DAMAGE MODELING OF REFRACTORY CONCRETE UNDER THERMAL SOLICITATIONS

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Because of thermal expansion difference between ceramics and metal parts, on heating or cooling of refractory linings, high level stresses may occur within the castable and leads to damage and fracture of the lining. First, an experimental study has been undertaken. The damage around one single anchor, embedded in castable submitted to a thermal gradient, has been followed by acoustic emission. Then, the behavior of such a small lining has been simulated with a finite element method, using a smeared crack model. The simulation results about cracking level and crack orientations, depending on the anchor geometry, are in good agreement with the experiments. A pull-out test is used in order to validate in a quantitative manner the loss of stiffness of the lining due to damage after a thermal loading.

INTRODUCTION

Among the new clean coal technologies, "Circulating Fluidized Bed Combustion", CFBC, is one of the most promising. The CFBC boiler has a very large combustor, lined with refractory materials in the lower part. The refractory lining system is monolithic castable refractory made. It is anchored to the steel support structure. The aim of this study is the optimization of the castable anchoring, in order to reduce the lining damage and to improve the service life of these refractory linings. A first step in the experimental research is to study the behavior of one single anchor, embedded in castable. The mechanical and thermal behavior characteristics of such a lining are needed to calibrate a finite element model, in order to establish a simulation of a complete structure. Thus, thermal cycling tests and pull-out tests have been performed on panels containing one anchor. The material used in this experimental study is a self flowing castable silicon carbide based. In a second time, the tests were simulated with a finite element method, using a smeared crack

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model for the castable behavior.

EXPERIMENT

In the CFBC boiler, the refractory castable is submitted to a non linear temperature gradient due to rapid heating or cooling, and to a linear temperature gradient, when the inner-face temperature is 900°C, and the back-face temperature is 350°C. At last, high level stress occurs in the castable, on heating or cooling, because of thermal expansion difference between steel and concrete. A first step in the experimental research is to analyze the behavior of one single axisymmetric anchor embedded in castable during thermal cycles. A special furnace (Figure 1) was built, in order to reproduce the thermo-mechanical conditions of the refractory lining in the CFBC boilers.

To evaluate the damage, the cracks were observed and a non destructive method (acoustic emission) and a destructive method (pull-out tests) have been used. The visual observations show that the main orientation of cracks around the anchor is radial (Figure 2). The acoustic emission (associated to crack openings) begins for an inner face temperature of 200°C, and presents a high increase at 490°C (Figure 3). There is no more acoustic emission for a constant temperature of 900°C. We can also observe that there is a lot of acoustic events during the first thermal cycle, and very less during the next cycles: the first heating appears to be the most damaging for the lining. The pull-out tests of an anchor (Figure 4) are performed on panels which have been previously submitted to thermal loadings (i.e. they are already damaged). They allow to measure the loss of stiffness due to micro-cracking: the slope of the load/displacement curve decreases as the damage increases. The observed failure surface is a cone (see Figure 4).

MODELING

To simulate the tests described above, an elastic-plastic behavior is used for the steel anchor, and a different behavior in compression and in tension for the castable. In compression, an elastic-plastic theory is used. In tension, it is a smeared crack model (Weihe et al (1)): cracks are supposed to affect the material stiffness, but are not treated as individual macro-cracks. When the material is under tension, cracking is assumed to occur when the stress reaches a three dimensional failure surface, which is called "crack detection surface", given by the equation (Andrieux et al (2), Andrieux (3)):

$$f_t = q - (3 - b\frac{\sigma_t}{\sigma_t^u})p - (2 - \frac{b}{3}\frac{\sigma_t}{\sigma_t^u})\sigma_t = 0$$

where σ_t^u is the failure stress in uniaxial tension, p is the effective pressure stress, q is the Von Mises equivalent deviatoric stress, and b is a constant. σ_t is a hardening parameter (σ_t is the equivalent uniaxial tensile stress, Figure 5). After cracking, the material softens (see Figure 5). The basis of the post-cracked behavior is the brittle fracture concept of Hilleborg (Hilleborg et al (4)): we assume that the fracture energy required to form a unit area of crack surface, G_f, is a material property. We can note that cracking introduces anisotropy in the material.

