Mode I Concrete Characterization using Rebar Induction Heating

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Abstract: **Reinforced concrete is a composite material consisting in a rebar embedded in a concrete matrix. The structural equilibrium depends of the quality of bond between the two materials as well as the intrinsic quality of each of the components. When the structure is submitted to heating, cracking can occur due to the difference in thermal expansion properties between the two materials. In the present work, a theoretical approach, correlating rebar expansion rate under a heating process, to the fracture properties of concrete is proposed. The validating test consists in a Double Cantilever concrete Beam, with an initial crack length a_0, a rebar embedded at a distance a_0 from the crack tip. The rebar is heated through an induction process and its expansion induces a crack opening displacement at the level of the concrete. The deformation of the concrete due to the rebar expansion induces at the level of the crack tip, a displacement as well as a stress field, leading to the crack propagation. In order to follow the development of the displacement field at the level of the crack front, a digital camera is used to capture pictures of that zone at various steps (two images per minute) of the heating process. The images are then analysed with image correlation techniques to obtain the displacement field as well as the strain field, and then the time of crack propagation. The critical crack opening displacement, the critical energy release and Stress Intensity Factor corresponding to the time of crack propagation, can be deduced with a good accuracy.**

Key words

Induction heating, rebar, crack opening displacement, images correlation, stress intensity factor, energy release rate.

I. INTRODUCTION

Concrete is a composite, constituted of a mixture of aggregates, cement, water, pores and various micro cracks due to shrinkages. Its physical as well as its mechanical properties changes with time, not only during setting and hardening periods, but are sensitive to the environmental weather. In this way, since its early age, it undergoes many volume variations, due to its interactions with the environment. This volume variation is very often one of the causes of concrete structural micro cracking (shrinkage). In this case, internal stress induced by concrete expansion is created and cracks appear when the stress in tensile zones is greater than the local ultimate stress of concrete or when the local critical stress intensity factor reaches its critical values. Among others concrete cracking due to it environment, there is corrosion. Corrosion is a progressive transformation of the iron embedded in concrete matrix into an expansive rust in presence of humidity, carbon dioxide or chloride ions penetration through concrete cover. As the quantity of rust increases between the iron and the surrounding concrete, internal pressure increases, leading to concrete cracking [1, 2, 3] and peeling. Behind the difficulty to model corrosion expansion around the rebar in corrosion process, joint model is sometimes used [2]. Under high temperature, due to the difference between concrete and rebar thermal properties, concrete cracking in reinforced concrete is a combination of two effects: the concrete shrinkage and reinforcement thermal expansion [4,5]. Many investigations have been done in order to understand the interactions between reinforcement and concrete under high temperature [4, 5, 6, 7]. The idea is to replace the rust thickness around the rebar by a rigid joint, expanding in the radial direction, under a hypothetical temperature variation. It appears from those various analysis, that the knowledge of the relation between fracture parameters and environmental effects is useful for a good modelling [8, 9, 10], as well as the numerical simulation[2,11,12,13] of concrete cracking under mechanical loading and its various interactions with the environment. At this end, many experimental techniques are often used to capture cracking properties of concrete in mode I loading [8, 10, 11, 13, 14]. The present work proposes a new way, consisting in the use of rebar induction heating expansion, to create mode I loading on a DCB specimen, from which fracturing properties of concrete can be deduced.

II.THEORETICAL BACKGROUND OF THE MODEL

A. The basic idea

One of the more important problems dealing with reinforced concrete structure is its behaviour under high temperature. In fact, reinforced concrete is a composite which components are aggregates, cement paste, water and reinforcement. Each of those components is characterized by its physical intrinsic properties. The values of the coefficient of thermal expansion ranges between 2.2 10^{-6} $°C^{-1}$to $3.910^{-6}°C^{-1}$ for concrete and is influenced by the quality and the proportion of coarse aggregates in the mix. For the steel, the coefficient of thermal expansion depends on the amount of carbon in its metallurgical structure. It ranges is between 10 to $12.10^{-6}°C^{-1}$ for low steel alloy and 16 to $22.10^{-6}°C^{-1}$ for austenitic steel. For concrete as well as well as for steel under high temperature, the coefficient of thermal expansion increases. The basic idea of the present study is to correlate the steel expansion rate under high temperature to the fracture properties of the concrete. This can be done through a double cantilever beam (DCB) test, in which the well known mode I force **P** (figure 1**)** is replaced by the pressure of a rebar transversal expansion under induction heating. The double cantilever beam is characterized by its thickness b, length L, height 2h, with an initial crack a_0. At a distance a_0 from the end of the specimen, a rebar with diameter ϕ is embedded, representing concrete reinforcement. The crack length is measured from the centre of the iron to the distance a_0 inside the specimen.

