Use of historical buildings to validate corrosion induced cracking models

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ABSTRACT: In order to predict the long term evolution of reinforced concrete structures exposed to environmental conditions, the French Atomic Energy Agency (CEA) has launched a project, called CIMETAL, which aims at characterizing and predicting the effects of corrosion of the reinforcements induced by carbon dioxide penetration.

One of the main objectives of this study is to evaluate the capability of a cracking model to predict the time required for the formation of visible cracks on a old building. For this purpose, a 50 years old water tower, classified as historical building, and showing degradations, has been selected. Various measurements have been performed on it to characterize, as much as possible, some data required for the modelling, such as the accurate position of the rebars in the structure, the nature of the iron oxides, etc.

A particular cracked zone of the tower has been selected for the mechanical analysis. Bidimensionnal transient analysis have been performed, in which the concrete, the reinforcements as well as the corrosion products layers are modelled.

1 INTRODUCTION

Cracking of concrete due to corrosion is a very common pathology that can be observed on various structures. Corrosion is initiated by the penetration of chlorides or of carbon dioxide in most cases. Usually, the associated deterioration process follows three sequential stages (Tuuti, 1982) (figure 1):

- Initiation: during this long period, the corrosion rate is very low despite of the ingress of aggressive species from the environment to the steel.
- Depassivation : this step happens when the conditions required for the onset of corrosion are fulfilled thanks to the transport of aggressive species through concrete cover.
- Propagation: the reinforcement corrosion causes significant loss of section of the reinforcements. Internal micro cracking and spalling of the concrete cover appear. They are due to the high tensile stresses generated by the expansive volume of the corrosion products.

The mechanical consequences of corrosions are (i) the reduction of the resistive section of reinforcements (ii) the creation of expansive products (commonly denoted rust) (iii) the fragilization of steel and finally (iv) the cracking of concrete (Andrade et al,1996, Petre-Lazar,2000).

As reinforced concrete is a common material used in the nuclear industry for the construction of power plants and nuclear waste storage facilities, the degradation of infrastructures has to be mechanically understood and modeled. In this context, the *CIMETAL* research program has been launched by the French *Commissariat à l'Energie Atomique* (CEA), for the prediction of the evolution of cement/metallic material systems in an open unsaturated environment. It deals with interactive studies dedicated to short term experimentations (corrosion (Huet et al, 2005) and mechanical behavior of structures), modeling to predict the corrosion (Huet et al, 2006) and the mechanical behavior of objects for several hundred years, and finally validate some hypotheses with analyses of old corrosion systems (ancient ferrous artifacts or archaeological analogues (Chitty et al, 2005)), and mechanical behavior of old reinforced concrete structures. The aim of this paper is precisely to show how a 50 years old water tower has been used to try to validate the modeling tools developed in the framework of the research program.

2 MODELING APPROACH FOR OLD REINFORCED CONCRETE STRUCTURES

2.1 *General features*

The overall process of corrosion development involves electro-chemical processes, heat and mass transport by convection and diffusion, and mechanical aspects. A totally predictive modeling requires a multi-physics approach, which is the final goal of the CIMETAL program, but which is not yet available. Therefore, at the present stage, the modeling approach is based on one hand on measurements and on the other hand on a sequential treatment of couplings.

First an accurate investigation of the steel-cementitious material interface is performed on the old reinforced concrete by means of various techniques, such as optical microscopy, spectrometry coupled to electronic microscopy, mercury porosimetry, Raman micro-spectroscopy, and X-ray diffraction. Of particular importance is the composition of the corrosion products, because the expansion coefficient may significantly differ between iron oxides.

Then, the average corrosion rate is determined from the measure of the iron oxides thicknesses coupled to a correction of the local density.

Finally, these data are used in a damage mechanical model, called CORDOBA, which can predict the consequences of the active corrosion phase, in terms of displacements, stresses and cracks pattern.

