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HOW DOES CORROSION MODIFY THE SEISMIC BEHAVIOR OF REINFORCED CONCRETE COMPONENTS?

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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. Three types of beam corrosion configurations are considered: C_1 for longitudinal bars corrosion, C_2 for stirrups corrosion and C_3 for the entire reinforcement corrosion. Three corrosion rates are targeted: 5%, 10% and 15%. An accelerated corrosion method with imposed current is used.

The corroded and non-corroded beams are subjected to a classical four points bending test as well as dynamic loads on AZALEE shaking table. The objective is to evaluate the modal properties, like eigenfrequencies and the static properties, in particular the bearing capacity as a function of corrosion rate.

In this paper, a detailed description of the experimental campaign is presented. Then, some results showing the influence of the corrosion rate and the corrosion configuration on the quasi-static and modal properties are exposed.

Keywords: Steel corrosion, shaking table, reinforced concrete, aging

1. 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 the natural hazard 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 the authors of [1] showed, concrete spalling and bond strength degradation due to high stresses resulting from the formation of corrosion products as revealed by [2]. All these consequences lead to a decrease of the bearing capacity and ductility offer.

The dynamic behavior of corroded RC elements has not been studied yet, to our knowledge. 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 [3] and [4]). Therefore, the dynamic behavior is certainly modified by the corrosion of the rebars.

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 experimental campaign especially the dynamic tests. Some experimental results are presented.

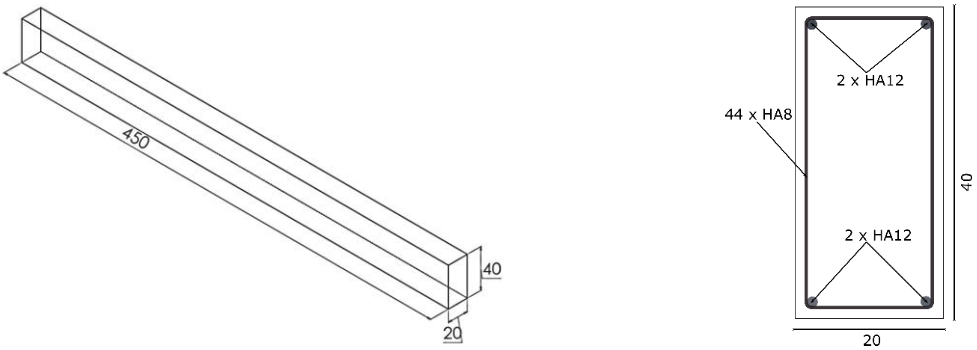
2. Experimental campaign: DYSBAC

The experimental campaign DYSBAC, a French acronym for "Dynamic behavior of corroded RC structures", is performed by means of the AZALEE shaking table and the strong floor, which are parts of the TAMARIS experimental facility operated by the French Alternative Energies and Atomic Energy Commission (CEA) located in Saclay, France. The main objective of this experimental campaign to study the influence of corrosion on the dynamic behavior in particular natural frequencies, damping ratios and mode shapes. The quasi-static behavior is also studied in order to determine whether through a quasi-static test the prediction of dynamic response is possible.

2.1. Specimens

For the sake of representativeness, the choice of large-scale RC beams has been made. Considering some design constraints related to 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 Fig. 1. a.

The reinforcement (Fig. 1. b) is designed according to the European standards Eurocodes 2 and 8. The considered concrete has a compressive strength measured on cubes equal to 30 MPa with a water cement ratio around 0.6 representative of concrete in aged RC structures. 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%.



