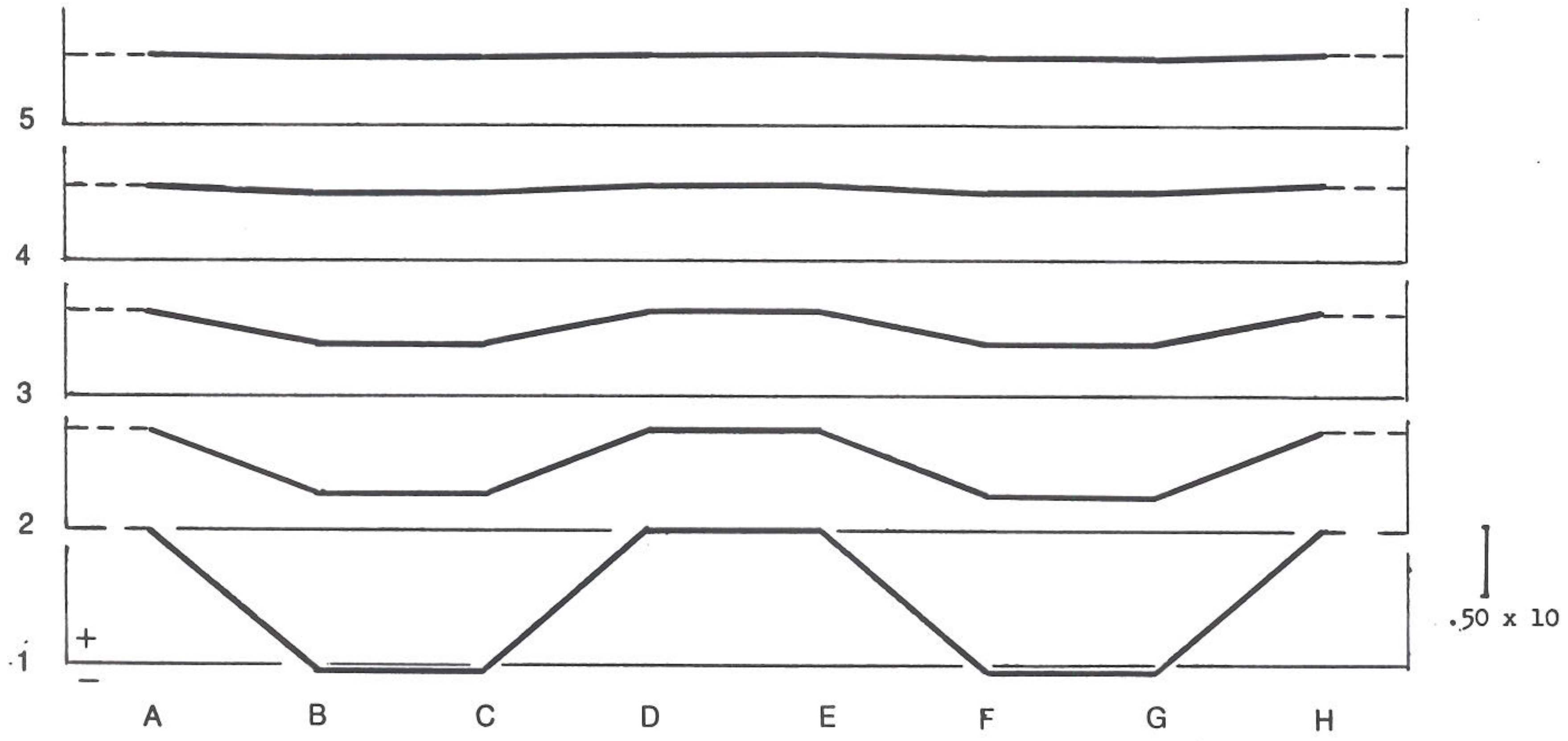


FIGURE 26 -B Y-Direction Normal Stress, Tacking Edge Effect FEM Model Output

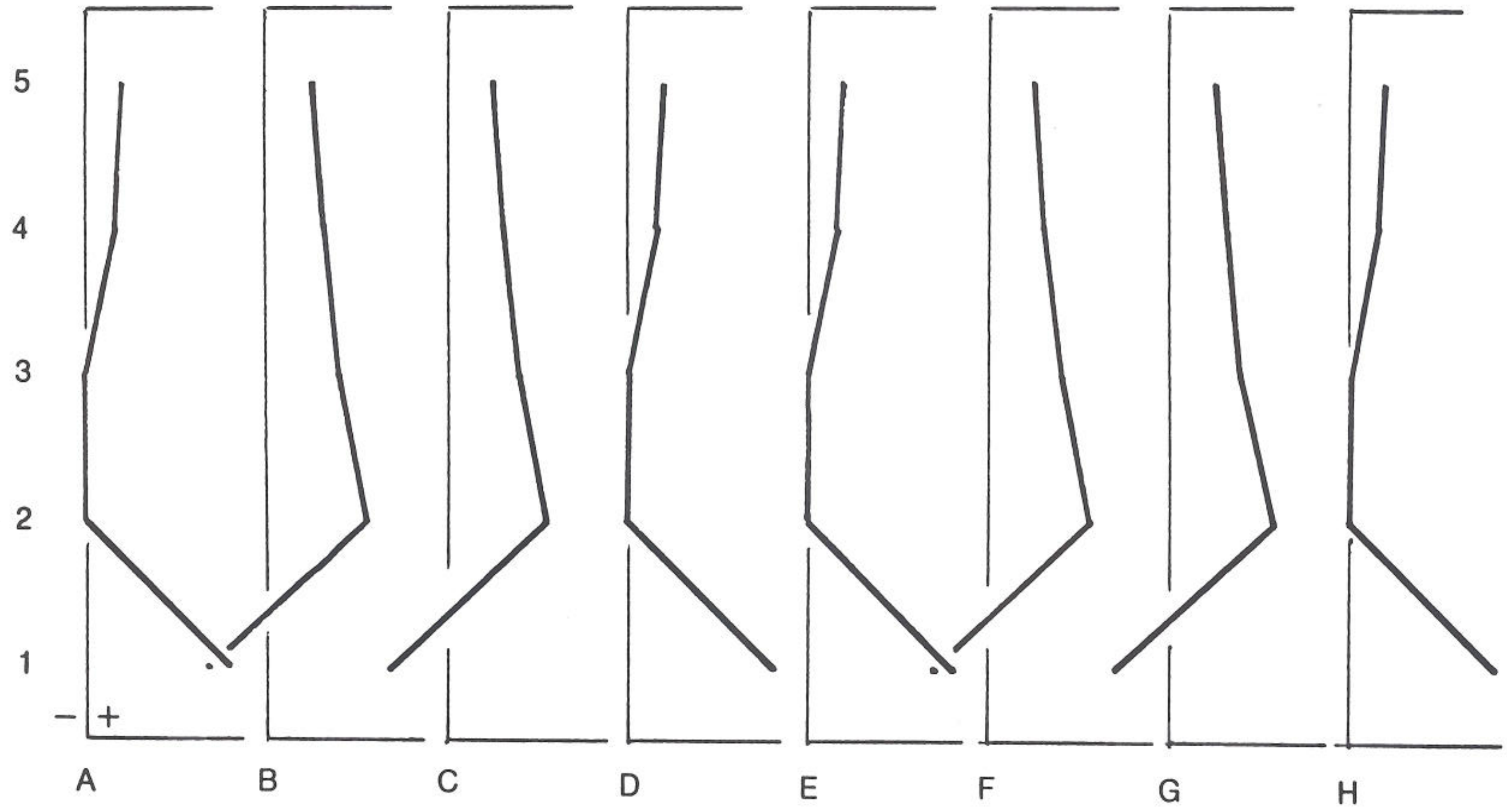


FIGURE 26-C X-Direction Normal Stress, Tacking Edge Effect
FEM Model Output

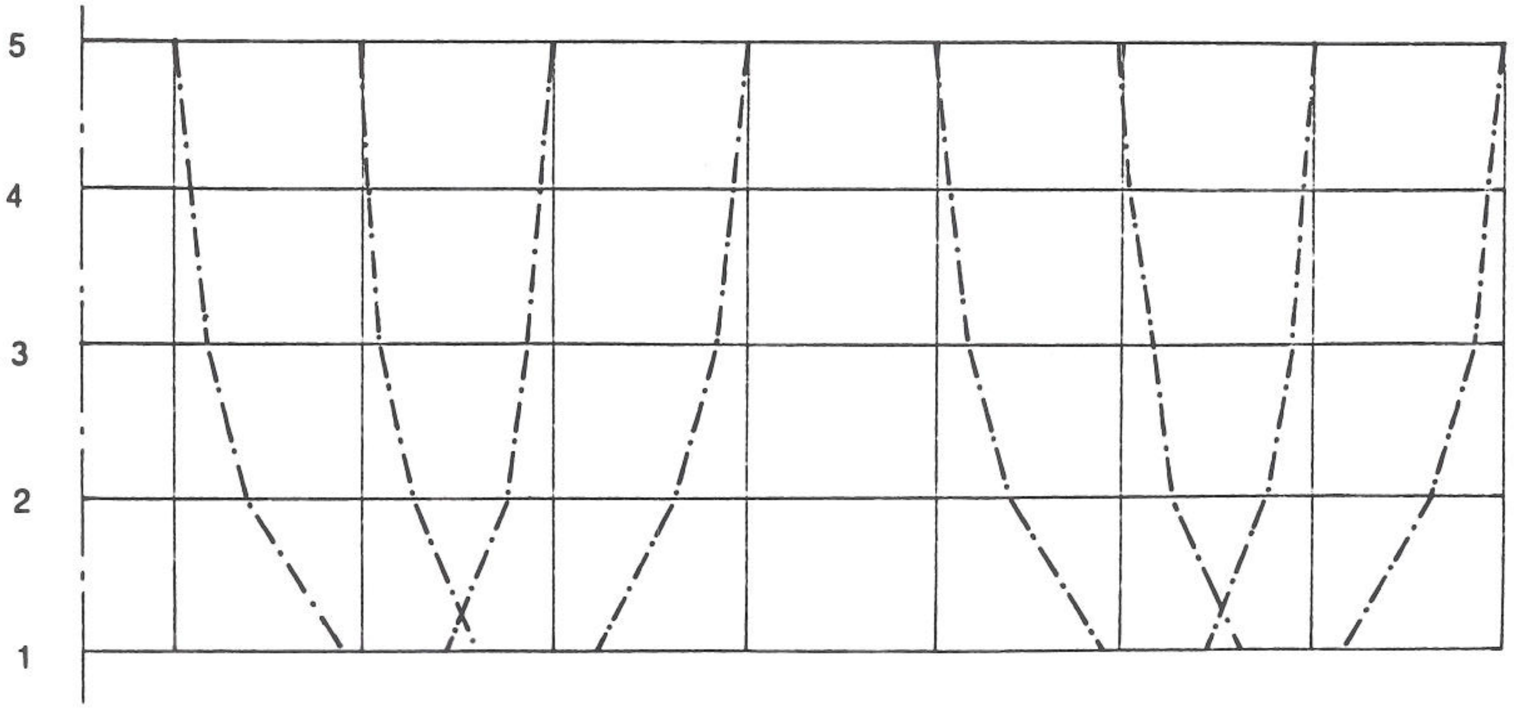


FIGURE 26-D X-Y Shear Stress, Tacking Edge Effect
FEM Model Output

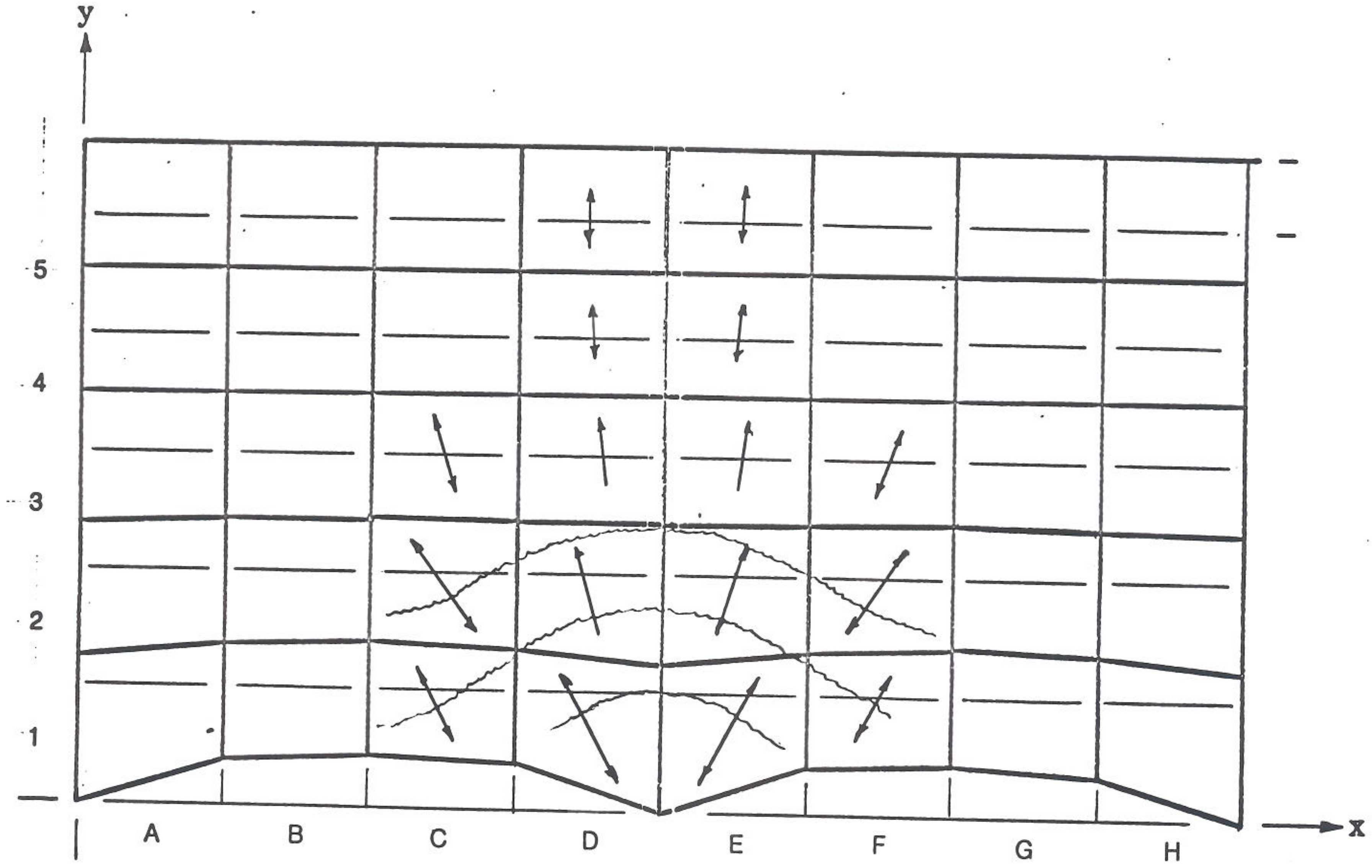


FIGURE 26-E Principal Stress Direction, Tacking Edge Effect Computed From FEM Model Output

The stress plots show a large variation between the stresses, resulting from the rapid decrease in stress as distance from the tacking edge increases. In all plots of the stress distribution, this decrease is stress concentration around the areas of the tack causes the stresses to become nearly uniform at a distance of about 1 tack space, d, from the tack location.

If the x and y normal stresses and the x-y shear stresses are combined to obtain the principal stresses, the results explain the reason for tension cracking at tack locations seen in many paintings.

Figure 26 E shows the variation in the principal stress directions adjacent to the tack location. Cracking will occur perpendicular to the principal stress directions and the general cracking pattern is also shown in Fig. 26E Photo (11) shows typical failures adjacent to tacks.

(c) Discussion of Results.

While the above numerical results demonstrate a common mechanism of mechanical deterioration of paint films, they also illustrate differing sources of damage at tack locations.

For example, Photo (12) illustrates a pattern of cracking that appears to be the result of fabric motion. However, this cracking pattern is the result of paint film contraction and not fabric motion. It is the resistance to this paint film motion provided by the restrained fabric that induces the cracking shown in Photo (12).

The cracks shown in Photos (11) and (12) are sketched in Fig. 27 A and B respectively.

