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► **To cite this version:**

Minh-Phong Luong. Infrared thermographic characterization of engineering materials. 34th Annual International Technical Symposium on Optical and Optoelectronic Applied Science and Engineering, 1990, San Diego, United States. pp.327, 10.1117/12.23108 . hal-04667431

HAL Id: hal-04667431

<https://hal.science/hal-04667431>

Submitted on 3 Sep 2024

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Infrared thermographic characterization of engineering materials

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ABSTRACT

This paper aims to illustrate the use of infrared thermography as a nondestructive and noncontact technique (a) to observe the physical processes of unstable crack propagation or flaw coalescence of engineering materials subject to various loadings, (b) to detect material defects or leakage phenomena and (c) to aid tribology experiments.

1. INTRODUCTION

Current technological developments tend towards increased exploitation of material strengths and towards tackling extreme loads and environmental actions. The tendency to extend the service life of materials and structures by increasing maintenance in lieu of replacements, increases the need for monitoring of structures and supports the need to perform global or local test loading. It must be noted that monitoring techniques have previously suffered from difficulties in the interpretation of recorded data.

Diverse damage analysis methodologies¹ for engineering materials have been developed in recent years which isolate the factors affecting crack initiation and growth, and enable the prediction of their cumulative effects on the fatigue performance of structural components. They are based on (i) the formulation of analytical models for fatigue crack and growth ; and (ii) the acquisition of supporting baseline data and validation of such models by means of a comprehensive testing procedure.

In cases where continuum mechanics can be applied, the concept of an effective stress $\sigma_{ef} = \sigma/(1-\delta)$ has been introduced with a continuous variable δ related to the scalar density of defects or faults. This has been the starting point of damage theories developed for fatigue, creep, creep-fatigue interaction in engineering materials. For rock-like materials, often characterized by their salient fracturing nature, a different approach has been proposed using the plasticity formalism with the concept of a fracturing stress or a fracturing strain to describe the inelastic behaviour of progressively fracturing solids². The difficulty in identification and determination of the governing functions and parameters involved in these theories have lead to a micromechanical approach³ which presents the advantage of giving both a comprehensive understanding of the damage mechanism at the macroscale and the guideline for a phenomenological approach to constitutive equations.

The existing partial damage hypothesis has been used, but it gives unsatisfactory results in evaluating the fatigue behaviour of plain concrete⁴. Volumetric, ultrasonic and acoustic emission measurements have not permitted a complete interpretation of the mechanical deterioration. Research on absorption of energy in fatigue loading has been investigated⁵ to aid understanding of the physical process of performance degradation when the material is subjected to varying dynamic loads. The absorbed energy is believed to be used in the material in forming microcracks, crushing material, redistributing stress and causing a rise in temperature. Unfortunately the difficulties involved with the measurement systems were such that the results obtained by these methods were not completely satisfactory.

In rock engineering, various geological formations are being investigated as possible sites for underground storage of oil and gas, and underground repositories of radioactive wastes. Much attention has been given to the saline deposits due to their widespread distribution, relative accessibility and ease of excavation. The mechanisms of rock salt deformation and fracture are thus fundamental for processes of strata control, for the support of excavations, and for the construction of salt cavities⁶. Rock salt generally displays failure characteristics intermediate between ductility and brittleness. It is relatively soft, can deform plastically and is extremely notch sensitive. Brittle fracture often occurs in the presence of flaws.

Additionally, the monitoring instrumentation and new systems of thermomechanical defect or anomaly determination are of prime importance for safety assessment of the facilities.

In wood industry, damage and failure behaviour of wood in tensile, compressive or shear loading is an important consideration in connection with designs or regulations of wooden structures subjected to high allowable working stresses or in cases where the dead load forms a smaller part of the total load capacity. In such a situation, failure of the construction material may occur at stresses below its static strength. Accurate knowledge should therefore be obtained of the mechanical behaviour of wood subjected to various loadings.

This phenomenological approach describes the use of infrared thermography as a nondestructive and noncontact technique for both laboratory testing and field inspection. In laboratory research, there is a fundamental need to examine the mechanism of cracking and failure processes of material specimens which are generally subjected to a given unconfined compression and a superimposed vibratory excitation. This technique offers the possibility of illustrating the onset of crack initiation by stress concentration in weakness zones. Thanks to the thermomechanical coupling, it permits the monitoring of the process of unstable crack propagation and/or flaw coalescence when increasing microcracking is generated by vibratory excitation. In field control, the problem of heat, gas or water insulation and heat transfer detection are also of great importance in many engineering projects. An attempt is made to provide a framework within which these various factors and their effects may be placed, for instance considering the mechanical characteristics of the following engineering materials.

