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INTRODUCING INFRARED THERMOGRAPHY IN DYNAMIC TESTING ON REINFORCED CONCRETE STRUCTURES

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ABSTRACT

This paper aims to illustrate the use of infrared thermography as a non-destructive, real-time and non contact technique to detect, observe and evaluate the evolution of temperature changes caused by the diverse physical processes of irreversible physical phenomena. The results obtained highlight the advantages of differential infrared thermography: first to observe the physical manifestation of damage and the mechanism of failure of concrete, second to detect the occurrence of intrinsic dissipation localization, and third to evaluate the fatigue strength in a very short time, compared to traditional testing techniques. This technique minimizes the thermal noise in real or industrial environments and thus facilitates the detection, discrimination and interpretation of the diverse dissipative phenomena involved in these non-linear coupled thermomechanical effects within the framework of a consistent theoretical background. At the structural level, breakdown appears as microcracking and possibly slippage at component interfaces. In addition to traditional techniques of mechanical strength evaluation, it provides a ready evaluation of a limit of acceptable damage under service loading beyond which the material will be rapidly destroyed, or of fatigue resistance under cyclic excitations or dynamic solicitations.

Keywords: Damage detection - Dissipation mechanisms - Non-destructive evaluation - Reinforced concrete structural walls - Shaking table testing.

1. INTRODUCTION

Current technological developments tend towards increased exploitation of materials strengths and towards tackling extreme loads and environmental actions such as offshore structures subject to wind and wave loading[2-17] or buildings in seismic areas[18]. Concrete is widely used as a construction material because of its high strength-cost ratio in many applications. Experience of earthquakes and laboratory tests has shown that well designed and detailed reinforced concrete[3] is suitable for earthquake resistant structures. The most severe likely earthquake can be survived if the members are sufficiently ductile to absorb and dissipate seismic energy by inelastic deformations[13]. This requires a designer to realistically assess the acceptable levels of strength and to ensure adequate dissipation[5]. This paper proposes the use of infrared thermography as a non-destructive, non-contact and real-time technique to examine diverse mechanisms of dissipation and to illustrate the onset of damage process, stress concentration and heat dissipation localization in loaded zones[10]. In addition, this technique can be used as a non-destructive method for evaluating the fatigue limit of concrete structure subject to repeated loading. This approach represents a departure from the traditional experimental-empirical approach to fatigue analysis and offers promise for improved estimation of fatigue performance in complex structures. The development of satisfactory design procedures not only enables a rational selection of allowable stresses, but also permits trade-off studies between allowable stresses, alternative materials fabrication procedures, and provides guidance in the selection of surveillance/maintenance policies.

2. CHARACTERISTICS OF CONCRETE

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. 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. Non-destructive and non contact tests are thus needed to define concrete properties: (a) to establish strength taking into account of a threshold of acceptable damage, (b) to optimize design values and (c) to insure quality control.

3. BACKGROUND OF THERMOMECHANICAL COUPLING IN SOLIDS

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. The work, reported in this paper, considers the intrinsic dissipation as a highly sensitive and accurate indicator of damage manifestation and assumes that intrinsic dissipation and damage present the same evolution under fatigue loading up to failure[6-9-12].

3.1 Theoretical Background

In the framework of thermodynamics of irreversible processes, the development of thermo-elastic-plasticity equations leads to the coupled thermomechanical equations[11]:

$$\rho C_v \dot{T} = r_o + K\nabla^2 T - \left(\beta : D : \dot{E}^e\right) T + S : \dot{E}^I \tag{1}$$

where ρ denotes the mass unit in the reference configuration, Cv the specific heat at constant deformation, T the absolute temperature, ro the heat supply, K the thermal conductivity, ∇2 the Laplacian operator, β the coefficient of the thermal expansion matrix, D the fourth-order elasticity tensor, Ee the elastic strain tensor, S the second Piola-Kirchhoff stress tensor and EI the inelastic strain tensor. The superposed dot stands for the material time derivative. The volumetric heat capacity of the material C = ρ Cv is the energy required to raise the temperature of a unit volume by 1°Celsius (or Kelvin degree).

