Transactions of the **14th International Conference on Structural Mechanics in Reactor Technology** (SMiRT 14), Lyon, France, August 17-22, 1997 **H04/6**

Infrared thermographic evaluation of fatigue behavior of concrete

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ABSTRACT

The paper aims to illustrate the relevant use of infrared thermography as a nondestructive, noncontact and real-time technique (a) to observe damage processes and mechanisms of concrete failure and (b) to detect the occurrence of intrinsic dissipation localization. The investigated parameter is the heat generation due to intrinsic dissipation of concrete subject to compressive loadings. Owing to the thermomechanical coupling, this technique provides a simple means for evaluating fatigue strength through dissipative phenomena.

1. INTRODUCTION

Current technological developments tend towards increased exploitation of materials strengths and towards tackling extreme loads and environmental action such as offshore structures subject to wind and wave loading. Fatigue of plain and reinforced concrete structural member has been studied for many years in order to design safe structures [5]. Empirical methods using Wöhler (or S-N) curves have traditionally been considered in conjunction with statistical treatment of data. The present paper proposes the use of infrared thermography as a nondestructive, noncontact and real time technique to examine the mechanisms of damage and to illustrate the onset of damage process, stress concentration and heat dissipation localization in loaded zones. In addition, this technique can be used as a nondestructive method for evaluating the fatigue limit of concrete under compression.

2. CHARACTERISTICS OF CONCRETE MATERIALS

Plain concrete is the most popular engineering material, consisting of coarse aggregates embedded in a continuous matrix of mortar that is a mixture of hydraulic binding materials, additives and admixtures distributed in a suitable homogeneous dosage. Under applied loading, the concrete as a whole deforms in spite of significant incompatibilities between the aggregates and the matrix that promote further breakdown. At the macroscopic level, breakdown is accompanied by both losses 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. The formation and propagation of microcracks have been detected using well known measuring methods as for example:

- The ultrasonic pulse velocity technique [17-19] 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 its propagation will be affected by the presence of more or less unstable cracks [13].
- The acoustic emission method [16] 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 readily detected by studying sounds emitted from the materials.

Stress concentrations occur and result in localized forces which are sufficient to promote plasticity and anelasticity or both. Damage and failure may thus be viewed as a microstructural process through the activation and 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. Macroscopically it occurs a localization of intrinsic dissipation before a visible failure. 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 concrete properties (1) to establish strength, (2) to optimize design values and (3) to insure quality control.

3. QUANTITATIVE MEASUREMENT OF DAMAGE

The term damage is commonly used in various ways by different investigators to describe the process of (1) crack initiation, fatigue lifetime and the early microcracking stages of crack growth, and (2) fatigue damage associated with macroscopic fatigue crack extension. Continuum mechanics assumes that damage is induced by the initiation and growth of microcavities. Damage theories usually rely on assumed discontinuous phenomena at the microscopic scale [4]. Damage parameters, considered as internal variables, are introduced according to the following main approaches:

3.1. Effective stress

In order to develop the concept of an effective stress, Kachanov [8] introduced a continuous variable D, related to the scalar density of defects. The elastic body is assumed to contain many cracks. It has been thought that the stiffness reduction, produced by the cracks, is due to the stress singularities at the crack tips. Because of this, the stress energy for prescribed surface fractions is increased by a finite amount, relative to the stress energy of the body without cracks. Thus the cracks increase the compliances and decrease the stiffnesses. This has been the starting point of damage theories that are developed for analyzing fatigue in metals, creep and creep-fatigue interaction [10].

3.2. Plasticity formalism

The plasticity formalism describes the inelastic behavior of progressively fracturing solids by introducing the concept of fracturing stress or fracturing strain. The elastic plastic fracturing model combines the elastic plastic law and the elastic brittle law [7] .Taking into account the most fundamental aspects of inelastic deformation and neglecting the details at the microstructural level, Mroz [14] suggests phenomenological constitutive models that are widely used in engineering applications.