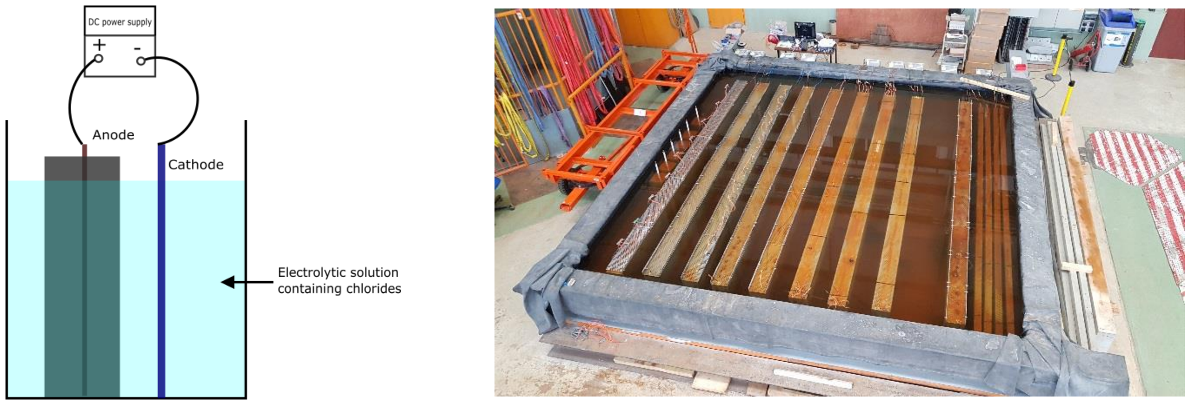
(a) (b)

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

2.2. Samples corrosion

In order to study the effects of corrosion on each reinforcement part, three beam 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 [5]. 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 de RC specimen. The whole specimen is immersed in an electrolytic solution containing chlorides to guarantee electrical conduction and to be representative of corrosion by chlorides. Fig. 2. a is a simplified representation of the setup for accelerated corrosion by imposed current. Fig. 2. b is a top view of campaign beams subjected to accelerated corrosion technique.



(a) (b)

Fig. 2 – Accelerated corrosion technique. (a) Principle of the set-up, (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;

- 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;
- 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 [5], the current density was limited to 100 µA.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 immerged in a 3.5% NaCl solution (Fig. 2. b). The exposure duration is estimated for each type of beam and each corrosion rate using Faraday's law (Eq. (1)) with α = 1.3.

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

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}), 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**	
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

2.3. 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 are used to quantify the evolution of the modal properties. In this way, the mechanical state due to corrosion is fully characterized. The setup is similar to the one used for the IDEFIX campaign [6] but adapted for high range displacements and rotations. The beams are 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.

2.3.1. Quasi-static testing

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 means 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 Fig. 3.

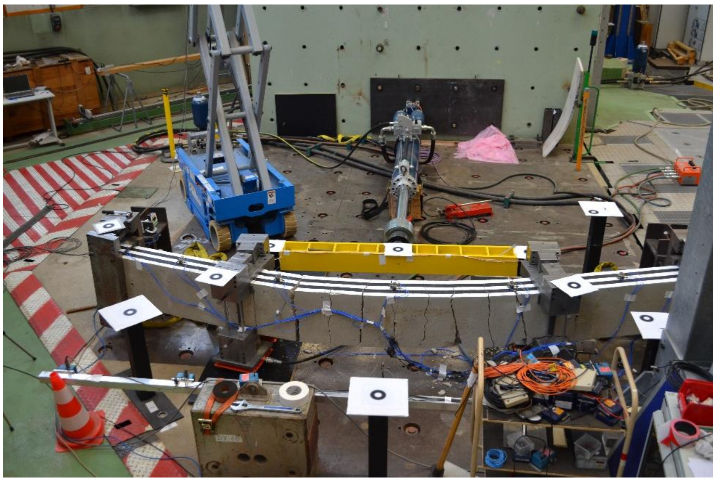


Fig. 3 – General view of the experimental setup for the quasi-static tests

The applied loading includes blocks of 3 identical cycles of prescribed displacement, with an increasing amplitude between two consecutive blocks (Fig. 4). Each cycle involves 4 phases: loading in one direction, unloading, loading in the other direction and unloading. Having 3 cycles allows to stabilize the new damage levels of the current block before moving on to the next one. It should be noted that as the mechanical response is dependent on the loading speed, the latter is kept constant equal to 0.5 $m.s^{-1}$. Hammer shocks testing between blocks is also planned in order to get the evolution of modal properties with damage.