During heating process, the pressure at the interface between rebar and concrete, due to the rebar expansion, increases, inducing crack opening displacement δ, which can be measured through a LVD sensor. If the pressure around the reinforcement is denoted p, and since its diameter, its length are respectively ϕ and b, the equivalent thermal induced force P is given as function of the pressure as

$$\vec{P} = \int_S -p\vec{n}ds \approx \int_S -E_s\vec{n}\,\alpha\,\Delta T ds \quad , \qquad (1)$$

where $\vec{n}$ is the positive normal to the concrete at the level of its contact with the rebar, S is the concrete area under the rebar pressure due to its expansion. S can be computed as the rebar diameter times the thickness of the specimen, α is the rebar coefficient of thermal expansion, E_s the rebar Young modulus and ΔT the temperature increase under heating.

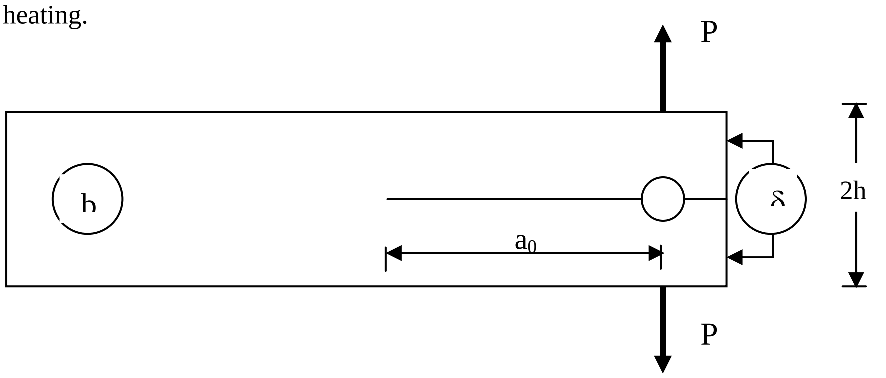

Figure 1: Principle of a DCB test in classical fracture mechanic test

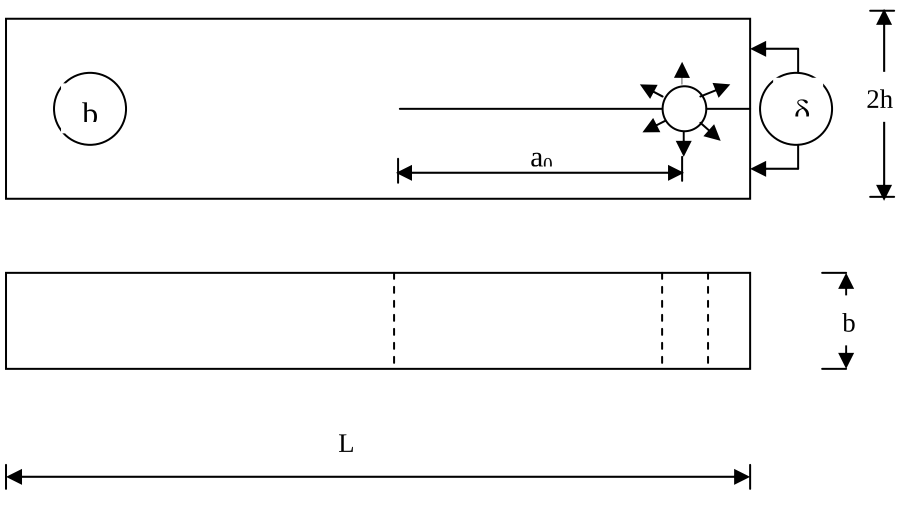

Figure 2: Detail of the induction heating fracture test

B. Thermodynamic approach of crack problem

Fracturing test in classical elastic fracture mechanics consists in applying force P as shown in (figure1) and measuring the corresponding crack opening displacement δ in the imposed force approach, or imposing a displacement crack opening displacement δ and reporting the corresponding force in the case of displacement imposed loading. In each of those cases, with the hypothesis that the material remains elastic, if W, U, K and Us are respectively the total work done by the system, the strain energy, the kinetic energy and the surface energy, the global distribution of the energy of the system is given by the relation

$$E_T = U_{el}-W+U_s \tag{2}$$

where E_T is the total free energy of the system. With the hypothesis of quasi static loading, kinetic energy K as well as the others forms of strain energy (non elastic), can be neglected, and the equation is therefore reduced to

$$E_T = U-W+U_s=\Pi+U_s \tag{3}$$

where Π is the mechanical potential of the system. Under equilibrium conditions, the total free energy is independent of the crack length leads to:

$$\frac{dE_T}{da} = \frac{d(\Pi + U_s)}{da} = 0 \tag{4}$$

And

$$\frac{dUs}{da} = -\frac{d(\Pi)}{da} = G_I \tag{5}$$

where G_I is the energy release rate in mode I fracture. G_I, for actual system is given as function of the force P, by the relation

$$G_I = \frac{1}{2}P^2\frac{\partial C}{\partial a} \tag{6}$$

where C is the complaisance of the beam of beam, with

$$\lambda= \delta/2 = CP \tag{7}$$

the deflection of the half beam under the loading force P. λ here represents the transversal rebar expansion effect on the concrete, that means its expansion over the initial rebar radius.