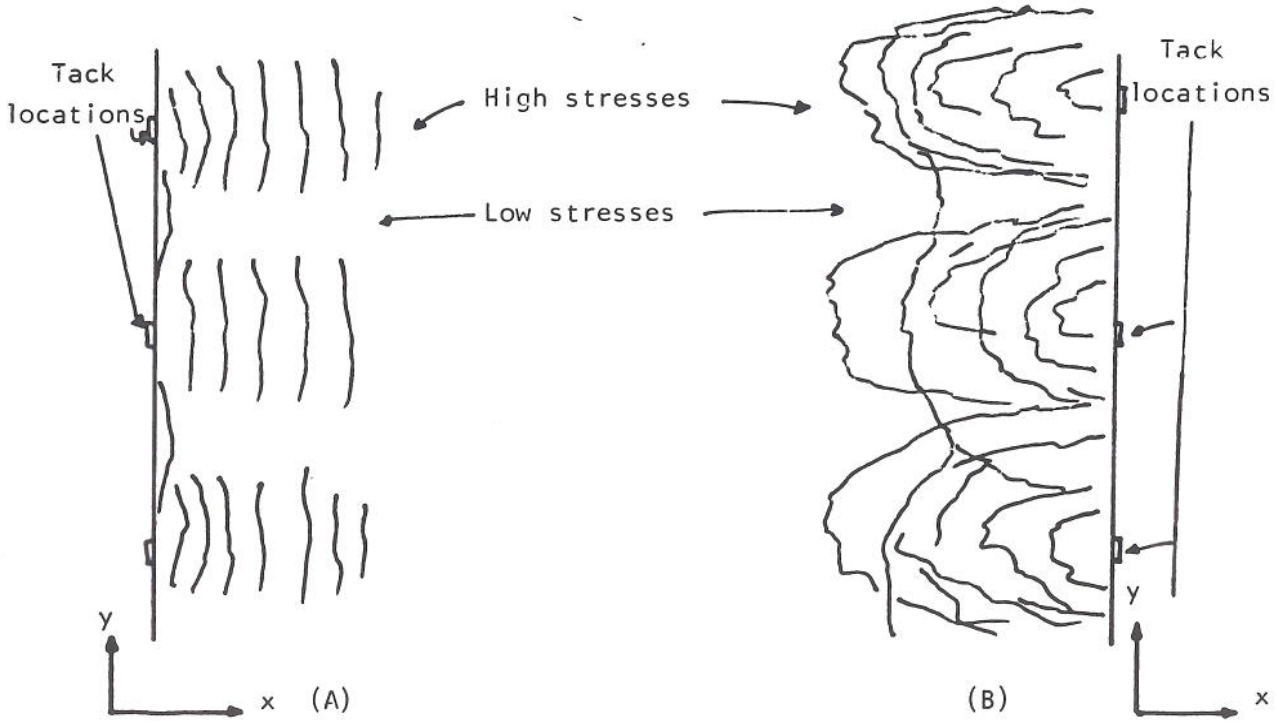


Figure 27

Photo 12 Influence of fabric on contraction cracks

In Fig. 27A the tacks restrain the fabric in the x direction and the expansion of the stretcher or contraction of the fabric induces maximum strains adjacent to the tacks. The majority of cracks form in this area of maximum fabric elongation. These cracks are all nearly perpendicular to the x direction since the fabric deformation induces like deformations into the paint film. Between the tacks there is a much lower crack concentration since the fabric has been allowed to yield with a reduction in elongation in these regions. Note also the lack of cracks perpendicular to the y direction between the tacks.

In Fig.27B,the cracks, while perpendicular to the x direction opposite to the tacks, deviate to a direction perpendicular to the y direction between the tacks. Away from the tacking edge, towards the painting center the cracking follows a random pattern. This complex pattern of cracking is a result of contraction of the paint film which is believed to have been a light induced condition.

The contraction of the paint film induced motion into the fabric allowing a random pattern where the fabric was uniformly restrained (central area of the painting) and a distinct pattern where the restraint was non-uniform (edges). Between tacks near the edge, the paint film was constrained to crack perpendicular to the y direction since the fabric was restrained and as in Fig. 27A the lack of crack formation perpendicular to the x direction was the result of the ability of the fabric to move inward with the contracting paint film reducing stress development in the direction of fabric contraction. It is also observed that there is no cupping of the paint film, and the ground is exposed and relatively intact.

Cracking of a contracting paint film is a stress release mechanism which will occur as the stress developed in the restrained paint film reaches the tensile strength capacity of the paint film. It is often observed that the contracted film is displaced relative to the ground. This relative displacement between paint film and ground is the reason for the lack of cupping. The limited in-plane stress developed in the film is not fully transferred to the fabric and out-of-plane distortions, which accompany mechanical cracking, are not developed.

If the painting shown in Photo (12) has been bonded to an inert panel prior to cracking, the crack pattern due to the paint film contraction would have been random thought the film.

10. Effects of Tears and Punctures.

(a) Introduction.

A common damage experienced by paintings on fabric is a tear or a puncture. If a uniformly stressed fabric is torn tension is suddenly lost in the broken fabric threads. It is interesting to note what happens to the unbroken threads adjacent to the tear. Figure 28 illustrates the concentration of stress in adjacent unbroken fibers. This is more pronounced when the ground and paint film contribute to the continuity of the fabric material, although it is possible that the peaks of stress concentration are not as great in inelastic paint films as in perfectly elastic materials. This stress concentration effect prompts the growth of an unrepaired tear.

The added effect of humidity oscillation also increases the tension stress in the undamaged support leading to movement of the fabric support away from the tear. This is illustrated in Photo (13).

(b) Numerical Tests.

A finite element analysis was performed to simulate the effect of a hole in the fabric support. The hole was placed near the center of the "painting" and the displacements produced by keying-out are shown in Fig. 29A. The results indicate that stress concentrations are developed in those elements adjacent to the imperfection. (Fig. 29B)

In Photo ~~8~~, 14 the concentration of cracks around the hole indicates the increase of tensile stress about the hole. Significant is the alignment of diagonal cracks in the area of the hole that suggest a uniaxial stress field. In reality there is stress in all directions with the highest principal stress directed radially from the corner.

In the areas of lower stress adjacent to the tear the increased openeing of the hole results from the free contraction of the unrestrained fabric. At this area the free contraction of the support causes compression of the paint film, and reverse curvature occurs. That is, at the edges of the tear the painting tends to deflect toward the reverse of the painting.

(c) Discussion of Results.

In Section 8 it was shown that cupping results from the stress induced displacement of the fabric support. At a paint film crack location the in-plane forces is carried entirely in the fabric while between cracks the forces are distributed between the fabric, ground and oil film. If at a tear or puncture in a painting, a fabric patch is attached to the back side of the damaged fabric as shown in Fig. 30 an analogous situation exists in the repaired structure.

