Assessment of the seismic behaviour of corroded RC beams: an experimental contribution

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ABSTRACT

Corrosion of steel reinforcement is one of the most widespread pathologies that leads to loss of structural performance of reinforced concrete (RC) members. The understanding of this pathology is of a great importance especially when it is combined with the natural hazard such as earthquakes. The aim of this study is to experimentally assess the influence of reinforcement corrosion on the quasi-static and dynamic behaviour of RC elements.

To reach this goal, an experimental campaign is conducted on large-scale beams. The specimens are corroded using an accelerated corrosion technique with imposed current. Three configurations of corrosion and three corrosion rates are considered.

The quasi-static and dynamic testing of corroded specimens will make possible the quantification on some quantities of interest such as eigenfrequencies, modeshapes and damping ratios as a function of corrosion rate and corrosion configuration.

Keywords: Reinforced concrete, corrosion, earthquake engineering, dynamic behaviour, experimental campaign

INTRODUCTION

Reinforced concrete (RC) has been, for many decades, the most widely used construction material. It is commonly used for buildings as well as nuclear facilities. This is mainly thanks to its low cost, good mechanical properties and satisfactory durability properties. However, the service-life of RC structures may be reduced, along time, due to the emergence of pathologies. Steel reinforcement corrosion is one of the most preponderant pathologies that leads to a decrease of structural performance of RC members.

In the nuclear industry, the steel reinforcement corrosion might potentially be a concern, especially for the Nuclear Power Plants (NPP) located in marine environment. For this reason, nuclear operators are required to carry out maintenance operations throughout the structure lifetime. Based on structural auscultation, these operations seek to restore the initial structure bearing capacity without considering the dynamic response, less studied in the case of corrosion pathology.

Therefore, understanding the mechanical consequences of such pathology is of a great importance especially when it is combined with the seismic risk. The aim of this study is to evaluate the influence of steel reinforcement corrosion on both quasi-static and dynamic behaviour of RC members.

In this paper, a brief state of the art will be presented. Then, the experimental campaign details will be displayed. The numerical perspectives of this work are revealed in another conference paper.

STATE OF THE ART

The alkaline medium provided by concrete (pH > 13) constitutes a protective environment against steel corrosion [1]. However, the introduction of aggressive agents, within the concrete pores, may compromise this equilibrium and lead to the steel corrosion. Within this context, we identify two types of corrosion: a first one due to chloride penetration [2] and a second one coming from the dissolution of the atmospheric carbon dioxide [3].

The corrosion induced by carbonation induces a uniform cross-section loss along the steel bar whereas, in case of corrosion resulting from chlorides penetration, a localized cross-section loss is observed along the bar. This is why this second type of corrosion seems to be the most damaging for RC structures.

In this paper, the focus is put only on corrosion induced by chlorides. Since corrosion is a long-lasting process [4], some laboratory technics are developed in order to get corroded specimens in a reasonable time duration. Among these practices, we find artificial environment [5], additives in concrete mixture [6-7] and galvanostatic method (whether by imposed current [8] or imposed voltage [9]).

Since the steel corrosion is an oxidation-reduction chemical reaction, the corrosion phenomenon is fully driven by electrons flow or, in other words, by the electrical current. Therefore, accelerated corrosion by imposed current technique is adopted in this study. It consists in applying current from a DC power supply between the cathode (which can be made from stainless steel [10], copper [11] or platinum [12]) and the anode (which is the reinforcement inside the RC specimen). The whole specimen should be immersed in an electrolytic solution (*Figure 1*) containing 3 to 5% of NaCl [5-12].

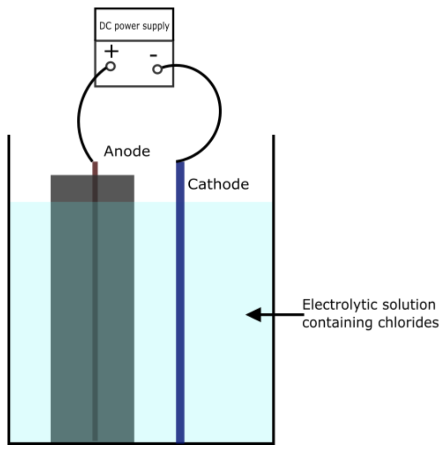


Figure 1. Set-up for accelerated corrosion by imposed current.