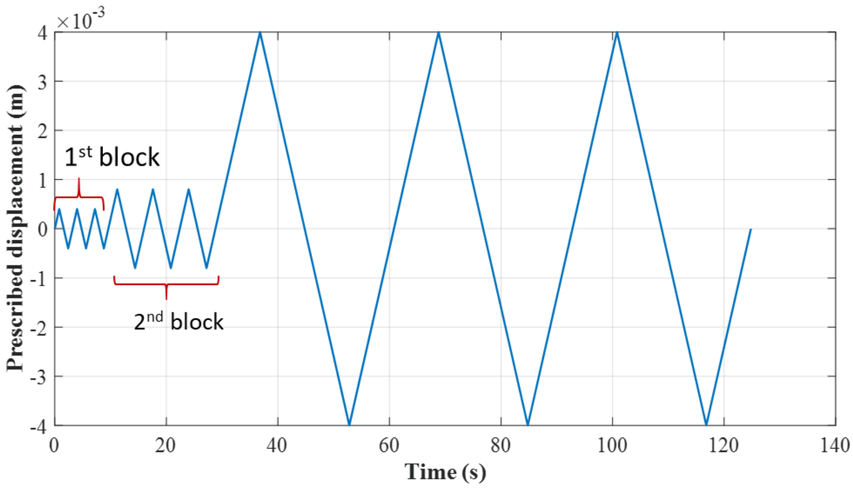


Fig. 4 – Planned load in quasi-static testing

The aim of quasi-static testing is to assess the evolution of the hysteretic energy dissipation within cycles. In addition, every specimen have been 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.

2.3.2. Dynamic testing

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) (Fig. 5).

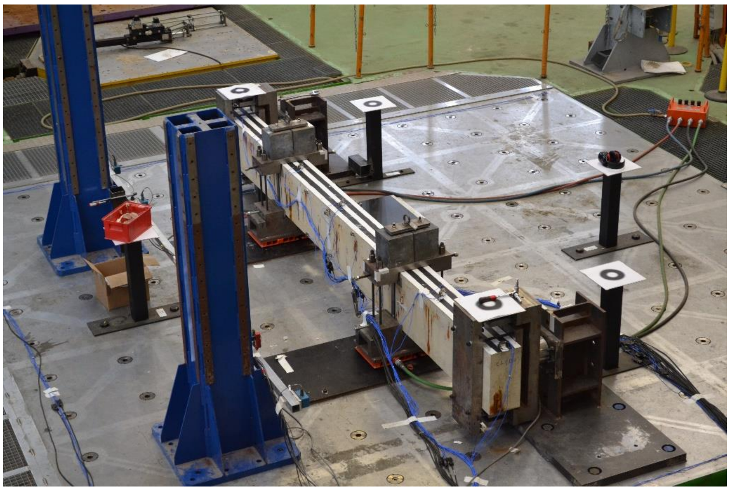


Fig. 5 – General view of the experimental setup for dynamic tests

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 2 Hz and 13 Hz (Fig. 6). This choice anticipates the modal frequency drop due to damage and allows to constantly excite the sought 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 (PGA = 0.1 g) is performed.

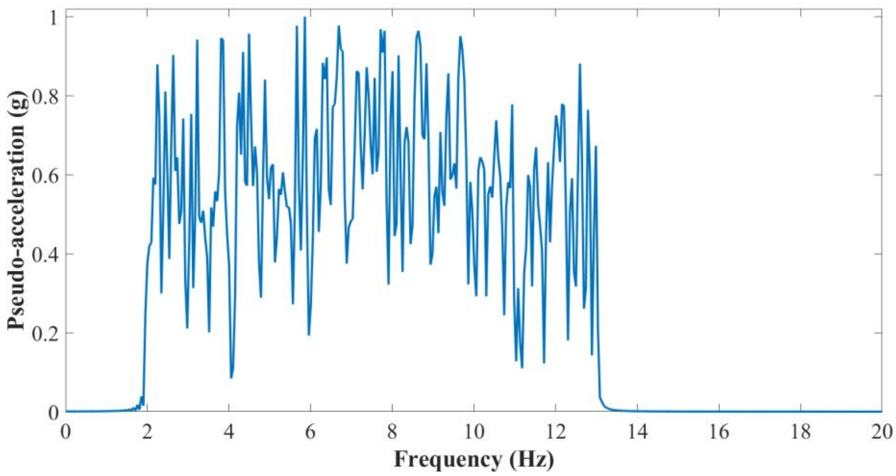


Fig. 6 – Spectrum of the applied signal

2.3.3. Measurements

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. Fig. 7 shows the type and position of the used sensors.

