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Identification of local phenomena of plasticity in concrete under compression test

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Abstract

In this paper are specifically derived parameters useful to estimate the fatigue behaviour of concrete subject to uniaxial compression. For this, methodologies and experience already adopted in the study of fatigue steel and composite materials are used. These parameters are obtained by detecting the surface temperature of the specimen in the traditional static compression tests. In this way, the beginning of the crisis of the concrete for fatigue stress is linked to the loss of linearity of the temperature-test time curve (ΔT- t) and correlated to stress-test time curve (σ- t) of the tested cubic concrete specimens. In fact, the thermal analysis performed on the cubic specimen surface extended to the whole test time, shows interesting data on the crack beginning and on the subsequent evolution that after a certain number of loading cycles could determine the complete material failure. The slope variation in the interpolating curve temperature-test time allows to identify the critical points of the start fracture. This suggests a methodology to apply to civil infrastructures to evaluate in-situ, during the approval phase or during the working, critical situations.
In this paper we propose a method to estimate the value of the "stress limit" (fatigue limit) of concrete material by means of an easy static uniaxial compression test according to an energetic method already proposed by Risitano.

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Keywords: crack; stress limit; specimen; temperature-test; loading cycles.

1. Introduction

In many concrete civil infrastructures, such as large bridges, viaducts and/or paving of airport runways, it is possible to verify concrete fatigue failures. They, in general, can be investigated with the same criteria used for mechanical structures.

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The demand of mega structures makes it necessary to predict the time of degradation due to fatigue stresses of the concrete which often has high strength class and therefore is brittle. Adopted methods and/or models that can help predict the service life of concrete or, even more, the residual life of the same is indispensable requirement. Today much has already been done in the field of methods and/or models to assess the damage, but many doubts remain about their solid reliability and adaptability to real cases. In fact, it is not always detectable with accuracy the beginning of the crack that will lead to crisis and how the crack propagates inside the structures.
The technical literature on the subject is full of proposals for methods and / or models, by Susmel in Susmel L (2014) Jadallah O. (2016), Luong M. P. (1987), Luong M. P. (1990), Luong M. P. (1993), Luong M. P. (1995) (1996) (1999), Luong M. P. et Eytard J.C. (1999), proposes an interesting calculus model. These works, by Susmel L (2014) Jadallah O (2016), Risitano A. and Risitano G (2013) Risitano, G., Clienti, C (2012) Fargione G., Risitano A., Giudice F., Patanè G.(2015), Fargione G., Risitano A., D. Tringali., E. Guglielmino (2013), Fargione G., Geraci A., La Rosa G. and Risitano A (2002), Fargione G., Risitano A., E. Guglielmino (2014), Risitano A., Corallo D. and Risitano G (2012), contain an extensive bibliography that highlights the efforts of researchers to arrive at suitable and reliable proposals. The methods proposed in literature and already adopted for metals, do not always lead to complete results:

a) Methods based on probabilistic data do not give certainties necessary for the adoption of standards models. The high dispersion of the results highlights the difficulty to adopt behavioural models which are able to consider the extremely variable loads and, also, the phenomena related to structural damage due to environmental causes;
b) The finite life evaluation, normally, is based on the assessments of crack propagation that are already evident in their initial stage;
c) Methods based on the average value of the strain energy density (SED), evaluated in a precise volume control positioned in the point of maximum intensity stress, are difficult to apply since it is not easy to identify the fracture lines due to the natural limited homogeneity of the material (concrete).

However, for a satisfactory prediction of the fatigue limit detectable by the latter methods (c) applied to homogeneous materials (such as steels), it necessary a valid definition of the local stresses and above all a complete energetic analysis, even if in elastic field.
As it is known, fatigue is a progressive and permanent internal damage process of the material subjected to repeated loads. The micro fractures, for the dynamic applied load, reach significant permanent deformation values with heat production and change in temperature.

