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Push-Over Analysis of RC Frame with Corroded Rebar

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Abstract. As known, the Italian building heritage largely consists of reinforced concrete frames designed before the '80s, which are, in many cases, built in the absence of specific anti-seismic criteria. Moreover, many of them, today, are characterized by bad structural conditions. Moreover, the problem of the structural conditions of the existing buildings, and their residual strength capacity, is often linked to the deterioration induced by the corrosive phenomena, which end up having a big impact on steel rebar mechanical properties. In this work, in order to investigate the influence of corrosion-damage on seismic response of existing reinforced concrete structures, a study has been carried out by analysing the non-linear behaviour of a reinforced concrete frame. The strength deterioration and reduction of the cross-section of steel rebar have been investigated and taken into account in the numerical analysis. This work shows the way in which the corrosion levels affected the push-over response, and the numerical results have been deeply analysed.

1. Introduction

The corrosion of steel reinforcement heavily affects the performances of Prestressed (PC) [1,2] and Reinforced Concrete (RC) [3] structures. It causes loss of load-carrying capacity of tendon and steel rebar, modifying both structural behaviour and capacity of elements [4,5].

In literature, there are several research works about the detrimental effects of corrosion in structures, because the problem is largely widespread [6] and the retrofitting is expensive [7].

Furthermore, it is important to develop adequate models to represent material degradation into seismic behaviour simulation of RC structures [8–11].

In this work, the seismic behaviour of a corroded framed RC structure is analysed by means of push-over analyses, which allow understanding the development of the global behaviour of the structure [12]. A degree of corrosion penetration has been simulated, by means of the reduction of bars diameters and concrete cover cracking and spalling.

At the begin, a database of experimental results on corroded steel rebar, available in literature, has been collected, and experimental laws have been calibrated to reproduce the corrosion-damage on mechanical proprieties of steel rebar.

Finally, the suggested experimental laws have been used to investigate the corrosion changes the curvature – bending moment relationship of RC cross-section, and the push-over response of a 2D RC frame.

2. Detrimental effects of corrosion on steel rebar mechanical properties

The damage-corrosion effects on the mechanical properties of materials involved were experimentally observed in different research works [5,13–19].

2.1 Concrete

The cross-section of rebar is reduced by corrosion. Moreover, the rust forms all around the cross-section of reinforcement, then a greater volume than the original thickness of rebar is occupied. Therefore, a round tensile stresses in the surrounding concrete is generated, then cracking of the cover and reducing of the compressive strength of concrete is observed.

This undesirable effect of corrosion has to take into account, thus the cylindrical compressive strength of corrosion-damaged concrete ($f_{cm,c}$) is calculated as follows [20]:

$$f_{cm,c} = f_{cm}/(1 + K\,\varepsilon_1/\varepsilon_{co}) \tag{1}$$

where $K = 0.1$ is the coefficient related to rebar roughness and diameter, ε_{c0} is the strain at the peak concrete stress f_{cm}; ε_l is the average tensile strain in cracked concrete at orthogonal direction of the applied compression.

The tensile strain can be evaluated as follows:

$$\varepsilon_1 = \left(b_{w,c} - b_w\right)/b_w \tag{2}$$

being b_w the width of the cross-section without corrosion; $b_{w,c}$ the increased width when corrosion cracks occur. In order, to give an estimation of the width increase, it can be calculated as $n_{bar}\,w_{cr}$, with n_{bar} = number of rebar in the compressed layer and w_{cr} = total crack width for a given corrosion level. The latter that can be evaluated as following [21]:

$$w_{cr} = \sum_i u_{i,corr} = 2\pi(u_{rs} - 1)Q_c \tag{3}$$

with u_{rs} = ratio volumetric expansion of the oxides (= 2), Q_c = corrosion depth and $u_{i,corr}$ = opening of single crack.

2.2 Steel Rebar

The corrosion-damage involves the steel rebar at the cross-section level by causing a reduction of steel thickness, which is interested by penetration of corrosion products. As consequence, a decrease of mechanical properties of steel rebar may be detected.

The spreaded corrosion effects may be taken into account by estimating the residual cross-sectional area of corroded rebar, i.e. reducing the bond strength [22]. However, the oxidation products of pitting corrosion are less wide, thus no signs of longitudinal cracking might become visible prior to significant cross-section loss [13].

In order, to investigate the corrosion effects on mechanical properties of steel reinforcement, Cairns et al. [13] carried out a series of tests on deteriorated steel rebar. The corrosion damage was simulated by eliminating part of rebar cross-section.