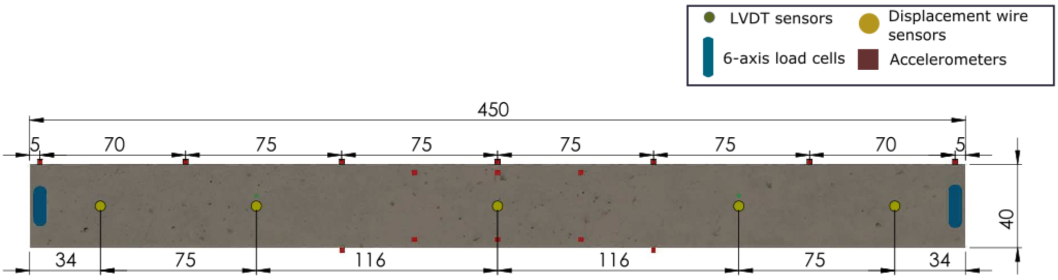


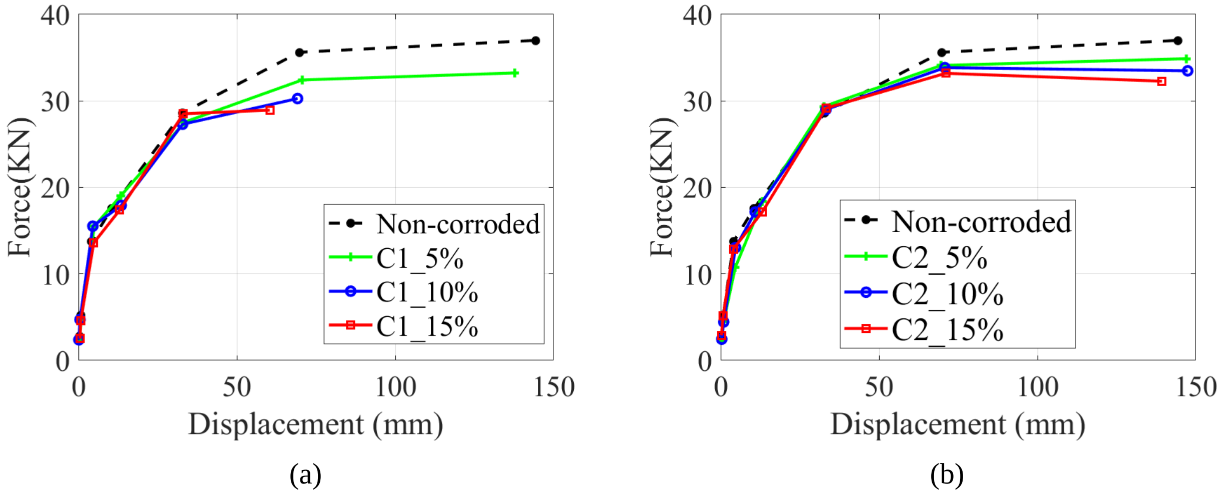
Fig. 7 – Sensors positions – front view- dimensions in centimeters

