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EXPERIMENTAL STUDY OF THE SEISMIC BEHAVIOR OF CORRODED RC BEAMS

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ABSTRACT

Corrosion of steel reinforcement is one of the most widespread pathologies that leads to a 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 not only on the quasi-static but also on the dynamic behavior of RC elements.

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

Dynamic testing of corroded specimens makes possible the quantification of some quantities of interest such as ductility ratios, decrease in eigenfrequencies and damping ratios as a function of the corrosion rate.

INTRODUCTION

Reinforced concrete (RC) is one of the most common building materials in the world. It is used for ordinary buildings as well as vital facilities. This is mainly due to its low cost, good mechanical and durability properties. However, due to the environmental interactions, specific pathologies may appear and lead to a decrease of the structural performance along with time. The understanding of these pathologies is of a great importance, especially when it is combined with natural hazards such as earthquakes.

Steel reinforcement corrosion is one of the most common pathologies that affects RC elements. This phenomenon can lead in its early stages to a loss of durability at the material scale, a loss of service ability, and lately, a loss of structural safety.

At the structural level, corrosion leads to a reduction of the resistant section and reinforcement ductility as Almusallam et al. (2001) showed, concrete spalling and bond strength degradation due to high stresses resulting from the formation of corrosion products as revealed by Zhu & François (2014) . All these consequences lead to a decrease of the bearing capacity and ductility offer.

Regarding the dynamic behavior 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 the hysteretic capacity and dissipation energy (see in particular the studies done by Ma et al. (2012) and Guo et al. (2015)). Therefore, the dynamic behavior might be modified by the rebars corrosion.

The aim of this study is to experimentally assess the influence of reinforcement corrosion on the quasi-static and dynamic behavior of RC elements and to develop a numerical model with a low computational demand capitalizing the new knowledge, applicable for the probabilistic safety assessment (PSA) study.

In this paper, the focus will be on the ongoing experimental campaign especially the dynamic tests. Some preliminary experimental will be presented.

EXPERIMENTAL CAMPAIGN: DYSBAC

The experimental campaign DYSBAC, a French acronym for “Dynamic behavior of corroded RC structure”, is performed by means of the AZALEE shaking table for the dynamic tests and a long range actuator on the strong floor for the static ones; these two devices are parts of the TAMARIS experimental facility operated by the French Alternative Energies and Atomic Energy Commission (CEA). The main objective of this experimental campaign is the study of the influence of corrosion on the dynamic behavior: natural frequencies, dynamic amplification and mode shapes.

Samples

For the sake of simplicity and representativeness of a real structure, the choice of large-scale RC beams has been made. Considering some design constraints related to the test facilities such as the size of the strong floor (4.5 m length), the maximal stroke of the available actuator (± 400 mm) and the operating frequency range of AZALEE shaking table (0 - 30 Hz); we come up with the geometry of DYSBAC specimens shown in *Figure 1.a*.

The reinforcement (*Figure 1. 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 (A_{gt}) equal to 2.5%.

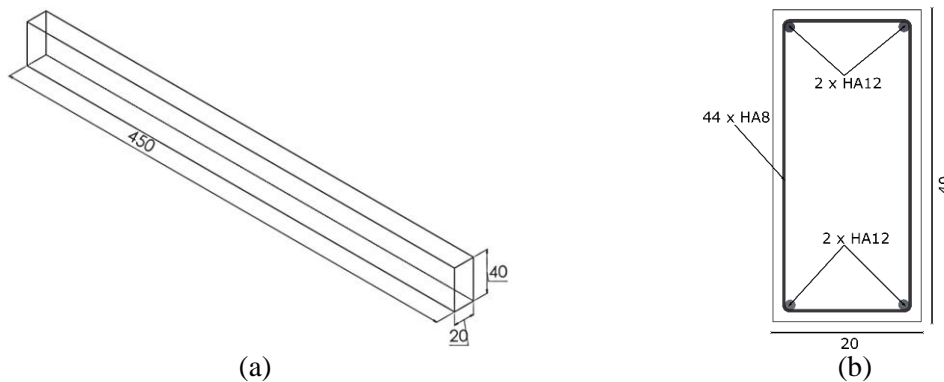


Figure 1. Specimen's design: (a) Geometry, (b) Reinforcement details. - dimensions in centimeters-

Samples corrosion

In order to study separately the effects of corrosion of each reinforcement part, three beam corrosion configurations are considered: C_1 for longitudinal reinforcement corrosion, C_2 for transverse reinforcement corrosion and C_3 for the complete reinforcement corrosion.