Now, if we consider the half specimen as a beam which length is denoted a_0, embedded at the level of the crack tip and submitted to an hypothetic force P, representing the effect of expanding rebar pressure on the concrete (figure 2), the deflection λ is given according to the beam theory and the Castigliano's theorem by

$$\lambda = \frac{Pa_0^3}{3EI} \tag{8}$$

where E and I are respectively the elastic modulus and the quadratic moment of the concrete specimen section. From the above relation, one can deduce the expression of the compliance of the concrete section as

$$C = \frac{a_0^3}{3EI} \tag{9}$$

The variation of the compliance with beam length can be expressed as

$$\frac{dC}{da} = \frac{a_0^2}{EI} \tag{10}$$

and therefore the expression of the energy release rate is given from (10) by the following relation

$$G_I = \frac{1}{2}P^2\frac{a_0^2}{EI} \tag{11}$$

In the present experimental approach, since the value of the force P is unknown, because no direct force is applied to the specimen, the only measured parameter is the crack opening displacement, representing the effect of rebar expansion. With the hypothesis that the material remains elastic until the beginning of crack propagation, and the hypothetical force P is proportional to the displacement λ=CP, the various fracture parameters involved in the fracturing process are as function of the displacement λ given by:

$$P = \lambda b\frac{E}{4}\left(\frac{h}{a_0}\right)^3 \tag{12}$$

$$p = \frac{P}{b\phi} = \lambda \frac{E}{4\phi}\left(\frac{h}{a_0}\right)^3 \quad (13)$$

$$G_I = \frac{1}{2}\lambda^2 \frac{a_0^2}{EI} = \frac{3}{8}\lambda^2 \frac{h^3}{a_0^4} \quad (14)$$

$$K_I = \sqrt{\frac{EG_I}{(1-\upsilon^2)}} = 0.61\frac{E\lambda}{a_0^2}\frac{h^{\frac{3}{2}}}{(1-\upsilon^2)^{\frac{1}{2}}} \quad (15)$$

P, p, G_I, K_I being respectively, the equivalent force at the level of the rebar, the local equivalent pressure, the energy release rate and the stress intensity factor at the level of the vicinity of the crack. The energy release rate G_I represents the energy stored in the material because of the presence of the initial stable crackand the stress intensity factor is an indication on the effect of the discontinuity on the stress field at the level of the crack vicinity. These relations become respectively, P_c, p_c, G_{Ic} and K_{Ic} when the crack is about to propagate and correspond to the critical crack opening displacement value. Over that value, the crack length a increase with the crack opening displacement, and therefore nonlinearity appears between the hypothetical force P and the crack opening displacement. It appears from these relations that the knowledge of the Poisson's ratio, the Young modulus and the geometry of the specimen together with the measurement of the critical crack opening displacement induced by rebar expansion, enable us to determine various mechanical cracking properties of concrete. The parameters KIC and GIC, characterize the material. The first characterize the ability of the material to resist to crack propagation and the second, its ability to store elastic energy before crack propagation.

C. Correlation between rebar thermal expansion rate and fracture properties of concrete

Let ϕ been the rebar diameter and ΔT the variation of its temperature during a time Δt. The deflexion of the half beam λ (figure 2) under rebar expansion is correlated to the variation of temperature ΔT by the following relation:

$$\lambda = \frac{1}{2}\alpha\phi\Delta T \quad (16)$$

The temperature variation ΔT rate and various cracking parameters can be correlated as follow:

$$P = \frac{1}{8}\alpha E_s \phi \Delta T\left(\frac{h}{a_0}\right)^3 \quad (17)$$

$$p = \frac{P}{b\phi} = \frac{1}{8b\phi}\alpha E_s \phi \Delta T\left(\frac{h}{a_0}\right)^3 \quad (18)$$

$$G_I = \frac{1}{2}\lambda^2 \frac{a_0^2}{EI} = \frac{3}{8}\left(\frac{1}{2}\alpha\phi\Delta T\right)^2 \frac{h^3}{a_0^4} = \frac{3}{32}\left(\alpha\phi\Delta T\right)^2 \frac{h^3}{a_0^4} \quad (19)$$

and

$$K_I = \sqrt{\frac{EG_I}{(1-\upsilon^2)}} = 0.61\frac{E\left(\frac{1}{2}\alpha\phi\Delta T\right)}{a_0^2}\frac{h^{\frac{3}{2}}}{(1-\upsilon^2)^{\frac{1}{2}}} = 0.3E\frac{\alpha\phi\Delta T}{a_0^2}\frac{h^{\frac{3}{2}}}{(1-\upsilon^2)^{\frac{1}{2}}} \quad (20)$$

Eventually, the critical time corresponds to the crack propagation, and this time will be defined through the analysis of the displacement and strain field at the level of the crack tip given by digital images correlation.

