Effects of corrosion on the damage and failure of concrete

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Abstract. *The Damage and failure of concrete is widely investigated in the framework of continuum damage mechanics. Various models exist in literature and describe quite well a variety of observed phenomena depending on their complexity. The main objective of this work is to investigate and model the effects of corrosion in the damage and failure properties of concrete.*

Initially, we will make traction and compression tests in some specimens of concrete, some of them submitted to corrosion in a salt spray chamber (1, 3, 6 months...) and others without any corrosion, to determine the mechanical behaviour of concrete taking into consideration the effect of corrosion. With these experimental results, using Continuum Damage Mechanics, an elastic model applied to damage will be used to model the behaviour of concrete. In the first stage, isotropic elasticity and isotropic damage (with only one scalar variable D) will be considered including the effects of corrosion.

The expected results analyze the evolution of damage in concrete with relation to the time of exposition of the specimens in the salt spray chamber and the function of the mechanical loading.

Keywords: *Continuum Damage Mechanics, concrete, corrosion.*

1. Introduction

For a better analysis of the degradation or damage of materials, in the last decades, the theory of the Continuum Damage Mechanics is consolidating. While the Fracture Mechanics treats macrocospic models, in the propagation of macrocracks, Damage Mechanics evaluates the microstructure of the materials, in the microscale or mesoscale. Thus, it analyzes the degradation of the mechanical properties of the material produced for irreversible processes that occur with degradation of the material in a microscopical level, in the contours of grains and in the hollow spaces, at last, with the evolution of the micro-defects.

The constitutive models of the Continuum Damage Mechanics theory have presented good results, however, they present a very complex formulation, and even presenting a good response, its computational implementation or practical application are impracticable. However, some simplified models have been implemented for particular cases and they have gotten satisfactory results with sufficient success.

The first one to introduce the concept of Damage Mechanics was Kachanov in 1958, with the intention to justify the rupture in metals precociously, observed in regimen of slow deformation. Since then, several other studies have been realized and today, Damage Mechanics has been applied successfully in many fields to evaluate the integrity of structural components.

The complexity of the microstructure of concrete is one of the causes of a particularity of its mechanical behavior. Concrete is a composite material composed by granulates in a brittle matrix: the hydrated cement paste. Each of these elements has a well-defined role, one of bonding for the cement paste and one of padding, mitigating the effects of volumetric variations (dilation and shrinkage) for granulates.

Some simplified models with bases in the theory of the Damage Mechanics have been developed, each one with its advantages and disadvantages, to explain the mechanical behavior of concrete. Jack Mazars contributed with his model for the study of damage in concrete. However, in the development of these models, a study of the effect of corrosion in the material has not still been made, in the degradation of the mechanical properties and consequently in the evolution of damage.

Being corrosion, one of the main causes for the degradation of concrete, even more for the fact that the area of Fortaleza is said to have one of the most corrosive environments in the world and this point is worth being included in the design process especially for offshore constructions made of steel but also for concrete (or reinforced concrete) structures in civil engineering. The main objective of the topic here is to investigate and model the effects of corrosion on the properties of damage and failure of concrete.

2. Damage Mechanics

2.1 Scale of the Phenomena of Strain and Damage

Concrete is, both chemically and mechanically, a very complex material. According to Wittmann (1983), there are at least three different levels (or scales) on which the physical and chemical processes can be observed. Following Wittmann (1983), with modifications appropriate for present purposes, the hierarchical sequence of scales can be arranged as shown in Table 1 below.

Table 1. Hierarchy of structural scales defining the mechanical response of concrete

Scale	Volume element	Defect	Model
Micro	Hardened cement paste, xerogel, aggregate	Atomic voids, crystal defects	Material science models
Meso	Unit cell containing statistically valid sample of phases	Microcracks, large pores	Micromechanical models
Macro	Concrete specimen	Macrocrack	Continuum theories, fracture mechanics

Krajcinovic and Fanella (1986) proposed the hierarchical system of scales to a certain degree arbitrary. In fact, it merely reflects the propensity to construct and use continuum models based on the assumption that the phase functions (displacement fields) are continuous and that their local fluctuations are negligible in comparison with the expected values. In the language of mechanics, a phenomenological continuum theory typically assumes the material to be simple of grade one. Thus, the influence of the mesostructure is reflected only in some appropriately averaged sense (effective moduli).