Using natural corrosion process to get corroded specimens is highly time-demanding. Thus, an accelerated corrosion technique by imposed current is used. It consists in applying an electrical current from a DC power supply (Direct Current) between the cathode (stainless steel grid) and the anode, which is the reinforcement inside the RC specimen, as showed in the study of Rinaldi et al. (2010). The whole specimen is immersed in an electrolytic solution containing chlorides (salted water) to guarantee electrical conduction and to be representative of corrosion by chlorides. *Figure 2.a* is a simplified representation of the setup for accelerated corrosion by imposed current. *Figure 2.b* is a top view of campaign beams subjected to accelerated corrosion technique.



Figure 2. Accelerated corrosion technique. (a) Principle of the setup, (b) Corrosion of the campaign beams.

In order to reach the corrosion targets for the three configurations, different parts of reinforcement were electrically insulated 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;
- one 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;
- 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;
- one DC power supply is used.

As recommended in Caré, S., & Raharinaivo, A. (2007), the current density was limited to 100 $\mu\text{A}/\text{cm}^2$ in order to be more representative of natural corrosion. Three corrosion rates expressed in terms of mass losses are targeted: 5% (which is the threshold of the bond loss between steel and concrete), 10% (rate from which civil engineering maintenance operations begin) and 15% (believed to be the threshold from which a change of failure mode is observed).

All the beams are immersed in a 3.5% NaCl solution (Figure 2.b). The exposure duration is estimated for each type of beam and each corrosion rate using Faraday's law (Equation 1) with $\alpha = 1.3$.

$$\Delta t = \frac{\alpha \cdot \Delta w \cdot z \cdot F}{M \cdot I} \quad (1)$$

where Δw is the mass of steel consumed due to corrosion ($\text{kg} \cdot \text{m}^{-2}$), I is the current density ($\text{A} \cdot \text{m}^{-2}$), Δt is the exposure time (s), F is the Faraday constant 96 500 ($\text{A} \cdot \text{s}^{-1}$), z is the ionic charge (2 for Fe), M is the atomic weight of metal ($\text{g} \cdot \text{mol}^{-1}$), α is a coefficient usually taken between 1 and 2 to take into account the duration of chloride ingress into concrete before reaching the rebar.

Table 1 sums up the estimated exposure time for each corrosion degree and each beam configuration.

Table 1: Exposure duration for different beams configuration.

Configuration C_1		Configuration C_2		Configuration C_3	
4 bars 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

Samples 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 conducted by Heitz et al. (2018), 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 between the beam and the shaking table's or strong floor's upper plate;
- two additional masses, of 360 Kg weight each, fixed at the intermediate supports bringing the first natural frequency of the beams between 12 and 13 Hz.

The dynamic tests are performed on AZALEE shaking table (Figure 3). It is a 6 x 6 m² shaking table able to reproduce seismic signals up to 5 g depending on the mass of the tested specimen. The table is controlled on the 6 degrees of freedom (3 rotations, 3 translations).

The dynamic loading consists in a synthetic signal able to excite only the first natural mode of the beam. It is a bandwidth signal between 1 Hz and 13 Hz. This choice anticipates the first modal frequency (initially around 12.5 Hz) drop due to damage and allows to constantly excite the first modal frequency all along the test. Five acceleration levels are tested: 0.125 g, 0.5 g, 0.8 g, 1.25 g and 2 g. A modal characterization of each beam before testing and between two consecutive testing sequences using a white noise signal (0.07 g) is performed.