3.3. Micromechanics

The micromechanical approach aims to provide a ready understanding of the damage mechanism at the macroscale. A random macrostructure is generated by computation from the known behavior of microstructures, each microstructure being characterized by a finite number of parameters [20]. On the basis of micro- and macroscale relationships, Dang-van [6] proposed a multiaxial fatigue criterion with a realistic physical interpretation of fatigue phenomena. During a polycyclic fatigue test, the stress at the macroscopic scale remains elastic. However, at the microscopic scale, the metal is neither isotropic nor homogeneous. It is constituted of randomly oriented crystals. This induces local fluctuations of the microscopic stress and defines the macroscopic stress. Thus the local microscopic stress can locally exceed the yield strength in certain unfavorably oriented grains, whereas the macroscopic stress remains elastic. If the cyclic plastic response of the grain to the solicitation is not elastic shakedown, some microcracks will appear. These microcracks coalesce to form a crack of detectable size.

Nevertheless, the main question still remains: *What is damage ?* More significant advances in understanding damage must take a clear distinction between: the *physical* damage, the *process* of damage and the *manifestation* of damage. 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 [3] or as a laboratory technique for investigating damage, fatigue and creep mechanisms occurring in engineering materials [11-12]. Based on the fact that plastic deformation is not homogeneous, the stress, acting upon a plastic inhomogeneity that is embedded in elastic surroundings, is a function of its plastic strain, diminishing with increasing strain.

4. THEORETICAL BACKGROUND

The development of the thermo-visco-elastic-plasticity equations [1-9-18] leads to the following relationship:

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

where

- K ($W.m^{-1}.K^{-1}$: Watt per metre per Kelvin degree) the thermal conductivity
- β denotes the coefficient of the thermal expansion matrix,
- C_v ($J.kg^{-1}.K^{-1}$) the specific heat at constant deformation,
- r_0 the heat supply,
- $\dot{E}^e$ the elastic strain tensor,
- $\dot{E}^I$ the inelastic strain tensor,
- S the second Piola-Kirchhof stress tensor,
- T and finally the absolute temperature.
- $\overset{4}{D}$ the fourth-order elasticity tensor,

This coupled thermomechanical equation defines the potential applications and various uses of infrared scanning technique in engineering problems. However the detected temperature change, resulting from four quite different phenomena, must be correctly discriminated by particular test conditions and/or specific data reduction. This is the main difficulty when interpreting the thermal images, obtained from experiments under usual conditions, and particularly in cases of difficult environments.

4.1 - Heat sources
The first term is related to the existence of heat sources in the scanning field. 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.

4.2 - Thermal conduction
The second term on the right hand side governs the heat transference by thermal conduction, in which the heat passes through the material to make the temperature uniform. Where an unsteady state exists, the thermal behavior is governed by its thermal conductivity and heat capacity. The thermal diffusivity $\alpha = K / C$ ($m^2.s^{-1}$) 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. A pulsed heat flux has been used to characterize a delamination in a composite by the break, caused in the temperature time history [2].

4.3 - Thermoelasticity
The third term illustrates the thermoelastic coupling 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 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 may be significant in cases of isentropic loadings. A stress analysis technique is known as SPATE (Stress Pattern Analysis by Thermal Emissions) that measures the temperature due to the thermoelastic heat variations of a body under cyclic loading [15].

4.4 - Intrinsic dissipation
The last term defines the energy dissipation, generated by viscosity and/or plasticity. The work, done in plastic deformation, can be evaluated by integrating the material stress-strain curve. This internal dissipation term constitutes a significant part of the nonlinear coupled thermomechanical analysis. The infrared thermographic technique in use is mainly concerned with differences in temperature (or thermal gradients) that exist in a material rather than the absolute value of temperature. This study considers the intrinsic dissipation as the most accurate indicator of damage manifestation. It highlights the advantages of the infrared thermographic technique, used for the detection and the discrimination of the nonlinear coupled thermomechanical effect within a consistent theoretical framework.

5. INFRARED THERMOGRAPHY OF CONCRETE UNDER LOADS

Infrared thermography is a convenient technique for producing heat images 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.

