Full Field Stress/Strain Analysis: Use of Moiré and TSA for Wood Structural Assemblies

Ronald W. Wolfe, Robert Rowlands, and C.H. Lin

Abstract

Moiré and thermoelastic stress analysis (TSA) methods were compared on the basis of an assessment of the stress distribution in metal plate connectors loaded in axial tension. For the 12.7 mm gauge length considered, the moiré technique had a strain resolution of 1,000 $\mu\epsilon$ without computer enhancement and 200 $\mu\epsilon$ with computer enhancement using digital image analysis and Fourier interpolation. Using the commercial SPATE® equipment, TSA had a resolution of roughly 145 psi (1 MPa) in steel, corresponding to a strain of 5 $\mu\epsilon$.

Results of these tests show the TSA test equipment to be superior for laboratory testing of metallic materials. For field evaluation of wood structures, however, the moire method has the potential to be more portable, to be less costly, and to have the same or a superior resolution when enhanced using digital image analysis.

An analysis of metal gusset plates stressed in tension confirm the expected stress distribution characteristics. Stresses arc rarely uniformly distributed over the width of the plate. The assumption of a uniform distribution of tooth loads along the length of a plate is reasonable for connections designed with a balance between tooth withdrawal and steel tensile failure. For longer plates prone to steel failure, the plate teeth nearest the joint carry a higher load than teeth closer to the end of the plate.

Introduction

Structural wood components and assemblies have been evolving for over 200 years in the United States to meet the ever-changing demands on available energy and material resources. Over the past 40 years, Americans have seen major changes in the way wood is used in structural applications: plywood has replaced board sheathing, trusses have replaced lumber rafters, and wood I-joists have regained a significant share of the commercial building market that was lost to steel in the early part of this century.

To compete with other materials in meeting the continuing demands for energy and material resources, the use of improved test and analytical procedures that facilitate the identification of design imbalances must be explored. Tools for performing full-field analyses of stress and strain enable stress concentrations to be identified and the range of stress/througth ratios to be quantified within a given structure. These tools provide the potential for further developments toward optimizing the use of wood fiber resources.

The use of two, full-field, analysis tools for the evaluation of wood-frame truss connections is examined in this paper. Moire and thermoplastic stress analysis (TSA) methods have been widely used in machine and tool design and to a more limited extent in the development of design guidelines for steel structures and connections. While these tools have been applied to wood and wood-fiber-based materials at the basic research level, they are rarely used in product development or for field evaluation. State-of-the-art developments in image analysis used in conjunction with these tools give them valuable potential for a broad range of applications in wood structures research and development.

Background And Theory

Moiré and TSA methods are convenient tools for the full-field analysis of member stresses. The moire method is a more mature technology with the advantage of a much broader experience base. Its uses range from high-resolution, laboratory, interferometry techniques to field applications where it is used simply to assess strain concentrations with relatively little concern for stress magnitude.

The TSA method has the advantage of enabling direct/remote assessment of member stresses. Measurements are calibrated on the basis of stress, giving some advantage where the modulus of elasticity varies or is unknown. It does not require arty applications of rulings to the structure surface. The primary disadvantage of TSA is the higher equipment cost.

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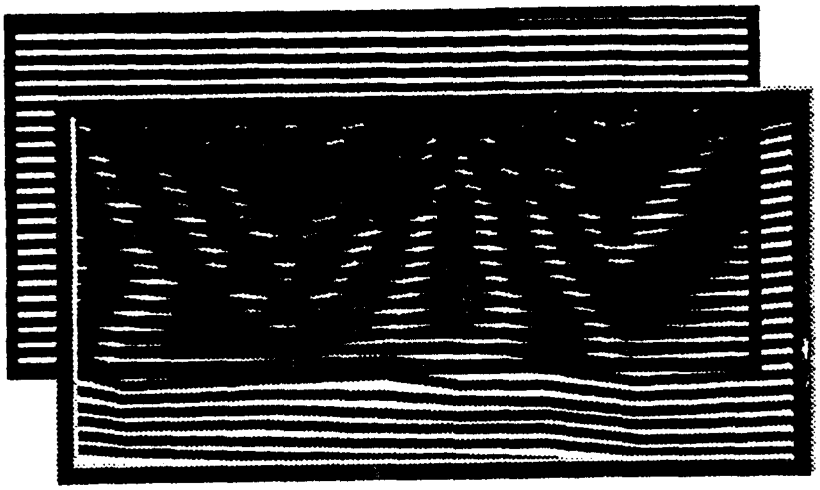