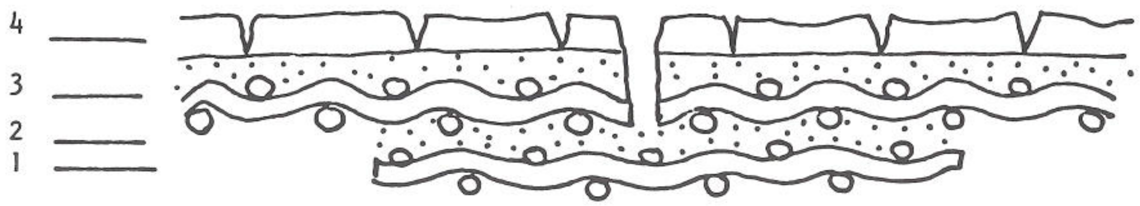


Figure 30

Photo 14 Cracks responding to stress concentration

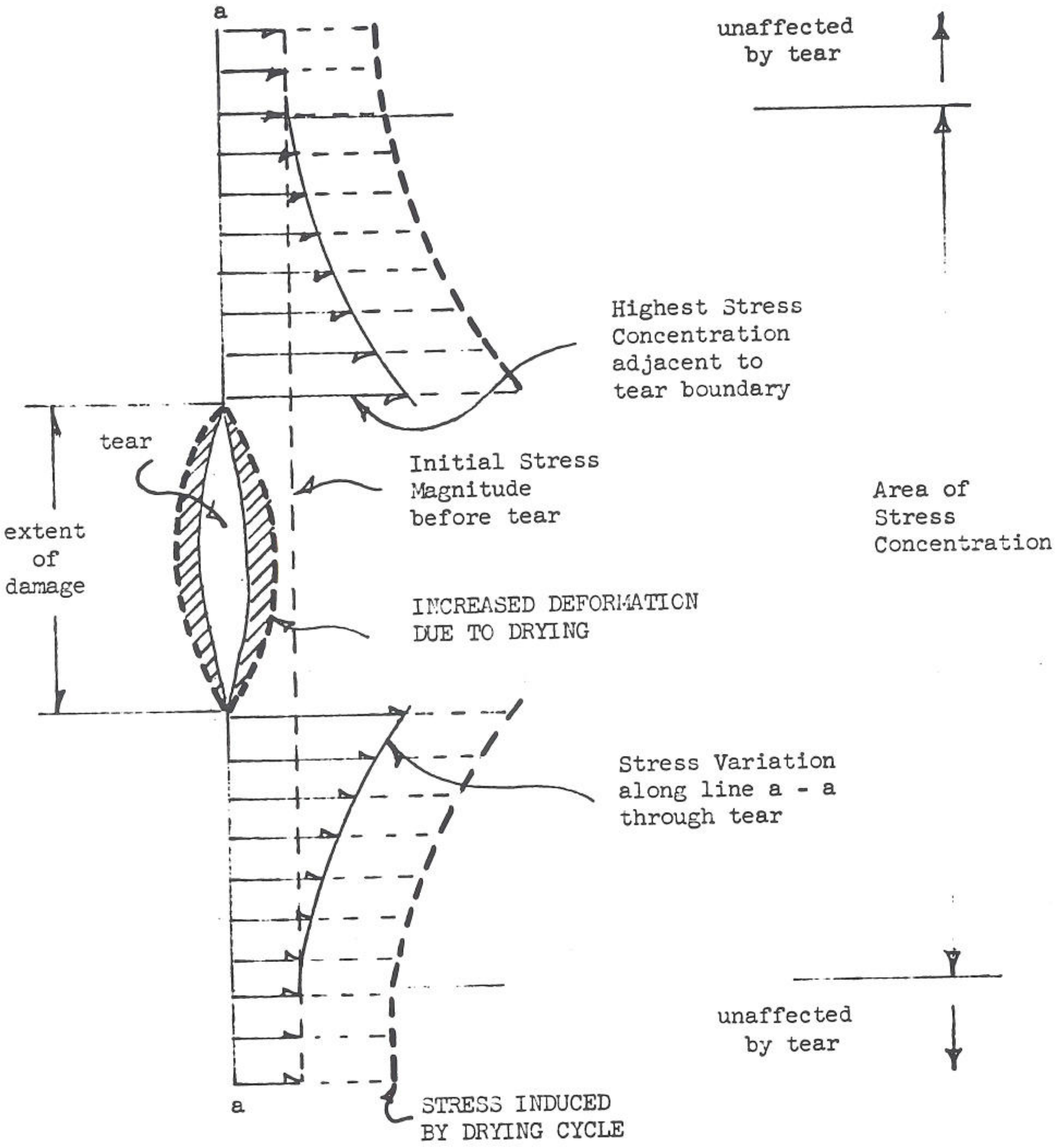

a
unaffected
by tear
Highest Stress
Concentration
adjacent to
tear boundary
tear
extent
of
damage
Initial Stress
Magnitude
before tear
Area of
Stress
Concentration
INCREASED DEFORMATION
DUE TO DRYING
Stress Variation
along line a - a
through tear
unaffected
by tear
a
STRESS INDUCED
BY DRYING CYCLE