5.1. Infrared scanner
A scanning camera has been used, which is analogous to a television camera. It utilizes an infrared detector in a sophisticated electronics system in order to detect radiated energy and to convert it into a detailed real time thermal image in a color and monochrome video

system. Response times are shorter than 1 μs. Temperature differences in the heat patterns are discernible instantly and represented by several distinct hues. 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 the emitted energy. Differences of radiated energy correspond to differences of temperature. Since the received radiation has a nonlinear relationship to the object's temperature, and can be affected by atmosphere damping and includes reflected radiation from object's surroundings, calibration and correction procedures have to be applied. Knowing the temperature of the reference, the object's temperature can then be calculated with a sensitivity of 0.1 °C at 20 °C. The infrared scanner unit converts electromagnetic thermal energy radiated from the tested specimen into electronic video signals. These signals are amplified and transmitted via an interconnecting cable to a display monitor where the signals are further amplified and the resultant image is displayed on the screen.

5.2. Infrared thermography of plain concrete specimens

Concrete 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 generation 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 technique for observing the damage process of concrete materials [12]. In laboratory, the high frequency servo-hydraulic test machine provides a means of vibration and dynamic testing of engineering materials. A vibratory loading at 100 Hz, applied on the specimen that is subjected to a given static compression, exhibits in a nondestructive manner the irreversible plastic strain concentrations around gaps or cracks. The contribution of the plasticity term is revealed by the rapid evolution of heat dissipation once the stable reversible stress domain has been exceeded, demonstrating the occurrence of an unstable crack propagation or coalescence of flaws existing in the concrete specimen. Experimental results have already shown that:

a) With a vibratory excitation between 25 and 50 percent of the nominal uniaxial compression $\sigma_N = F/S_o$, the heat dissipation, detected for 2,000 load cycles, is small, even at the hottest location.

b) When $0.50 \leq \sigma/\sigma_N \leq 0.75$, stress concentrations around cracks or defects are readily detected at the 1,000th load cycle.

c) For $0.63 \leq \sigma/\sigma_N \leq 0.88$, cracking occurs increasingly in the reduced section part of the specimen.

Infrared thermography readily depicts intrinsic dissipation localization announcing quite different mechanisms of damage preceding concrete failure. 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 (Figure 1). The rate of heat generation at the hottest location is used to detect the threshold of the failure process if compared with the traditional stress-strain curve.

5.3. Short-time evaluation of concrete fatigue limit

In accordance with the coupled thermomechanical equation, the analysis of thermal images consists in isolating the intrinsic dissipation from thermal noises by simply subtracting the thermal image at reference time from the thermal image at 1,000 load cycles. A computer aid

thermography software allowed the data reduction of the thermal images using the function subtraction of images. The resulting image is a subtracted image showing the temperature difference between two compared images that provided quantitative values of intrinsic dissipation. This procedure has been applied for each load step. The manifestation of the fatigue damage mechanism is revealed by a break of the intrinsic dissipation regime. The starting load level must be chosen below the fatigue limit. It significantly depends upon concrete characteristics. For example, we started the test at a stress level of about 20% of failure nominal stress, then 30%, 40%, etc. This is continued until temperature rise reaches some Celsius degrees. For each load step, an averaging treatment (among 4, 8, 16 or 32 thermograms) provides more stable thermal images.

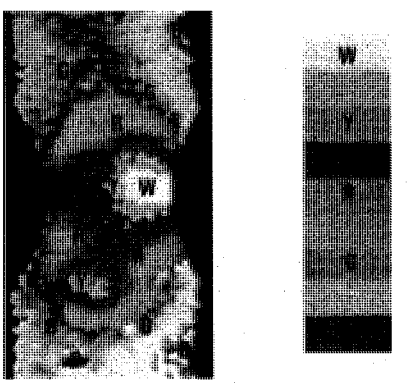

Fig. 1 Infrared thermography of a concrete specimen under vibratory compressive excitation: weakness zones are readily detected by heat patterns after 7,000 load cycles(0.2 °C for each color hue).

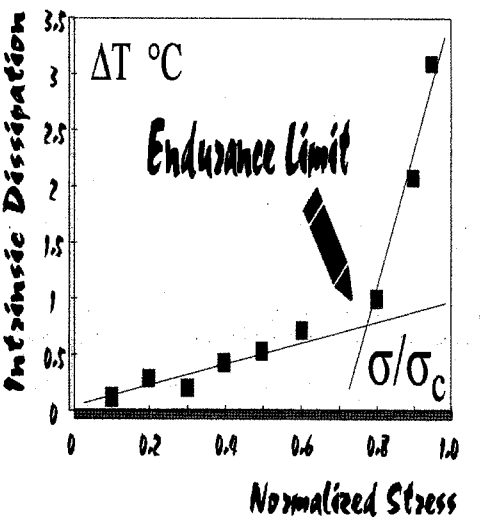

Fig. 2 Graphical determination of the fatigue limit of a concrete specimen.