As far as the accelerated corrosion by imposed current technique is concerned, some empirical equations exist to describe this phenomenon. The most used one is Faraday's law Eq. (1) [11].

$$\Delta w = \frac{M.I.\Delta t}{z\,.F} \tag{1}$$

where Δw is the mass of steel consumed due to corrosion ($kg.m^{-2}$), I is the current density ($A.m^{-2}$), Δt is the exposure time (s), F is the Faraday constant 96 500 ($A.s^{-1}$), z is the ionic charge (2 for Fe), M is the atomic weight of metal ($g.mol^{-1}$).

The Faraday's law is suitable for the corrosion of bare bars, in which case the chlorides are present at the bar surface since the beginning of the process. In the case of RC specimens, chlorides need to reach the steel bar surface from the electrolytic solution through the concrete pores. This means that the applied current initially is used to depassivate the steel reinforcement by spreading the chlorides into the concrete matrix. To take into account this aspect, an additional coefficient α between 1.3 and 2 is considered in the Faraday's law [13] Eq. (2).

$$\Delta t = \frac{\alpha\,.\Delta w\,.z.F}{M.I} \tag{2}$$

The choice of the considered current density is crucial. Depending on the considered current density, the effects of accelerated corrosion can be more or less similar to the natural corrosion regarding many features such as the crack patterns for example. Most of studies recommend not to exceed $100\,\mu A.cm^{-2}$ to have similar structural effects as the ones obtained in natural corrosion [14-15-16].

Corrosion induced by chlorides has various mechanical effects at both the material and the member scales. It leads to a reduction of cross-section and reinforcement ductility (*Figure 2.a*), concrete spalling and bond strength degradation due to high stresses resulting from the formation of corrosion products (*Figure 2.b*).

At the member scale, a decrease of the bearing capacity and the ductility offer is observed [17]. Regarding the dynamic behaviour of corroded RC elements, to our knowledge, no study has been done on this subject. However, some cyclic loads applied on corroded specimens show a decrease of hysteretic capacity and dissipation energy [18-19]. Therefore, the dynamic behaviour might be affected.

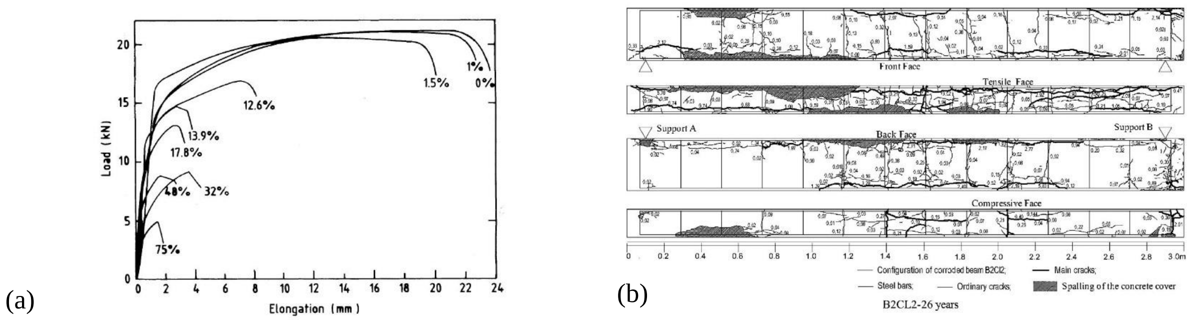


Figure 2. Mechanical effects of corrosion: (a) Ductility loss [17], (b) Concrete spalling [20].

