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Damage Mechanics Applied for Steel Reinforcements in Concrete Structures Under Corrosion

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Abstract

Structures of reinforced concrete, as any another structure that uses metallic components, are subjected to corrosion, being this, one of the main factors for the degradation of these structures. Thus, a study of this phenomenon is very important to describe the mechanical behavior of them. This study has as main objective to analyze the degradation of the mechanical properties of steel bars used in the civil construction, considering the effect of corrosion in these properties, and to develop a simplified model for the evolution of the damage, through the Continuum Damage Mechanics theory. Steel bars specimens were confectioned and submitted to an accelerated corrosion test (Salt Spray) for different intervals of time. After the corrosion test, the specimens were submitted to a tensile strength test with loading and unloading, getting the elasticity modulus for each unloading. Then, the concept of measure of damage through the variation of the Elasticity Modulus, introduced by Lemaitre, was applied. The damage in function of the deformation for each specimen was obtained. Finally, with the analysis of the damage in the different specimen, the variable Damage in function of the mechanical loading and the corrosion was written.

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Keywords: corrosion, damage mechanics, reinforced concrete, steel bars.

1. Introduction

Some types of materials have been used in the civil construction, however, the reinforced concrete are applied, due its mechanical properties and low cost.

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The first application of the steel rebars, in the concrete, occurred in 1850, in France, by Joseph Lambot (KAEFER, 1998), where Lambot used steel rebars and a mesh of wires, in a concrete boat. This experience was very important to increase the application field of the concrete that was limited for some properties. Loadings as bending were enough to promote a fracture in the material, because the concrete is a fragile material. However, with the addition of the steel rebars, this material shows now ductility and avoids the excessive opening of the fissures. In this way, the reinforced concrete could be used in many applications of the civil construction.

2. Corrosion in Reinforced Concrete

The mechanism of the corrosion in reinforced concrete is a specific manifestation of the electrochemical corrosion in wet way and so that is necessary three basic conditions:

- Existence of an electrolyte - the water is always present in the concrete, and the many times in amount enough to act as electrolyte. It's necessary transport of ions to the reactions of electrochemical corrosion.
- Difference of potential - the difference of humidity, aeration, saline concentration, tension in the steel, it can generate a difference of potential of electrode capable to create electrochemical cells.
- Presence of oxygen - it is necessary, therefore it participates in such a way of the anodics reactions how much of the cathodics reactions that occur for the formation of a rust, product of the corrosion, as for instance:

$$2Fe + O_2 + 2H_2O \rightarrow 2Fe(OH)_2$$

3. Continuum Damage Mechanics (CDM)

The Damage Mechanics is a part of Solid Mechanics based on metallurgy, which gives a better understanding of rupture problems in structures by the definition of a variable, which represents the deterioration of the materials before the initiation of a macro-crack (LEMAITRE, 1983).

The effective stress concept was introduced in 1968 by RABOTNOV (LEMAITRE, 2009). It is defined considering a situation of uniaxial request on the element of volume, consisting of a force F applied in the opposing faces guided by direction n. Admitting itself that the set of defects is total incapable to transfer stress, we can define effective stress taking itself in account the complete part of the section. Effective stress is defined accomplishes for a unidimensional case, as:

$$\tilde{\sigma} = \frac{F}{\tilde{S}} \tag{1}$$

$$\tilde{S} = S - S_D = S(1 - D) \tag{2}$$

Taking in account the relation (3) it follows that:

$$\tilde{\sigma} = \frac{\sigma}{(1 - D)} \tag{3}$$

3.1. Mathematical Model of Damage

Either **S**, the area of the transversal section of the element of Figure 01, situation (a), S_{Dc} the area of the defects due to corrosion and S_{Dm} the area of the defects proceeding from mechanical requests and other natures. Then, the total area of the defects (S_D) is:

$$S_D = S_{Dc} + S_{Dm} \tag{4}$$

It considers $\tilde{S}$ as being the complete area (area that effectively resists the efforts) of considered section S. Then the area of the defects (S_D) is:

$$S_D = S - \tilde{S} \quad (5)$$

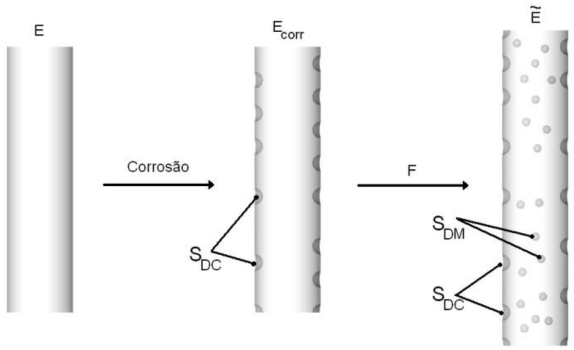

Fig. 1. Schematical representation, damage due to corrosion and to a mechanical shipment.