This equation shows the potential applications and various uses of the infrared scanning technique in engineering problems. Temperature changes result from four distinct physical phenomena: heat sources, conduction effect, reversible thermo-elastic coupling and intrinsic dissipation.

3.2 Infrared Scanner

A scanning camera is used, which is analogous to a television camera. It uses 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 1μs. Temperature differences in the heat patterns are discernible instantly and represented by several distinct hues. The quantity of energy W (W.m-2.μm-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 non-linear 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 room temperature. 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.

3.3 Infrared Thermography of Plain Concrete Specimen

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 that 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 vibro-thermography as a non-destructive and non-contact technique for observing the damage process of concrete materials9. In laboratory, the high frequency servo-hydraulic test machine provides a means of vibration and dynamic testing of engineering materials. A vibratory loading at 100Hz, applied on the specimen that is subjected to a given static compression, exhibits in a non-destructive 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 is exceeded, demonstrating the occurrence of an unstable crack propagation or coalescence of flaws existing in the concrete specimen (Figure 1). Experimental results have already shown that:

1) Under a vibratory excitation between 25 and 50 percent of the nominal uniaxial compression $\sigma N = F/S0$, the heat dissipation, detected for 2000 load cycles, is small, even at the hottest location.

2) 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.

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

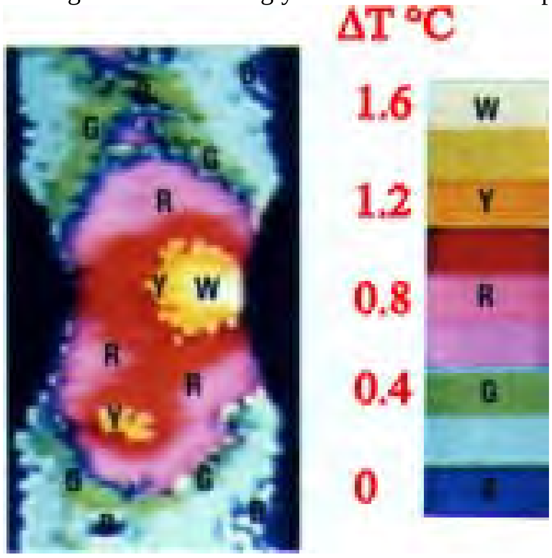

Figure 1. Infrared thermography of a plain concrete specimen subject to compressive vibrations (temperature changes are given in degrees Celsius).

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. 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. These results have been readily extended to rock materials8.

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 1000 load cycles. 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 change between two compared images, obtained under nearly identical test conditions. This image processing provided quantitative values of intrinsic dissipation.

This procedure is 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.

Experimental results are summarized in Figure 2 that 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 traditional standard staircase method. These results are consistent with those obtained on concrete prisms subjected to compressive fatigue testing16. This so determined stress limit could also be understood as a threshold of acceptable damage for plain concrete under compressive loading.

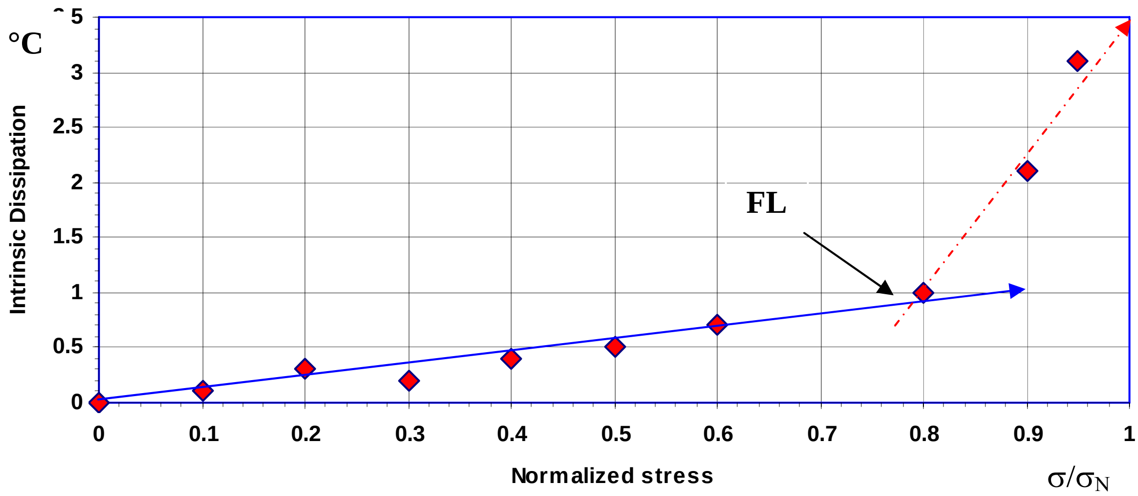

Figure 2. Graphical determination of the fatigue limit FL of a plain concrete (dissipation is given in degrees Celsius proportional to energy).