2. CHARACTERISTICS OF SOME COMMON ENGINEERING MATERIALS

2.1 Plain concrete

Plain concrete is the most popular engineering material consisting of coarse aggregates embedded in a continuous matrix of mortar which is a mixture of hydraulic binding materials, additives and admixtures distributed in a suitable homogeneous dosage. This construction material has been extensively used for structural applications because of its excellent processibility, low cost and versatility in manufacture together with desirable mechanical properties for engineering design. Under applied loading, the concrete as a whole deforms in spite of significant incompatibilities between the aggregates and the matrix which promote further breakdown. At the macroscopic level, breakdown is accompanied by both loss in stiffness and accumulation of irrecoverable deformations. At the structural level, breakdown appears as microcracking and possibly as slippage at the aggregate-cement paste interfaces.

2.2 Rock salt

Natural rock salt appears to be a discontinuous mass with a medium to coarse grained polycrystalline structure. It contains cracks, defects, joints, dispersed clay impurities and eventually bedding planes with varying degrees of cohesion along these discontinuities. It sometimes exhibits variable mineralogy and crystal sizes. Depending on its crystal structure, bond character, and the temperature, it may be completely brittle, semi-brittle or ductile⁷. Elucidation of the various mechanisms responsible for fracture is related to the plastic resistance associated with grain boundaries and the effects of plastic anisotropy. When it is loaded, the rock salt deforms also as a whole in spite of significant incompatibilities between the crystal aggregates. Stress concentrations occur and result in localized forces which are sufficient to promote plasticity and crack formation or both. Quite similar to the concrete case at the macroscopic level, breakdown is accompanied by both loss in stiffness and accumulation of irrecoverable deformations. At the structural level, breakdown appears as microcracking and possibly slippage at the crystal interfaces.

Failure in plain concrete, rock salt or in any other engineering material may be viewed as a microstructural process through the activation and the growth of one preexisting flaw or site of weakness, or through the coalescence of a system of interacting small flaws and growing microcracks. The stress level corresponding to the activation of the flaws is related to the flaw size and connected with the encompassing microstructure. Flaw initiating concrete failure may be divided into two classes : the intrinsic flaws develop during the processes of hydration and curing of the cement paste, the extrinsic flaws result

from significant incompatibilities between the aggregate and the matrix when the material as a whole deforms under applied loading. It may be said that fatigue of concrete is associated with the development of internal microcracks, probably both at the cement matrix/aggregate interface and in the matrix itself. For rock salt, it may occur at the crystal interface and in the crystal itself. The occurrence of microcracking and slippage leads to nonlinearity and softening in the stress-strain response of concrete with a marked dependance on the mean normal stress⁸. Under repetitive stresses, fatigue mechanism is a progressive, permanent, internal structural change occurring in the concrete and in the rock salt. These changes result in progressive growth of cracks and complete fracture.

2.3 Wood building materials

Wood is a natural product of biological origin⁹⁻¹⁰. It is a very variable and heterogeneous material. Its mechanical properties are affected by the presence of knots, checks, shakes, splits, slope of grain, reaction wood and decay... Stress concentrations occur because the knot interrupts wood fibers. Checks, shakes and splits all constitute separations of wood fibers. Slope of grain has a marked effect on the structural capacity of a wood member. Reaction wood or abnormal wood is hard and brittle and its presence denotes an unbalanced structure in the wood. Decay is a disintegration of the wood caused by the action of fungi. These damages are generally very difficult to measure.

When the span becomes long or when the loads become large, the use of sawn lumber may become impractical. In these circumstances and possibly for architectural reasons, structural glued-laminated timber or glulam can be used. Glulam members are fabricated from relatively thin laminations of wood. These laminations can be glued together and spliced in such a way to produce wood members. Glues are capable of producing joints which have horizontal shear capabilities in excess of the capacity of the wood itself. The efficient use of materials and the long length of many glulam members require that effective end splices be developed in a given lamination. Butt joints are poor splices and are considered ineffective in transmitting both tension and compression. Finger joints can produce high-strength joints when the fingers have relatively flat slopes. With scarfed joints, the flatter the slope of the joint, the greater the strength of the connection.

Veneer is the thin sheet of wood obtained from the peeler log. When veneer is used in the construction of plywood it becomes a ply. The cross-laminated pieces of wood in a plywood panel are known as layers. Layers are often simply an individual ply, but they can consist of more than one ply. It is the cross-laminating that provides plywood with its unique strength characteristics. It provides increased dimensional stability over wood that is not cross-laminated. Cracking and splitting are reduced, and fasteners, such as nails and staples, can be placed close to the edge without a reduction in load capacity.

A connector or fastener is a mechanical device (nails, bolts, screws,...) or mechanical assembly (bolted shear plates, nailed metal truss plates,...), a glue or an adhesive used to hold together two or more pieces of wood or wood based products.