Experimental results are summarized in Figure 2 which illustrates how the fatigue limit is determined using a graphical procedure. The threshold of critical thermal dissipation is roughly the same for different chosen number of load cycles. It roughly corresponds to the value deduced from standard procedures. These experiments have shown that the infrared thermographic technique can provide the fatigue limit of concrete within a few hours instead of several months when using for instance the standard staircase method.

5.4. Infrared thermographic scanning of an earthquake resistant concrete structure

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 concrete structures. The phenomenological behavior in consideration is therefore the standard of reference, allowing the use of the methods and results of continuum mechanics for analyzing and modeling their engineering performance. Information about the location and significance of structural defects 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 the energy is dissipated during the process of accumulative damage when internal cracks or flaws develop. Figure 3 describes an experimental reinforced 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. 4 shows the progressive evolution of heat dissipation at a column base before crack line becomes visible.

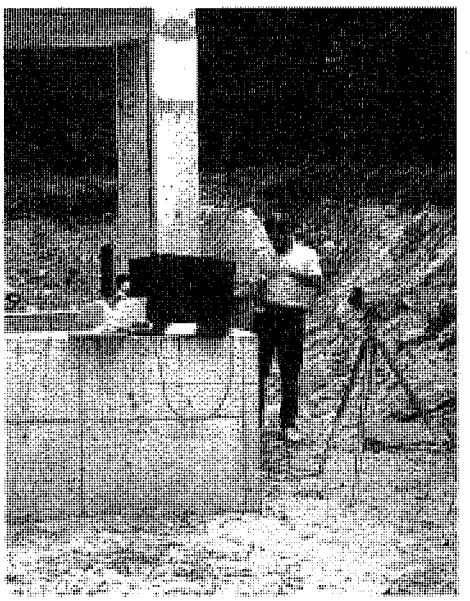

Fig. 3 Experimental concrete structure under a seismic type loading.

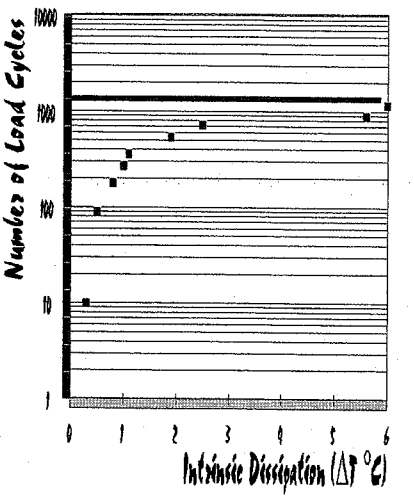

Fig. 4 Fatigue lifetime evaluation of a column base of the reinforced concrete structure subjected to seismic type loading.

6. CONCLUDING REMARKS

This work has demonstrated that the *dissipativity* of the tested materials under loading is the most sensitive and accurate *manifestation of damage*.

Owing to the thermomechanical coupling, infrared thermography provides a nondestructive, noncontact and real-time test to observe the physical process of concrete degradation and to detect the occurrence of its intrinsic dissipation. Thus it readily provides a measure of the material damage and permits to evaluate the limit of a progressive damaging process under load beyond which the material is susceptible to failure. The method allows not only qualitative work such as finding flaws, defects or weakness zones, but also quantitative analysis of the effects of flaws and defects on strength and durability of concrete structural components. This useful and promising technique offers an accurate illustration of crack

initiation, and readily detects the onset of its unstable propagation through the material and/or flaw coalescence when increasing irreversible microcracking is generated by cyclic loading. The main interest of this energy approach is to unify microscopic and macroscopic test data. The parameter *intrinsic dissipation* under consideration is a scalar quantity, easy to evaluate with accuracy. Subsequently it may suggest multiaxial design criteria, highly relevant for full scale testing on engineering structures.

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