Since it is difficult to perform a tension test on concrete, it is necessary to identify the model with a structural test: a four point bending test. An inverse method (Bui (5)) is used to determine the parameters of the model, comparing experimental results and numerical results obtained by a finite element method.

The heating and cooling tests, and the pull-out tests were simulated with a finite element method, with an axisymmetric model (since the anchors are axisymmetric in this study for simplicity reason), including contact with friction between anchor and concrete. The damage around the anchors is shown Figure 6 (thermal loading) and Figure 7 (thermal loading followed by a pull-out test). For the thermal loading simulation, the global distribution and the main orientation of cracks that are observed on the probes are found. The first damage appears for an inner-face temperature of 170°C (200°C were found experimentally). For the pull-out test, the shape of the volume containing the damaged elements is near a cone (Figure 7) and corresponds fairly well to the experimental failure surface. The numerical load/displacement curve is in rather good agreement with the experimental one, proof that the model fits the reality, and that the damage is correctly predicted.

The damage around different shapes of anchor have also been computed (Andrieux (3)). Three dimensional simulations are necessary for non axisymmetric anchors. The comparison of the damaged zone around the different anchors allows to know what shape is more or less damaging for the castable during thermal cycles.

CONCLUSIONS

A smeared crack model, identified with four point bending tests, allowed us, with a finite element method, to simulate the damage evolution around an anchor embedded in castable, during thermal loadings. Comparisons between numerical simulations and experimental results validate our model in a simple axisymmetric geometry: orientation of cracks, temperature of first cracking and loss of stiffness (measure of damage with pull-out tests). Castable anchoring optimization will be the industrial application of this study. It is now possible to choose the less damaging couple anchor/castable.

Accounting for the large number of anchors in an industrial boiler, the next step of the study is the definition of an homogenized material behavior for the set composed of the refractory, the anchors and the metallic casing.

SYMBOLS USED

ε = strain tensor

ε^{el} = elastic strain tensor

ε^{an} = anelastic strain tensor

σ = stress tensor

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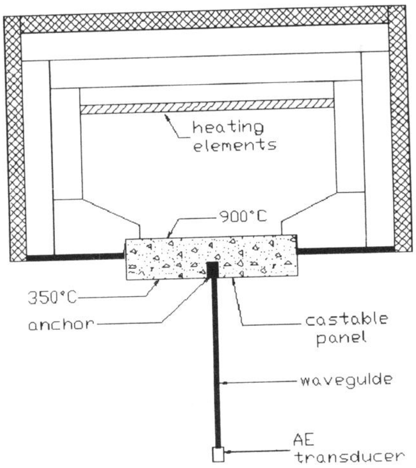

Figure 1 Thermal cycling experimental device with acoustic measurement

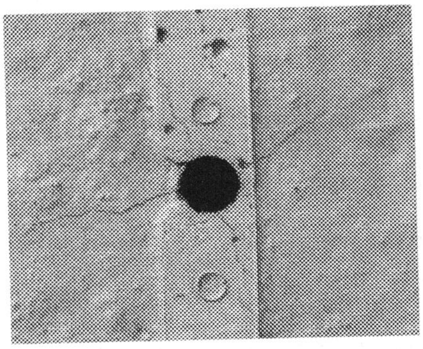

Figure 2 Cracking of an anchored panel after thermal loading-unloading (900°C)