When a wood or a structural wood product is loaded, it deforms as a whole in spite of its heterogeneous characteristics and its localized defects. Stress concentrations occur and result in localized forces which are sufficient to promote plasticity and anelasticity or both. At the macroscopic level, breakdown is accompanied by both loss in stiffness and accumulation of irrecoverable deformation. At the structural level, breakdown appears as microcracking and possibly slippage at component interfaces. Damage and failure may thus be viewed as a microstructural process through the activation and the growth of one preexisting flaws or of a site of weakness, or through the coalescence of a system of interacting small defects and growing microcracks. The stress level corresponding to the activation of the defects is related to the defect size and connected with the encompassing microstructure. Nondestructive and noncontact tests are thus needed to define wood and wood product properties to establish strength, to optimize design values and to insure quality control.

The formation and propagation of microcracks have been detected by means of different well known measuring methods :

a) The ultrasonic pulse velocity technique involves measurement of the transit time of an ultrasonic pulse through a path of known length in a specimen. The velocity of the ultrasonic pulse in a solid

material will depend on the density and elastic properties of the material and it will therefore be affected by the presence of cracks.

b) The acoustic emission method is based on the principle that the formation and propagation of the microcracks are associated with the release of energy. When a crack forms or spreads, part of the original strain energy is dissipated in the form of heat, mechanical vibrations and in the creation of new surfaces. The mechanical vibration component can be detected by acoustic methods and recorded, hence microcracking may be detected by studying sounds emitted from the materials.

It can be considered that the failure mechanism of engineering materials consists primarily in the formation and propagation of microcracks. The formations of microcracks are often associated with points of stress concentration. The stress concentrations are located on flaws present in the material, or on existing cracks and notches. Cracks initiate quite early at a site of weakness or stress concentration, then propagate through the plastic zone and into the elastic region. In others cases, flaws are inherent in the material owing to the process of fabrication of concrete or crystallisation of rock salt. These defects exist prior to the application of any load. There may be some initiation period during which the material, at the tip of the flaw, undergoes dislocations pile-up, microvoid formation and coalescence, etc... prior to the onset of progressive growth with increasing plastic deformations. The work done in plastic deformation results in the generation of heat, readily detected and analysed by infrared thermography.

3. HEAT PRODUCTION MECHANISMS

Cases in which heat is produced in the materials are becoming increasingly important in technical applications. Heat may be produced by the passage of an electric current, dielectric or induction heating, radioactive decay, absorption from radiation, mechanical generation in viscous or plastic flow, chemical reaction, including in this such diverse matters as the hydration of cement. In this last case for example, the rate of heat production is roughly of the form $k \exp(-\alpha t)$, the heat generated in three days being of the order of 50-100 cal per gramme of cement ; this is sufficient to have important technical consequences, particularly in the design of large dams.

3.1. Coupled thermo-visco-elastic-plastic analysis

Traditionally, thermomechanical coupling effects have been neglected in thermal analyses. It is generally assumed that the inelastic deformation is rate(time)-independent at low homologous temperatures. The theory of plasticity is consequently formulated in a rate(time)-independent fashion and phenomena such as loading rate sensitivity, creep and relaxation are excluded. The temperature field and the deformation induced by thermal dilation and mechanical loads were solved separately. However this effect could become noticeable if the material is significantly loaded beyond its reversible threshold.

The development of the thermo-visco-elastic-plasticity equations requires three types of basic assumptions¹¹⁻¹²⁻¹³⁻¹⁴⁻¹⁵ :

a) The basic thermomechanical quantities describing thermodynamic processes : the motion x , the second Piola-Kirchhoff stress tensor S , the body force per unit mass b , the Helmholtz free energy ψ , the specific entropy s , the heat supply r_0 , the absolute temperature T , the heat flux vector per unit area q , the inelastic strain tensor E^I and a set of internal state variables $\alpha^{(l)}$ characterizing the material.

b) The fundamental equations of mechanics postulating for the balance laws of linear momentum, angular momentum, and energy, as well as the second law of thermodynamics expressed in the variables given in a) :

(i) balance of linear momentum

$$\nabla S F^T + \rho (b - \ddot{x}) = 0 \tag{1}$$

where F denotes the transformation gradient.

(ii) conservation of energy

$$\rho (\dot{\psi} + \dot{s}T + s\dot{T}) = \rho \dot{e} = S : \dot{E} - \text{div } q + r_0 \tag{2}$$

(iii) second law of thermodynamics

$$-\rho (\dot{\psi} + s\dot{T}) + S : \dot{E} - q \cdot (\nabla T)/T \geq 0 \quad (3)$$

where ρ (kg m^{-3}) is the mass density in the reference configuration, e the specific internal energy and E the Green-Lagrange strain tensor $E = (\nabla x^T \cdot \nabla x - 1)/2$. The superposed dot stands for the material time derivative. The continuity equation and the balance of angular momentum are implicitly satisfied in the fundamental equations.

c) The constitutive assumptions describing the material response and abiding the compatibility of the constitutive equations with the fundamental equations of mechanics.

