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INFRARED THERMOGRAPHY OF FRACTURE OF CONCRETE AND ROCK

M.P. LUONG

ABSTRACT

Infrared thermography has been used as a nondestructive and noncontact technique to examine the mechanical response of concrete and rock specimens subjected to given static unconfined compressions and to a superimposed vibratory excitation. The parameter investigated in this paper is the heat generation due to energy dissipation by the material which has been excited beyond its stable reversible limit. This useful technique allows accurate illustration of the onset of unstable crack propagation and/or flaw coalescence when increasing irreversible microcracking is generated by vibratory loading.

INTRODUCTION

Fatigue and damage behaviour of plain concrete in compressive loading is an important consideration in connection with design or regulations of bridges, offshore concrete structures, earthquake resistant buildings, subjected to high allowable working stresses or in cases where the dead load forms a smaller part of the total load capacity. In such situations, failure of the construction material may occur at stresses below its static strength. Accurate knowledge should therefore be obtained of the mechanical behaviour of concrete subjected to various loadings.

In response to these problems, various fatigue analysis methodologies have been developed in recent years which isolate the factors affecting crack initiation and growth, and enable the prediction of their cumulative effect on the fatigue performance of structural components. They are based on (1) the formulation of analytical models for fatigue crack and growth ; and (2) the acquisition of supporting baseline data and validation of such models by means of a comprehensive testing procedure.

The existing partial damage hypothesis gives unsatisfactory results in evaluating the fatigue behaviour of plain concrete [1]. Volumetric, ultrasonic and acoustic emission measurements have not permitted a complete interpretation of the deterioration of concrete [2]. Research on absorption of energy in fatigue loading of plain concrete has been investigated [3] to aid understanding of the physical process of degradation when concrete 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. Unhappily the difficulties involved with the measurement systems were such that the results obtained by these methods were not completely satisfactory.

In rock mechanics, 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 cavities [4].

Rock salt generally displays failure characteristics intermediate between ductility and brittleness. It is relatively soft and can deform plastically, but it is extremely notch sensitive. In the presence of a flaw, brittle fracture often occurs with the onset of yielding.

The present paper proposes the use of infrared thermography as a nondestructive and noncontact technique to examine the mechanism of the cracking and failure of concrete or rock salt specimens which are subjected to a given unconfined compression and a superimposed vibratory excitation.

The aim of this study is to illustrate the onset of crack initiation by stress concentration in weakness zones, followed by unstable crack propagation and/or flaw coalescence caused by the thermomechanical coupling, when increasing microcracking is generated by vibratory excitation.

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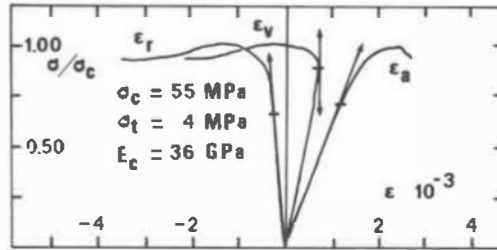


Fig. 1. Axial (ϵ_a), radial (ϵ_r) and volumetric (ϵ_v) strains of a concrete specimen subjected to a uniaxial unconfined compression.

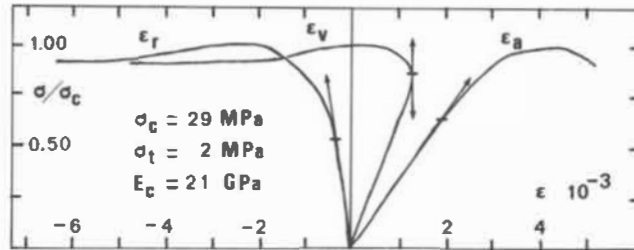


Fig. 2. Uniaxial unconfined compression on a cylindrical specimen of rock salt.

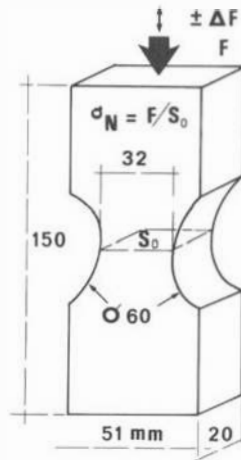


Fig. 3. Geometry and dimensions of the specimen.