EXPERIMENTAL CAMPAIGN: DYSBAC

The name of this experimental campaign, DYSBAC, is a French acronym for "Dynamic behaviour of corroded RC structure". This campaign will be performed by means of the AZALEE shaking table and the strong floor, which are parts of the TAMARIS experimental facility [21] operated by the French Alternative Energies and Atomic Energy Commission (CEA). The main objective of this campaign is the study of the influence of corrosion on:

- The quasi-static behaviour (bearing capacity, energy dissipation, hysteretic capacity…)
- The dynamic behaviour (natural frequencies, solicitation amplification, mode shapes…)

Samples

In order to mitigate scale effect, large-scale RC beams are considered. The final design, shown in *Figure 3.a*, takes into consideration some constraints related to the test facilities such as the size of the strong floor (4.5 m), where quasi-static tests will be performed, the maximal stroke of the available actuator (± 500 mm) and operating range of AZALEE shaking table (0.5 – 30 Hz).

The reinforcement (*Figure 3.b*) is designed according to the European standards Eurocodes 2 and 8. The RC beams were cast with a low strength concrete, representative of concrete in existing RC structures. The concrete has a compressive strength measured on cubes equal to 30 MPa. The steel reinforcement can be classified as B500A, according to French steel classification, with an average yield strength equal to 500 MPa and an ultimate strain (Agt) equal to 2.5%.

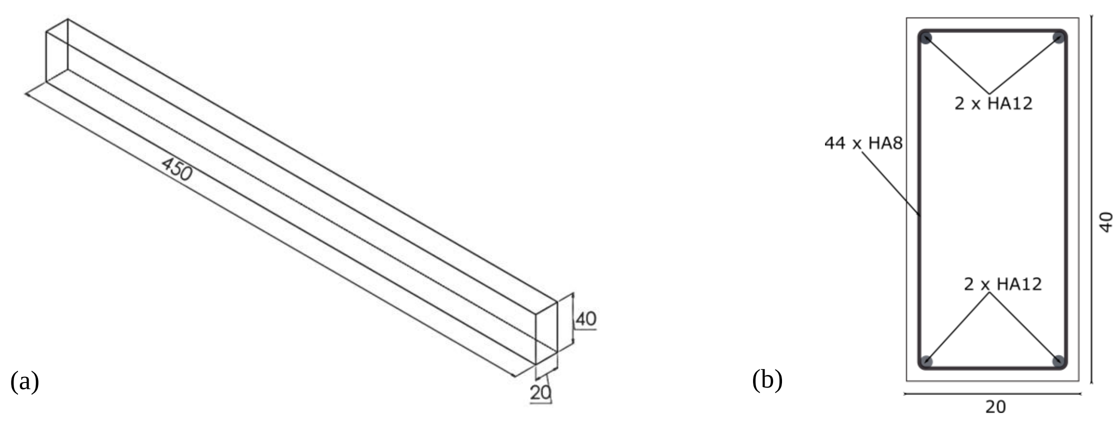


Figure 3. Specimen's design: (a) Geometry, (b) Reinforcement details. - dimensions in centimeters-

Samples corrosion

In order to be able to study different effects independently, three beams configurations are considered: C_1 for longitudinal reinforcement corrosion, C_2 for transverse reinforcement corrosion and C_3 for the complete reinforcement corrosion.

The accelerated corrosion by imposed current technique is used. In order to reach the corrosion targets for the three configurations, different parts of reinforcement were electrically insulated[1] and different cathode settings were adopted, depending on the configuration.

For the C_1 beam configuration:

- an insulation is put on the stirrups so as to keep only the longitudinal bars crossed by the electrical current;
- every longitudinal bar is considered as an anode with an independent cathode in stainless steel (*Figure 4.a*);
- a four channels DC power supply is used.

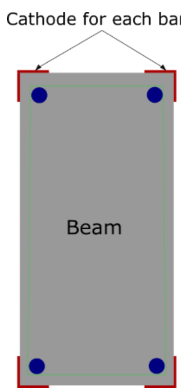
For the C_2 beam configuration:

- the insulation is put on the longitudinal bars at the connection points with the stirrups, thus only stirrups are crossed by the electrical current;
- the full beam is wrapped with the stainless steel grid (*Figure 4.b*);
- one DC power supply is used.