3.4 Infrared Observation of Energy Dissipation on Reinforced Concrete Structures Subjected to Shaking Table Loading

Load bearing walls in reinforced concrete structures are of common use in France. Within the framework of the ECOEST2 (European Consortium of Earthquake Shaking Tables) and ICONS (Innovative Seismic Design New and Existing Structures, Topic 5 Shear wall structures) research project supported by the European Commission, two large-scale specimens (36 tons) representing 1/3rd scaled five-story buildings (so-called CAMUS III and CAMUS IV) have been tested under dynamic seismic-like loading on the major shaking table Azalée at CEA Saclay. The loading input signal is the so-called Nice artificial accelerogram (far-field earthquake) characterized by its PGA (peak ground acceleration) values. These performed mock-up tests aim to demonstrate the major influence of boundary conditions at the base of the model, and the feasibility of optimizing low ratio and adequate distribution of reinforcements in order to obtain multi-cracking zones (multi-fuse concept) in opposition with the traditional pseudo plastic hinge localized at the base of a R/C wall (mono-fuse concept).

3.4.1 CAMUS III highlighting the effects of reinforcement ratios

The CAMUS III specimen, composed of two lightly reinforced walls anchored to the shaking table, is designed as recommended Eurocode 8 allowing a plastic hinge at the base. Special attention has been paid on the influence of different reinforcement ratios and boundary conditions15. During the performed tests, CAMUS III mock-up suffered from high damage levels. Its behavior was mostly conditioned by its flexural bending. Examination after tests evidenced failure of steel reinforcements. In this case, the dissipation mechanism caused by plasticity of steel reinforcements can be considered as an internal parameter so that the equation (1) has to be completed with two supplementary terms representing the cross coupling effects4: the former is caused by the dependence of the stress tensor on temperature (reversible) while the latter is induced by the same dependence of the generalized force conjugates to the internal state vector (irreversible). This phenomenon appeared on the concrete surface with a delay depending on the depth of reinforcements. Thus infrared thermography readily evidenced and localized, on the scanned wall surface, the plasticity of steel reinforcements with a delay due to heat conduction characteristics of concrete (Figure 3).

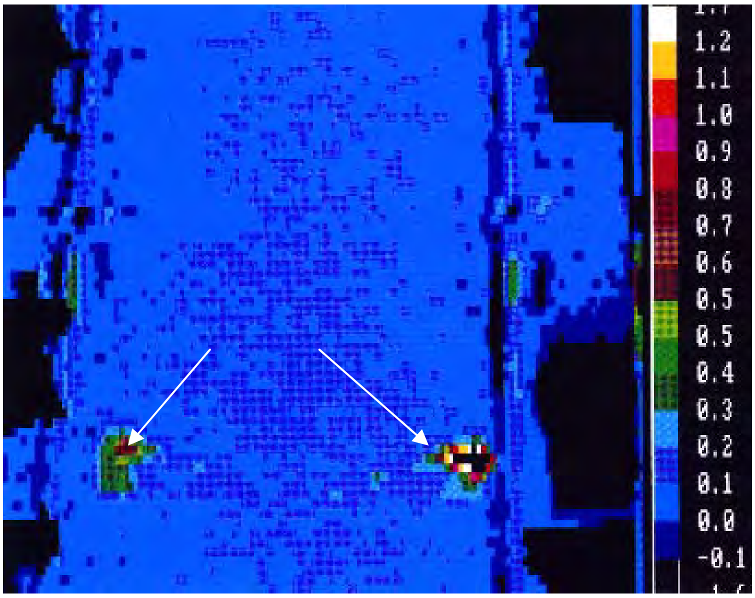

Figure 3. Infrared thermographic determination of dissipation caused by plasticity of steel reinforcements (temperature changes are given in degrees Celsius).

