Engineering Structures 76 (2014) 112–123

Contents lists available at ScienceDirect

Engineering Structures

journal homepage: www.elsevier.com/locate/engstruct

# Experimental evaluation of the corrosion influence on the cyclic behaviour of RC columns

Alberto Meda [a], Serena Mostosi [b], Zila Rinaldi [a,*], Paolo Riva [c]

[a] University of Rome Tor Vergata, Italy
[b] Tecnochem Italiana S.p.A., Italy
[c] University of Bergamo, Italy

ARTICLE INFO

*Article history:*
Received 17 January 2014
Revised 25 June 2014
Accepted 26 June 2014
Available online 18 July 2014

*Keywords:*
Reinforcement corrosion
Bare bars
Embedded bars
RC columns
Cyclic tests

ABSTRACT

Corrosion of reinforcement is one of the leading causes of the deterioration in reinforced concrete structures. RC structures damaged by reinforcement corrosion can exhibit not only reduction of the bearing capacity but also an alteration of the collapse mechanism with a reduction of the structural ductility. In order to study the problem, full scale experimental tests on column specimens have been performed under cyclic loads. Preliminary tests for the calibration of the corrosion process have been carried out both on bare and embedded bars. The results of the cyclic experimental tests show how the reinforcement corrosion can lead to a reduction of the structural ductility, such that it could become a critical aspect particularly for buildings in seismic regions.



## 1. Introduction

The reduction of the service-life of reinforced concrete structures, mainly due to reinforcement corrosion, is a cause of concern for several RC buildings, particularly when low strength concrete is used. This aspect is becoming an important issue since several RC structures have an age close to their design life. The structural consequences of the corrosion phenomenon are multiple: besides the obvious reduction of the resistant section, a reinforcement ductility reduction can take place [1,2]. Furthermore the formation of corrosion products can cause cracking and high stresses in the elements, and it affects bond behaviour [3–5]. The relevance of steel corrosion, with reference also to its economical implications, is witnessed by the many theoretical and experimental research projects documented in the literature, mainly concerning reinforced-concrete or prestressed beams subjected to static loads [6–12].

The prediction of the bearing capacity of RC elements affected by reinforcement corrosion is, in recent guide lines [13], usually made with simplified approaches, based on the reduction of the steel area. These methodologies could be useful for the prediction of the ultimate loads, but could be misleading in the evaluation of the local and global ductility, that can be significantly affected by the corrosion [2,6,8].

Aim of the paper is the evaluation of the structural behaviour under cyclic loads of RC columns subjected to corrosion. Some researches on the cyclic behaviour of corroded rebars are available in the literature [14–17], fewer studies can be found on the cyclic response of structures with corroded reinforcement. In [18] the behaviour of reinforced concrete ties subjected to cyclic tension and corrosion is experimentally analysed with the main aim of evaluating the effect of the chemical attack on the crack opening. The results of experimental tests on beams are highlighted in [19], while experimental outcomes on circular corroded columns subjected to axial loads and cyclic horizontal displacements are discussed in [20]. Finally numerical models are proposed in [21]. The presented paper provides in-depth information on the test set-up (able to provide vertical load and cyclic horizontal displacement) and on the calibration of the corrosion process. Furthermore the presented experimental results on columns, validated with the outcomes available in the literature, allow to highlight the influence of corrosion on the cyclic structural response, in order to move, in a next future and with the support of other tests, towards its assessment and a way of facing it in the design and check of structures.

The first part of the research is devoted to the calibration and optimisation of the corrosion process, through electrolytic cells, and to the evaluation of the constitutive relationships of the steel rebars affected by different damage levels. The second part is conducted at the structural level. In particular, in order to evaluate the corrosion effects with reference to strength and ductility reduction,

* Corresponding author. Tel.: +39 0672597080.
*E-mail address:* rinaldi@ing.uniroma2.it (Z. Rinaldi).

http://dx.doi.org/10.1016/j.engstruct.2014.06.043
0141-0296/

two full-scale experimental cyclic tests on column specimens have been performed. One column was used as reference specimen, the other was tested to estimate the residual structural strength after the artificial corrosion of the rebars. The tests were performed up to failure by applying cyclic horizontal loads of increasing amplitude in order to verify the influence of corrosion on the structural behaviour.

## 2. Description of the experimental campaign

The evaluation of corrosion effects on the cyclic response of a column is not a simple issue, as many different factors, often difficult to foresee and simulate, can influence the structural behaviour. For this reason, the research described in this paper can be divided in two phases related to the evaluation of corrosion influence on the rebars (bare and embedded), without any external load, and the corrosion influence on the cyclic behaviour of columns. In the first phase, the aim is the calibration of the artificial corrosion process, in order to foresee the corrosion levels and morphology, and to evaluate the influence of the chemical attack on the constitutive relationship of steel bars. The second phase is devoted to the experimental evaluation of the cyclic behaviour of columns with corroded rebars.