2.2 *Composition of the long term corrosion products*

The general pattern encountered on old corroded metallic reinforcements in binders is made up of a multi-layer structure (Figure 1). The corrosion layout can be described as: the metallic substrate (M), the dense product layer (DPL), the Transformed Medium (TM) and the Binder (B). This corrosion pattern has been precisely described previously (Chitty et al, 2005). X-Ray Diffraction analyses reveal that Dense Product Layer is mainly made of iron oxy-hydroxides (goethite α-FeOOH, lepidocrocite γ-FeOOH, and akaganeite β-FeOOH), and iron oxides (maghemite γ-Fe_2O_3 and magnetite Fe_3O_4). The local structure of the Dense Product Layer has been studied by µXRD on some samples. Two different phases were noticed in the diffracted volume: goethite and magnetite (or/and maghemite). Indeed the fact that mixes of different phases are observed can be linked to the relatively large diffracted volume (20 x 20 x 50 μm^3) compared to the size of the marbling observed by Scanning Electron Microscope and Optical Microscope. In order to study more in detail the structure of the marbling, the microscopic laser beam of the µRaman microscope was used. These analyses show that veins are only made of iron oxides *i.e.* maghemite and/or magnetite and that matrixes are made of iron oxy-hydroxides *i.e.* goethite, lepidocrocite and akaganeite.

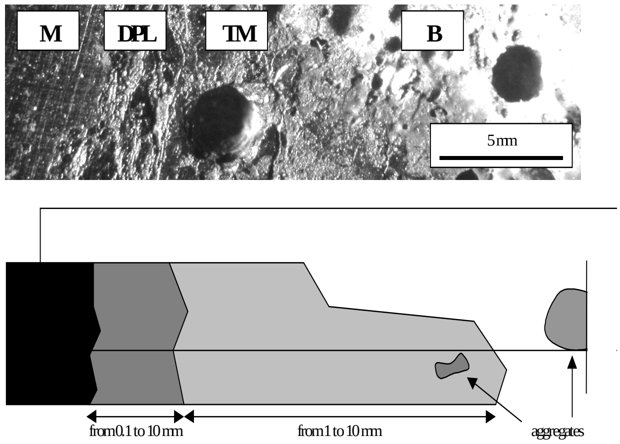

Figure 1 - Macro photograph of a cross section (GR) and schematic section f the corrosion system (M: metal; DPL: Dense Product Layer; TM: Transformed Medium; B: Binder).

The following table 1 gives the values of the expansion coefficient of the iron oxides, according to their composition.

Table 1. Relative increase in volume for different iron oxides compared to the initial iron volume.

Iron oxide	Relative volume (oxide/Iron)
FeO	1,8
Fe_3O_4	2,0
Fe_2O_3	2,0
$Fe(OH)_2$	3,7
$Fe(OH)_3$	4,1
$Fe(OH)_3$, $3H_2O$	6,2

2.3 *Average corrosion rate*

Systematic studies of corrosion of old reinforced concrete structures and archaeological analogues reveal characteristics that can be helpful for modelling purposes:

- Corrosion layers seem to be mainly composed of goethite that presents a volumetric expansion of 4 (according to values in Table 1).
- The average corrosion rates estimated on archaeological analogues are about 4 µm/year.

In order to dispose of a more accurate evaluation of the average corrosion rate, the total iron quantity involved in the corrosion products can be measured by compositional analyses. Then, a density correction allows converting this quantity into metal loss. For this purpose, average composition profiles lead to access on one hand to the evolution of the iron contents from the metal/oxide interface to the binder, and on the other hand to the thicknesses of the different layers (Dense Product Layer and Transformed Medium). A more precise description of this estimation can be found in Chitty et al, 2005.

2.4 *Modelling of corrosion products growth*

Average corrosion rates and nature of corrosion products identified during the characterization, can then be used as input data for the CORDOBA mechanical model.

Thanks to the Tuutti's model (Tutti, 1982) on stages of concrete damage due to the reinforcements corrosion (figure 2), two periods can be distinguished for the structure life. A first phase called "passive corrosion phase" when the unsaturated carbonation front penetrates into the concrete cover. We assume that no mechanical damage is induced by the passive layer growth. After the depassivation of the steel, expansive corrosion products growth leads to the mechanical damage of the concrete. The CORDOBA model is used for the estimation of this second period, until the appearance of the first through crack. This means that the predictions require the time of initiation of the depassivation as input data, which is unfortunately difficult to appraise.