The aim of the present work is the estimation, by means of classic static compression test, of the load for which the previously mentioned values of deformations produce a detectable change in temperature (ΔT) due to an irreversible micro fracture, from which, by progressive damages there shall be structural failure.

In the technical literature, Luong M.P. (1997) and Luong M.P et Eytard J.C.(1999), has already used the thermographic methodology, based on radiant energy emitted by a concrete specimen subjected to cyclic stresses, to assess the compression fatigue limit. Risitano A. and Risitano G (2013) Risitano A., Corallo D. and Risitano G. (2012), have, in turn, analysed the variation of temperature during static tensile testing of metallic materials, identifying, as a possible fatigue limit, the stress corresponding to the end of the perfect linearity in the temperature–time test curve (ΔT- t). Colombo C.,Vergani (2012) and Vergani L., Colombo[a] C., Libonati F., Pezzan F. I., Salerno A.(2011), Vergani L., Colombo C (2014), have had similar results in composite materials by applying the same Risitano's analysis and observation. Meneghetti G. (2016) and Vergani L., Colombo[a] C., Libonati F., Pezzan F. I., Salerno A.(2011), have detected the temperature during the static tests on steels, to derive thermo-physical parameters of the material.

In the present work, is applied the same method adopted in, Risitano A. and Risitano G (2013), for homogeneous metallic materials, to the concrete cube specimens subjected to uniaxial compression. The variation of increasing in temperature, resulting from intrinsic dissipations and/or from internal damage, gives indications on the concrete "limit stress" (fatigue limit).

Nomenclature

ΔT	temperature change of the solid
K_m	constant of thermoelastic material
T	temperature of the solid in ° K
α	thermal expansion coefficient
ρ	mass density
c_p	specific heat at constant pressure
σ	applied compression stress
σ_0^*	stress limit
t	time
Rc	strength of the concrete

2. Elements of thermo-elasticity

The change of gas volume due to application of forces produces temperature variations; this phenomenon is also present in the solids although with much more limited variations. Under the conditions of homogeneous solids and in conditions of adiabatic processes, the relationship between the temperature change of a solid and the applied stress, is:

$$\Delta T = - K_m \, T \, (\sigma_1 + \sigma_2 + \sigma_3) \quad (1)$$

in which:

ΔT = temperature change of the solid;

$K_m = \alpha/\rho c_p$ = constant of thermoelastic material (with α = thermal expansion coefficient; ρ = mass density, and c_p = specific heat at constant pressure)

T = temperature of the solid in ° K

$(\sigma_1 + \sigma_2 + \sigma_3)$ = the first invariant of the stress.

In the case of the uniaxial static compression test, the (1) becomes:

$$\Delta T = - K_m \, T \, \sigma \quad (2)$$

with σ = applied compression stress.

The previous equation, surveyed into the surface (size detectable graphically by a defined pixel number) of a high speed loaded cube specimen (in conditions of high loading speed in confrontation to the exchange thermal time of the surface for conduction and convection), highlights (in the phase of complete elastic behaviour of the material) the perfect linearity between the applied stress σ and temperature variation ΔT of the hottest point (zone) of the specimen surface. When a point (zone) of the specimen concrete reaches the condition for which the stress reaches the local yield value, the thermos-elastic linearity law is no longer valid. Consequently the temperature evolution is governed by the thermal release for local plastic deformation that gradually evolves and so will affect an large portion of the material. In correspondence of this released heat, qualitatively detectable by colour variations of the thermal images and by loss of linearity in the curve (ΔT- t), the value of "limit stress" (fatigue stress) σ_0^* of the concrete is deducible by the linked diagram (σ-t) of the compressive test machine.

Summing up, for the non-homogeneous concrete material, at a first perfectly linear phase in the diagram (ΔT- t) (detected by thermographic sensor) follows a later stage in which the temperature variation ΔT vs time t ($\Delta T = f(t)$) shows a different gradient which reveals a discontinuity for the forming of micro fractures in proximity of the observed zone. The related stress value on the curve stress-time test (σ-t) will be indicated with the symbol σ_0^* and will be defined as “stress limit” (Fatigue) of the material. This is justified by the fact that for the macroscopic stress (applied load/specimen area) repeated in time, after a defined number of cycles, the material would reach the its failure point.