Figure 1—A linear moiré line pattern showing that hot interferance fringes are generated by grid overlay. The deformed (specimen) grid blocks light passing through the undeformed (analyzer) grid at locations where the accomulated mismatch in the spacing of specimen line intervals equals the analyzer line spacing.

Moiré Fringe Analysis

Full-field strain analysis using moire techniques is a fairly well-established procedure in the field of experimental mechanics. Moiré analyses employ optical geometric interference as a tool for assessing strain. While interferometric moiré techniques have tended to be confined to laboratory conditions, techniques employing film overlays have expanded its use to less restrictive applications. Optional techniques used to enhance the moiré technique include grid vs. line patterns for biaxial vs. uniaxial strain measurement, initial rotational or linear mismatch, digital image analysis to amplify conventional resolution, and fractional fringe and interferometry.

The basic theory of the moiré method is easy to understand and to apply. When two, closely spaced line arrays having similar, but not identical, patterns are superimposed and viewed with transmitted or reflected light, interference fringes are generated where lines from one line array block the light transmitted between the lines of the second array (fig. 1). Any distortion of one (active/specimen) array relative to the other (analyzer) array will result in changes in this fringe pattern that can be used to assess the location as well as the magnitude of surface strain.

Two methods of enhancing the interference patterns are to begin with a slight rotation of the analyzer (fig. 2) and to use a small mismatch in the analyzer array vs. the specimen array. An initial rotational mismatch facilitates the differentiation of tension and compression zones. Initially, the rotation causes an array of fringes oriented at one-half the rotational angle from the strain direction. As the specimen is strained, compression on the specimen will

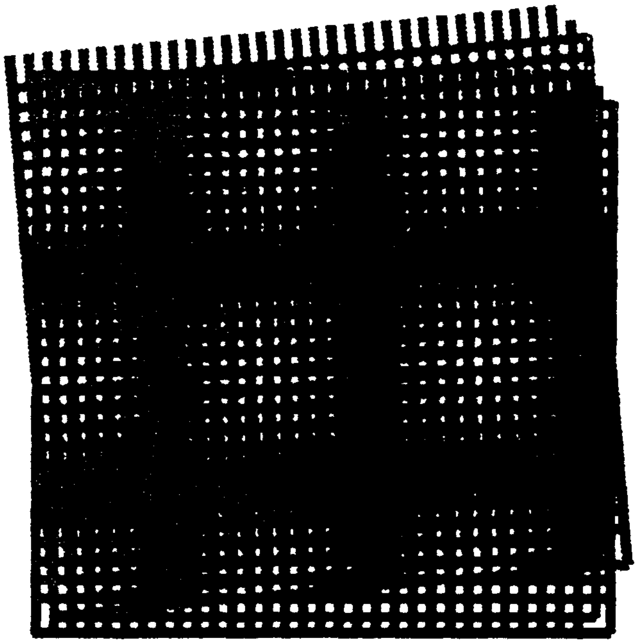

Figure 2—The rotational mismatch of moiré, biaxial, grid patterns shows initial interference fringes with no distortion of the specimen.

cause a decrease in the rotational angle of the fringes while tension will cause an increase in fringe rotation. A small, linear mismatch results in an initial fringe pattern running perpendicular to the principal strain direction. Tension will cause a gain in the number of fringes, and compression will cause a reduction in the number of fringes per unit length.

By recording the progression of the moiré image using a charge-coupled device (CCD) camera, the variation in shades of gray between fringes, quantified using an image processor, may be characterized as a periodic function using Fourier series to interpolate strains across the entire strain field. This technique can be used to divide a visible fringe into four or five quantifiable increments, thus increasing strain resolution.