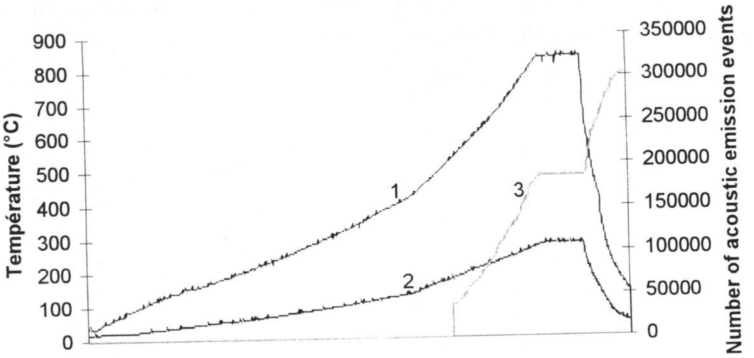

Figure 3 Acoustic emission on an anchored panel: inner-face temperature (curve 1), back-face temperature (curve 2), and acoustic emission (curve 3).

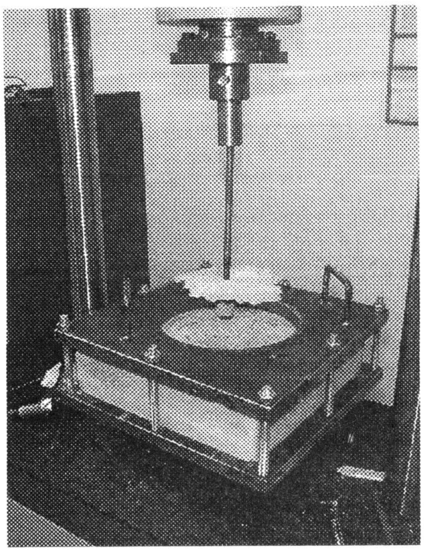

Figure 4 Pull out test of an anchor

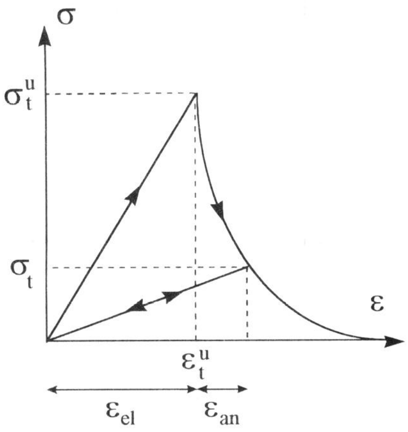

Figure 5 Uniaxial tension behavior

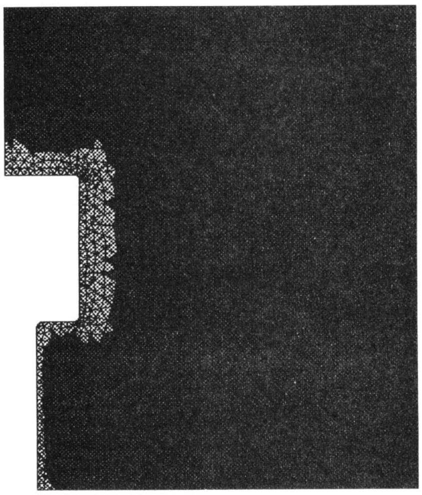

Figure 6 Damage in the concrete around the anchor (thermal solicitations)

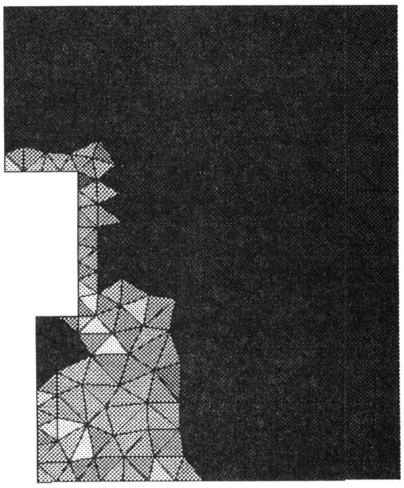

Figure 7 Damage in the concrete (pull out test after a thermal loading)