On the basis of the experimental results, the degradation of mechanical properties due to the corrosion effects, was reproduced by suggesting a linear equation:

$$p_c = p\left(1 - \alpha_p Q_c\right) \tag{4}$$

where the generic property (p) can, alternatively, be: the yield strength ($f_{y,c}$), the ultimate tensile strength ($f_{u,c}$) or strain ($\varepsilon_{u,c}$) corresponding to ultimate strength after corrosion; f_y, f_u and ε_u are yield strength, ultimate strength and strain of the non-corroded rebar, respectively; and $\alpha_y = 0.012$, $\alpha_u = 0.011$ and $\alpha_l = 0.030$ are empirical coefficients obtained by a statistical analysis.

The empirical coefficients suggested by Cairns et al. [13] were calibrated on own experimental results. With the aim to improve the performances of the linear detrimental models, a database of tests, carried out on corroded steel rebar subjected to tensile stress, has been collected.

Three test campaigns, for a total of 164 specimens, have been chosen [5,6,14]. In each test campaign, different degrees of corrosion were achieved. They were obtained by varying the application time of average current density. Then, the longer the current was applied the greater the corrosion effects were in rebar.

The specimens had variable diameter, ranging from 6 to 20 mm. The mechanical properties investigated have been: the yield strength ($f_{y,c}$), the ultimate strength ($f_{u,c}$), and the ultimate strain ($\varepsilon_{u,c}$) of corroded steel rebar.

By analysing the experimental test results, it was observed that the steel rebar mechanical properties were degraded with the increase of the corrosion degree. Then, corroded steel rebar was less ductile and strength than the non-corroded rebar, as expected.

Therefore, the experimental results have been used to retuned the empirical coefficients, by taking also in account the role of the rebar diameter (ϕ):

$$p_c = p\left(1 - \alpha_p \phi Q_c\right) \tag{5}$$

The values of the coefficients, obtained by the fitting procedure, have been: $\alpha_y = 0.00055$; $\alpha_u = 0.00057$; and $\alpha_l = 0.00214$. The calculated values are different from the analogues suggested by Cairns et al. [13]. It is due to the fact that the decay law has been modified introducing also the diameter of the rebar.

In Figure 1 the experimental versus numerical values, for each mechanical property ratio ($f_{y,c}/f_y$, $f_{u,c}/f_u$, and $\varepsilon_{u,c}/\varepsilon_u$), are shown. The points have grouped all around the optimal line (*exp = num*) for both $f_{y,c}/f_y$ and $f_{u,c}/f_u$, while are slightly dispersed for $\varepsilon_{u,c}/\varepsilon_u$. It is because the ultimate strain of corroded steel rebar is influenced by several parameters, then a different equation form for the regression curve should be used. Moreover, most of the values for the ratios $f_{y,c}/f_y$ and $f_{u,c}/f_u$ are within the cone ±20% and the statistical coefficients, Mean and Coefficient of Variation (CoV), state that the assumed linear law fits with enough precision the experimental data.
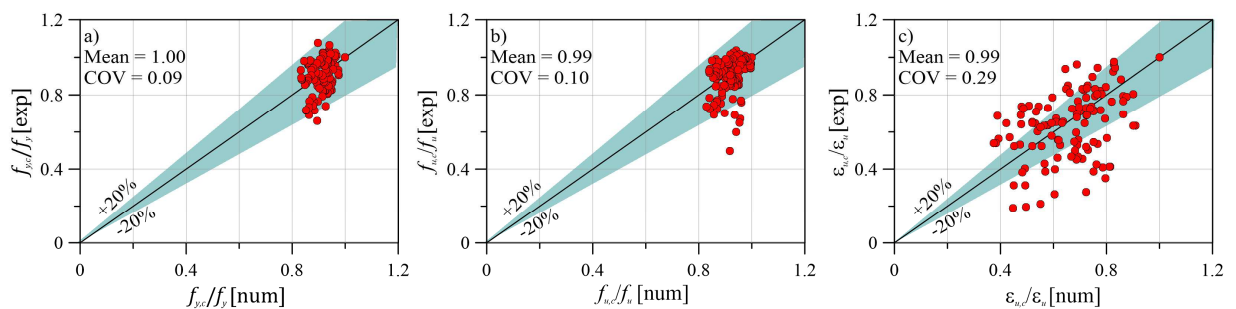

Figure 1. Experimental versus numerical value for: a) $f_{y,c}/f_y$; b) $f_{u,c}/f_u$; and c) $\varepsilon_{u,c}/\varepsilon_u$.

3. Curvature – bending moment relationship of corroded RC cross-section

Before to perform the push-over analysis of a corroded RC frame, the influence of corrosion on the cross-section properties of beams and columns has been investigated. It is known that the global non-linear static behaviour of RC structures is strictly related to the cross-section properties. Moreover, in this study, the push-over analysis has been performed, as it is explained in the following section, by using the classical theoretical model of concentrated plastic hinge.

The plastic hinge is modelled by the curvature - bending moment (χ-M) relationship and normal force-bending moment (N-M) interaction diagram (this last only for columns).