3.Tests carried out

The tests were performed on concrete cubic specimens of 15 cm side, whose mix design per cubic meter is: a) inert for 1820 da N (4-16 size for 25%, 0-4 size for 65% , 0-2 size for 10%); b) cement CEM I 52.5 R for 410 da N; c) water for 172 liters; d) additive MAPEI "Dynamon NSG 1022" for 3.5 liters. The concrete has density: 2404 kg /

m^3, slamp tests: 210 cm, class of consistency: S4. Static strength have been obtained with the test machine: CONTROLS, cat: C7600, series: 08.006.660, capacity: 5000 kN, year: 2008 and the thermal images have been acquired by thermal infrared Camera: FLIR SC300.
Figure 1a, shows the image of the concrete specimen loaded by uniaxial static compression with the thermal image of one cube face at start of test (Fig. 1b); This image is used to identify investigative points (spots) and to detect the comparative temperature of the test (zero image).

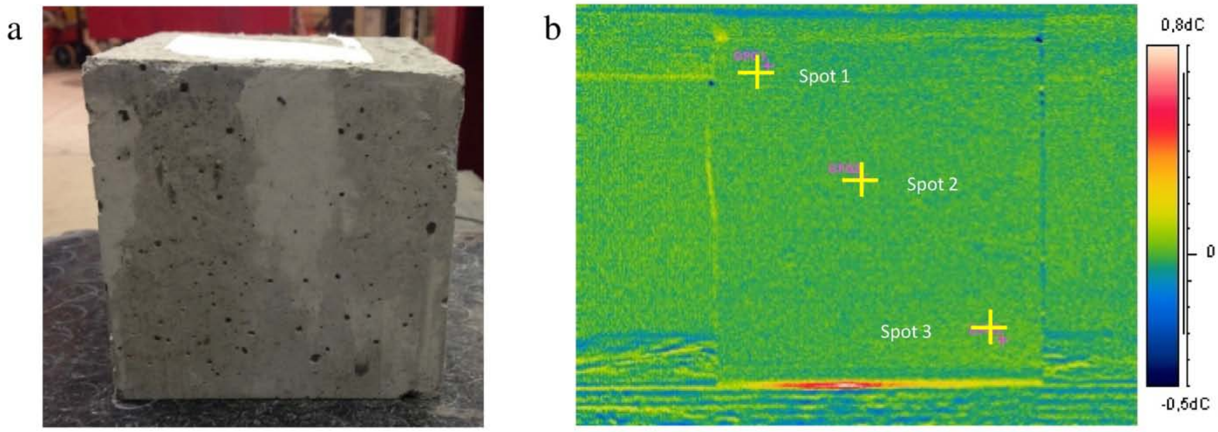

Fig. 1. (a) adopted specimen; (b) Thermal image of one face at the beginning of the test

In Figure 1b , the detected points (spots) are straight along the right diagonal of the specimen face: at the top left (spot n.1), at the center (spot n. 2) and at the bottom right (spot n. 3). The frequency of image acquisition is 10 Hz. The following figures (2a, b) show the thermal images at two different times of the test, respectively, at the application of about 70% of the ultimate load (Fig. 2a) and immediately before failure (fig. 2b). Because of high temperatures, the zones of the most stressed specimen (for example for positioning defects and/or for unrefined surfaces) are clearly visible on the analysed cube face.