Figure 28

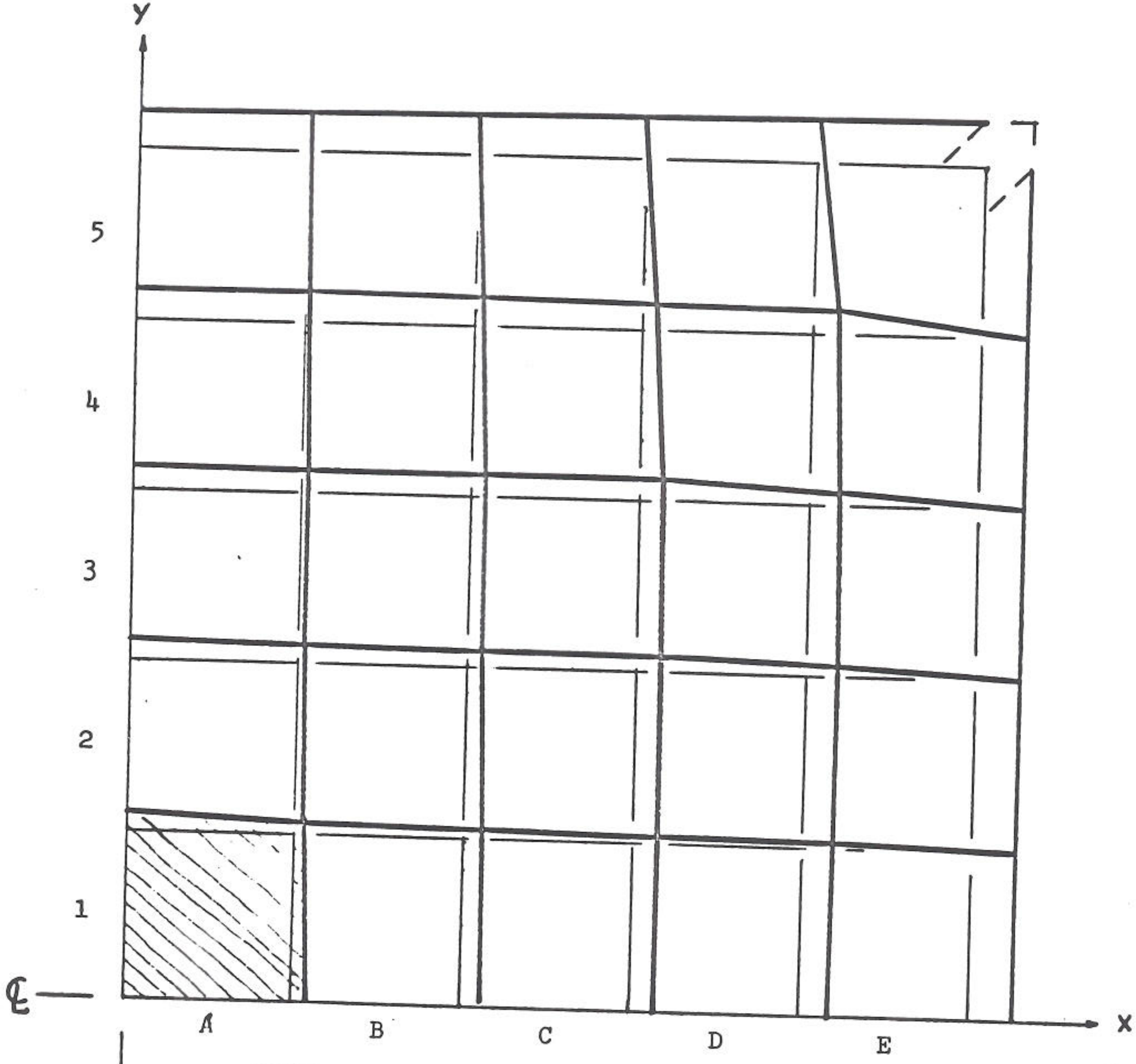


FIGURE 29-A Painting Displacement, With Hole @ Center FEM Model

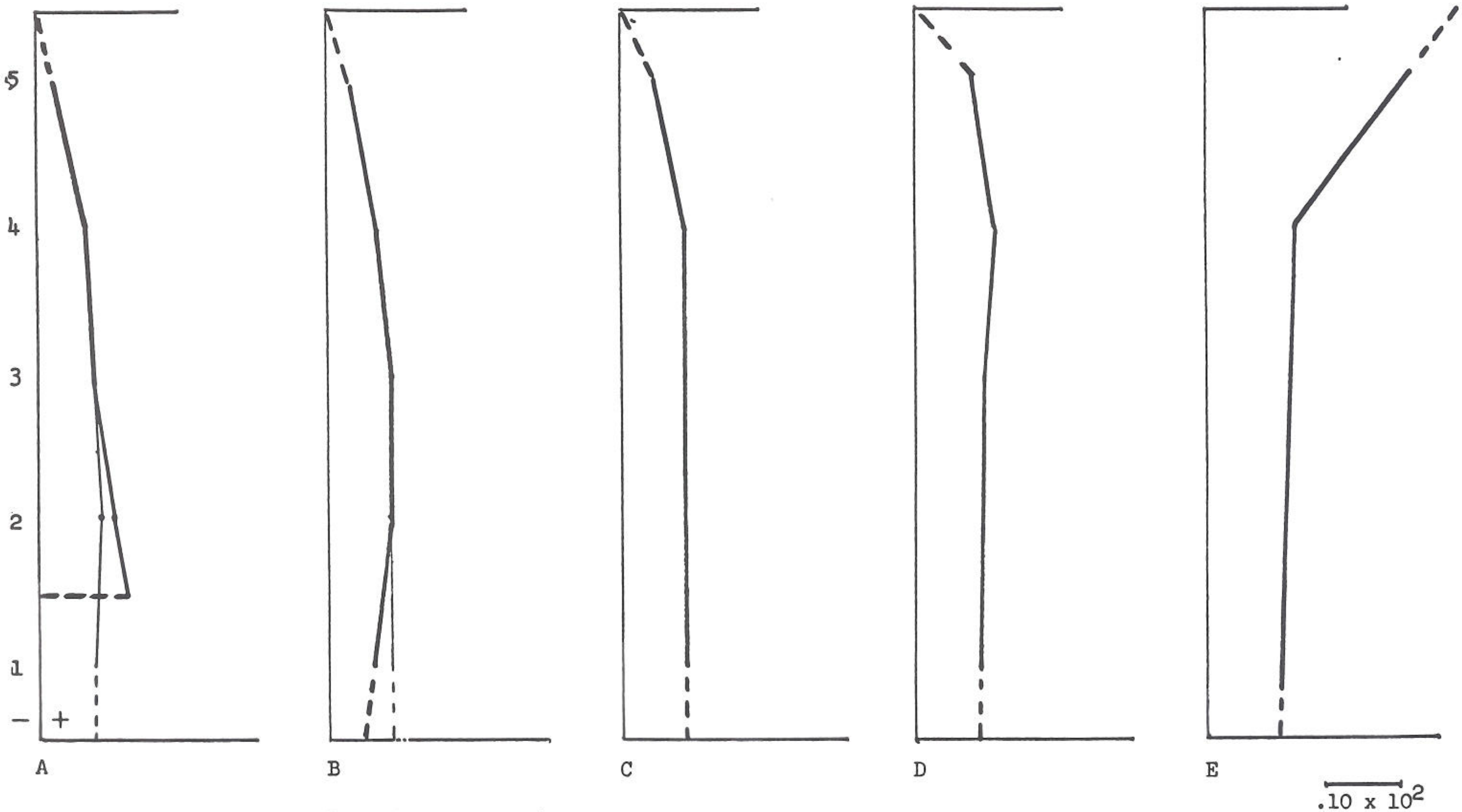


FIGURE 29-B X-Direction Normal Stresses, With Hole @ Center FEM Model

Undamaged Section Stress ———

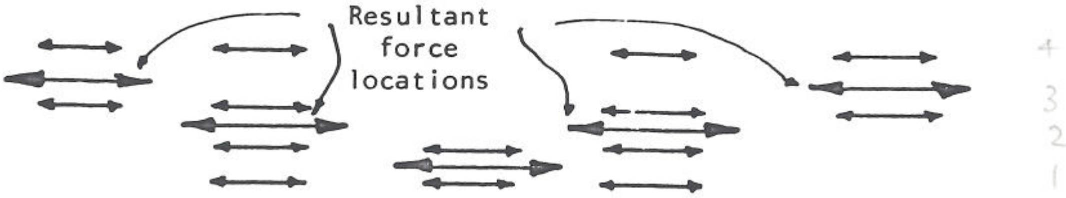


Figure 31

Assume that the numbered horizontal lines shown in Fig. 30 represent the following:

(1) line 1 - a line through the center of the patch fabric

(2) line 2 - a line through the adhesive used to attach the patch

(3) line 3 - a line through the center of the original fabric support

(4) line 4 - a line through the center of the paint film

Although the exact location of the resultant in-plane force cannot be exactly determined along the length of the composite system shown in Fig.30 , it is reasonable to assume relative locations as shown in Fig.31 . Thus, for example, at the puncture location the in-plane force must be transmitted entirely through the patch fabric, whereas at section A' this force is distributed between both the original support fabric and uncracked paint film. It is believed that most of the force at this location will be in the support fabric since the cracked film has been stress relieved and cannot be highly stressed.