For the C_3 beam configuration:

- no insulation is put;
- the full beam is wrapped with the stainless steel grid (*Figure 4.b*);
- one DC power supply is used.

(a)



(b)

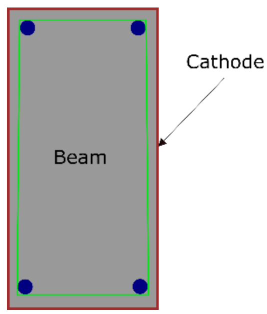


Figure 4. Cathode position (a) C_1 configuration (b) C_2 and C_3 configurations.

For all beams, a current density of 100 µA/cm² is considered [22]. Three corrosion rates expressed in terms of mass losses are targeted: 5% (which is the threshold of the bond loss between steel and concrete [23]), 10% (rate from which civil engineering maintenance operations begin [24]) and 15% (believed to be the threshold from which a change of failure mode is observed [25]).

All the beams are immerged in a 3.5% NaCl solution (*Figure 5*). The exposure duration is estimated for each type of beam and each corrosion rate using Faraday's law (Equation 4) with $\alpha = 1.3$. Table 1 sums up the estimated exposure time for each corrosion degree and each beam configuration.

[1] An electrical insulating painting and a heat-shrinkable covering have been put on the specimens' rebars.

Figure 5. Specimens subjected to imposed current corrosion technique.

Table 1. Exposure duration for different beams configuration.

Configuration C_1		**Configuration C_2**		**Configuration C_3**	
For each bar HA12		44 stirrups HA8		4 bars HA12 and 44 stirrups HA8	
Corrosion rate (%)	Exposure duration (days)	Corrosion rate (%)	Exposure duration (days)	Corrosion rate (%)	Exposure duration (days)
5	47	5	31	5	36
10	94	10	62	10	72
15	141	15	94	15	109

Sample testing

Samples testing consists of quasi-static as well as dynamic characterization. Quasi-static test results should focus on energy dissipation aspects due to material nonlinearities including ductility evolution. Dynamic tests will be used to quantify the evolution of the modal properties. In this way, the mechanical state due to corrosion will be fully characterized.

The setup is similar to the one used for the IDEFIX campaign [26], but adapted for high range displacements and rotations. The beams will be excited along their weakest flexural axis; the boundary conditions are the followings:

- spinning supports allowing the rotation at the beam extremities;
- two air-cushion systems to bear the beam weight and to reduce drastically the friction be-tween the beam and the shaking table's or strong floor's upper plate.

Regarding the quasi-static tests, the corroded and non-corroded beams are subjected to a classical four-point alternate bending test on Tamaris strong floor. The loading is applied by the mean of a long-stroke actuator linked with a reinforced metal beam able through swivels at its ends to distribute the loading on two points of the DYSBAC beam. A general view on the experimental setup is given in *Figure 6*.

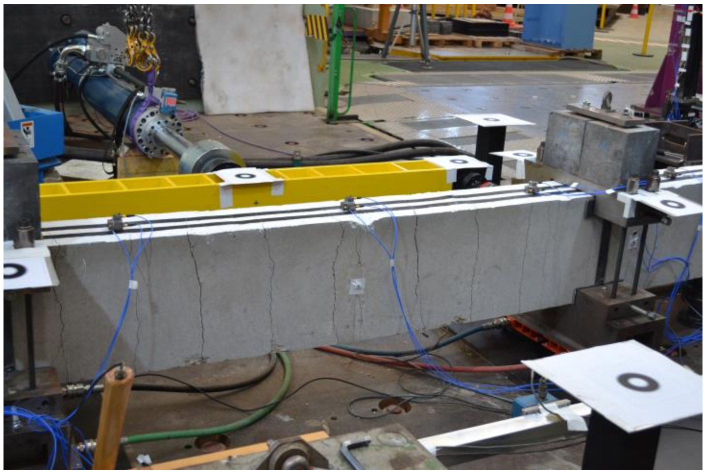


Figure 6. Quasi-static tests setting.