D. Digital images correlation

Digital image correlation is a non contact way of capturing full field surface displacement and the corresponding strain on a zone of a structure under loading. The fundamental difference between this technique and the classical gauge is that, since there is not any contact between the specimen and the camera, the test is not disturbed by the measuring system and the measurement can be done in a zone which access is not easy. The principle developed since early 1980 consist in taken N pictures of the zone of study with a frequency Δt, the first, before the loading, being taken as reference. The images are in the first step digitized, that means transformed from a continuous signal into a discrete one (pixels) and stored in a computer. Each of the N-1 pictures is then compared to the reference image. The difference between the reference and a given image gives an idea on the modification of displacement field during the period of time n*Δt, n corresponding to the sequence number of the picture by analysing the picture, it can be known approximately the time at which crack propagates. This analysis has been carrying out using a specific program, called CORRIELI_LMT.

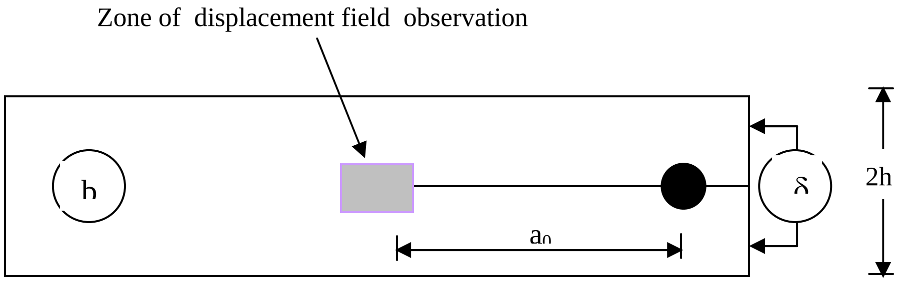

Figure 3: Zone of camera observation

E. Rebar induction heating

Induction heating is a non contact way of providing fast, consistent heat for various applications such as: joining, metal treating. It consists in using high frequency electricity to heat electrically a conductive materials. Its principle is as follow: a high frequency current is used to create an alternating current through a coil. The passage of the alternating current generates an intensive and alternating magnetic field. The alternating magnetic field generates according to Faraday's law an induced current (eddy currents) in the conductive material, which in this case behave like a short circuit, generating a localized and fast increased heat without any physical contact between the coil and the work piece. The temperature as well as the rate of heating depends on the intensity of the alternating current and the initial power as well as the frequency of the current. Magnetic materials are easier to heat than non-magnetic, due to the effects of hysteresis heating. Magnetic materials naturally resist the rapidly changing magnetic fields within the induction coil. The resulting friction produces its own additional heat hysteresis heating in addition to eddy current heating. A metal which offers high resistance is said to have high magnetic "permeability". Permeability can vary on a scale of 100 to 500 for magnetic materials; non-magnetic have a permeability of 1. Hysterisis heating occurs at temperatures below the "Curie" point the temperature at which a magnetic material loses its magnetic properties.

III. EXPERIMENTAL PROCEDURE

A. **Experimental setup**

The figure 4 shows the global setup used to perform the present test. It is composed of:

- LVD sensor for the measurement of the crack opening displacement d;
- A thermocouple for the measurement of the temperature of the rebar;
- A CDD camera for the capturing of the images of the zone of interest;
- A coil connected to high frequency alternative current generator, and generating at the level of the rebar an inductive current inducing a temperature rise;
- A computer is used to collect and analyse all informations from the measurements.

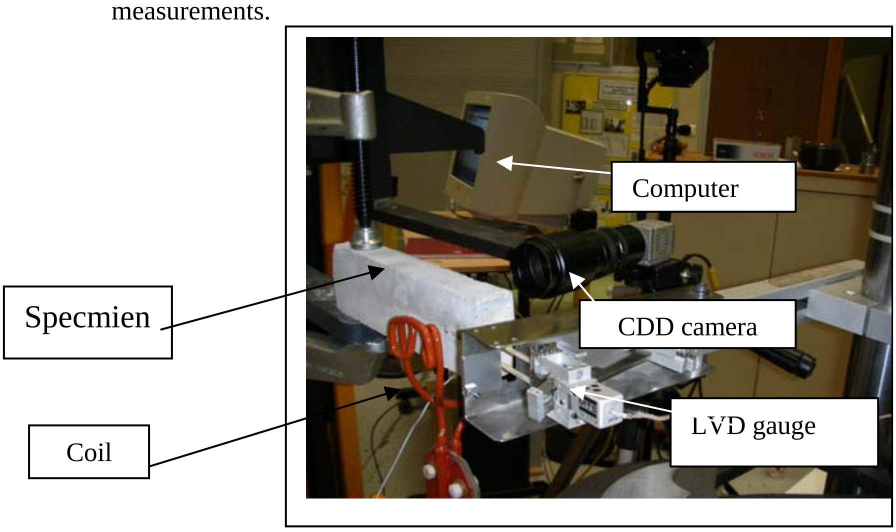

Figure 4 : Global setup

B. Materials

The material used for the present test is a mortar made with the mix weight proportion of 1/0.5/2.3 respectively for the cement, water and sand, with a maximum aggregate size of 5mm The initial crack a_0 was obtained through a very thin plastic sheet introduced in the formwork during the casting. The mortar is characterized by Young modulus E=20GPa, and a Poisson ratio ν=0.2 and h=20mm. The rebar is characterized by a length b=30mm corresponding to the thickness of the specimen, a diameter ϕ=10mm, a yield stress σ_y = 520MPa and a Young modulus E=210 GPa. The length of the initial crack is a_0=55mm.