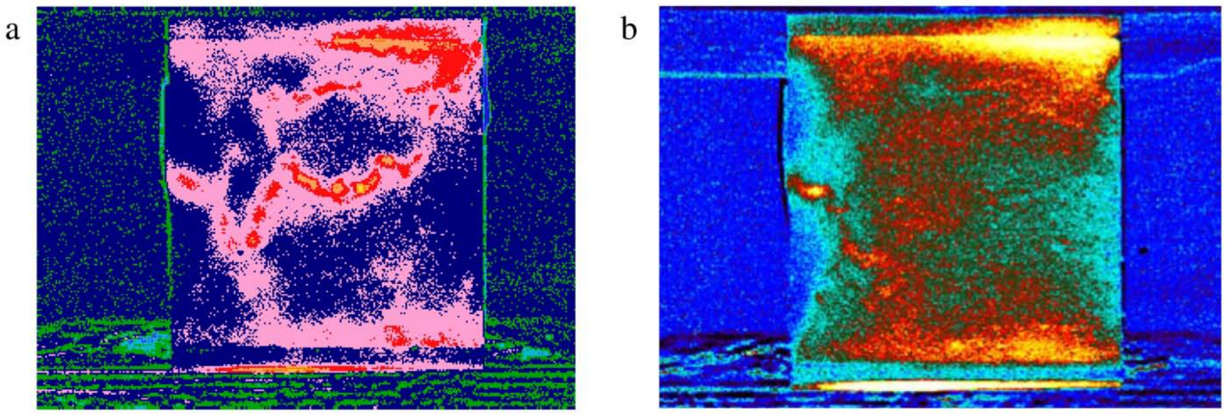

Fig. 2 Thermal image of a face of the specimen (a) at 70% of the ultimate load; (b) close to the ultimate load

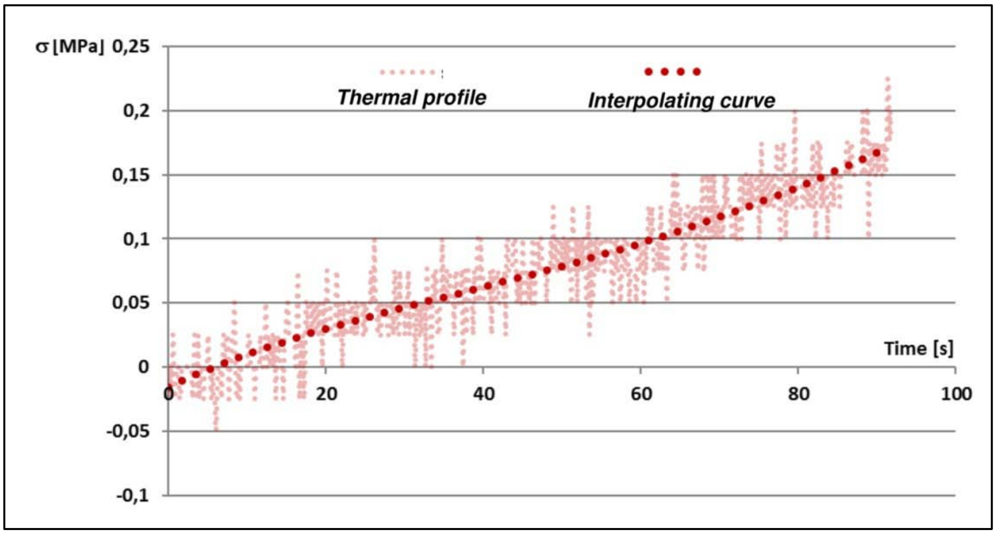

Fig. 3 interpolating curve (ΔT- t)