In addition, an application of this technique is presented as a nondestructive method for inspection and evaluation of stress concentration on a concrete structure subjected to an earthquake type loading.

CHARACTERISTICS OF CONCRETE AND ROCK SALT

Concrete is a composite 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 deformation. At the structural level, breakdown appears as microcracking and possibly slippage at the aggregate-cement paste interfaces.

Natural rock salt appears to be a discontinuous mass with a medium to coarse grained polycrystal 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 ductile [5]. 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. 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 the crystal interfaces.

Failure in plain concrete or in rock salt 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 dependence on the mean normal stress [6].

The figure 1 presents a monotonic uniaxial compression test on a two years old concrete specimen.

The figure 2 describes the response of a cylindrical specimen of rock salt under uniaxial unconfined compression.

The volume change detected by strain gages in transverse and longitudinal directions of the cylindrical specimen is seen to be highly relevant in characterizing the deformation of concrete under loads. It may be attributed to (1) elastic variations of minerals, (2) or to dilatancy due to growing microcracking.

Under repetitive stresses, fatigue mechanism is a progressive, permanent internal structural changes occurring in the concrete and in the rock salt. These changes result in progressive growth of cracks and complete fracture.

The formation and propagation of microcracks have been detected by means of different 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 concrete or the rock salt.

It can be considered that the failure mechanism of concrete and rock salt consists primarily in the formation and propagation of microcracks.

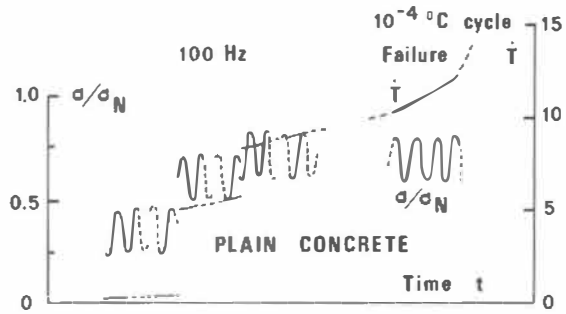


Fig. 4. Vibratory excitation on a concrete specimen subjected to various static uniaxial compression and evolution of the growth rate of heat on the warmest point.

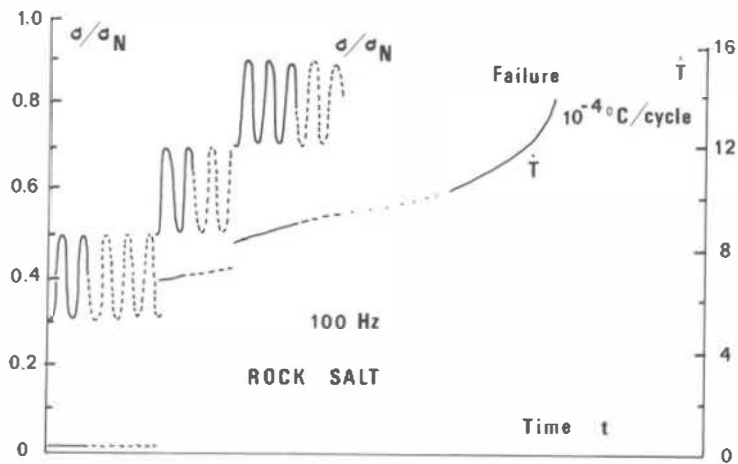


Fig. 5. Vibratory excitation on a rock salt specimen subjected to various static unconfined compression and evolution of the growth rate of heat at the warmest point.

The formations of microcracks are often associated with points of stress concentration in the material. 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 other 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.

THERMAL DISSIPATION

Infrared thermography has been successfully used as an experimental method for detection of plastic deformation during crack propagation of a steel plate under monotonic loading [7] or as a laboratory technique for investigating damage, fatigue and creep mechanisms occurring in engineering materials [8,9 and 10].