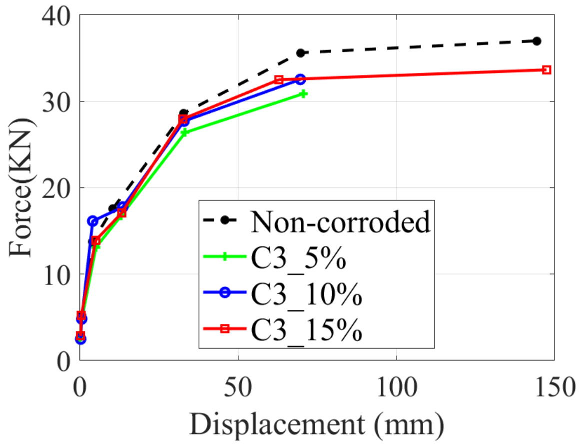
3. Experimental Results

3.1. Quasi-static test

3.1. 1. Capacity curves

Through the measurements carried out during the quasi-static testing, the evaluation of some quantities of interest, depending on the corrosion rate and the corrosion configuration, is possible. One of the structural performance indicators is the capacity curve obtained by considering only the envelope of the force-displacement curves. The capacity curve obtained through the cyclic quasi-static loads is comparable to the one resulting from a pushover analysis assuming that the compressed cracked concrete regains its initial properties when the cracks are closed. The force considered is the sum of the reactions measured on each beam support in the direction of the force application, whereas the displacement is measured at mid-span. Only the loading phase is considered in each block. The results are shown in Fig. 8.





(c)

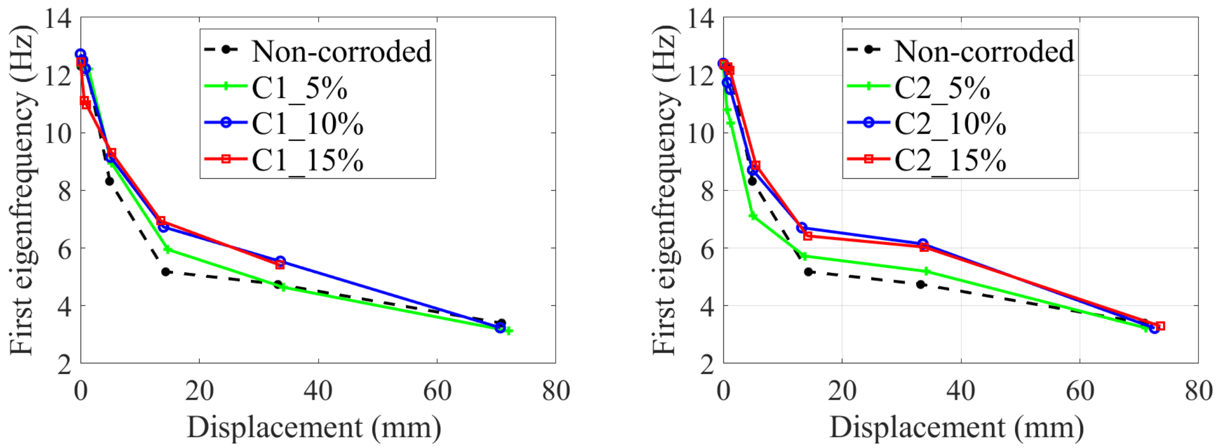
Fig. 8 – Capacity curves obtained from quasi-static tests : (a) C_1configuration, (b) C_2configuration, (c) C_3configuration

For the C_1configuration, the corroded beams show a decrease of the capacity with respect to the non-corroded one. The obtained results are in good agreement with the results presented in different studies reported in the literature, like [7].

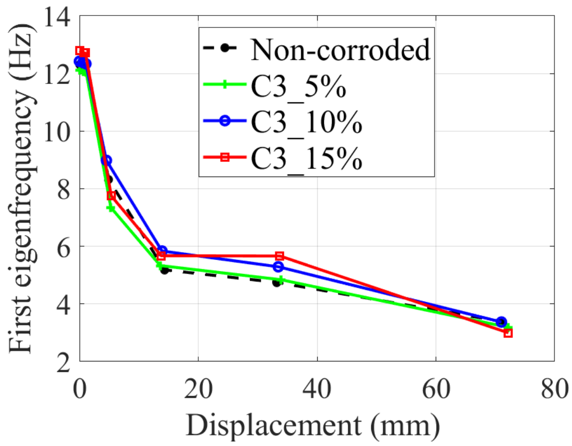
For the C_2configuration, the corroded beams show almost the same capacity as the non-corroded one. This can be explained by the fact that stirrups do not provide bending stiffness. The trend of the C_3configuration capacity curves is difficult to explain: the corroded beams at 5 and 10% corrosion rates show a decrease of the capacity with respect to the non-corroded one as expected. Whereas, the 15% corroded beam exhibits surprisingly a similar capacity as the non-corroded beam. It is probably due to the significant sliding between on the one hand the concrete cover and on the other hand the reinforcement and the confined concrete.