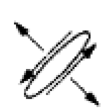
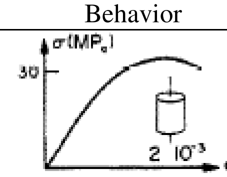
Mazars (1986) said that from the mechanical point of view, there is an interaction between these two phases, and we are going to show that the analysis of the local phenomena allows us to deduce realistic hypotheses for the formulation of behavior models. Thus, a microscale analysis leads to a macroscale description.

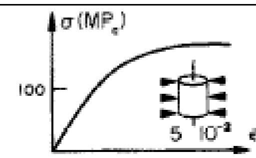
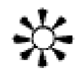
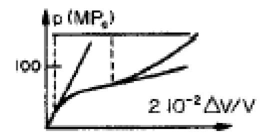
2.2 A Continuous Damage Model for Concrete

Mazars (1986) proposed a model in the following context:

- application domain: type A previously defined (extensions exist);
- behavior: elasticity coupled with damage and respecting the dissymmetry of traction-compression;
- type of damage: existence of a threshold and isotropy.

Table 2. Damage mode and behavior of concrete

Type	Particularity	Local damage mode	Behavior
A	Extensions ($\varepsilon_i > 0$) may be possible	 Mode I or I + II	 With instability

B	Without extension	 Mode II (or III)	 With ductility
C	Hydrostatic pressure	 Consolidation	

2.2.1 Damage Mechanics

The model of Mazars (1986) considers the following hypotheses:

- The concrete behaves as a damage medium, where the permanent deformations are rejected;
- The damage is considered isotropic;
- The damage is caused only by extensions and the rupture develops by the mode I or I + II, Table 2.

Introduced by Kachanov (1958) and developed by Lemaitre (1996), the variable damage notion was used with the concept of effective stress:

$$\tilde{\sigma} = \frac{\sigma}{(1-D)} \qquad (1)$$

($\tilde{\sigma}$: effective stress tensor; σ : usual stress tensor; *D*: damage variable).

Then for an isotropic linear elastic virgin material, the behavior for a given state of damage is described by

$$\sigma = (1-D)\,\boldsymbol{A}{:}\varepsilon \qquad (2)$$

A: fourth-order elasticity tensor. *D* is a scalar whose value is in the domain [0, 1]; the damaged material then remains isotropic.

2.2.2 Damage threshold for concrete

The importance of extensions in the damage of concrete has been seen before. According to a previous paper of Mazars (1981), he has suggested evaluating the local intensity of extensions, the equivalent strain notion:

$$\tilde{\varepsilon} = \sqrt{\sum_i < \varepsilon_i >_+^2} \qquad (3)$$

$$\langle \varepsilon_i \rangle_+ = \varepsilon_i, \quad se \quad \varepsilon_i > 0 \qquad (4)$$

$$\langle \varepsilon_i \rangle_+ = 0, \quad se \quad \varepsilon_i < 0 \qquad (5)$$

The damage threshold is then defined by:

$$f(D) = \tilde{\varepsilon} - K(D) = 0 \qquad (6)$$

with $K(0) = \varepsilon_{d0}$ (initial damage threshold).

2.2.3 Combination of two kinds of damage

The dissymmetry between tensile and compressive behaviors is due to the fact that in the first case microcracks are created directly by extensions which are in the same direction as stresses; in the second case extensions are transmitted by the Poisson effect and then are perpendicular to the direction of stresses; the phenomena then increase more slowly.

In the uniaxial case we put

$$D_t = F_t(\tilde{\varepsilon}) \text{ for traction} \quad (7)$$

$$D_c = F_c(\tilde{\varepsilon}) \text{ for compression} \quad (8)$$

a combination between D_t and D_c is necessary for the multiaxial case:

$$D = \alpha_t D_t + \alpha_c D_c \quad (9)$$

Taking into account what we said above, α_t and α_c are, respectively, linked to the tensile and compressive stresses, according to Mazars (1986). These values respect the fact that $\alpha_t = 0$ if σ is only compressive and $\alpha_c = 0$ if σ is only a tensile one.