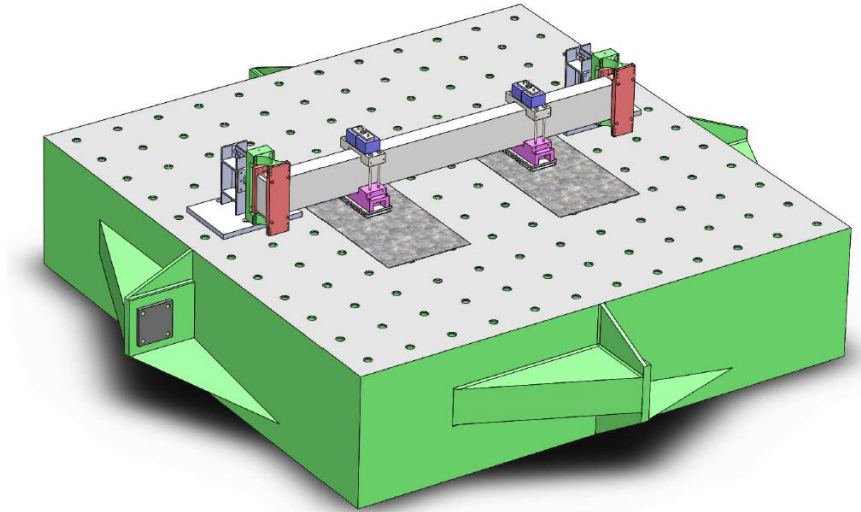


Figure 3. General view of the experimental setup for dynamic tests.

In order to fully characterize the mechanical response of the specimens during the tests, different types of sensors are used: LVDT sensors, displacement wire sensors, load cells and accelerometers. In addition, digital image correlation technique (DIC) is used. 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. Figure 4 shows the type and position of the used sensors.

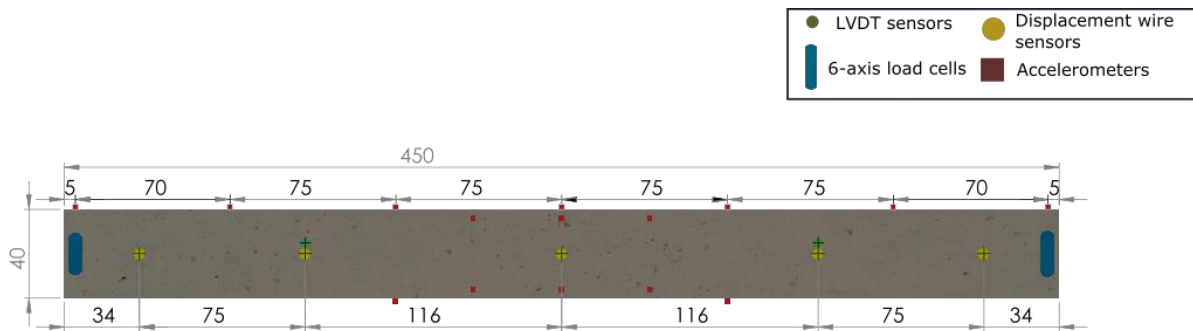


Figure 4: Sensors positions – front view- dimensions in centimeters- .

PRELIMINARY EXPERIMENTAL RESULTS

General observations

At the end of testing, the non-corroded beam exhibits bending cracks at the concrete level, with a yielding of reinforcement rebars, and plastic hinges appearing at midspan. Regarding corroded beams, the behavior depends on the configuration and on the corrosion rate. A number of beams has experienced a concrete damage as well as a formation of plastic hinges, whereas another reached failure, meaning that the fracture occurred in the longitudinal rebars. Table 2 summarizes results of the dynamic tests. Figure 5 shows the non-corroded beam and a corroded beam failing at the end of testing.

Table 2 : Summary of results obtained at the end of dynamic testing.

Configuration	NC	C1			C2			C3		
Corrosion rate (%)	0	5	10	15	5	10	15	5	10	15
Concrete damage + plastic hinges										
Failure										