3.1. 2. Modal properties

The experimental eigenfrequencies have been determined by the mean of a hammer shock test after each applied block of the quasi-static testing. The objective is to follow the evolution of the modal properties as a function of damage, for each beam configuration and each corrosion rate. The data analysis was done based on the covariance driven subspace methods developed by the authors of [8] and [9] . Fig.9 shows the evolution of the first eigenfrequency as a function of the maximum displacement measured at mid-span during the application of the previous loading block.



(a) (b)



(c)

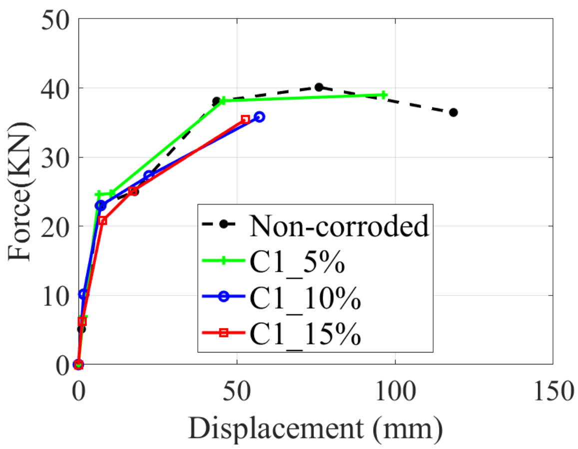
Fig.9 – The evolution of eigenfrequencies obtained from hammer shock tests : (a) C_1configuration, (b) C_2configuration, (c) C_3configuration

We can notice that the observed curves are almost the same for each beam configuration and each corrosion rate. This is essentially due to the nature of the hammer shock: the energy transmitted to the beam is not enough to activate all the non-linearities that have occurred at the beam level after each loading block.

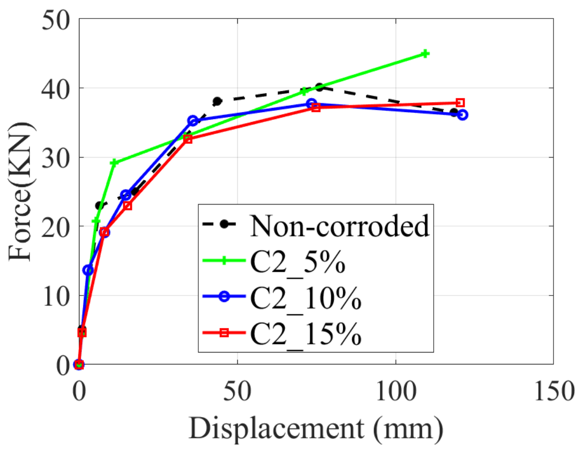
3.2. Dynamic testing

3.2. 1. Capacity curves

Through the measurements carried out during the dynamic testing, we obtain the capacity curves plotted in Fig. 10. The force considered is the sum of the reactions measured on each beam support in the direction of force application during a test sequence corresponding to an acceleration level, whereas the displacement is the maximum of displacement measured at mid-span during a test sequence. The same observations as the capacity curves obtained from quasi-static testing can be made.



(a)