C. Loading procedure

A displacement is imposed to the concrete according to the figure 2, through a radial expansion of a rebar embedded in the mortar. The rebar expansion is created by imposing high frequency current to the rebar through a coil. This high frequency current creates an inductive current inside the rebar which is this case behave like a shot circuit, inducing a rapid increase of the temperature according to Faraday's induction law. The variation of the temperature of the rebar induces a variation of its diameter and therefore the pressure at the level of the interface between the rebar and the concrete. This pressure is the only mechanical load involved in the test. The plot of the crack opening displacement as function of time, gives an idea on the rate of variation of the pressure on the concrete.

D. Crack front pictures

The images of the crack front are taken using a CDD ultra rapid camera with a frequency of one picture each thirty seconds. The sequence of images depends of the estimated duration of the test and the capacity of the computer hard disc. An increasing number of images increases the time of image correlation computation and needs a heavy memory space. Figure 5 shows schematic representation of the zone of interest on the whole specimen. Figure 6 shows a photo of a zone of interest, taken before the beginning of the thermal loading. This picture together with the roller enable to convert numerical dimensions (pixels) and usual metric units. It shows for this particular case that 1040 pixels correspond to 39.4mm meaning that one pixel equal to 37.8µm. At each image taken corresponds a value of a crack opening displacement and the time at which it has been taken. It will then be easy to analyse the various pictures and determine the critical time that means the time of crack propagation. Before that time, energy under rebar expansion pressure is elastically store in the concrete, and the length of the crack, remains constant, but the stress intensity factor as well as the energy release increases. This time correspond to the critical values of the material cracking properties K_{IC} and G_{IC} and the pressure pc.

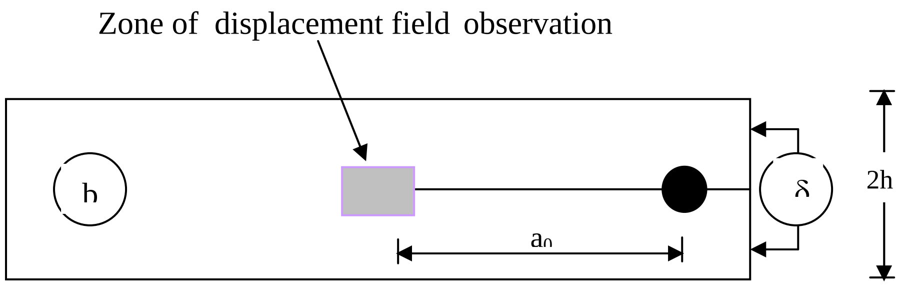

Figure 5: Zone of camera observation

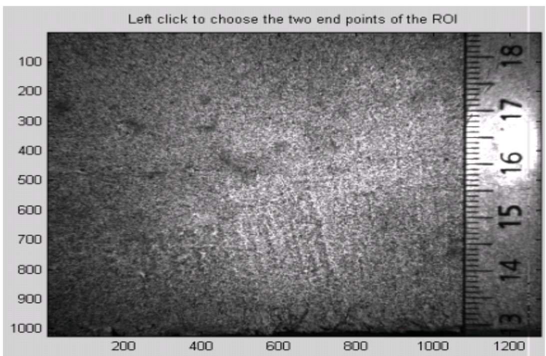

Figure 6 : photo of the zone of interest

4. RESULTS AND DISCUSSION

Figure 7 shows for the first column the mesh of the zone of interest, for the second, the strain field, and the third the displacement field of the zone. The first line corresponds to state of the zone before heating that mean undeformed field (see on figure 6). It is not possible to distinguish even en the position of the existing crack. The second line corresponds to the state at which crack begin to propagate. The time of cracking here, correspond to 400 seconds. Figure 8 and 9 show respectively the measured rate of heating and the corresponding variation of the measures displacement λ during the experiment. Those critical values corresponds respectively to 600°C and 5.10^{-2}µm. When the maximum capacity of energy storage of the concrete is reached, crack propagates. The capacity to stock elastic energy before crack propagation depends on the material properties. The elastic energy stored is transformed into crack extension. During the phase of crack propagation, the crack opening displacement continues to increase under rebar expansion, but no elastic energy is stored, but transformed into new surface. The relation between the crack opening displacement, the cracking parameters and crack length become non linear.