A 2,000 line-per-inch moiré film used to assess strain over a gauge length of 12.7 mm [the approximate length of tooth slots in metal plate connectors (MPC'S)] will show only a fringe when displacement in that gauge length reaches 0.0254 mm, which is close to the yield point of steel. Being able to detect one-third of the fringe displacement within 12.7 mm will give the strain in the range of design load.

In addition to its use for evaluating stresses in MPC's, the use of the moiré method for evaluating the performance of composites is being contemplated. The use of the moiré method is not confined to uniaxial strain analysis. By using a moiré grid, one can evaluate biaxial strains, including shear strain. This technique has been documented by Post (1965).

Thermoplastic Stress Analysis

Belgen (1967) first documented the use of noncontact TSA. In 1982, a British company, Ometron Ltd., began marketing the first commercial TSA system, which they called SPATE® [Stress Pattern Analysis (by measurement of) Thermal Emission].

$$\Delta T = -K_m T \Delta (\sigma_x + \sigma_y + \sigma_z)$$

The theoretical basis for thermoelastic stress analysis lies in the first and second laws of thermodynamics. The most commonly referenced derivation for the relationship between temperature change and material stress relates only to elastic deformation (Rauch and Rowlands 1993). Under cyclic loading, this derivation can be simplified to a direct linear relation (Eq. 1) that estimates the change in temperature as a function of the change in stress times a thermoplastic material constant and ambient temperature. The thermoplastic material constant is inversely related to material density and specific heat, and directly related to the coefficient of thermal expansion. If the material is orthotropic, the coefficient of thermal expansion is likely to vary with the principal axis of the material, causing the thermoplastic material constant to be different in each direction.

A limiting factor in the application of TSA techniques is the required control on the loading frequency, which must be acceptable for adiabatic material response; that is, the thermodynamic process must be reversible, requiring a balance between the thermal and the mechanical energy. For most metals, this require a frequency above 2 Hz. For materials of decreasing thermal conductivity, however, the necessary frequency for adiabaticity increases. For example, wood requires 18 Hz or more.

SPATE provides digital output, which, when color calibrated, gives a graphic interpretation of how stresses vary over the stressed field. While an observer cannot pick up the resolution of the color thermograph when it is copied in black and white, figure 3 gives some idea of the kind of output obtained from SPATE. In this figure, the lighter strands are heavily stressed over the region of the butt joint. Above the third row of strands, there is evidence of nonsymmetric load as stresses are larger for areas on the right side of the plate.

Numerical techniques were used to smooth the digitized output and give stress distribution plots as shown in figures 4 through 7. A slight compressive stress shown near the end of the plots in figures 4 and 5 was caused when the row of teeth farthest from the joint began to peel out of the wood, bending the plate and compressing the surface.

An analysis of the digitized data suggests a fairly uniform distribution to the various rows of teeth for a 7.6 by 12.7 cm plate designed with a balance between tooth-holding and steel tensile stresses (fig. 5). As would be expected. stress in the steel strands is greatest between the first and second rows of teeth. The drop in stress is due to the load being transferred by the teeth into the wood. The drop in surface stress is roughly the same across each double row of teeth, suggesting that the load transferred to the wood is the same for each double set.

The TSA analysis of a 7.6 by 25.4 cm plate (fig. 8) at 4.45 kN shows that the drop in axial stress is not uniform over the length of the plate. This analysis suggests that for longer