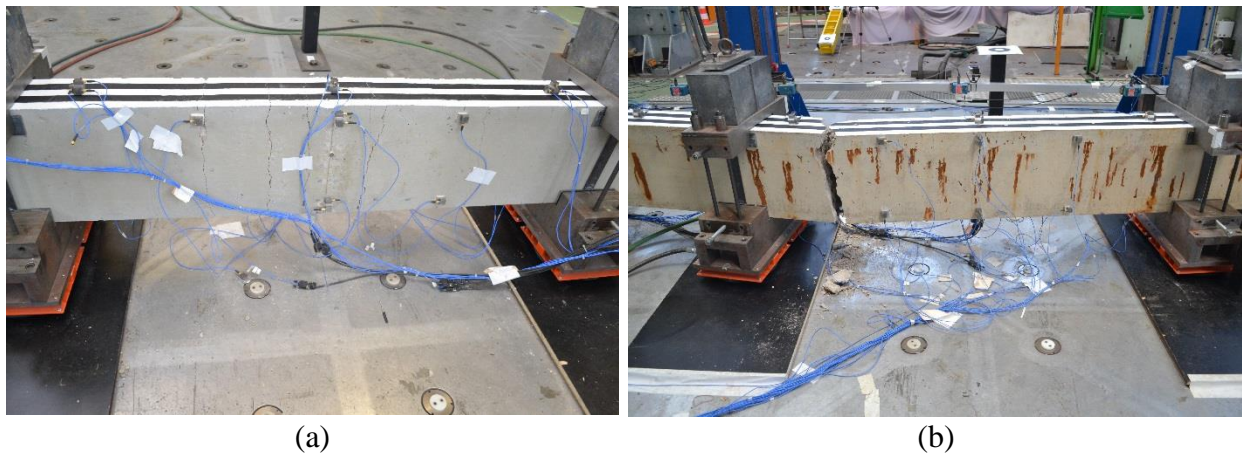


Figure 5. General overview on the beam at the end of testing. (a) Non-corroded beam, (b) Corroded C1 beam at 15% corrosion rate.

Figure 5.b shows that the failure has not occurred at the beam midspan. A finite element computation has been conducted, using a multifiber Timoshenko beam model presented in Davenne et al. (2003). The model includes a concrete constitutive law developed by Richard et al. (2013) suitable for cyclic loadings, and a steel constitutive law developed by Ouglova et al. (2004). The steel constitutive law takes into account the cross section loss and the decrease of steel ductility as a function of corrosion. The results coming from this computation do not predict a failure for any beam and the plastic hinges are formed systematically at midspan, which is not consistent with the observation made in Figure 5.b.

Quantitative results and discussion

The ductility ratio defined in Equation 2 is determined for all C₁ configuration beams at different targeted corrosion rates. Figure 6.a shows the evolution of ductility ratio as a function of targeted corrosion rates for C₁ beam configuration.

$$\mu = \frac{\max|u(t)|}{u_y} \quad (2)$$

Where $\max|u(t)|$ is the maximum absolute value of relative displacement of the SDOF system with respect to the ground, and u_y is the yield displacement of the system.

The experimental eigenfrequencies and damping ratios have been determined by the mean of white noise after each acceleration level. The white noise (WN) corresponds to a random signal characterized by equal intensity at different frequencies; the WN chosen in DYSBAC campaign is a low level acceleration signal meaning that no damage due to modal characterization is expected to occur in the beam. The data analysis were done based on the covariance driven subspace methods developed by Benveniste & Fuchs (1985), Viberg et al. (1991). Figure 6.b and Figure 6.c show the evolution of first eigenfrequency and first modal damping ratio as a function of PGA (Peak Ground Acceleration) which corresponds to the highest peak ground acceleration experienced by the beam in its time-history.