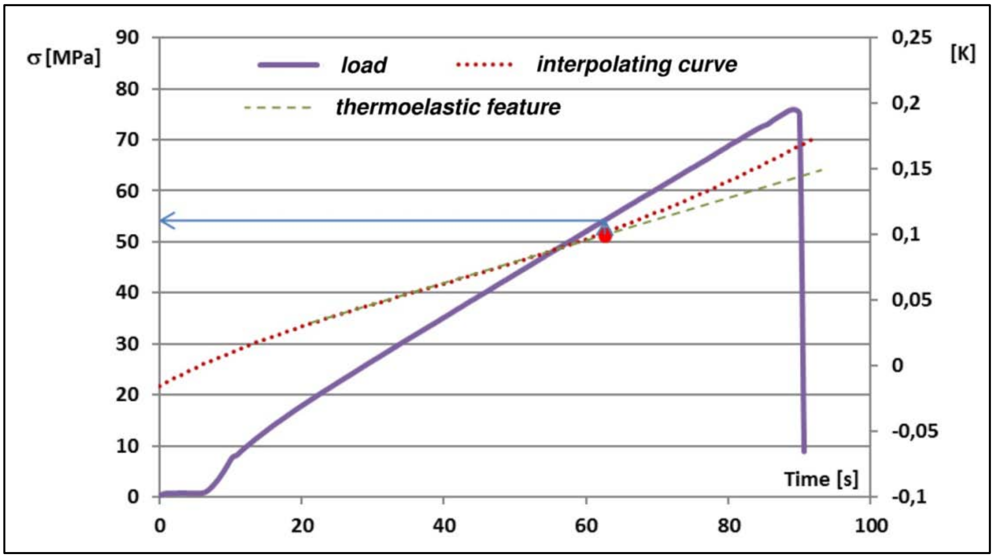

Fig. 4 interpolating curve (ΔT- t) for specimen 2 and diagram (σ-t) for the spot n.2

4. Analysis and Results

Table n.1 summarizes the data obtained in relation to the objective pursued. The first column shows the number that characterizes the specimen, in the second column is shown the strength of the concrete, in the third column is reported the "limit stress" (fatigue) in uniaxial compression (σ_0*) and in the fourth the ratio between the mono-axial compression "limit stress" (fatigue) and the strength of the concrete. The values of the "limit stress" (fatigue) have been determined as average of the values for the three spots. These values have not shown differences more than 5% circa.

Table 1. ultimate stress and "limit stress " σ0* (fatigue) of the concrete

Specimen	Ultimate stress [MPa]	“limit stress” σ_0* [MPa]	“limit stress” σ_0* [MPa]
And an entry	82	45	0,55
And another entry	77	54	0,70
And another entry	88	68	0,77
	79,3	50,5	0,64

For the constancy of the results, in what follows, are reported only the thermographic results of some specimen. The images of Fig. 1b and Figs. 2a and 2b show an increasing in temperature of about 4 tenths of a degree Celsius between the start and end of test. The chromatic variations represents the temperature of the whole which is coherent with the hourglass shape characteristic of the cube crisis lines (Fig. 5 a, b). Normally it is possible to identify through colour variation, the lines along which the material begins to failure. This happens for a local stress value which is lower than the ultimate specimen stress.

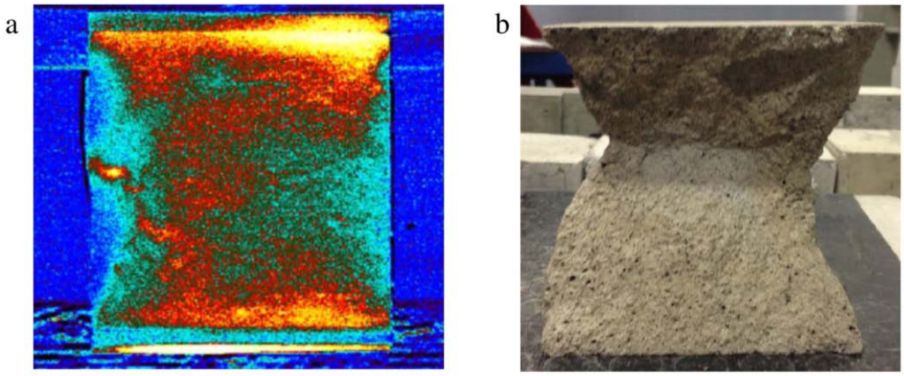

Fig. 5. (a) thermal image of the specimen at the failure; (b) hourglass shape of the specimen at the failure

The Fig. 5 shows, in the three detection points (spots) of the specimen face and at each instant of test, the variation of the increasing temperature while the stress is gradually increasing.