When adopting the separability of the strain tensor

$$E = E^e + E^I + \beta (T - T_R) \quad (4)$$

where β is the coefficient of the thermal expansion matrix and T_R the reference temperature, the requirement of inequality (4) yields :

- (i) The response functions S , ψ and s are independent of the temperature gradient ∇T .
- (ii) ψ determines both the stress tensor and the specific entropy through

$$S = \rho \partial\psi/\partial E^e \quad \text{and} \quad s = -\partial\psi/\partial T + (\partial\psi/\partial E^e) : \beta$$

(iii) ψ , E^I and q obey the general inequality

$$(S - \rho \partial\psi/\partial E^I) : \dot{E}^I - q \cdot \nabla T/T \geq 0 \quad (5)$$

The above thermodynamic restrictions may now be applied to equation (2) yielding :

$$\rho (\partial\psi/\partial E^I - T \partial^2\psi/\partial T \partial E^I) : \dot{E}^I - T(\partial S/\partial T) : \dot{E}^e - \rho T(\partial^2\psi/\partial T^2)\dot{T} + \dot{S} : \beta T = S : \dot{E}^I - \text{div } q + r_0 \quad (6)$$

Assuming

$$\psi = \psi_0 + (E^e : \overset{4}{D} : E^e)/2 - C_v T \ln (T/T_R - 1) \quad (7)$$

and the Fourier heat conduction law

$$q = -K \text{ grad } T \quad (8)$$

where ψ_0 , $\overset{4}{D}$, C_v and K are material constants. $\overset{4}{D}$ stands for the fourth-order elasticity tensor. C_v ($\text{J kg}^{-1} \text{K}^{-1}$: Joule per kilogramme per Kelvin degree) is the specific heat at constant deformation and K ($\text{W m}^{-1} \text{K}^{-1}$: Watt per metre per Kelvin degree) is the thermal conductivity.

Finally we get the coupled thermomechanical equation :

$$\rho C_v \dot{T} = K \nabla^2 T - (\beta : \overset{4}{D} : \dot{E}^e) + S : \dot{E}^I + r_0 \quad (9)$$

which shows the varied potential applications and uses of the infrared scanning technique in rock engineering. The volumetric heat capacity $C = \rho C_v$ of rock material is the energy required to raise the temperature of an unit volume by 1 °C (or Kelvin degree).

3.2. Thermal conduction

The first term on the right hand side of the thermomechanical equation governs the transference of heat by thermal conduction in which the heat passes through the material to make the temperature uniform in the specimen. The second-order tensorial nature of the thermal conductivity K may sometimes be used for the detection of anisotropy of heavily loaded rock-like materials. Where an unsteady state exists, the thermal behaviour of a rock is governed not only by its thermal conductivity but also by its

heat capacity. The ratio of these two properties is termed the thermal diffusivity $\alpha = K/C$ ($m^2 s^{-1}$) which becomes the governing parameter in such a state. A high value of the thermal diffusivity implies a capability for rapid and considerable changes in temperature. It is important to bear in mind that two materials may have very dissimilar thermal conductivities (e.g. rock and insulator) but, at the same time, they may have very similar diffusivities.

3.3. Thermoelasticity

The second term illustrates the thermoelastic effect. Within the elastic range and when subjected to tensile or compressive stresses, a material experiences a reversible conversion between mechanical and thermal energy causing it to change temperature. Provided adiabatic conditions are maintained, the relationship between the change in the sum of the principal stresses and the corresponding change in temperature is linear and independent of loading frequency. It is the reversible portion of the mechanical energy generated ; this thermoelastic coupling term may be significant in cases of isentropic loading.

3.4. Intrinsic dissipation

The third term is the energy dissipation generated by viscosity and/or plasticity. The work done in plastic deformation per unit volume ϕ can be evaluated by integrating the material stress/strain curve. This internal dissipation term constitutes an important part of the nonlinear coupled thermomechanical effect. The quantification of this intrinsic dissipation for rock-like materials is an extremely difficult task if infrared thermography is not used. This chapter emphasizes the advantages of the infrared thermographic technique for the detection of this effect.

3.5. Heat sources

The last term shows the existence of sources or sinks of heat in the specimen. The surface heat patterns displayed on the scanned specimen may be established either by external heating referred to in literature as "passive heating" where local differences in thermal conductivity cause variations on isothermal patterns or by internally generated heat referred to as "active heating" where isothermal patterns are established by the transformation of internal energy into heat. In the case of forced convection, if fluid at the temperature of the medium is forced rapidly past the surface of the solid, it is found experimentally that the rate of loss of heat from the surface is proportional to the surface conductance or coefficient of surface heat transfer. This fact has been used for the detection and location of heat, gas or fluid leakage through rock-like materials.

4. INFRARED SCANNING OF ENGINEERING MATERIALS

Infrared thermography has been successfully used as an experimental method for the detection of plastic deformation during crack propagation of a steel plate under monotonic loading¹⁶ or as a laboratory technique for investigating damage, fatigue and creep mechanisms occurring in engineering materials¹⁷⁻¹⁸⁻¹⁹. This experimental tool is used to detect the onset of unstable crack propagation and/or flaw coalescence due to the thermomechanical coupling, when increasing irreversible microcracking is induced by vibratory loading.