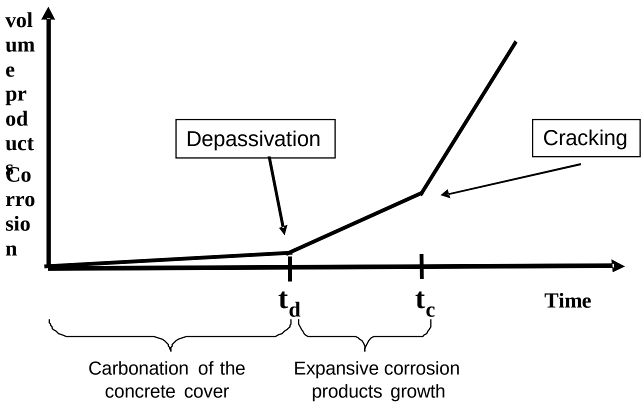

Figure 2 - Tuutti's diagram for a reinforced concrete structure degradation

The mechanical model mimics, at a macroscopic scale, the above depicted multi-layers structure, by assigning different material behaviour laws to the concrete (Binder and Transformed Medium), the reinforcements (Metallic Substrate) and the interfaces (Dense Product Layer).

For the concrete, a model capable of describing cracking must be used. Two kinds of such models have been tested : the Mazars' damage model (Mazars, 1984) formulated in an integral non-local framework, and the Ottosen's elasto-plastic model (Mersseman et al, 1994) using the Hillerborg's fracture energy based regularization technique.

For the reinforcements, since no plasticity is expected, a simple linear elastic material model is used.

The development of the corrosion products is simulated by means of special interface finite elements which are placed between the rebars and the concrete, and which can swell with time.

One difficulty in this model lies in the determination of the parameters of the interface, in terms of stiffness (Young's modulus for example) and swelling to reproduce the development of corrosion. Since the interface elements are composed of two superposed surfaces (or lines in a bidimensionnal case), their thickness must be given through their equivalent stiffnesses, k_n the normal one, and k_t the shear one, which are proportional to the Young's modulus of the rust.

The two stiffnesses are then calculated as:

$$k_n = \frac{E}{t_h} \quad \text{and} \quad k_t = \frac{E}{2(1+\upsilon)\times t_h} \qquad (1)$$

where ν is the Poisson's ratio of the rust, and t_h is the thickness of the rust layer, calculated as the product of the expansion rate by the time. The expansion rate depends itself on the average corrosion rate as well as on the volumetric expansion of the corrosion products.

The Young's modulus of the iron oxides has been determined by small scale experiments, on cylindrical concrete samples containing an embedded reinforcement (Millard et al, 2004, Ouglova,2004). According to the type of oxide formed (mainly goethite), the Young's modulus is found equal to 0.1 GPa.

It as to be mentioned that this first step of the development of the CORDOBA model does not consider any initial cracks within the concrete that could induce corrosion locally. Concrete is considered as mechanically sound when the active corrosion is initiated.

The model has been validated by means of experiments on centimetric concrete plates containing a reinforcement (Nguyen et al, 2006). The corrosion was due to the penetration of chlorides, accelerated by prescribed electric current. The developments of the cracks could be followed by image analysis and strain gauges, and compared to the numerical predictions.

The computations were performed using the CEA finite elements code CASTEM 2000 (Verpeaux et al, 1989). For plate geometries such as the one shown on Figure 3, a good agreement is obtained up to the formation of a through-crack. The comparison of the strain measured across the through-crack, and the calculated one, is displayed on figure 4. For this purpose, equal reference lengths have been used in the measurement and in the calculation. Concerning the cracks formation, the image analysis technique revealed that the cracks first form close to the rebars, then others may initiate on the outer boundary and finally coalesce with some initial one.