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.

1 - Thermoplasticity

The heat energy emitted in a loaded element is the main factor associated with the damage process initiating the failure of concrete and rock salt. In the case of concrete or rock salt at room temperature, it can be assumed that the mechanical transformation is small : changes in geometry are neglected. This permits the use of the small strain tensor as the variable of the deformation state [11].

If the material is elastic and perfectly plastic, the density of free energy per unit mass is $W = W(\epsilon - \epsilon^P, T)$ and the stress is $\sigma = \rho \frac{\partial W}{\partial \epsilon}$. The plastic strain is denoted by ϵ^P and the absolute temperature by T . The entropy S per unit mass is defined as $S = -\partial W / \partial T$.

The two laws of thermodynamics are written for any volume v :

$$\dot{E} + \dot{C} = \dot{W}_e + \dot{Q} \quad (1)$$

$$\dot{Q} = \int_V \rho T \dot{S} dv - \int_V D dv \quad (2)$$

$$\text{where } \int_V D dv \geq 0$$

The letter D denotes the dissipated intrinsic power per unit volume ; Q the heat supply per unit mass ; $E = \int_V (TS) + W) \rho dv$ is the internal energy per unit mass in v ; W_e the work of external forces and C the kinetic energy.

Eliminating S in (1) and (2), the balance of mechanical energy leads to the equation :

$$\dot{C} + \int_V \sigma \dot{\epsilon} dv = \dot{W}_e \quad (3)$$

and

$$D = \sigma \dot{\epsilon}^P \quad (4)$$

If q denotes the heat flux, it can be written :

$$\dot{Q} = - \int_{\partial V} q \cdot n ds + \int_V \phi dv = \int_V (\phi - \text{div } q) dv$$

where n is the exterior normal vector and ϕ the eventual specific density of heat sources in v .

The equation (2) becomes locally :

$$\phi - \text{Div } q = \rho TS - D \quad (5)$$

The Fourier heat conduction law $q = -k \text{ grad } T$ leads to the heat conduction equation :

$$\phi + \text{div } k \text{ grad } T = \rho TS - \sigma \dot{\epsilon}^P \quad (6)$$

Now :

$$\rho \dot{T} S = -\rho T \left(\frac{\partial^2 W}{\partial T \partial \epsilon} \dot{\epsilon} + \frac{\partial^2 W}{\partial T \partial \epsilon^p} \dot{\epsilon}^p + \frac{\partial^2 W}{\partial T \partial T} \dot{T} \right)$$

Taking into account the form of the free energy $W(\epsilon - \epsilon^p, T)$, it follows that :

$$\rho \dot{T} S = -\rho T \frac{\partial^2 W}{\partial T \partial \epsilon} (\dot{\epsilon} - \dot{\epsilon}^p) - \rho T \frac{\partial^2 W}{\partial T \partial T} \dot{T}$$

The quantity $c = \rho T \frac{\partial^2 W}{\partial T \partial T}$ is the specific heat per unit volume and $\lambda_{ij} = -\rho \frac{\partial^2 W}{\partial T \partial \epsilon_{ij}^e}$ are thermoelastic coefficients.

Finally, the coupled heat conduction equation of thermoelastic plasticity is obtained :

$$c \dot{T} = \text{div } k \text{ grad } T - T \alpha \dot{\sigma} + D + \phi \quad (7)$$

where c denotes the specific heat, T the absolute ambient temperature, k the heat conductivity, α the thermal dilatation, σ the stress tensor, D the intrinsic dissipation and ϕ the heat source per unit volume.

The first term on the right side governs the thermal diffusion which tends to make the temperature uniform in the specimen. The second term represents the thermoelastic effect that may be significant in cases of isentropic loading. The nature of factors k and α is tensorial in case of anisotropic material. The third term is the thermal dissipation generated by viscosity or plasticity. The last term show the existence of heat source in the specimen.