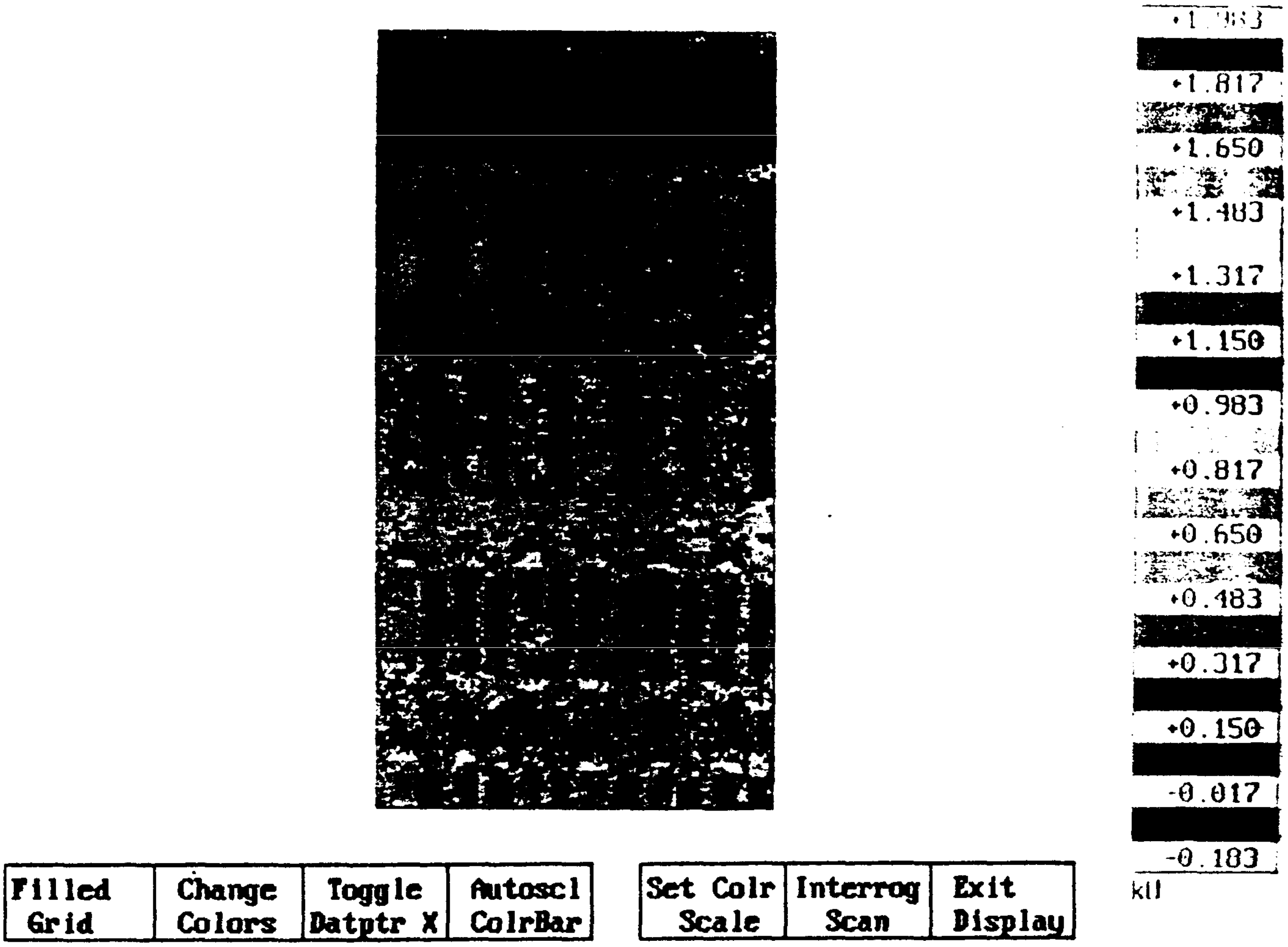

Figure 3—A black-and-white copy of a color thermogram showing the distribution and variation of stress in a metal connector plate stressed in axial tension.

plates, the tooth load decreases from the joint to the ends of the plate.

When looking at a more confined region, along steel strands between rows of teeth, the effects of stress concentration at the root of the strands can be seen (fig. 6). Axial stress appears to decrease toward the middle of the strands. Shear stress, however, increases toward the middle of the strand, where the failure occurs in a steel plate under axial stress.

While the popular use of TSA is for stress evaluation in metal parts, it can be applied directly to wood. Figure 9 shows a piece of wood containing a knot stressed by compression. This application has not received much attention, but as this technology evolves, it has potential for use in lumber grading product development, and structural evaluations, as well as in basic research.