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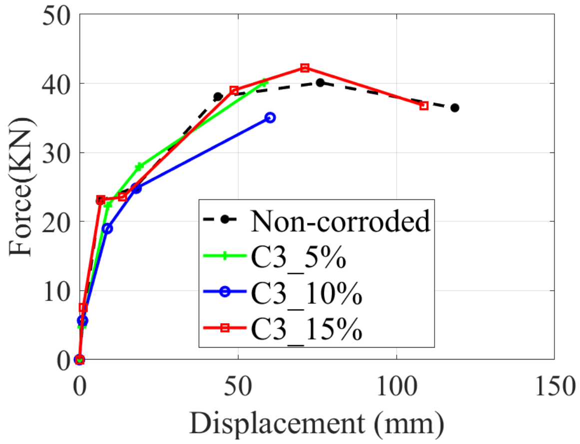
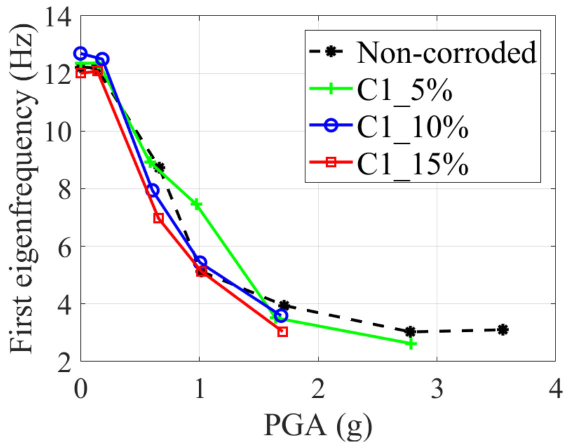


(c)

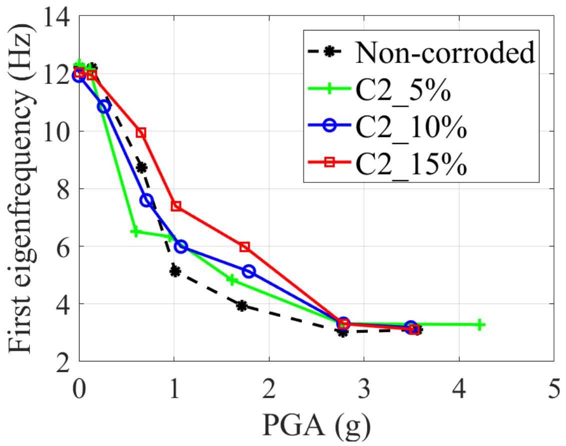
Fig. 10 – Capacity curves obtained from dynamic tests : (a) C_1configuration, (b) C_2configuration, (c) C_3configuration

3.2. 2. Modal properties

The experimental eigenfrequencies during the dynamic testing have been determined by the mean of a white noise after each acceleration level. The white noise (WN) corresponds to a random signal characterized by equal intensities 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 same method as used for the analysis of hammer shock tests. Fig. 11 shows the evolution of the first eigenfrequency as a function of PGA (Peak Ground Acceleration) which corresponds to the highest peak ground acceleration experienced by the beam for the loading period.



(a)



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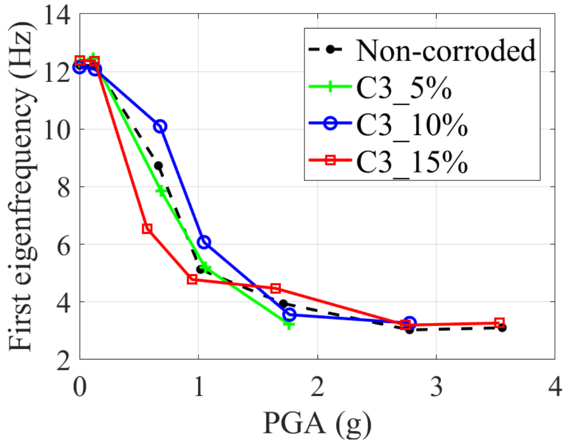

(c)

Fig. 11– The evolution of eigenfrequencies obtained from white noise tests: (a) C_1configuration, (b) C_2configuration, (c) C_3 configuration

Regarding the evolution of the first eigenfrequency, we can notice that the C_1corroded beam at 5% corrosion rate behaves in a similar way or even better than the reference. In other words, the eigenfrequency drop off is faster for the reference beam than the 5% corroded beam, considering that the eigenfrequency reflects the overall level of damage occurred in the specimen. This trend changes at the seismic level (≈ 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. Given that the corroded beam rebars are characterized by a reduced cross section, the observed trend was expected. For the two other corrosion rates of the same configuration, the decrease of the first natural frequency is a consequence of the degradation of bond strength and steel ductility properties.