3.4.2 CAMUS III highlighting the effects of boundary conditions

The CAMUS IV specimen, composed of two lightly reinforced walls, was designed according to PS92 recommendations1 and simply rested on a 40 cm thick sand layer. This test aimed to reproduce the phenomena of uplift and the fact that such a non-linear phenomenon was capable of isolating the structure from ground-borne excitation. In this case it is expected that soft boundary conditions will determine the seismic behavior of structural walls. As in the above case, infrared thermography evidenced the friction mechanism between steel reinforcements and concrete matrix with a delay necessitated by heat conduction through the concrete layer (Figure 4).

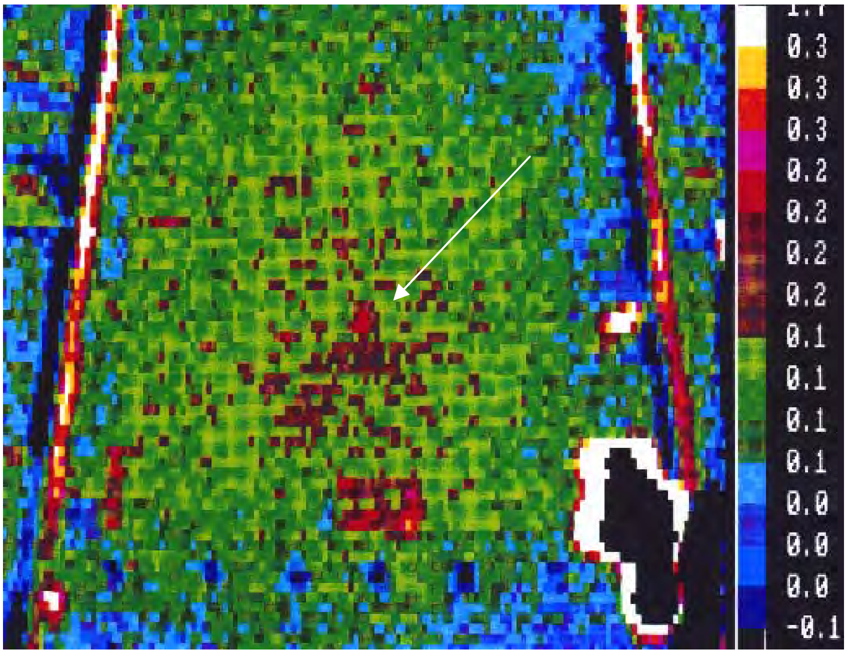

Figure 4. Infrared thermography of dissipation caused by slippage of steel reinforcements embedded in the concrete matrix (temperature changes are given in degrees Celsius).

3.5 Dissipative Mechanisms and their Range of Temperature Changes

Experimental results showed that the discrimination of the involved dissipative mechanisms is very delicate. Fortunately this work, originally intended to validate diverse different dissipative mechanisms, provided the following interesting discriminative characteristics of temperature changes (Table I).

Table I. Magnitude order of temperature changes.

Dissipative mechanism	**Range of temperature changes**	**Time delay**
Plasticity of concrete under compression	Up to 10 degrees Celsius	In real time
Plasticity of reinforcements	Some degrees Celsius	Some minutes of delay
Slippage between steel reinforcements and concrete matrix	Tenths of degrees Celsius	Tens minutes of delay

4. ConcluDing remarks

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

Owing to the thermomechanical coupling, infrared thermography provides a non-destructive, non contact 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 define a limit of acceptable damage or fatigue limit of concrete under load beyond which the material is susceptible to failure. It should be pointed out that the inelastic strain due to compressive loading provides information only on the current geometry while the internal state variables provide information on the internal state and on the micro-structural defects.

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 cyclic loading generates increasing irreversible micro-cracking.

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. Mechanical test data generated under non-cyclic conditions are insufficient to provide a comprehensive insight into the damage development in brittle concrete under cyclic loading. Design procedures ignoring fatigue phenomena may be seriously flawed, if the concrete structures concerned are loaded cyclically.

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