2 - Electromagnetic radiation

Electromagnetic radiation is a form of energy characterized as waves or as particles called photons. Visible light is the most familiar form of electromagnetic energy. Other forms include radio waves, heat radiation, ultraviolet rays, X-rays and gamma rays. All this energy is similar and radiates in accordance with basic wave theory. Electromagnetic radiation is produced by the acceleration of charged particles. More rapid acceleration produces higher energy (shorter wavelength) waves. The electromagnetic spectrum is a categorization by wavelength of electromagnetic energy. The range from 2 to about 100 micrometres is called "thermal infrared".

All matter radiates energy because it contains charged particles being accelerated (changing speed or directions), the higher the temperature the greater the acceleration. The amount of energy radiated depends on the object's temperature and its ability to radiate.

3 - Infrared vibrothermography

Infrared thermography utilizes a photovoltaic detector composed of indium antimonide InSb in a sophisticated electronics system in order to detect radiated energy and to convert it into a detailed real time thermal picture on a video system. Response times are shorter than a microsecond. Temperature differences in heat patterns as fine as 0.2°C are discernible instantly and represented by several distinct hues.

This technique is sensitive, nondestructive and noncontact, thus ideally suited for records and observations in real time of heat patterns produced by the heat transformation of energy due to stress concentration and/or plastic strains. No interaction at all with the specimen is required to monitor the thermal gradient.

The quantity of energy W_r emitted by infrared radiation is a function of the temperature and the emissivity of the specimen. The higher the temperature, the more important is the emitted energy. Differences of radiated energy correspond to differences of temperature, since $W_r = h T^4 \omega$, where h denotes a constant, T the absolute temperature and ω the emissivity.

Concrete and rock salt presents 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 method for observing the damage process of concrete and rock salt.

4 - Experimental set-up and results

The high-frequency servo-hydraulic test machine Servotest, used at the Laboratoire de Mécanique des Solides, 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 sample is observed in a nondestructive, noncontact manner by means of an infrared thermographic system AGA THERMOVISION 782. The thermal image is shown on the monitor screen.

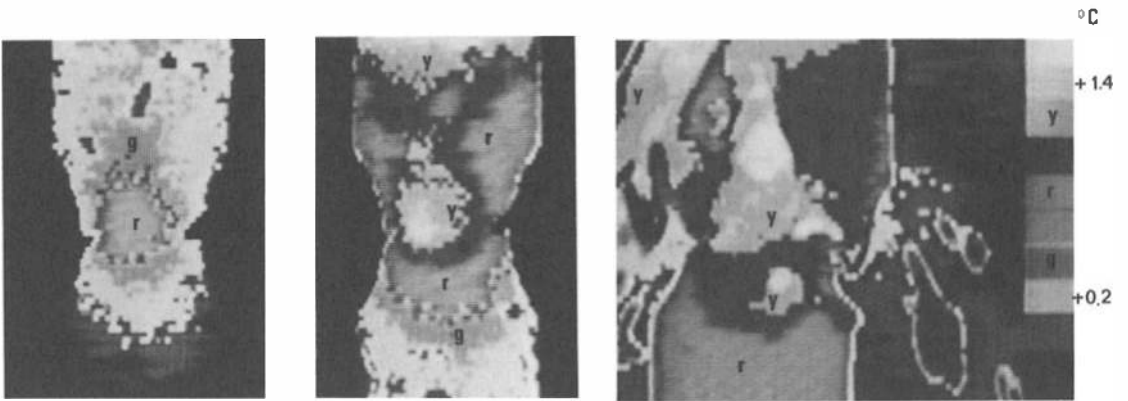


Fig. 6. Thermograms of a plain concrete specimen evidencing the process of unstable failure.