The function $\mathbf{D_{corr}}$ represents the addition of damage due to corrosion and due to a mechanical shipment ($\mathbf{D_m}$):

$$D_{Corr} = 1 - \left(\frac{E_{corr}}{E} \right) \quad (6)$$

$\mathbf{D_{corr}}$ is the function of the corrosion (corrosive way, concentration of aggressive ions, the time of exposition etc.) and can be quantified by means of the reduction of the modulus of elasticity due to corrosion:

$$D_M = \frac{E_{corr} - \tilde{E}}{E} \quad (7)$$

$E_{corr} = E_0$ and $\tilde{E} = \tilde{E}_0$ where E_0 it's the elasticity modulus gotten in the beginning of the first shipment, therefore equations 6 and 7 can be rewritten as:

$$D_{Corr} = 1 - \left(\frac{E_0}{E} \right) \quad (8)$$

$$D_M = \frac{E_0 - \tilde{E}_0}{E} \quad (9)$$

4. Materials and Methods

In this paper it was carried out a study of the process of corrosion in damage of steel bars CA-50A. Therefore, samples of steel bars "integrate" (no submitted to corrosion) was submitted traction test, it had been defined as standard samples, and other samples were initially submitted to accelerated corrosion test (Salt Spray), exposition in the saline fog. At a first time, specimens of steel bar CA-50A had been confectioned, with nominal diameter of 10mm and total length (Lt) of 220mm. The useful length, Lu, (distance between machine grips in Traction Testing) is 100mm, determined according to standards NBR 7480 - 1996 and NBR ISO 6892 - 2002. Figure 2 shows a specimen and its dimensions in mm.

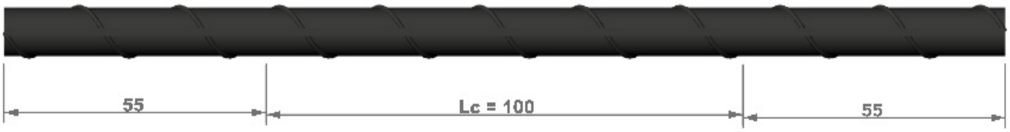

Fig. 2. Steel bars CA-50A.

4.1. Corrosion Test

Very used test is the Salt Spray Test, exposition to saline fog. It was used in the development of this paper. The corrosion test was carried out according to standard NBR 8094 - metallic material coated and not coated corrosion for exposition in saline fog and standard ASTM 117, or either, used a 5% solution sodium chloride (NaCl) with pH of the salt spray solution enters 6,5 to 7,2 and the temperature in the zone of exposition of the chamber, was kept 35 °C. Figure 3 shows to steel bars specimens after 2016 hours of test.

Fig. 3. Specimens after 2016 hours of exposition in the corrosion chamber.

5. Results and Discussion

After the corrosion test had been carried through traction test (Figure 04), the values of elasticity modulus had been substituted in Equation (8) for the attainment of the damage.

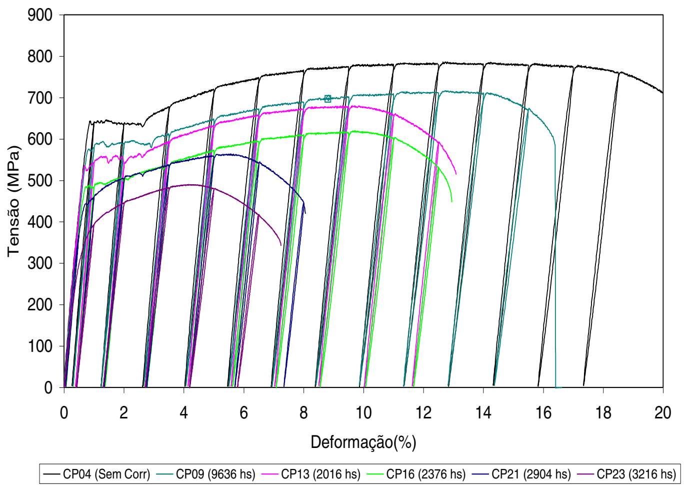

Fig. 4. Graphical tension x deformation of the Specimens submitted to salt spray test, shown reduction in the tension and deformation due to corrosion.