The applied loading includes blocks of 5 identical cycles of prescribed displacement, with an increasing amplitude between two consecutive blocks (*Figure 7*). Each cycle involves 4 phases: loading in one direction, unloading, loading in the other direction and unloading. The goal behind having 5 cycles is to stabilize the new damage levels of the current block before moving on to the next one. Hammer shocks testing between blocks is also planned in order to get the evolution of modal properties with damage.

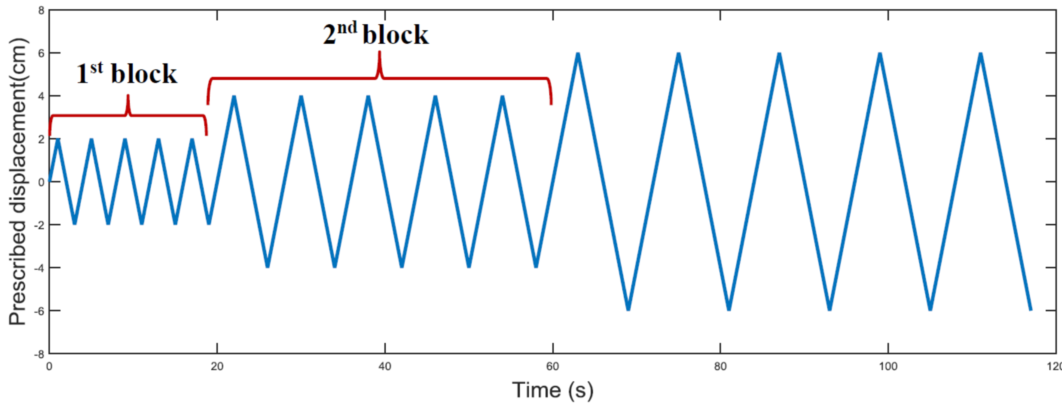


Figure 7. Planned load in quasi-static testing.

The aim of quasi-static testing is to assess the evolution of the hysteretic energy dissipation within cycles. In addition, every specimen will be subjected to hammer shock tests in different boundary conditions to get the evolution of the natural frequencies as well as the modeshapes as a function of the corrosion rate and the corrosion configuration.

The dynamic tests are performed on AZALEE shaking table. It is a 6 x 6 m² shaking table able to reproduce seismic signals up to 1.5 g. The table is controlled on the 6 degrees of freedom (3 rotations, 3 translations) (*Figure 8*).

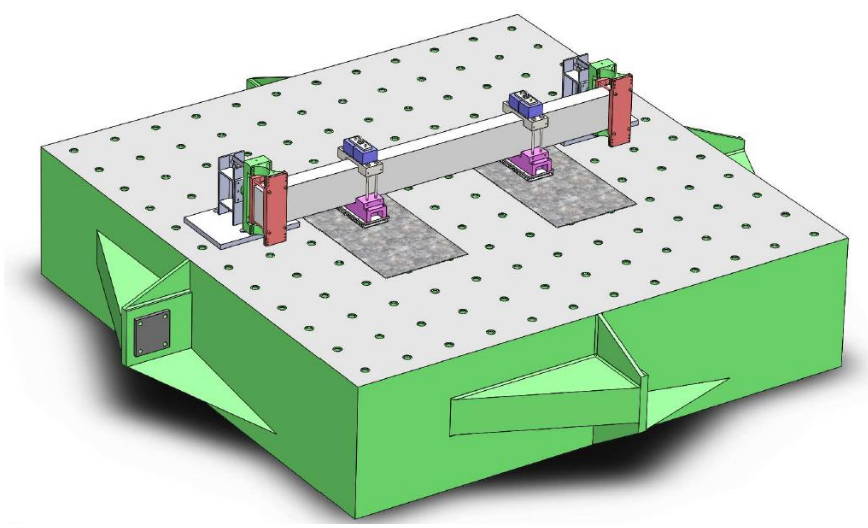


Figure 8. *General view of the experimental setup for dynamic tests.*

Before dynamic testing, a modal characterization of each specimen is performed using both hammer shocks and a white noise signal (PGA = 0.1 g). The dynamic loading consists in a synthetic signal able to excite only the first natural mode. This signal might be different for each beam configuration and each corrosion rate, so it is designed after the modal characterization of each beam. Increasing levels of the signal are tested.