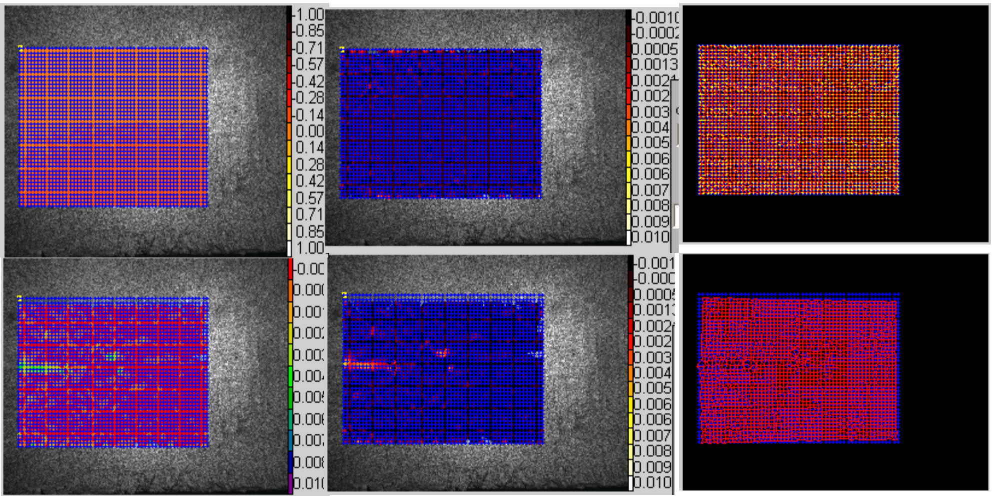

Figure 7 : Mesh, strain field and displacement field of the zone of interest
Before loading and at crack propagation

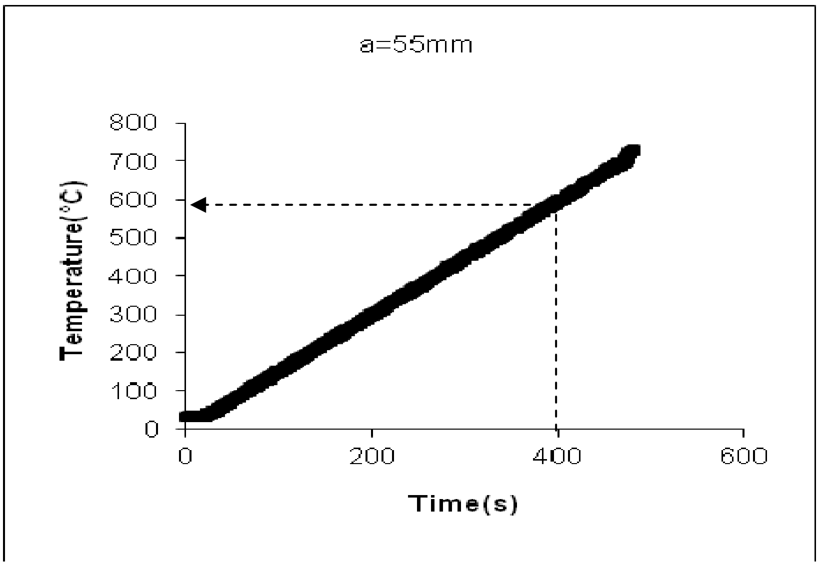

Figure 8 : Rate of heating during the test

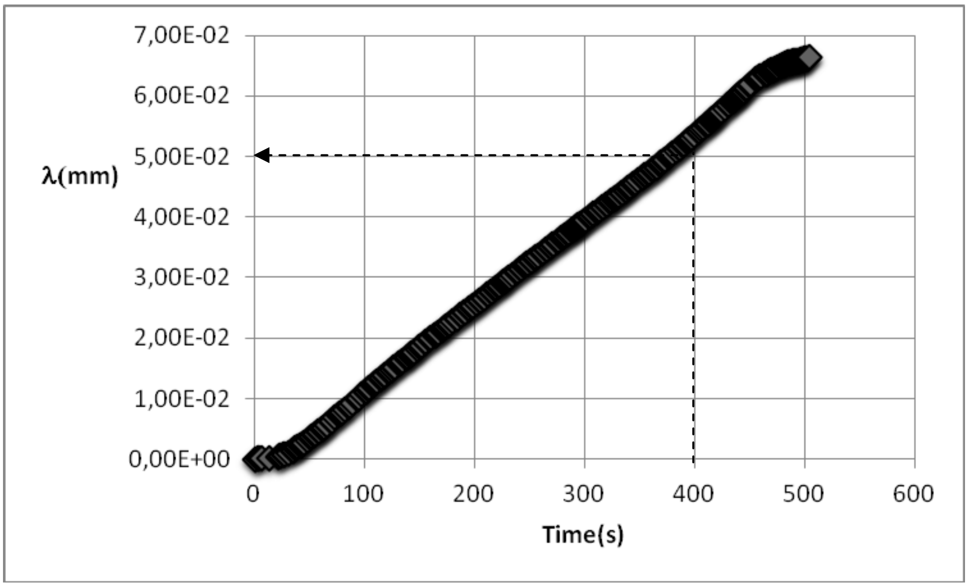

Figure 9 : Rate of displacement

On figure 10 and 11 are shown respectively the variation of stress intensity factor and the corresponding energy release rate, computed from measured values of time and displacement λ, together with equations (19) and (20). The values obtained are in the order of magnitude of the ones usually founded in the literature[10,14,15].Figure 12 and 13 show respectively the evolution of the resultant force and the contact pressure around the rebar, computed from equation (12) and (13) together with the measured value of the displacement λ and the time. As the temperature rises, the pressure around the rebar increases leading to a mode I loading. Table 1 summarize the various critical values obtain from the present test.