Conclusion

Both the moir and TSA methods have potential for future developments that will make use of growing computer technology. While moiré technology is more mature than TSA and has been applied to many different problems, developments in the area of digital image correlation can enhance its value as a precision tool for full-field strain analysis.

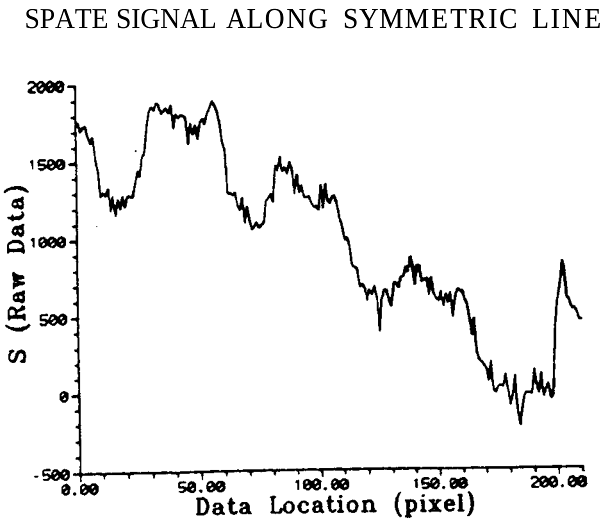

Figure 4—The measured distribution of stress in plate strands and cross bars over half the length of a 7.6 by 12.7 cm plate extending from the joint to the end of the plate.

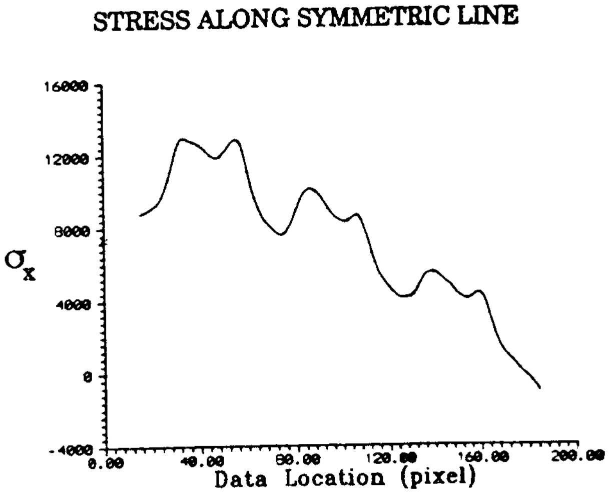

Figure 5—A smoothed, axial stress distribution plot over half the length of the plate.

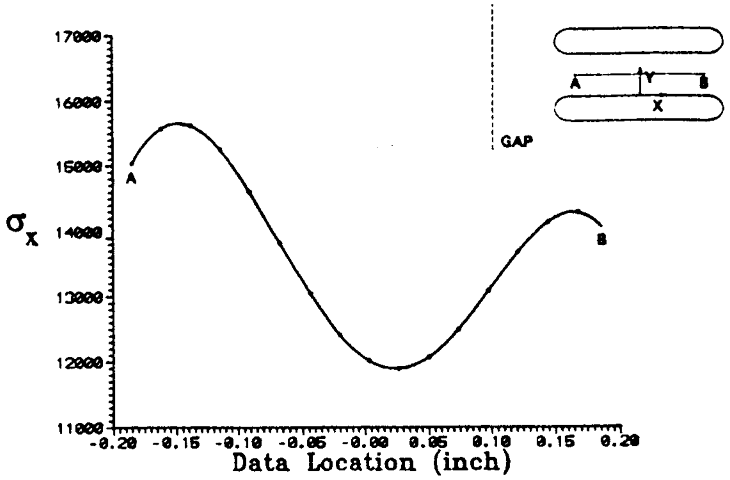
STRESS ALONG SYMMETRIC LINE

Figure 6—The distribution of axial stress along the length of a single strand shows that the highest axial stresses were near the roots of the strand due to stress concentrations.