The applied signals are generated using the inverse Fast Fourier Transformation (FFT) from a defined spectrum. In order to anticipate the modal frequency drop due to damage, a crenel spectrum is considered with nominal acceleration between 0.5 times and 1.05 times the first natural frequency and equal to zero outside (*Figure 9*). This choice anticipates the modal frequency drop due to damage and allows to constantly exciting the sought modal frequency all along the test.

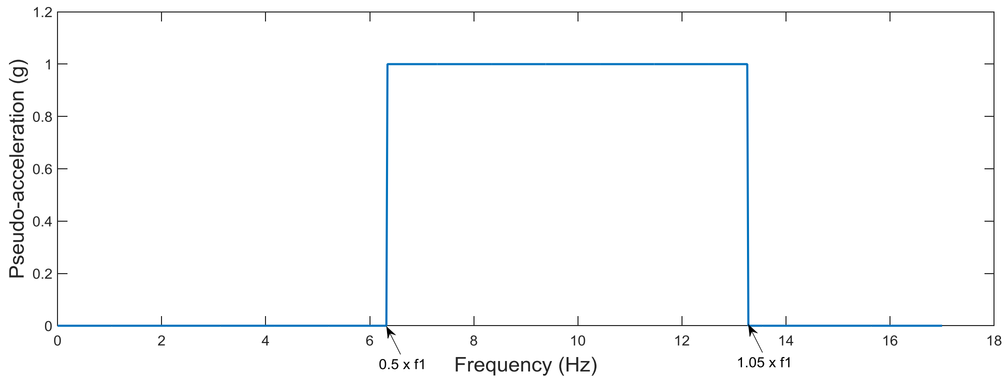


Figure 9. Crenel spectrum used in signal generation.

It is to be noted that digital image correlation technique will be used for quasi-static and dynamic tests. Indeed, it consists of a painted strip on the upper surface of the beam. The displacement of this strip will be followed in time using a stereoscopic system, to compute the shape of the beam during the tests.

CONCLUSIONS

DYSBAC experimental campaign (planned to last form February 2019 to August 2019) will improve the state of the art concerning dynamic behaviour of corroded RC structures. Indeed, through quasi-static and dynamic testing, the quantification of some quantities of interest, such as the eigenfrequencies, the modeshapes or the damping ratios will be possible. As a perspective of the experimental campaign, a numerical model able to simulate the effect of corrosion on the dynamic behaviour of RC structures is developed.

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REFERENCES

[1] Pourbaix M. (1974). Applications of electrochemistry in corrosion science and in practice. Corrosion Science, 14(1):25–82.
[2] Ghali, E. (2010). “Électrochimie, corrosion et protection”.
[3] Lea, F. (1972). “The Chemistry of Cement and Concrete, Chemical Publ. Comp”, Inc., New York.
[4] Maslehuddin, M., Ibrahim A., Ghazi, J., Abdulaziz, A., and Sahl, N. (1990). “Effect of Rusting of Reinforcing Steel on its Mechanical Properties and Bond with Concrete”, Materials Journal.
[5] Yuan, Y., Ji, Y., and Shah, S. P. (2007). “Comparison of two accelerated corrosion techniques for concrete structures”, ACI Struct. J., vol. 104, no 3, p. 344.
[6] Xu, J., Jiang, L., Wang, W., & Jiang, Y. (2011). “Influence of CaCl2 and NaCl from different sources on chloride threshold value for the corrosion of steel reinforcement in concrete”. Construction and Building Materials, 25(2), 663-669.
[7] El Maaddawy, T., Soudki, K., & Topper, T. (2005). “Long-term performance of corrosion-damaged reinforced concrete beams”. ACI Structural Journal, 102(5), 649.
[8] Paradis, F. (2009). “Influence de la fissuration du béton sur la corrosion des armatures : caractérisation des produits de corrosion formés dans le béton”.
[9] S. Altoubat, M. Maalej, and F. U. A. Shaikh, “Laboratory Simulation of Corrosion Damage in Reinforced Concrete”, Int. J. Concr. Struct. Mater. vol. 10, no 3, p. 383‑391, sept. 2016.
[10] Azad, A. K., Ahmad, S., & Azher, S. A. (2007). “Residual strength of corrosion-damaged reinforced concrete beams”. ACI Materials Journal, 104(1), 40.