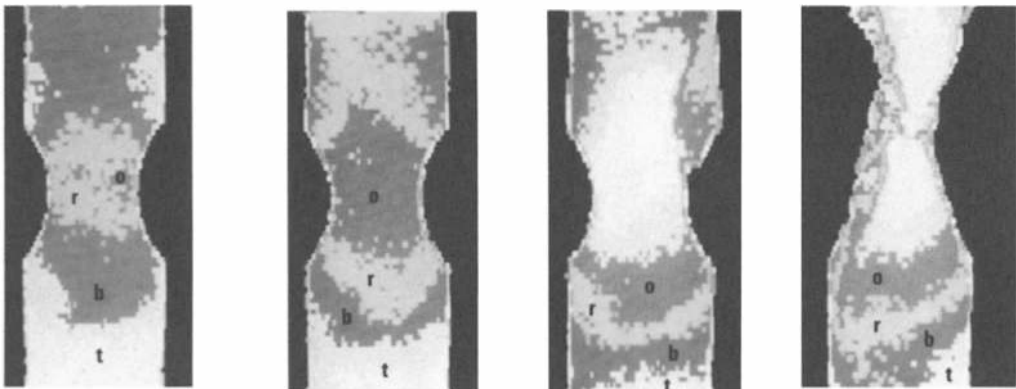


Fig. 7. Heat dissipation describing the process of unstable failure in rock salt specimen.

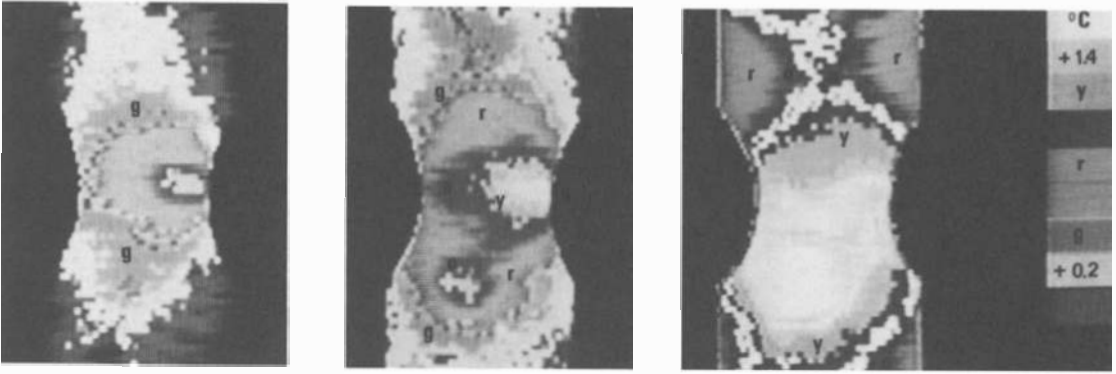


Fig. 8. Flaw coalescence mechanism occurring during concrete failure.

Room temperature

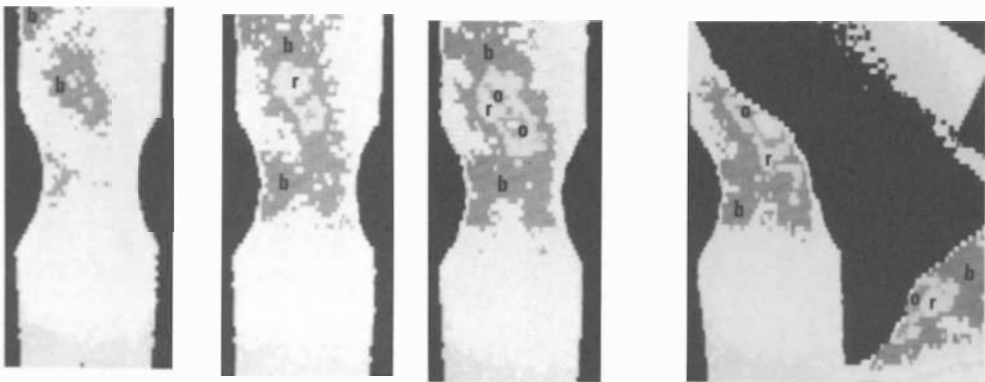
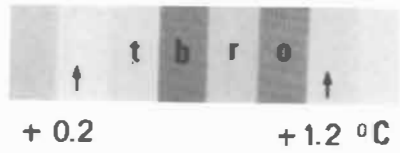


Fig. 9. Flaw coalescence achieving the progressive failure of rock salt specimen.