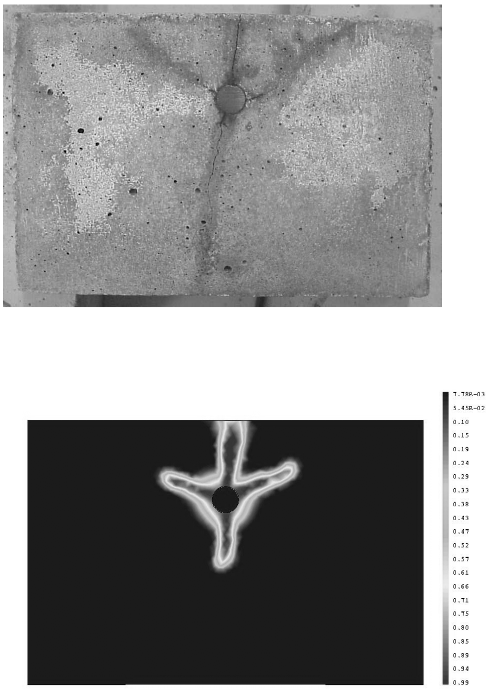

Figure 3 – Comparison of cracks pattern, after 40 hours, between experiment and prediction.

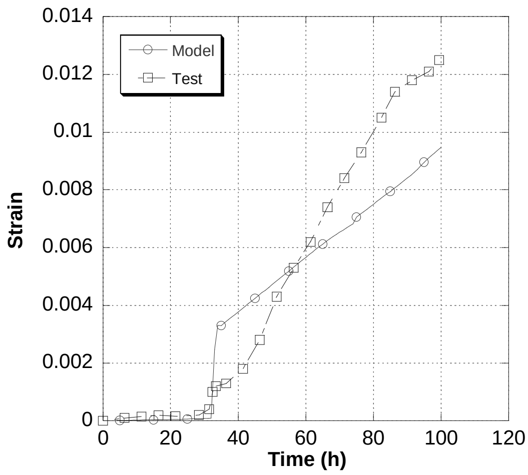

Figure 4 – Comparison between experimental strain across the crack, and calculated one (Nguyen et al, 2006)

The next step consists in trying to validate the model on a real size structure, subjected to atmospheric corrosion.

3 APPLICATION TO A HISTORICAL BUILDING

3.1 *Presentation of the structure*

The chosen building is a water tower, built in 1950 at Saclay, France, and classified as historical. Before its repair in 2004, some degradations such as spalling have been recorded. They occurred mainly on some of the vertical columns supporting the tank, located on the side of the tower exposed to winds. On these columns, two representative damaged zones have been selected for the simulation (figure 5) : One zone at the outer corner of the column, and the other close to the junction of the column with the wall . The section dimensions are 51cm x 90 cm.

Unfortunately, construction reports and drawings were no longer available. Measurements on some specific zones of the tower performed prior to its repair in 2001 have shown significant variations on the concrete cover thickness as well as on the rebars diameters. Therefore, additional measurements have been conducted, using a Ferroscan tool, in the two zones selected. In particular, the real number of rebars and their positions have been precisely determined. It has also been found that the cover varies between 25 and 47 mm.

Figure 5 – The two zones of the structure selected for simulation

3.2 *Finite element model*

In view of the slenderness of the columns, a bidimensional analysis of an horizontal cross-section of the column is considered. In such a calculation, only the longitudinal reinforcements are considered. This simplification may lead to a non conservative prediction of the time to rupture, since the transverse frames also contribute to inception of corrosion induced cracking. However, it prevents the use of more expensive three-dimensional calculations.

A typical mesh is shown on figure 6. The mesh has been densified around the rebars to capture the cracks formation. For symmetry reasons, only half of it is used in the calculations.