In order to reach the goals, nine bare bars were first subjected to different corrosion levels and then tested in tension. Four reinforced concrete columns were also cast, with the same concrete, same section geometry and longitudinal steel reinforcement. The rebars of the first two specimens (named D and E) were subjected to corrosion, extracted from the element and eventually tested in tension, in order to check the influence of the concrete presence during the corrosion process. The time necessary for obtaining the required corrosion level was evaluated with a Faraday law, suitably modified, as shown in the following. Finally, on the basis of the obtained results, the steel rebars of the third column (named CC) were corroded up to a desired level, and the element was subjected to cyclic loading. The last column (UC) was left as reference un-corroded element and its cyclic behaviour was compared with the corroded one.

The reinforcement details and the concrete strength of the columns are typical of structures built in Italy in the 60s and 70s. In particular, all of the columns were cast with a low strength concrete, whose average compressive strength, measured on 150 mm side cubes, is equal to 20 MPa. The steel reinforcement (Tempcore, dual phase) can be classified as B500C, as the rebars exhibited an average yield strength equal to 520 MPa and an average maximum strength equal to 620 MPa.

## 3. Calibration of the rebar corrosion

In order to calibrate and optimise the corrosion process, an experimental campaign has been set-up first on bare bars, and eventually on embedded bars. The aim of these preliminary tests was the check of the corrosion morphology, the influence of the corrosion on the steel constitutive relationship, and the effect of the concrete in the rebar corrosion process.

### 3.1. Bare bars

Nine bare Ø16 specimens, with a length of 600 mm have been subjected to different corrosion levels, as reported in Table 1.

In order to preserve from corrosion the bar ends for correct clamping during the tensile tests, a protective film was placed as shown in Fig. 1a. As a consequence, the exposed surface presented a length of 200 mm (Fig. 1a). The corrosion was given with an accelerated process through electrolytic cells (Fig. 1b) with the bars dipped in a 3% saline solution. The current intensity was set equal to 0.1 A. (density of 50 mA/cm$^2$). In order to evaluate the mass loss, assumed as corrosion index, the steel rebars were accurately weighted before the accelerated corrosion process and the measured values were compared with the theoretical one, given by the product of the density for the actual volume. After the corrosion process, the rebars were cleaned from the rust with 3.5% hydrochloric acid solution [22], and then carefully weighted again.

The time necessary for obtaining the required corrosion levels was evaluated with the Faraday law. In Table 1, the actual corrosion levels, measured as mass loss, were also reported, highlighting the effectiveness of this formulation.

At the end of the corrosion process, after the bar cleaning, a visual inspection showed an almost uniform distribution of the corrosion, mainly for the A bars (10% mass loss). In this case, the rib reduction was the main consequence of the chemical attack (Fig. 2). In the cases related to a mass loss of 20% (bars C), the corrosion concerned all of the bar, in an almost uniform way, but a higher reduction of the resistance section was noted at the edges, close to protected part of the bars (Fig. 2). In this case, most of the ribs had almost disappeared.

The corroded bars were finally subjected to tensile tests; the obtained results are summarised in terms of force–strain and stress–strain relationships in Fig. 3. Both the stress related to the actual reduced and to the nominal un-corroded section are shown. The strain was measured on a 200 mm base, equal to the extensometer length.

It can be clearly noted the influence of the corrosion on the yielding and ultimate forces ($F_y$ and $F_u$, respectively), and ultimate strain ($A_{gt}$). The values of these properties are reported in Table 2. In particular, a reduction of ultimate force $F_u$ of about 22% and 34% occured for a mass loss of about 10% and 20%, respectively. The ultimate strain ($A_{gt}$) was reduced of about 37% for a corrosion level of about 10%, and up to about 46% for a mass loss of about 20%. Finally, it is worth remarking the corrosion influence on the plastic plateau, which tends to disappear for higher corrosion levels. The bars after the test are shown in Fig. 3a. The failure section is clearly visible.

### 3.2. Embedded bars

In order to calibrate the Faraday's law for bars embedded in concrete and to check the corrosion distribution and its effects on the tensile behaviour, steel rebars in concrete specimens were subjected to artificial corrosion and then to tensile tests.

Two 1.50 m height columns with square 300 mm × 300 mm section, reinforced with 4 Ø16 longitudinal steel bars have been cast (Fig. 4a), and named E and D. The foundation (700 mm × 700 mm × 100 mm) was made with fiber reinforced concrete Refor-tec GF5®, realised after the column cast (Fig. 4). All the rebars were measured and weighted, before their placement.

The specimens were subjected to an accelerated electrolytic corrosion. The saline solution (3% NaCl) is contained inside a PVC Ø500 mm pipe, placed around the column as shown in Fig. 4b, and fixed to the foundation through specific sealing products. The saline solution reached the height of 1000 mm; the current intensity was equal to 0.5 A for each bar. The scheme of the electrolytic cell is shown in Fig. 5. The four Ø16 embedded bars represent the anodes, while four Ø10 diameter steel bars, placed inside the pipe, worked as cathodes. The desired corrosion level was set equal to 20% and 15% in mass loss, for specimens D and E, respectively.

The time necessary to obtain the desired level of corrosion was evaluated with the Faraday's law, suitably modified in order to account for the concrete presence [2].