The important point with respect to the force locations shown in Fig. 31 is that these forces are misaligned. As a result the system will deform over a relatively short period of time in an attempt to produce alignment of these forces. The resistance to deformation will be a function of both the in-plane and flexural stiffnesses of the materials involved. This tendency to deform will result in the lifting of the assembly in the vicinity of the patch observed in practice and illustrated in Fig. 32.

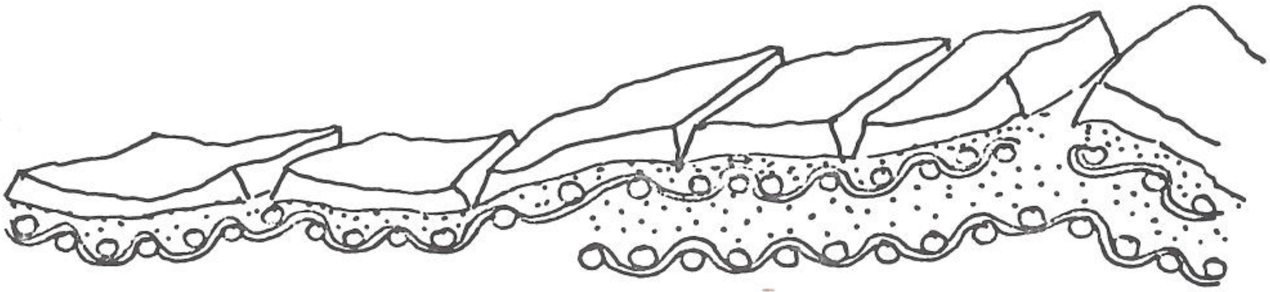


Figure 32

In this manner, patches impress themselves on the surface of paintings and edges of tears and punctures lift out of plane towards the viewer of the painting. Re-lining the entire painting prevents the effect of patch impression but does not inhibit the out-of-plane lifting adjacent to tears.

The addition of fabric strips to the reverse of a painting at tackover edges, known as strip lining, is a method currently used to reinforce fractured tackover edges. In those cases where the fabric is so badly damaged that the edges need reinforcement, the strip lining practically guarantees future damage of paint films where the film has a high stiffness and low strength in contrast to the low stiffness of the fabric. Thus this technique can be expected to induce further cupping, cracking and flaking.

11. Adhesives.

Most of the above discussion of the defects, distortion and failure of fabric supported paint films has concentrated on the mechanisms of in-plane stresses and strains and the sources of these effects. While the degree of distortion and magnitudes of stresses developed can only be accurately established by the refinement of the mathematical model including a better understanding of the properties of the materials, certain clear concepts are developing.

For example, if in-plane movement can be reduced by conservation treatments, then distortions can be minimized. If distortions of the principal materials can be cut down then the use of strong, stiff adhesives becomes less meaningful. The restriction of fabric support movement can be a multi-faceted operation. Thus, the requirements for an adhesive used for consolidation of a fragile support fabric that is to be reinforced with a stable substate support must be identified.

Although this and other questions may be posed with respect to the adhesives used in conservation, and at present definitive answers to these questions are not available the following points seem in order:

(1) Adhesives should not become a major source of structural rigidity in painting constructions. Alternate supporting systems are available for that function which have significant in-plane and bending stiffnesses and are not susceptible to movement due to environmental effects.

(2) If in-plane motion of the supporting medium is reduced, the stiffness requirements of adhesives will certainly be reduced. In fact, overly stiff adhesives used to adhere paint films to a relatively inert support may increase damage in the paint film due to movements initiating in the paint film itself. In this case the film can only be relieved by cracking of the paint. General consideration should therefore be given to both the cohesive and adhesive nature of the materials selecting for bonding purposes.

12. Further Aspects of the Behavior of Materials Used in Conservation.

Long term effects of the alteration of the chemical and physical properties of paint films and grounds in a matter worth considerable investigation since an understanding of these effects holds the key to the establishment of meaningful conservation guidlines. At present, treatment of paintings is based on the concepts of material "compatability," "traditional techniques" and that elusive "intuitive feel for the materials."

In view of the information uncovered in the literature search and the development of an improved understanding of the structural properties and behavior of the materials involved, a review of recent articles by practicing conservators reveals the confusion generated by a misunderstanding of the basic principles and mechanisms involved. A few of these are discussed briefly in the following.

(1) Great controversy among conservators has arisen recently over the use of wax adhesive as a lining adhesive. In 1975, Gustav A. Berger and Harold I. Zeliger presented a paper titled, "The Detrimental and Irreversible Effects of Wax Impregnates on Easel Paintings" to the ICOM meeting in Venice, and an earlier version of this presentation was published in the IICAG bulletin, vol. 12, No. 2, 1972. In these articles the authors attempt to show that wax adhesives;

(a) cause swelling and compression of paint films thereby destroying them.

(b) are not strong enough and in time affect detrimentally the strength of any adhesive used in the future consolidation of a painting.

(c) cannot be removed from fabric supports.

(d) increase the solvency of a paint film, thereby enhancing the possibility of solvent drainage during future cleaning.

Their tests were performed with numerous wax mixtures some of which contained beeswax and some of which were in effect pure microsrystalline wax. The above conclusions presented by Berger and Zeliger (BZ) are based on the following reasoning:

(1) Photographs showed that areas of the paint film impregnated with beeswax showed a marked increase in cleavage due to paint film compression. The microcrystalline wax impregnated areas showed considerably less cleavage. Since the authors accepted Dr. Urban's (Institue Centrale del Restavre Roma) observation that beeswax' impregnation does not cause canvas to shrink, it was concluded that the wax impregnation caused lateral swelling of the paint islands. However, it is important to note that BZ were unable to reproduce this effect on isolated paint films (i.e., with no substata).

(2) It was also concluded that the wax cannot be removed completely,

since after dissolving as much wax as possible from the fabric support, the specimen were dissolved in nitric acid, extracted, and shown to floresce under ultra-violet light.

However, the authors' interpretation of the observed test results should be evaluated in light of the following information uncovered in the literature search.