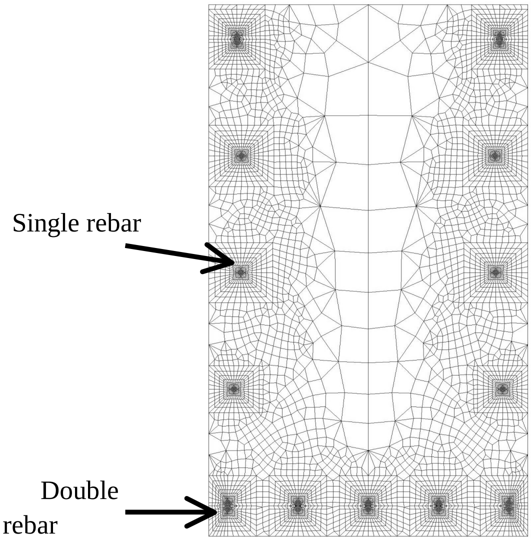

Figure 6 – Mesh of a transverse cross-section of a column

3.3 *Determination of the corrosion data*

As outlined above, input data such as the composition of the corrosion products, as well as the corrosion rates are required. During the repair of the tower, concrete samples containing reinforcement pieces have been cored. The analysis of the interface has revealed that corrosion products consist mainly of goethite. After 50 years, the corrosion products thickness reaches 100 µm (see figure 7). The figure shows that the rust thickness is not uniform around the rebar, the maximum being obtained where the cover is minimum. Nevertheless, in the computation it has been assumed uniform for simplicity.

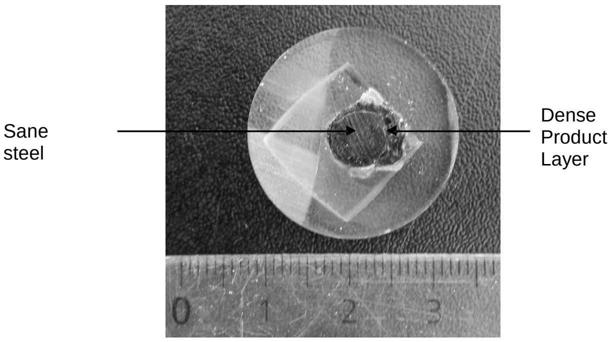

Figure 7 – View of interface cored from the tower column, and placed in resin

In addition, an initial rust thickness of 30 µm has been measured from a reinforcement still in a passive corrosion phase. The remaining difficulty lies in the determination of the starting time of the active corrosion phase. Unfortunately, for the water tower, concrete samples cored from the column were not long enough to localize the carbonation front. Since no reliable data was available, we decided to let the corrosion start from the beginning, thus producing the 70 µm in 50 years. From this assumption, and assuming a $t^{0.5}$ time evolution law, it is possible to derive the rust expansion rate. For the mechanical properties of the rust, Young's modulus has been taken as 0.1 GPa, and Poisson's ratio 0.2 .

3.4 *Concrete and steel properties*

Some concrete properties have been measured in 2001 :
- Young's modulus = 30 GPa
- Compression strength = 34 MPa

The other properties required by the non linear behaviour models have been either determined from usual recommendations or estimated from parametric investigations.

The rebars are smooth, their diameter is either 10 or 12 mm. They are considered as elastic. Their properties have been taken as :
-Young's modulus = 210 GPa
- Poisson's ratio = 0.3

3.5 *Parametric investigations*

Because of the uncertainties on the evolution of the corrosion products, various expansion laws have been compared : linear expansion with time using the average value of 4 µm/year recorded on archeological analogues, and expansions as square root of time, either fast (200 µm in 50 years) or slow (30 µm in 50 years).

In addition, the rebars diameter has been changed from 10 to 12 mm, the concrete traction strength from 2.5 to 3 Mpa, and the cover from 30 to 40 mm. The various cases studied are summarized in table 2.

Table 2. Various cases studied in the parametric analysis.

Expansion law	Square root						linear	
	fast					slow		
ft (MPa)	2,5			3		2,5	2,5	3
rebars (mm)	10	10	12	10	12	10	10	10
Rear cover (mm)	40	30	40	40	40	40	40	40
Reference	M1	M2	M3	M4	M5	M6	M7	M8

The calculations are run over a 50 years period. Because of the uncertainties of the data, only the cracks pattern then obtained can be reasonably compared to the real observations. Nevertheless, the influence of the parameters can be appraised.

3.6 *Main results*

The results presented here were obtained with the Mazars' concrete model. Depending on the parameters, the observed cracks at the front (F) or at the rear (R) of the column are predicted or not, after 50 years. It is also possible to compare the time of first cracking, and the corresponding thickness of the corrosion products. All these results are summarized in table 3.