4.1. Infrared thermography

Infrared thermography is a technique for producing heat pictures from the invisible radiant energy emitted from stationary or moving objects at any distance and without surface contact or in any way influencing the actual surface temperature of the objects viewed. A scanning camera is used which is analogous to a television camera. It utilizes a infrared detector in a sophisticated electronics system in order to detect radiated energy and to convert it into a detailed real time thermal picture in a video

system both colour and monochromatic. Response times are shorter than a microsecond. Temperature differences in heat patterns as fine as 0.1 °C are discernible instantly and represented by several distinct hues. This technique is sensitive, nondestructive and noncontact, thus suited for records and observations in real time of heat patterns appearing on the surface of an object being scanned. No interaction at all with the specimen is required to monitor the thermal gradient.

The quantity of energy W ($W\ m^{-2}\ \mu m^{-1}$) emitted as infrared radiation is a function of the temperature and emissivity of the specimen. The higher the temperature, the more important is the emitted energy. Differences of radiated energy correspond to differences of temperature.

4.2. Infrared Scanner

As an example, the AGA 782 SW infrared scanner unit²⁰ comprises :

a) a set of infrared lens which focusses the electromagnetic energy radiating from the object being scanned into the vertical prism,

b) an electro-optical scanning mechanism which discriminates the field of view in 10 000 pixels by means of two rotating vertical (180 rpm) and horizontal (18 000 rpm) prisms with a scanning rate of 25 fields per second,

c) a set of relay optics containing a selectable aperture unit and a filter cassette unit which focusses the output from the horizontal prism onto a single element point detector, located in the wall of a Dewar chamber,

d) a photovoltaic SW short waves infrared detector composed of Indium Antimonide InSb which produces an electronic signal output varying in proportion to the radiation from the object within the spectral response 3.5 μm to 5.6 μm ,

e) a liquid nitrogen Dewar which maintains the InSb detector at a temperature of -196 °C allowing a very short response time of about one microsecond,

f) and a control electronics with preamplifier which produces a video signal on the display screen.

Since the received radiation has nonlinear relationship to the object temperature, and can be affected by atmosphere damping and includes reflected radiation from object surroundings, calibration and correction procedures have to be applied. Knowing the temperature of the reference, the object temperature can then be calculated with a sensitivity of 0.1 °C at 30 °C.

4.3 Infrared observations of rock failure

Rock-like materials present a low thermomechanical conversion under monotonic loading. Plastic deformation, whereby microcracking and slips occur creating permanent changes globally or locally, is however one of the most efficient heat production mechanisms. Most of the energy which is required to cause such plastic deformations is dissipated as heat. Such heat development is more easily observed when it is produced in a fixed location by reversed applied loads. These considerations define the use of vibrothermography as a nondestructive and noncontact method for observing the damage process of rock-like materials²¹.

In laboratory, studies on geomaterial mechanical behaviour use specific equipments to set up experimentations. The high frequency servohydraulic test machine provides a means of vibration and dynamic testing of engineering materials. Control of the machine is provided by a sophisticated closed-loop electronic control system. This utilizes feedback signals from the force and displacement transducers. The programming section comprises a digital function generator and a frequency sweep controller which enables resonant phenomena testing. The specimen is observed in a nondestructive, noncontact manner by means of an infrared thermographic system. The thermal image is shown on the monitor screen.

The parameter investigated in this test is heat generation due to the energy dissipated by the material which has been excited beyond the stable reversible domain. A vibratory loading at 100 Hz on the specimen subjected to a given static compression exhibits in a nondestructive manner the irreversible plastic strain concentrations around gaps or cracks generated by stresses exceeding locally the stability limit of the material. The contribution of the plasticity term is revealed by the rapid evolution of heat dissipation once the stable reversible domain has been exceeded demonstrating the occurrence of an

unstable crack propagation or the coalescence of flaws existing in the natural rock salt specimen (Fig. 1).

It can be seen that :

a) With a vibratory excitation between 30 and 50 percent of the nominal uniaxial compression $\sigma_N = F/S_0$, the heat dissipation detected for 2 000 load cycles is small, even at the hottest location.

b) When $0.50 \leq \sigma/\sigma_N \leq 0.70$, stress concentrations around cracks or defects are readily detected at the 1 000th load cycle.

c) For $0.70 \leq \sigma/\sigma_N \leq 0.90$, cracking occurs increasingly in the reduced section part of the specimen.

The different phases of heat dissipation operating during an unstable failure are readily described by heat patterns. When defects or weakness zones are present on the specimen, infrared observations evidence the progressive mechanism of defect coalescence. The rate of heat generation at the hottest location may be used to detect the threshold of the failure process if compared with the traditional stress-strain curve.