[11] Ou, Y. C., & Nguyen, N. D. (2016). "Influences of location of reinforcement corrosion on seismic performance of corroded reinforced concrete beams". Engineering Structures, 126, 210-223.

[12] Loukil, O., Adelaide, L., Bouteiller, V., Quiertant, M., Chaussadent, T., Ragueneau, F., ... & Trenty, L. (2016, August). "Experimental study of corrosion-induced degradation of reinforced concrete elements". In International RILEM Conference on Materials, Systems and Structures in Civil Engineering Conference segment on Electrochemistry in Civil Engineering.

[13] Imperatore, S., Rinaldi, Z., & Drago, C. (2017). "Degradation relationships for the mechanical properties of corroded steel rebars". Construction and Building Materials, 148, 219-230.

[14] Andrade, C., Alonso, C., & Molina, F. J. (1993). "Cover cracking as a function of bar corrosion: Part I-Experimental test". Materials and structures, 26(8), 453-464.

[15] El Maaddawy, T. A., & Soudki, K. A. (2003). "Effectiveness of impressed current technique to simulate corrosion of steel reinforcement in concrete". Journal of materials in civil engineering, 15(1), 41-47.

[16] Richard, B., Quiertant, M., Bouteiller, V., Adelaide, L., Tailhan, J. L., & Cremona, C. (2012). "Influence of accelerated corrosion on the reinforced cover concrete cracking behavior: experimental and numerical study". European Journal of Environmental and Civil Engineering, 16(3-4), 450-459.

[17] Almusallam, A. A. (2001). Effect of degree of corrosion on the properties of reinforcing steel bars". Construction and Building Materials, 15(8), 361-368.

[18] Ma, Y., Che, Y., & Gong, J. (2012). "Behavior of corrosion damaged circular reinforced concrete columns under cyclic loading". Construction and Building Materials, 29, 548-556.

[19] Guo, A., Li, H., Ba, X., Guan, X., & Li, H. (2015). "Experimental investigation on the cyclic performance of reinforced concrete piers with chloride-induced corrosion in marine environment". Engineering Structures, 105, 1-11.

[20] Zhu, W., & François, R. (2014). "Corrosion of the reinforcement and its influence on the residual structural performance of a 26-year-old corroded RC beam". Construction and Building Materials, 51, 461-472.

[21] http://www-tamaris.cea.fr/

[22] Caré, S., & Raharinaivo, A. (2007). "Influence of impressed current on the initiation of damage in reinforced mortar due to corrosion of embedded steel". Cement and concrete research, 37(12), 1598-1612.

[23] Auyeung, Y. (2002). "Bond properties of corroded reinforcement with and without confinement".

[24] " Projet APPLET : Durée de vie des ouvrages en béton : Approches prédictives performantielles et probabilistes ", 2006.

[25] Ouglova, A. (2004). "Etude du comportement mécanique des structures en béton armé atteintes par la corrosion " (Doctoral dissertation, Cachan, Ecole normale supérieure).

[26] Heitz, T., Le Maoult, A., Richard, B., Giry, C., & Ragueneau, F. (2018). "Dissipations in reinforced concrete components: Static and dynamic experimental identification strategy". Engineering Structures, 163, 436-451.