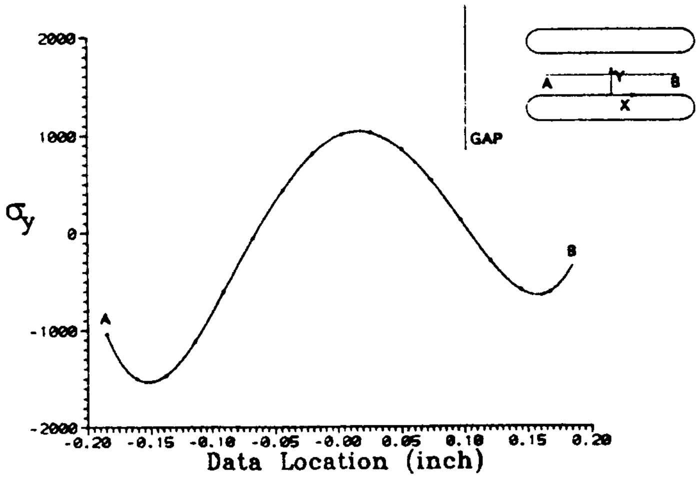
STRESS ALONG SYMMETRIC LINE

Figure 7—The variation of the average transverse stress along the strand length.

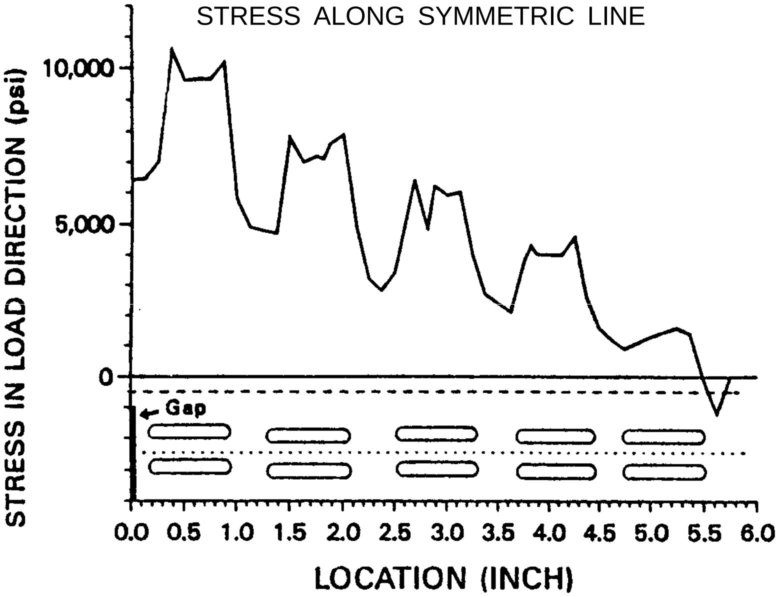

Figure 8—The distribution of axial stresses over half the length of a 7.6 by 25.4 cm plate.

This study demonstrated the first known application of TSA to wood. While it suggests some serious limitations, it shows TSA'S potential for future applications in lumber or veneer stress grading.

The application of both the moiré and TSA methods to MPC joints has shown variations in stress along the length of the plate and at stress concentration points. Either of these techniques would be useful in optimizing connector plate configurations.

Advantages of the moiré method over the TSA method include cost, portability, and the ability to easily take a reading at any load. The ease of using moiré film overlays, along with development of CCD cameras and digital image correlation techniques, provides the potential for taking full-field strain measurements in the field. By permanently attaching a moiré pattern to highly stressed members in a structure, periodic checks can be made to assess changes in the state of stress. Availability of a new portable interferometric camera should greatly increase the effectiveness and versatility of moiré applications to wood.

The primary advantages of TSA are its direct measurement of member stress and its resolution. The TSA measurements have a resolution comparable to that of strain gauges with the advantages that nothing has to be attached to the specimen and that the measurements are directly correlated to stress

Companies concerned with the development of products whose performance is sensitive to stress concentrations may choose to conduct studies using the moiré method on their own, or contract with a private testing lab or university such as the University of Wisconsin, to take advantage of the capabilities of TSA.