The parameter investigated in this test is heat generation due to the energy dissipated by the concrete which has been excited beyond the stable reversible domain. A vibratory loading at 100 Hz on the specimen subjected to a given static compression (figure 3) 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.

The figures 4, 5 and 6, 7 show the different stages of heat dissipation describing the process of unstable crack propagation which occurs in specimens of plain concrete and natural rock salt.

The figures 8 and 9 record respectively the flaw coalescence mechanism in concrete and rock salt.

The growth rate of heat on the warmest point enables the detection and the location of the onset of specimen failure.

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 [12].

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 application of infrared scanning to inspection of concrete structure relies on the fact that energy is dissipated during the process of failure when internal cracks or flaws develop. It is indeed well known that the fatigue process involves crack initiation and/or nucleation, stable crack propagation, and final fracture or unstable crack propagation.

Figure 10 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. It is recognized that the connections present adequate ductility in order to undergo large 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.

Figure 11, 12 and 13 show the progressive evolution of heat dissipation at a column base before crack line is visible.

CONCLUDING REMARKS

Owing to the thermomechanical coupling infrared vibrothermography offers the possibility of a nondestructive, noncontact test of concrete and rock salt degradation. 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.

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.

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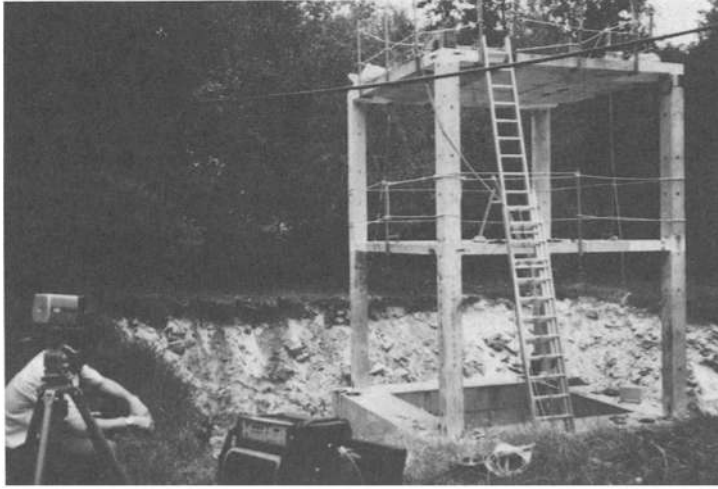


Fig. 10. Experimental concrete structure under seismic type loading generated by a rotating mass excitator on its top.

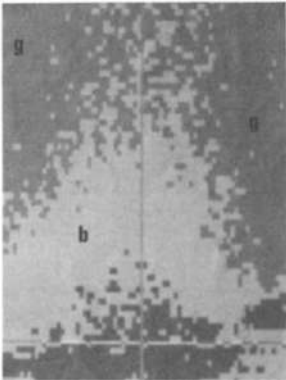
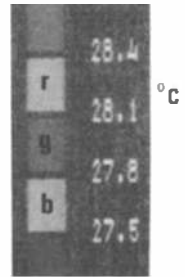


Fig. 11. Thermogram of the base of a column before the start of the excitation

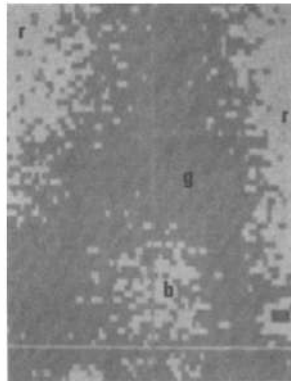


Fig. 12. Thermogram at the same location recorded during loading

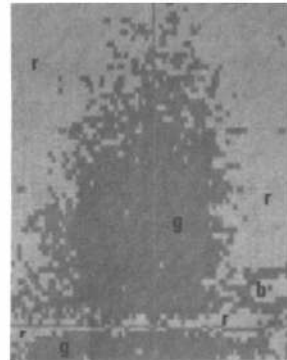


Fig. 13. Thermogram at the same location recorded before cracks are visible.

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