Table 3. Summary of predicted results.

Reference	Crack location	Time at cracking (years)	Rust thickness (μm)
M1	F	0.9	9.4
	R	-	-
M2	F	0.9	9.4
	R	1.8	13.3
M3	F	0.8	8.9
	R	2	14
M4	F	1.2	10.3
	R	-	-
M5	F	0.9	9.4
	R	-	-
M6	F	2.2	6.3
	R	-	-
M7	F	1.6	6.4
	R	-	-
M8	F	1.9	7.6
	R	-	-

For the case M2, corresponding to the smaller rear cover, the final cracks pattern is compared to the real one on figure 8.

The above results show that for all parameters combinations, cracking is always predicted at the front face of the column, which is not the case for the rear corner. As can be observed on figure 5, the real damage is more important on the front face.

It is well known that the durability of a reinforced concrete structure is mainly influenced by the concrete traction strength as well as the cover. This fact is recovered by the model. Beyond that, the model confirms that the increase of the rebars diameter leads to an earlier cracking, which can be interpreted by the fact that the volume of the corrosion products formed around a rebar with a large diameter, is more important. Moreover, through-craking is only observed where reinforcement is made of two adjacent rebars. This means that accounting for the transverse frames in a three-dimensional analysis would certainly lead to a more important damage.

Concerning the influence of the rust expansion rate, table 3 shows that cracking occurs for a rust thickness which highly depends on the rust expansion. One explanation could be that the rapid increase of the rust thickness is accompanied by a decrease of its stiffness, thus reducing the pressure exerted on the concrete. However, additional calculations with a constant rust thickness have shown a similar trend. A clarification of this issue will require additional studies.

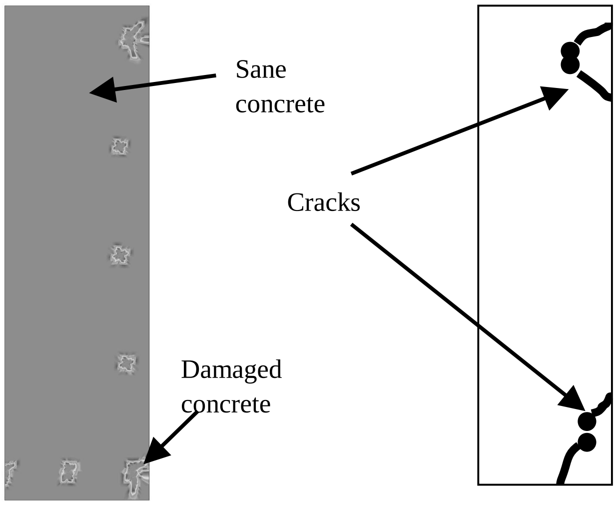

Figure 8 – Comparison of predicted and observed cracks pattern

4 CONCLUSION

The use of historical buildings to validate corrosion induced cracking models is not a straightforward exercise. Indeed, much information related to the initial state of the structure is not known. In the present case, it has not been possible to find maps and drawings and even with the recourse to techniques such as Ferroscan analysis, the real positions and diameters of the rebars are difficult to estimate. Moreover, the concrete properties evolve with time, and only some of them were measured in 2001.

Another important issue is the determination of the parameters associated with the corrosion products: beginning of the active corrosion phase, rust expansion rate, nature of the iron oxides, and initial rust thickness. It has been shown that some of them can be deduced from analysis on cored samples. However, the corrosion modeling approach proposed is based on simplifying assumptions, such as a square root of time expansion law, which might not account for the real complexity, for example induced by variable environmental conditions.

Finally, concerning the mechanical modeling, a more realistic calculation would require a three-dimensional description, including the transverse frames. Nevertheless, despite of all the above mentioned uncertainties, it has been possible to simulate the crack pattern observed on the 50 years old water tower, for a combination of realistic values of the parameters.

Of evidence, this does not constitute a validation of the model. For this purpose, it is most probably necessary to design long term large scale experiments, in the same spirit as the experiments performed on reinforced concrete beams by François et al, 1994.

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