Acknowledgments

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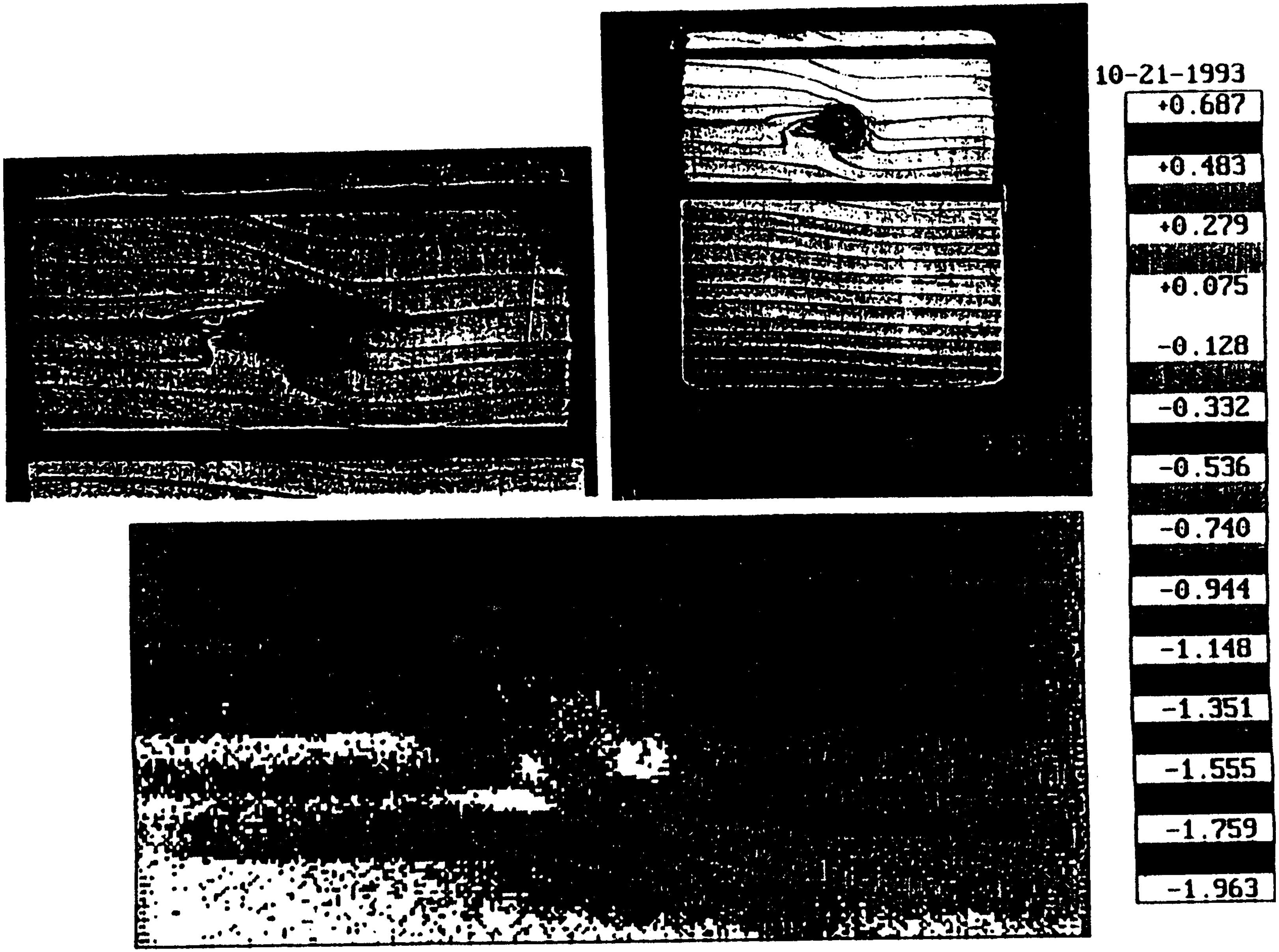

Figure 9—A TSA thermogram around a knot in wood under axial compresision.

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