Thus the thermomechanical coupling offers a quantitative evaluation for the growth rate of thermal dissipation monitoring the damage evolution of the material. The damaged areas are located and highlighted by heat patterns. These results support and validate the assumptions to be taken into consideration in numerical procedures for stability assessment of rock structures. The phenomenological behaviour of the rock materials in consideration is therefore the standard of reference, allowing the use of the methods and results of continuum mechanics for analysing and modelling their engineering performance.

4.4. Infrared observations of damage in wood specimen

Fig. 2 shows the heat dissipation caused by the process of damage in wood specimens subjected to shear loading. The growth rate of heat on the warmest point enable the detection and the location of the onset of specimen failure.

Fig. 3 records the different stages of heat dissipation describing the process of failure of a steel-wood connector.

4.5. Detecting heat transfer

A laboratory test has been carried out on a rock salt cube of 0.50 m in dimension for analysing the thermal diffusion through natural rock salt (Fig. 4). A spherical heat source is installed off centre so that the boundary influence can be estimated by thermistors and by heat patterns displayed on the different faces of the rock salt cube. The isotropic thermal diffusion assumption has been confirmed in spite of the layered structure of rock salt and the axisymmetrical geometry of the experimental lay out.

It has been found that the infrared thermography is particularly useful in detecting infiltration problems, missing insulation and construction defects. It permits to survey heating system in industrial plants in addition to the thermal, electrical and mechanical systems to find areas suggesting integrity conserving actions²²⁻²³. This qualitative survey has been found to be an excellent method to detect environmental heat losses, water or gas leakages in process equipment and auxiliary systems.

In the construction of any complex facility or structure for radioactive waste disposal, the construction defects can arise through human error. Detection is a problem for visual inspection, but not severe, if the defect is located on the surface. The detection of such defects poses greater problems after construction has covered up the work area as, for example, in defects in wall construction. Hand-held probes for examining the surface have been used with limited success. The size of the involved structure related to the size of the defect makes the job nearly impossible unless the area of defect location is reduced to a small region by a separate method. Ultrasonic techniques using computer enhancement to detect remotely not only the defect, but also the location by triangulation were proposed but found unworkable in this application because normal random noise would null or obscure the noise caused by a slight diffusion leak. In many cases, once a defect has been located with thermography, a retrofit measure can be implemented to correct it. But it cannot be assumed that because a retrofit has been performed, the defect is necessarily corrected. Infrared thermography is also useful in showing if a retrofit measure corrected the defective area.

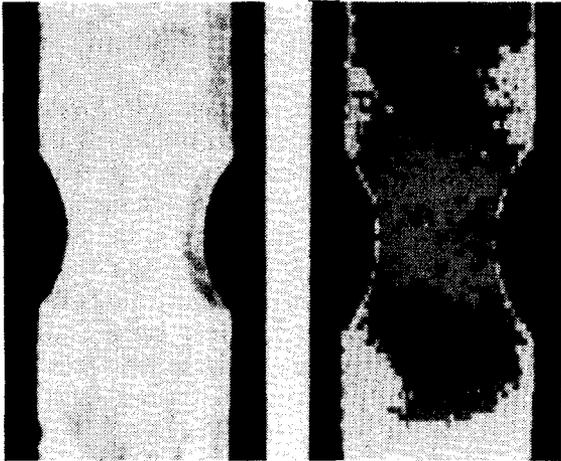


Fig. 1 - Thermogram of a rock salt specimen under vibratory excitation (0.2 °C for each color hue).

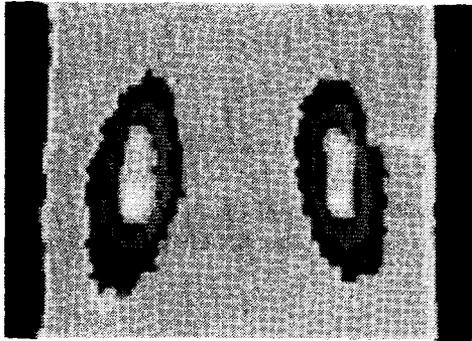


Fig. 2 - Infrared observation of wood specimen subject to shear loading (0.2 °C for each color hue).



Fig. 3 - Records of failure process of a steel-wood connector (0.5 °C for each color hue).

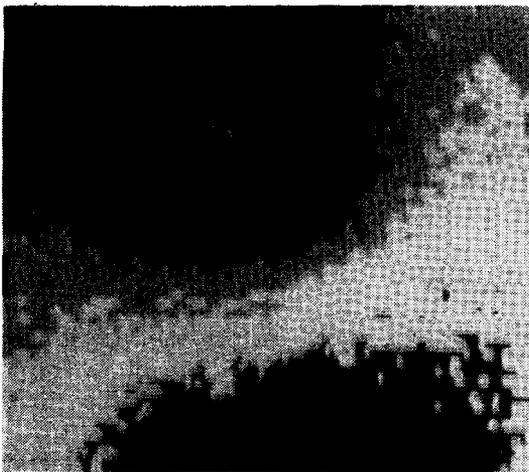


Fig. 4 - Thermal diffusion in rock salt (0.2 °C for each color hue).