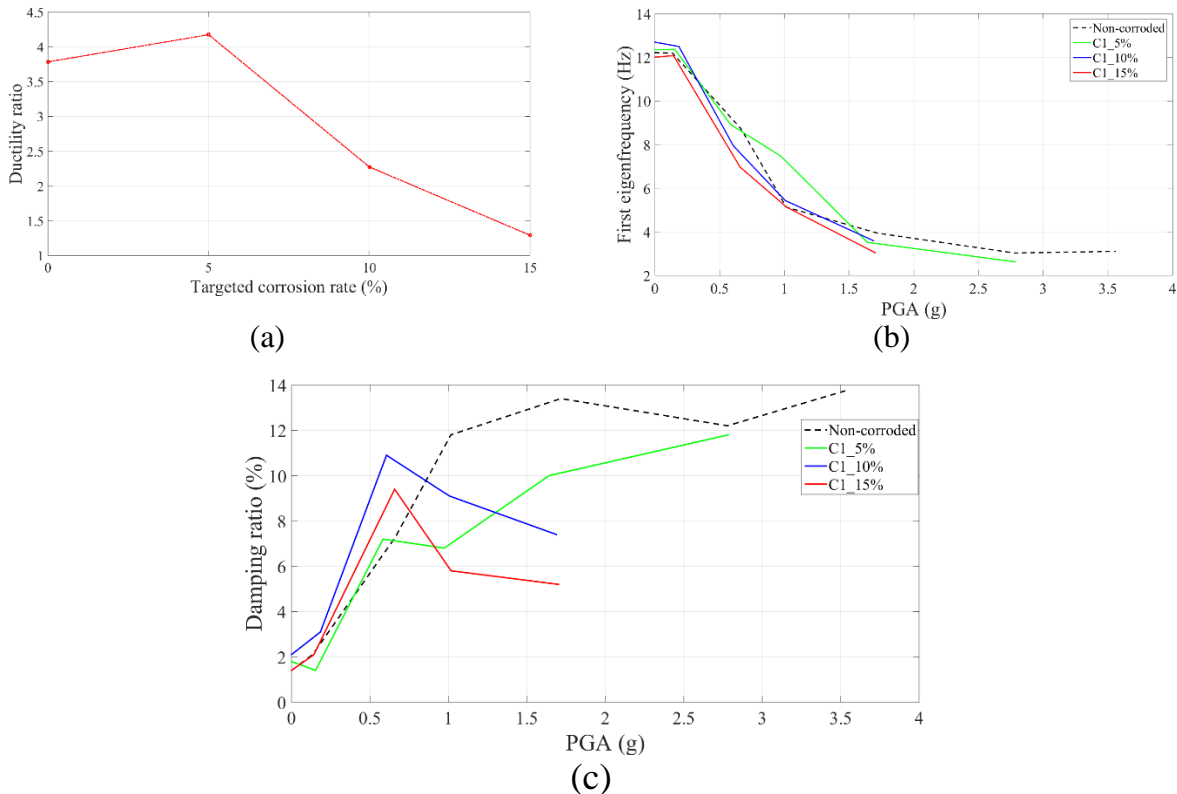


Figure 6. Experimental results. (a) Evolution of the ductility ratio, (b) Evolution of the first eigenfrequency, (c) Evolution of the first modal damping ratio.

The corroded beams show a decrease of the ductility offer with respect to the non-corroded one except for the 5% corrosion rate beam. The obtained results for high corrosion rates are in good agreement with the results presented in different studies reported in the literature, like Maslehuddin et al. (1990). Fang et al. (2006) explained that for low to medium corrosion rates (less than 4%) corrosion improves the bond strength between steel and concrete, which enhances mechanical properties of RC elements. It is to be noted that the measured mass loss on dedicated specimens shows that real mass losses are less than the targeted ones: 2% for 5% targeted mass loss, 8% for 10% targeted mass loss and 12% for 15% targeted mass loss. This is due to the chosen value of the coefficient α (Equation 1) depending on several parameters such as

the concrete porosity, the concentration of chlorides in the electrolytic solution and the availability or not of oxygen in the medium.

Regarding the evolution of first eigenfrequencies, we can notice that the 5% corroded beam behaves in a similar way or better than the reference. In other words, the eigenfrequency drop off is quicker for the reference beam than the 5% corroded beam, considering that the eigenfrequency reflects the level of damage occurred in the specimen. This trend changes at the seismic level ($\approx 1.5g$) for which the bond strength between steel and concrete becomes significantly reduced, and the only phenomenon that leads to the degradation of the beam is the steel yielding. Knowing that corroded beam rebars are characterized by a reduced cross section, the observed trend was expected. For the two other corrosion rates, the decrease of the first natural frequency is a consequence of the degradation of bond strength and steel ductility properties.

The evolution of the damping ratios can be explained the same way as the eigenfrequency evolution. For the 5% corrosion rate beam, the micro-cracks present at the interface between steel and concrete are filled with the corrosion products. However for 10% and 15% corrosion rate beam, concrete is subjected to high stresses due to the expansive nature of the corrosion products. Thus, cracks are already formed before the dynamic loading, and the system becomes more damped.

CONCLUSION

The issue related to the corrosion effects of steel reinforcement on the dynamic behavior of RC beams is analysed in the paper, in an experimental way through dynamic testing of large-scale corroded beams. The results obtained from the tests concerning longitudinal bars corrosion can be summarized as follows:

- for low corrosion rates, the corroded beam behaves better than the non-corroded one regarding the degradation of the first eigenfrequency. In addition, corrosion makes the system less damped than the reference one.
- for high corrosion rates, the first eigenfrequency decreases further for corroded beams with respect to the non-corroded one during the loading. In addition, cracks due to corrosion makes the system more damped than the reference one.
- a finite element computation carried out with the most recent steel constitutive law taking into account corrosion, has shown the limits of such constitutive law to predict the dynamic response of RC elements.

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