The thermo-elastic effect is clearly visible as it is identifiable the moment/time of linearity loss in the (ΔT- t) curve to which corresponds the "limit stress" σ_0^* linked to the (σ-t) curve. The temperature deviates from the straight line for a load of 54 MPa (average value for the three spots) equal to about 70% of the concrete specimen strength.

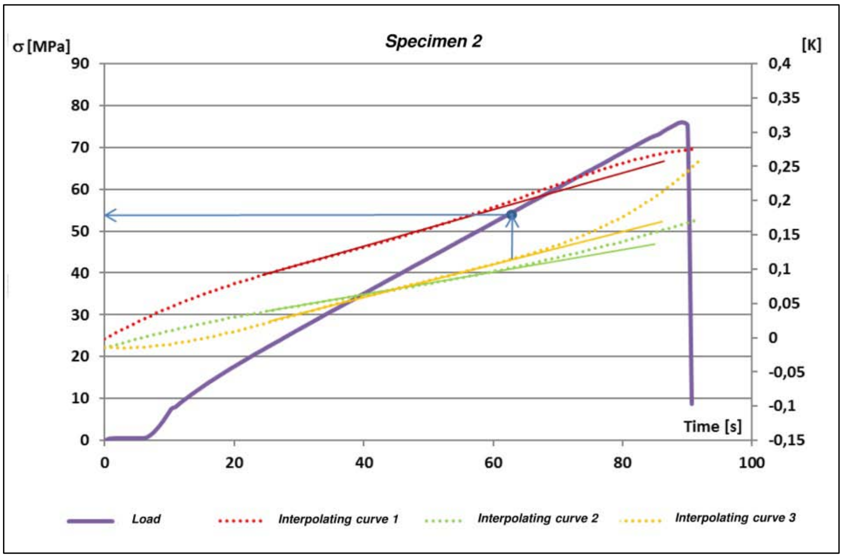

Fig. 6. interpolating curve (ΔT- t) and diagram (σ-t) for spot n., 1 spot n.2 and spot n.3

The Fig. 7, for the specimen under test n. 4, shows analysis results quite similar to those of the specimen n. 2. Also in this case, referring to the average value of the "limit stress" (fatigue) of the three spots, the loss linearity of the temperature curve take place for a stress value of 50.5 MPa, equal to approximately 64% of the concrete specimen strength.

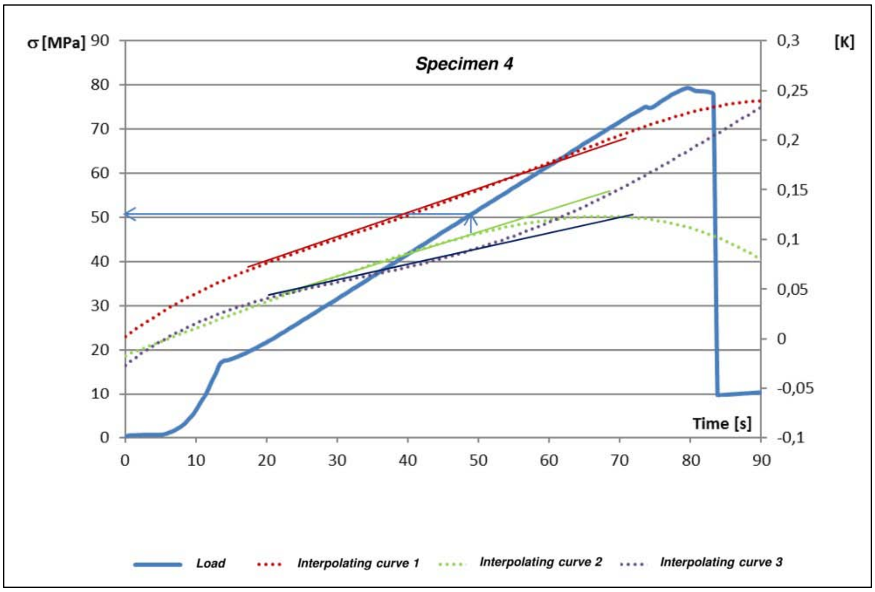

Fig. 7. interpolating curve (ΔT- t) and curve (σ-t) for spot n.1, spot n.2 and spot n.3

Similar results are obtained for the specimen 1 and 3 as shown in Table 1.