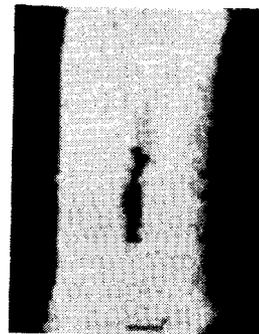


Fig. 5 - Gas leakage through a sandstone specimen (0.2 °C for each color hue).

4.6. Detecting leakage

The infrared radiometric measurement is sometimes proposed as a means of not only locating the presence of the leak, but also of the location. Fig. 5 demonstrates in laboratory the feasibility of detecting the location of gas leakage through very small crack when a pressure difference of about several kPa is applied. Infrared scanning system can provide a wide field of view and a full field of data in a short period of time with a good spot resolution. If the leak causes a change in thermal radiation, the defect will show up on the scanner display scene as a cooler or hotter area depending upon the technique of leak stimulation. The extent of the defect will be more difficult to pin down with infrared alone, but the speed at which the leak becomes visible at the surface is a function of flow and defect size. Consequent measurements using probe techniques which are more directly related to flow can indicate the extent.

When an abnormal thermal pattern appears, it is most often a hot or cold spot on the wall surface. Its origin is usually an area of accidental damage which can occur due to fault, etc. The resultant thermal pattern is sharp, well defined and easily marked for repair. A less defined indication can be warmer areas which appear as bands or zones. these involve cracking or weakness zones and are due to diffuse leakage. If any abnormal areas are found they are marked for repair and occasionally further instrumented to allow continuous monitoring of the problem area while the test and scanning continue. After the problem area has been repaired the test is repeated to verify the adequacy of the repair.

4.7. Detecting temperature rise during friction

Interest in the science of friction and wear is at present increasing, and research requires to determine the temperature rise produced during sliding. This can be readily observed by infrared thermography as illustrated by Fig. 6 in the case of relative motion between two bodies simulating a braking system with a rotating glass disc. Heat is generated in a thin surface layer as a result of the deformation of the material involved in the formation and breakdown of frictional bonds.

4.8. Full scale experimental inspection of a concrete structure

Information about the location and significance of structural defects needed as a basis for maintenance decisions, including the extreme case of removal from service, can be obtained through inspection and nondestructive evaluation. The proposed infrared thermographic procedure involves careful examination of areas where defects are most likely to occur. The critical areas can be identified by analyzing the structure and the service histories of similar structures in similar environments.

The applications of infrared scanning to inspection of concrete structure relies on the fact that the energy is dissipated during the process of failure when internal cracks or flaws develop. Fig. 7 describes an experimental reinforced concrete building frame, intended for earthquake resistance studies. The most severe likely earthquake can be survived if the members are sufficiently ductile to absorb and dissipate seismic energy by inelastic deformations with little decrease in strength. Under seismic loading, simulated by a rotating mass exciter placed on the top of the building, plastic hinges form progressively at the column bases where heat dissipation can be observed by infrared thermography. Fig. 8, 9 and 10 show the progressive evolution of heat dissipation at a column base before crack line is visible.

5. CONCLUDING REMARKS

Owing to the thermomechanical coupling, infrared vibrothermography offers the possibility of a nondestructive, noncontact test of mechanical degradation on concrete, rock salt or any other engineering materials. It allows a measure of the material damage and permits the detection of the limit of a progressive damaging process under load beyond which the material is destroyed.

It is of particular interest that the method allows not only qualitative work such as flaw detection, but also quantitative analysis of the effects of flaws on strength and durability of structural components. This useful and promising technique allows accurate illustration of the onset of unstable crack propagation and/or flaw coalescence when increasing irreversible microcracking is generated by vibratory loading.

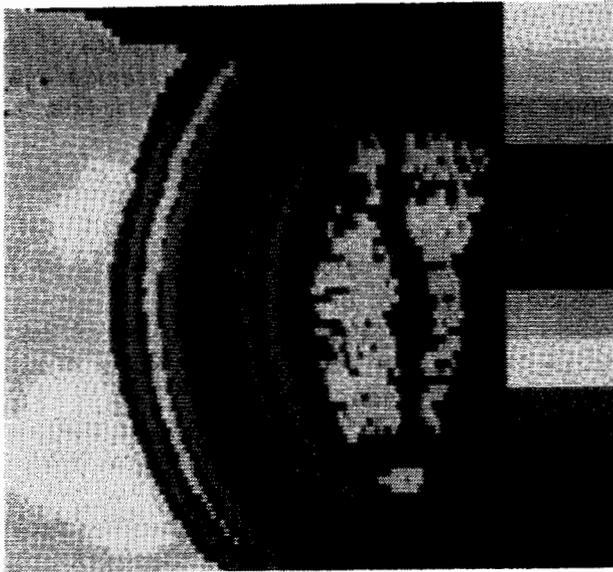


Fig. 6 - Heat dissipation during a tribology experiment (5 °C for each color hue).