Table 1 presents the percentile reduction the maximum stress observed in function of the time of corrosion test. For a time of corrosion test of 2528 hours had a percentile reduction of 32,5 for maximum stress.

Table 1. Behavior of the stress in function of exposition time of Specimens - salt spray test.

Time of exposition (hours)	***Maximum Stress*** (MPa)	**Percentile reduction**
0	782	0
504	714	8,7
936	711	9,1
1848	635	18,8
2376	616	21,2
2472	564	27,9
2904	541	30,8
3216	536	31,5
3528	528	32,5

From the graphical stress-strain determined the elasticity modulus in each unloading and substituted these in the Equation 08 the damage was gotten. Table 2 presents the elasticity modulus (E_0) gotten in the first loading and the rupture (E_r), as well as the initial damage (D_0) and the damage in the rupture (D_c) in function of the time of corrosion test.

Table 2. Values of elasticity modulus and damage, initial and of rupture in function of the corrosion time.

Time (hours)	E_0 (GPa)	E_r (GPa)	D_0	D_c
0	210,3	111,8	0	0,468
2016	193,8	113,7	0,078	0,459
2376	166,2	109,6	0,207	0,479
2904	153,1	115,0	0,271	0,453

In Figure 5 it is observed approximately that the Specimens had breached the same with critical damage (D_c), of 0,46. The initial damage, which had the corrosion, grows with the time of corrosion test, for 2904 hours of test the gotten initial damage was of 0,27.

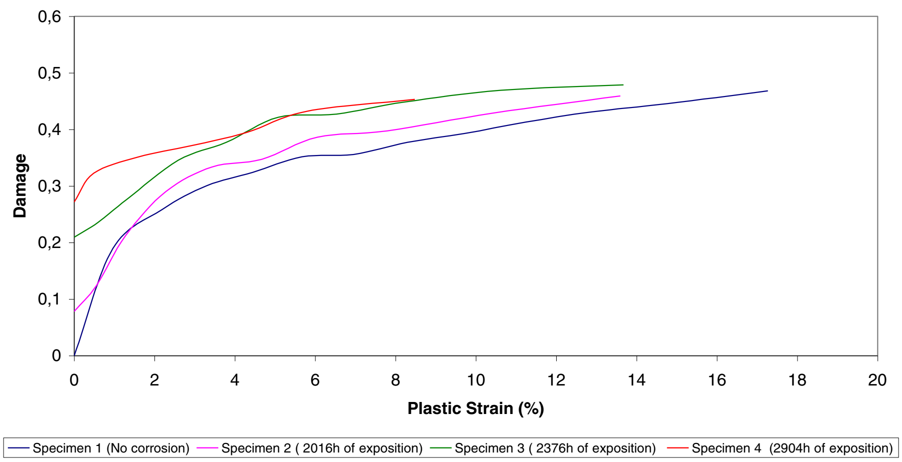

Fig. 5 - Graphical Damage x Plastic Strain (%): **(a)** – Specimen without corrosion; **(b)** - Specimen with 2016 hours Salt Spray, presented an initial damage due to corrosion (D_0) of 0,078; **(c)** - Specimen with 2376 hours salt spray, D_0 = 0,207 and **(d)** - Specimen with 2904 hours of test salt spray, D_0 = 0,271.

6. Conclusions

The rupture of the Specimens without corrosion and of that they had been displayed in the chamber of corrosion for up to 2376 h, occurred approximately with exactly critical damage (D_c), D_c = 0,45. Proving, thus, the validity of the used mathematical model, therefore the critical damage is a characteristic of the material and the conditions of test, or either, for a material, in the same conditions of test, they must present the same critical damage.

For time of exposition above of 2376 hours, we observed that some Specimens submitted to corrosion test for the same time, had presented a different behavior in the evolution of the damage (they had presented different initial damage, such as different critical damage). This indicates, that the mathematical model used in this papers is only valid until a certain period of exposition to corrosion (2376 hours), therefore, from this period of exposition, the defect distribution due to corrosion can't be considered homogeneous, or either, the conditions of representative volume element which the formularization of this mathematical model is not satisfied.

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