Summing up, the thermographic images allow to identify the critical areas in which the material reaches its elastic limit The (ΔT- t) curve correlated to the stress-test time curve (σ- t), allows to define the value of "limit stress" for which linearity in the (ΔT- t) curve is lost.

The examination of figures 6 and 7 shows interpolating curves in the (ΔT-t) diagram. In the diagram, after the settling phase of the system (approximately 15 s), two distinct stages can be identified:

1) first stage: the thermo-elastic characteristic is well represented by a perfectly straight line lying on the interpolating curve. The behaviour of the material is practically homogenous and even locally there are not micro cracks. In this phase, the stresses increases gradually with increasing loads.

2) second stage: the interpolating curve may be approximated with a broken line. The first change of slope of the broken line, lying on the interpolating curve, take place when in the concrete such local stress values are reached to produce the first micro plasticization. In situation like this the produced heat is due to plastic deformation and/or for internal friction along the crack). It is realistic to assume that the moment/time in which the slop of thermo-elastic characteristic (broken line) changes defines on the diagram (σ-t) the value of the stress σ_0^* that, if applied in a cyclic manner, would bring to failure ("limit stress").

5. Conclusions

Static compression tests on concrete cube specimens were performed in order to identify phenomena of thermal energy release. This phenomena is shown through full field thermographic images of one exposed specimen face. The application of the load, according to a protocol already established for homogeneous materials (steel) from Risitano A. and Risitano G (2013) Risitano, G., Clienti, C (2012) Fargione G., Risitano A., Giudice F., Patanè G.(2015), Fargione G., Risitano A., D. Tringali., E. Guglielmino (2013), Fargione G., Geraci A., La Rosa G. and Risitano A (2002), Fargione G., Risitano A., E. Guglielmino (2014), Risitano A., Corallo D. and Risitano G (2012), highlights that:

1. During the test of concrete, it is possible to identify on the exposed specimen face the maximum stress points that shall produce localized cracks even before reaching the strength of the specimen (50% -70% of the ultimate load);
2. The thermo-elastic behaviour of the material is well defined and its analysis is useful for the detection of early local micro plasticity;
3. The development of local micro plasticity can be observed during the test and the stress σ_0* (applied load/cross area) that determines the beginning of local micro-plasticity can give indications of concrete fatigue limit;
4. A suitable protocol may be adopted as a non-destructive method to determine the fatigue limit of concrete structures during the approval phase and/or during working life;
5. The current Italian code of practice NTC 2008 (paragraph 4.1.2.2.5.1) by Italian Code D.M. 14 gennaio 2008, which defines serviceability limit state as the stress value $\sigma_c \leq (0.45\text{-}0.60)\ f_{ck}$, seems to be precautionary.

What is been highlighted is the result of a limited number of tests having as purpose the evaluation of a defined protocol applicability for the estimation of the non-homogeneous materials (such as concrete) fatigue limit. This work anticipes the implementation of a larger stochastic investigation in order to define optimal protocols for assessment fatigue limit of concrete with different strength class. The results of this work indicate the possibility to define an "acceptable" damage limit both during the design and the testing stage as during working phase. This through the monitoring of particular areas of the structures (exposed to important stresses) with systems sensitive to temperature variation, .

P.S. Thanks for the supply of concrete specimens to I.C.E.A. companies LTD - Industry and premixed concrete - S.P. n. 3 km 0:30 - Zona Industriale Piano Tavola 95032 Belpasso - CT)

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