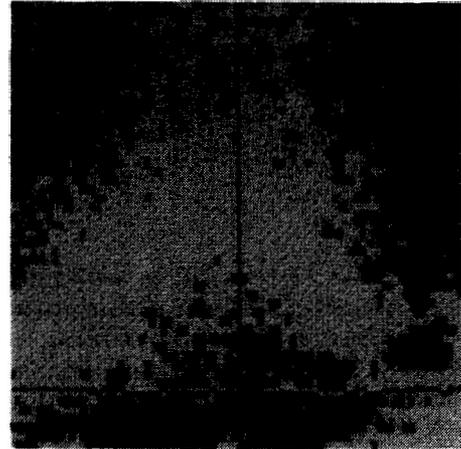


Fig. 8 - Thermogram of the base of a column before the start of the excitation (0.2 °C for each color hue).

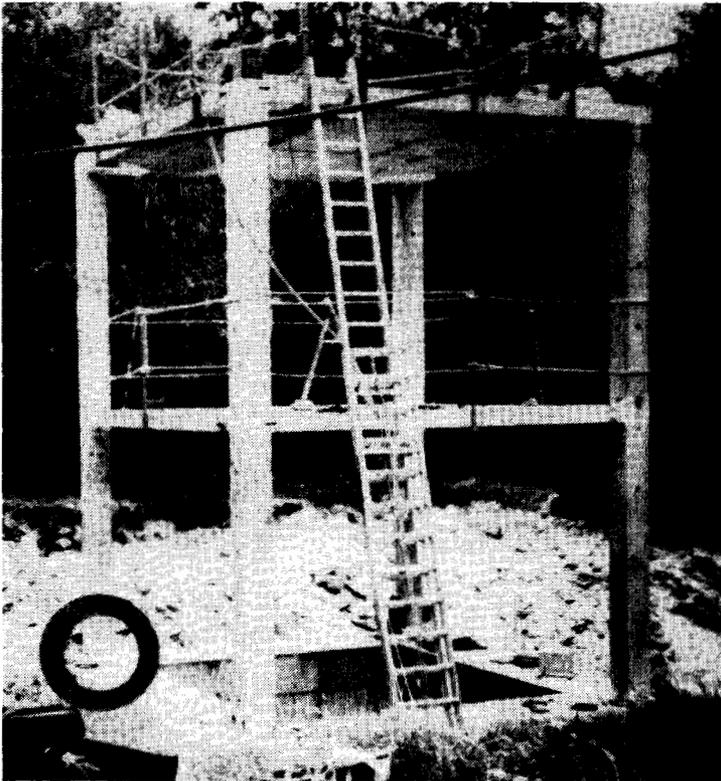


Fig. 7 - Experimental concrete structure under a seismic type loading generated by a rotating mass exciter on its top.

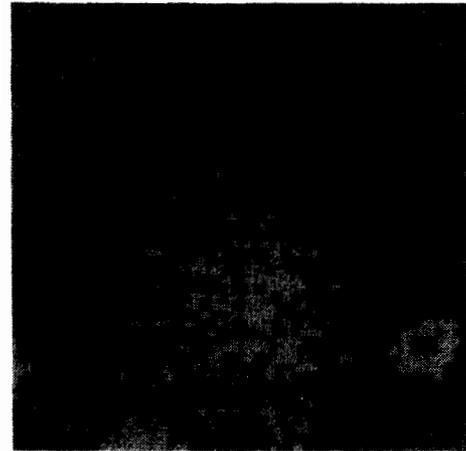


Fig. 9 - Thermogram at the same location recorded during loading (0.2 °C for each color hue).

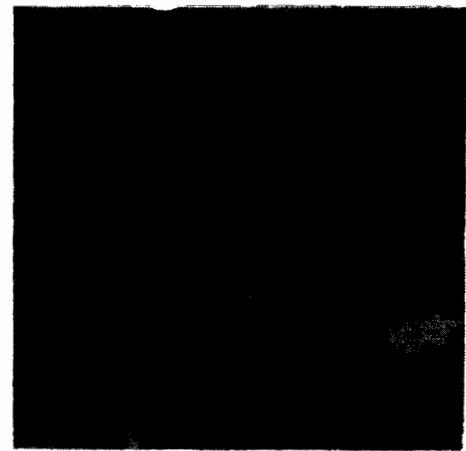


Fig. 10 - Thermogram at the same location recorded before cracks are visible (0.2 °C for each color hue).

Infrared thermography is a useful tool for scanning industrial equipment and processes to detect excess heat losses and malfunctions which result in temperature changes. A quality improvement may be gained in the practices of builders and contractors either through improved construction standards and better building codes.

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