For the C_2configuration, the evolution of the eigenfrequency for the corroded beams at the three corrosion rates follows the same trend as the non-corroded one.

For the C_3configuration, we can notice that for the 5 and 10% corrosion rate the corroded beams get more damage compared to the non-corroded one. Whereas, the behaviour of the 15% corroded beam is comparable with the behaviour of the non-corroded in regards to the decrease of the first eigenfrequency.

4. Conclusions

The issue related to the corrosion effects of steel reinforcement on the dynamic behavior of RC beams is analyzed in the paper, in an experimental way through dynamic testing of large-scale corroded beams. Some elementary experimental results are presented in this paper and can be summarized as follows:

- regarding the capacity curves, the same conclusions can be drawn from those extracted from the dynamic tests and those extracted from the quasi-static tests. For the C_1configuration, the corroded beams show a decrease of the capacity with respect to the non-corroded one. Regarding the C_2configuration, the results show almost the same bearing capacity as the non-corroded one. However, for the C_3configuration the corroded beams at 5 and 10% corrosion rates show a decrease of the capacity with respect to the non-corroded one as expected, the 15% corroded beam exhibits surprisingly a similar capacity as the non-corroded one;
- the experimental first eigenfrequencies have been determined by the mean of hammer shock tests and white noise signals. We can observe for the C_1configuration a more noticeable decrease of the first eigenfrequency as the corrosion rate increases. The C_2corroded beams keep the same trend as the non-

corroded beam. However, for the C_3corroded beams at 5 and 10% corrosion rates a more significant decrease of the first eigenfrequency is observed with respect to the non-corroded one; the 15% corroded beam behaves the same way as the non-corroded one.

5. Acknowledgements

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6. Copyrights

7. References

[1] A. A. Almusallam, « Effect of degree of corrosion on the properties of reinforcing steel bars », *Construction and Building Materials*, vol. 15, nº 8, p. 361-368, déc. 2001, doi: 10.1016/S0950-0618(01)00009-5.

[2] W. Zhu et R. François, « Corrosion of the reinforcement and its influence on the residual structural performance of a 26-year-old corroded RC beam », *Construction and Building Materials*, vol. 51, p. 461-472, janv. 2014, doi: 10.1016/j.conbuildmat.2013.11.015.

[3] Y. Ma, Y. Che, et J. Gong, « Behavior of corrosion damaged circular reinforced concrete columns under cyclic loading », *Construction and Building Materials*, vol. 29, p. 548-556, avr. 2012, doi: 10.1016/j.conbuildmat.2011.11.002.

[4] A. Guo, H. Li, X. Ba, X. Guan, et H. Li, « Experimental investigation on the cyclic performance of reinforced concrete piers with chloride-induced corrosion in marine environment », *Engineering Structures*, vol. 105, p. 1-11, déc. 2015, doi: 10.1016/j.engstruct.2015.09.031.

[5] S. Caré et A. Raharinaivo, « Influence of impressed current on the initiation of damage in reinforced mortar due to corrosion of embedded steel », *Cement and concrete research*, vol. 37, nº 12, p. 1598–1612, 2007.

[6] T. Heitz, A. Le Maoult, B. Richard, C. Giry, et F. Ragueneau, « Dissipations in reinforced concrete components: Static and dynamic experimental identification strategy », *Engineering Structures*, vol. 163, p. 436–451, 2018.

[7] M. Maslehuddin, I. A. Allam, G. J. Al-Sulaimani, A. Al-Mana, et S. N. Abduljauwad, « Effect of rusting of reinforcing steel on its mechanical properties and bond with concrete », *Materials Journal*, vol. 87, nº 5, p. 496–502, 1990.

[8] A. Benveniste et J.-J. Fuchs, « Single sample modal identification of a nonstationary stochastic process », *IEEE Trans. Automat. Contr.*, vol. 30, nº 1, p. 66-74, janv. 1985, doi: 10.1109/TAC.1985.1103787.

[9] M. Viberg, « Subspace Methods in System Identification », *IFAC Proceedings Volumes*, vol. 27, nº 8, p. 1-12, juill. 1994, doi: 10.1016/S1474-6670(17)47689-0.