2.2.4 Evolution laws

From experimental results, Mazars (1986) proposed the next damage evolutions laws:

$$D_t(\tilde{\varepsilon}) = 1 - \frac{\varepsilon_{D_0}(1 - A_t)}{\tilde{\varepsilon}} - \frac{A_t}{\exp[B_t(\tilde{\varepsilon} - \varepsilon_{D_0})]} \quad (10)$$

$$D_c(\tilde{\varepsilon}) = 1 - \frac{\varepsilon_{D_0}(1 - A_c)}{\tilde{\varepsilon}} - \frac{A_c}{\exp[B_c(\tilde{\varepsilon} - \varepsilon_{D_0})]} \quad (11)$$

where ε_{D_0} is the initial damage threshold and A_t, B_t, A_c, B_c are characteristic parameters of the material.

The identifications are obtained uniaxial compressive tests for A_c and B_c and flexion tests for A_t and B_t because of the great instability of the direct tensile test.

3. Experimental investigation

Firstly, 40 specimens of concrete were prepared for testing. These specimens are cylindrical with dimensions of 10cm of height and 5cm of diameter. Different mechanical tests are needed: tension and compression to derive the behaviour of the material.

Some of these will serve for damage and failure in the absence of any corrosive mechanism and will obtain the damage behaviour of concrete without corrosion. This is obtained by tension and compression tests up to failure. It has to be mentioned here that the testing procedures are completely different in tension and compression and care must be put for their realization. While a compression test is rather easy to carry out, a tension test is much more involved due to localization phenomena and the difficulty to achieve a homogeneous test.

The other specimen were put in the corrosive ambiance, in a Salt Spray chamber for different durations (one month, two months, etc… depending on the strength of the corrosive process). For each duration, the same tests as above will be carried out. Measure of damage at the beginning of the test gives the damage due to corrosion alone. The evolution of damage during these tests and their comparison with the tests with no corrosion allow exhibiting the roles of corrosion on the damage evolution process.

3.1 Compression and traction tests

The compression test is made in the traditional way and the traction test is shown in the figure below.

In contrast to the compression test, the traction test was much more complicated, therefore the intention of this test was getting the stress-strain graph to do the analysis of the theory of Damage Mechanics. This graph is difficult to obtain, because usually, we have to only get the resistance for traction for the case of concrete, however, for resistance test in traction, there are already efficient and simple methods.

For the accomplishment of this test, the manufacture of a device formed of steel parts was necessary and they had been machined in such a form to be able themselves to glue the specimens to make the traction tests. The parts consist of two claws of 20mm of diameter for the setting in the machine where the inferior claw is fixed and the superior is a system of parts that form a joint that serves for a better setting and to minimize the torsion effect. These claws are fixed to the bases through a threading.

Figure 1. Traction test

3.2 Modelling

An elastic model coupled to damage will be used to model the behaviour of the concrete. At a first stage, isotropic elasticity and isotropic damage (with only one scalar variable D) will be used. But to include corrosion effects, another variable should be introduced. This is of course dependent on the corrosion mechanism that it is responsible for the degradation of the material and some physical and chemical information are necessary to make this link. In the meantime and if this information is not available, a purely phenomenological approach can be followed. A variable C is introduced that is supposed to describe in average and at a macroscopic scale the effects of corrosion on the degradation of the material. A simple possibility is to relate C to the time spent under the corrosive atmosphere.

It will be assumed (and checked a posteriori) that the corrosion mechanism has only an effect of the degradation process. Under uniaxial tension or compression, the stress σ is related to the strain ε through the classical relation

$$\sigma = (1 - D)E\varepsilon \qquad (12)$$

In absence of corrosion, the evolution of damage is governed by the strain ε or more precisely by the force associated to damage, namely Y and damage will start at a stain threshold ε_0 (or a threshold Y_0), i.e. when

$$Y - Y_0 = 0 \tag{13}$$

However, after unloading and reloading, this threshold is modified. A period of increase in stress is observed after which a continuous decrease up to failure follows. The threshold Y is therefore taken in the form

$$F(Y, D) = Y - Y_0(D) = 0 \tag{14}$$

and the evolution of damage is given by

$$D = g(D) \tag{15}$$

In presence of corrosion, damage can start with no mechanical loading and the threshold has to be modified consequently. Further the damage is dependent not only on strain but also on the corrosion process. We will define a threshold function in the form

$$F(Y, D, C) = Y - Y_0(D, C) = 0 \tag{16}$$

and the evolution law for damage as

$$D = g(D, C) \tag{17}$$

The explicit expression of and Y_0(D,C) and g(D,C) will be invoked from experimental results.