Table 1: Various parameters obtained from the test

Parameter	Time to Cracking(s)	Temperature at cracking(°C)	Displacement at cracking (m)	GIC (J/m)	KIC $MPa\sqrt{m}$	Pc (N)	Pc (MPa)
Value	400	600	0.5	64	1.15	395	1.35

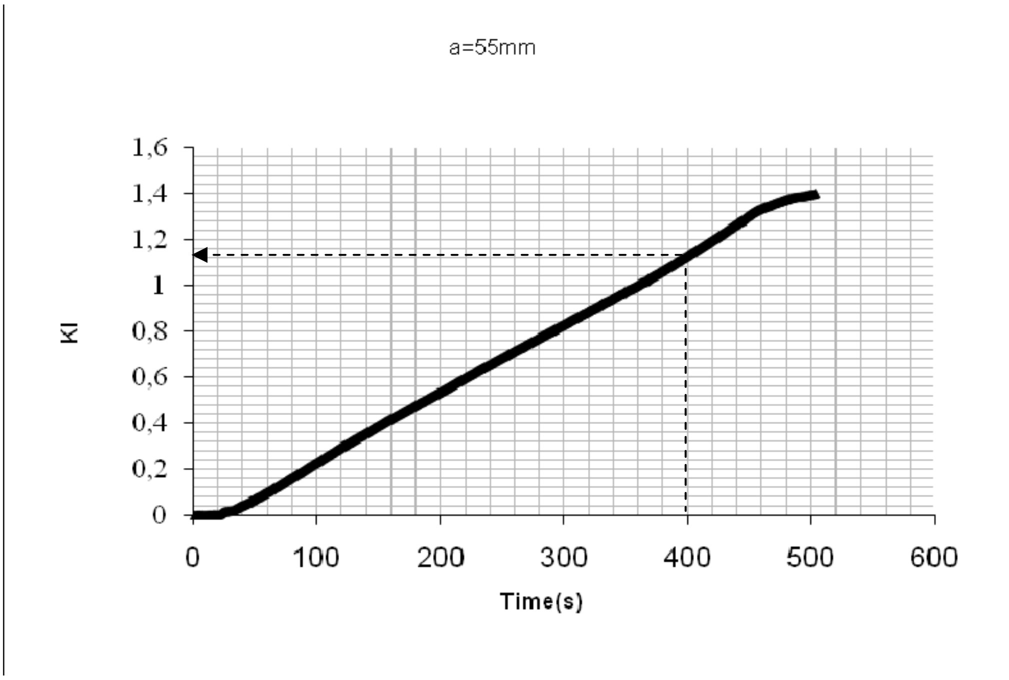

Figure 10 : Evolution of the Stress intensity factor with time of heating

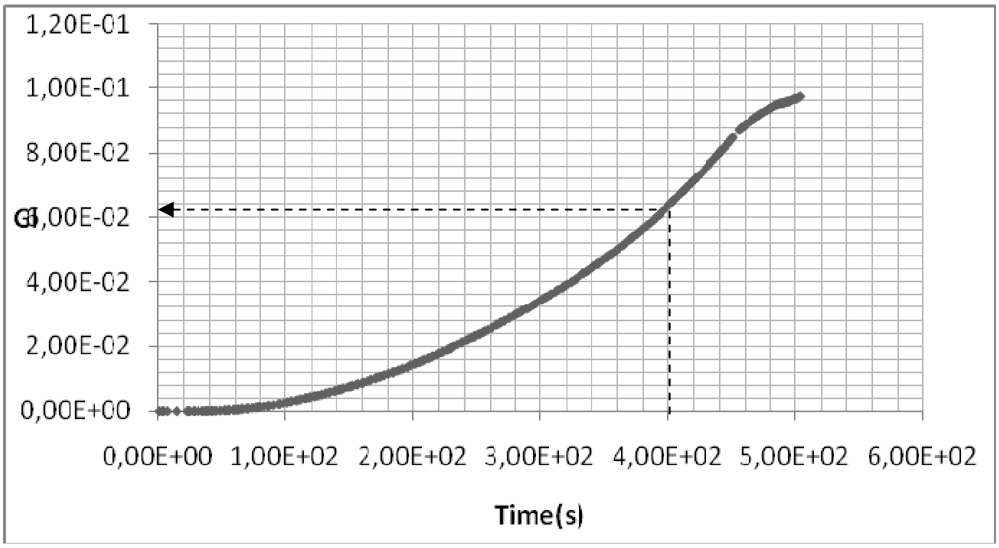

Figure 11 : Evolution of the energy release with the time of heating

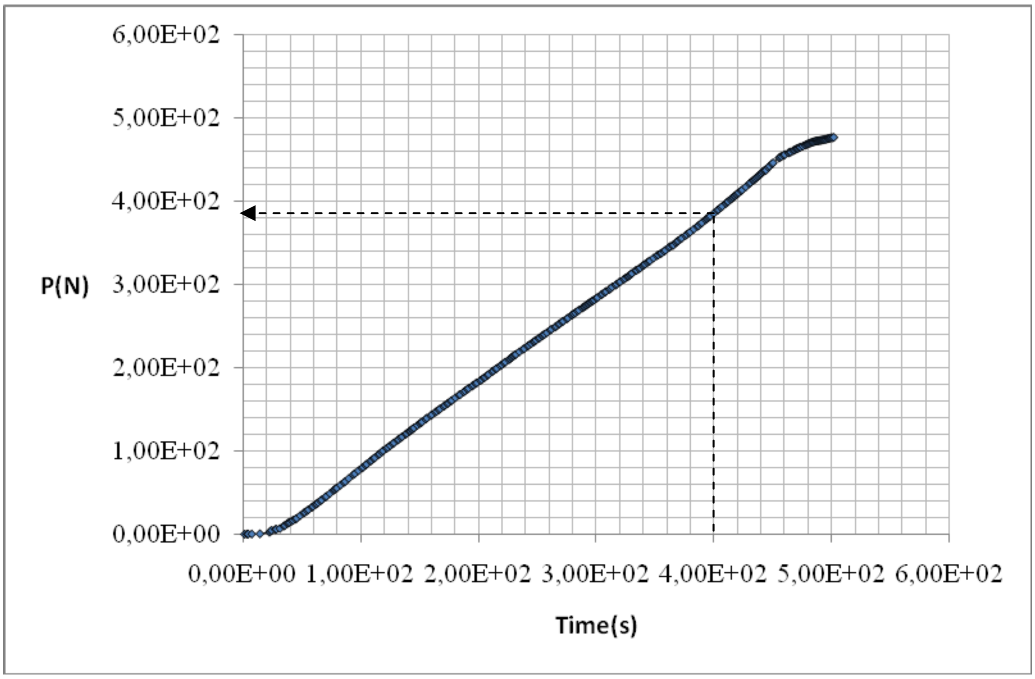

Figure 12 : Evolution of the equivalent force P with the time of heating at the level of the rebar

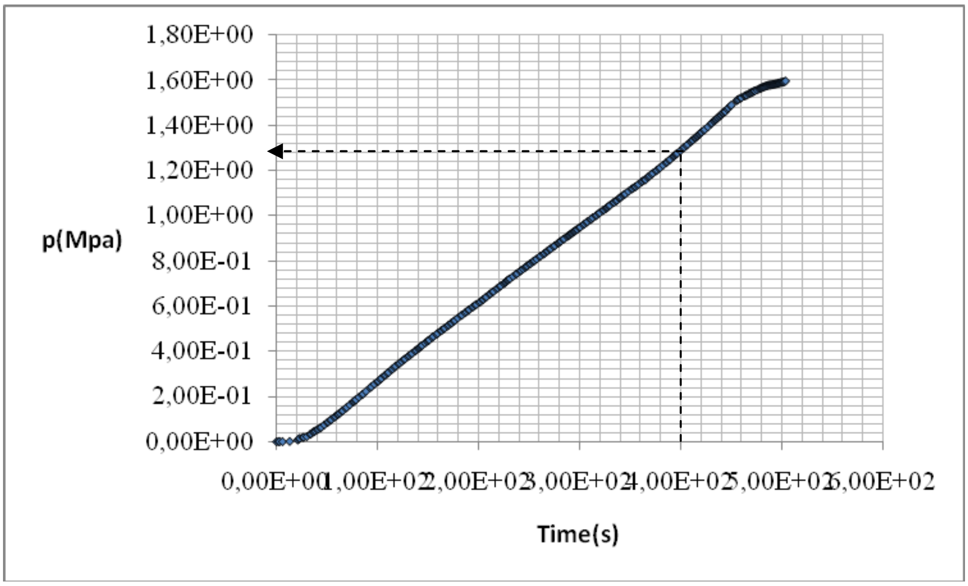

Figure 13 : Evolution of the pressure p around the rebar with the time of heating

IV. CONCLUSION

Using the magnetic properties of iron together with Faraday's law of induction heating and image correlation analysis, this study have presented a new method to determine fracturing properties of concrete. This experimental approach enables to:

- Correlates concrete fracture properties of concrete with the expansion of the rebar expansion in a reinforced concrete structures under heating;
- Gives an estimation of the pressure as well as equivalent force acting on the concrete around the reinforcement during a fire process;
- Estimates the value of the critical energy release as well as the fracture toughness through induction heating.

In the usual fracture mechanic test very heavy apparatus are used and one needs generally many samples to have an estimation of the fracturing properties of concrete. In the present approach, the samples are very small in size, the apparatus is very simple and an order of magnitude of the material can be obtained from one specimen. One other advantage of the method is the possibility to conduct two or more tests at the same time from the same high frequency generator if many cameras and displacement tools measurement system are available.

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