(1) Paint films become quite plastic when subjected to heat. In fact, the stress required to deform a paint film drops from 110 kg/cm^2 to 54 kg/cm^2 if the temperature is raised from 0°C to 40°C (104°F).

(2) Humidity affects paint film dramatically since at a given temperature a relative humidity (RH) change of 20% to 100% can reduce the stress required to deform a paint film 30% from 85 kg/cm^2 to 45 kg/cm^2.

(3) Relatively low stress levels can lead to considerable paint film deformation over long periods of time.

(4) Fabric subjected to high humidity will shrink. For example tests conducted at Washington Conservation Studios show that new linen can deform as much as 8% at 100% RH, 75°F while F. Dupont Cornelius shows an 8% warp direction shrinkage in changes from 20% RH to 95% RH at 21°C (70°F).

Specimen tested by Berger and Zeliger were placed in an environment of 54°C (129°F) and 45% RH. Assuming an initial condition of 21°C (70°F) and 45°RH, the specimen were subjected to a 33°C (60°F) temperature increase with a resulting massive softening of the paint film. Also while relative humidity is defined as the ratio of vapor pressure of water at a given temperature to the saturated vapor pressure at the same temperature, it is actually a misleading indicator of the actual amount of moisture present. The amount of water present at 54°C (129°F), 45% RH is (at standard pressure) about 5 times the moisture present at 21°C (70°F), 45% RH. This significant amount of additional moisture will tend to soften the paint film even more than the temperature increase and will also cause considerable fabric shrinkage. Also in this case the effectiveness of the wax as a moisture barrier is greatly reduced since 54°C (129°F) is only about 25°F below the wax melting point. Furthermore if swelling of the paint film did occur as concluded by Berger and Zeliger the visible failure mechanism would not have been cleavage but a convex cupping of the paint islands.

With respect to the problem of wax removal from linen it is sufficient to note that biologists in examining a slide specimen under a microscope, first embed the specimen in paraffin, slice it and then remove the wax prior to staining. If the wax remains the stains will not take. With respect to violet light fluorescence it may be stated that since glue size, and lignens which constitute the cell structure of a fabric all fluoresce in a manner similar to wax.

Finally it is ironic that Berger and Zeliger actually suggest that microcrystalline wax is in fact a good moisture barrier which would inhibit fabric motion due to moisture effects.

The main thrust of the above discussion is that the Berger and Zeliger article contributed greatly to the ICOM Resolution of 1975 to abandon the lining of paintings and to strip line them if necessary. Preliminary computer studies indicate that strip lining is one of the worst possible treatments for paintings on fabric. See Section 10, Part II.

(2) In the book, "On Picture Varnishes and Their Solvents," Feller, R.L., Stolow, N., Jones, E. H., Case Western Reserve University Press, Cleveland, 1971, Nathan Stolow discusses the loss of soluble matter in oil film as a result of solvent action. He concluded, as a result of tests, that solvents used in cleaning paintings caused the paint film to first, swell and then upon drying to contract to a volume less than that existing prior to solvent application. Other studies indicated that oil films are similarly affected by water. The resulting conclusion is that the oil medium has been affected to the extent that its molecular structures have been damaged.

However in the IIC-AC Technical Papers 1968-1970, (1970), pp. 121-143, Margaret M. Watherston reports on the treatment of cupped paintings on a vacuum hot table. The recommended procedure is to apply solvents, a mixture of water, cellulose acetate, dimethyl formamide, and pyecdine to the painting, then heat (160°F) for six hours under a vacuum pressure of 5" - 7" Hg. Under these conditions, the co-investigators of this research report agree that the cupped painting will surely be flattened. However, the structure of an oil film remaining after such a treatment is highly questionable.

(3) In the 1975 ICOM meeting in Venice a paper titled, "Some Empirical Determinations of the Strain Distribution in Stretched Canvases," was presented by G. A. Hedley. Mr. Hedley states, "There is often a tendency to ascribe the forms of 'mechanical cracking' in canvas paintings solely to the different climatic conditions between areas backed by the stretcher and those open to the environment. But this phenomenon cannot account for the types of 'mechanical' cracking as the cracks at the corners of paintings which run 45° to the axis of the painting ---."

This statement by Mr. Hedley is in contradiction to the findings of the current research work.

Mr. Hedley also states that a stretched fabric (under tension) produces distortion due to uneven tension. He concludes, "Stretching a canvas does not imply that the whole canvas is extended, many directions of the canvas will in fact suffer compression as a result of the stretching process."

This statement is misleading and essentially incorrect as stated, since a source of compression in fabric supported paint films has been shown in this report to be due to non-uniform variations in fabric tension.

(4) The controversy over the use of adhesives is extensive. A review of the lining, patching and consolidation techniques and the adhesives used throughout the world, (see AATA Vol. 14, No. 1, Summer 1977 Supplement: The Lining of Paintings) indicates that few conservators agree on the choice of adhesives.

(5) Although the source of much of the deterioration of canvas paintings is related to environmental conditions, many museums and institutions do not have major air conditioning facilities. Also a large number of private collections are not maintained in controlled environments. In spite of these facts, it is the general consensus in the field of conservation that paintings will be displayed in controlled environments.

13. Summary

In the previous sections of this part of the report the effects of fabric deformation and stretcher movement on the supported paint film have been discussed.

Although the present state of knowledge concerning both the sources and magnitudes of these movements and the resulting influences on paint films is incomplete, the results of work to date indicate that damage of paintings due to these effects can be controlled. Final opinions and judgements concerning rational conservation techniques must be deferred until more accurate modeling of the composite structure can be completed. This in turn is dependent on the acquisition of more definitive data on the structural properties of the constituent materials under variable conditions including age of paint film, rate of loading and humidity and temperature fluctuations.

Damage of paint films due to effects originating within the paint film itself, such as aging cracks and temperature and humidity effects will conceivably be less easily controlled and prevented.

The completion of this first phase of research which has been of a preliminary nature, has led to a much clearer understanding of the state of knowledge of pertinent material properties. As a result of this, the needed research in this area is more clearly defined. Application of an approximate finite element analysis based on linear material properties has suggested logical reasons for some of the problems of deteriortation most common in fabric supported paintings. Consequently, even with the results of only a limited number of clinical tests and analytical computations, considerable progress has been made towards developing an understanding of the interactions induced in the complex system composing a fabric supported painting.