4 Results and expected results

4.1 Indentification

The identification procedure is meant to obtain the threshold function Y_0(D,C) and the damage evolution law g(D,C) from the experimental results. Y_0(D,0) and g(D,0) are obtained from the tests carried out on concrete that has not been subjected to any corrosive environment. Indeed measurements of Young's modulus after successive unloadings allow to compute the damage for different strains (or Y). Fitting of the results gives function g(D,0). The initial threshold is related to the strain where the damage starts, i.e when Young's modulus starts to decrease.

In the same way Y_0(0,C) and g(0,C) are obtained from the first loadings of the specimens that have been put in the Salt Spray chamber for different time periods. The measurement of Young's modulus during these first loadings and its comparison with the modulus obtained for a specimen that did not suffer any corrosion allow to evaluate damage due to corrosion. The rest of the test will be used to see if there is any interaction between damage due to mechanical loads and damage induced by corrosion. The final structure of the evolution law can only be concluded with these results.

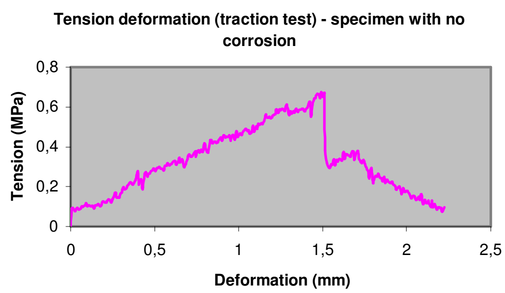
4.2 First Results

We made a traction test with a specimen with no corrosion. With these data, we applied the theory of damage Mechanics developed by Mazars (1986).

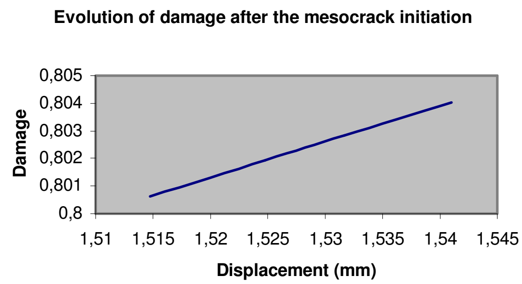
The data show us that the tension of rupture is 0,67Mpa and the initial damage threshold ε_{D_0} 1,51mm. According to Mazars, we used the following values to the parameters: A_T = 0,8 and B_T = 20000 for the traction test and A_C = 1,4 and B_C = 1850 for the compression test. We also considered the Poisson number, in this case, ν = 0,2 to calculate α_t and α_c that are, respectively, linked to the tensile and compressive stresses to make the combination between D_t and D_c to obtain the variable *D*.

For an uniaxial test, we have $\tilde{\varepsilon}$ only in the y direction. In conclusion, for the first traction test, we have the initial damage threshold a scalar value D = 0,8006.

For the first specimen, we have the graph of the tensile test in graph 1 and in graph 2 the evolution of damage after the mesocrack initiation in relation to the displacement.



Graph 1. Tension deformation (traction test)



Graph 2. Evolution of damage after mesocrack initiation in relation to the displacement

5. Conclusions

We have the first results for concrete submitted to the traction test for specimens with no corrosion and soon, we will have the results for the compression test also with no corrosion and then the results for the mechanical comportment to the specimens submitted to the Salt Spray chamber.

We will have the relation for the combination of damage in compression and in traction, and also the same damage with specimens submitted to corrosion for different periods of time.

The specimens were made with one of the traces of concrete that are very common in the civil construction (1:1,88:3,30:0,59).

Finally, we will analyse the evolution of damage in concrete in relation to the time of exposure of the specimens in the salt spray chamber and the function of the mechanical loading with the formulation detailed in this work.

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