Because, the RC frame analysed has been part of a real corroded RC structure, built in 70's in the Messina (Italy) seismic area, all cross-sections have been modelled, assuming a corrosion degree that

decrease the material mechanical properties, on the basis of the predictive model described in the previous section [Eq. (5)].

Two RC cross-sections have here been reported. The geometry of beam is 300×700 mm, with a flexural reinforcement of $3\phi20 + 2\phi14$ in compression (A_{top}) and $2\phi18 + 2\phi14$ in tension (A_{bot}). The geometry of column is 300×800 mm and the longitudinal reinforcement is $3\phi22$ both on top and bottom of cross-section.

The corrosion degree has been assumed equal to 15%, then the suggested linear model allows to estimate the mechanical properties of corrosion-damaged materials. They are listed in Table 1, together with the non-corroded ones and the percentage decay (Δ) due to the corrosion effects.

Table 1. Mechanical properties of materials without and with corrosion.

Corrosion degree [%]	f_{cm} [MPa]	f_y [MPa]	f_u [MPa]	ε_u [mm/m]
0	10.7	417.6	590.9	0.219
15	8.9	360.0	512.4	0.107
Δ	17%	14%	13%	51%

The estimation of mechanical properties is preparatory to calculate the curvature – bending moment of cross-section. The plastic hinge of beams and columns has been characterized by using a software, namely RC-ABC [23], based on a sectional-fibre model [24].
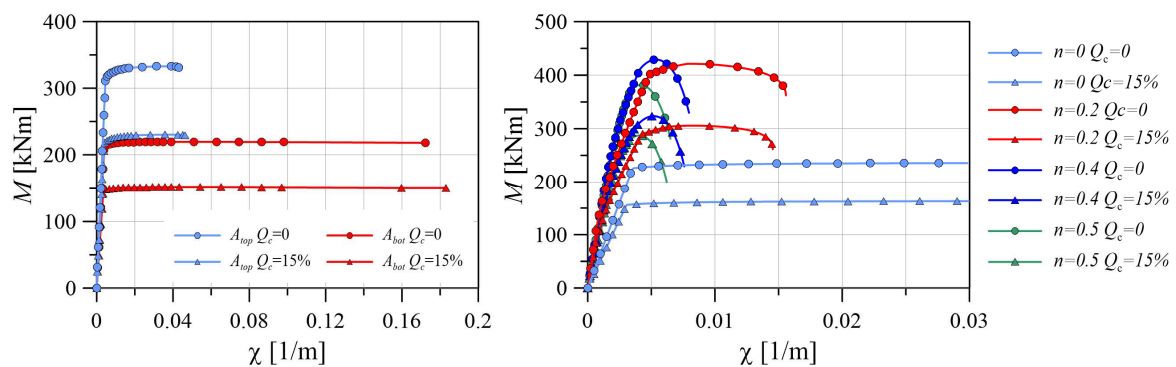

Figure 2. a) Curvature – Bending Moment relationships for RC beam. B) Curvature – Bending Moment relationships for RC column.

In Figure 2, the curvature - bending moment curves for beam and column are shown. For RC beam, two cases have been considered: a) with top reinforcement in tension; and b) with bottom reinforcement in tension. For RC column, four values of non-dimensional axial load (n) have been considered: 0, 0.2, 0.4, and 0.5.

The corrosion degree influences both the maximum bending moment and curvature. These values are decreased and, in both cases, the ductility also.

In Figure 3, the *N-M* interaction domain of column is plotted. It is evident as the corrosion drastically decreases the combined loads bearing capacity of the column (the shadow area in Figure 3).

A more sophisticate model than the used linear law [Eq. (5)] may allow to obtain more refined numerical results. However, the improvements in terms of χ-*M* curves and *N-M* interaction domains would be of little significance if compared to the complication of a more sophisticate model.

Furthermore, the estimation of steel rebar ultimate strain (ε_u) influences the non-linear behaviour of RC cross-section, by getting a brittle or ductile failure mode. To investigate this topic, further numerical analysis should be carried out.
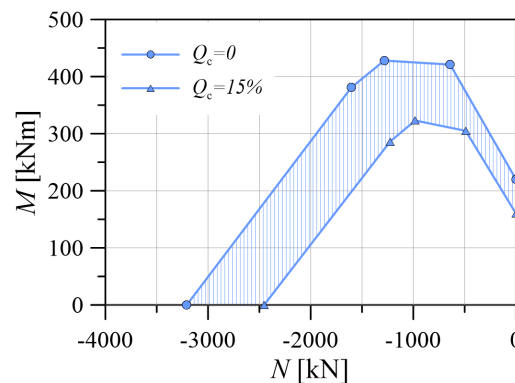
Figure 3. Axial load – Bending Moment interaction domain for RC column.

4. Push-Over Response of Corroded RC Frame

A push-over analysis has been carried out, by using the SAP2000 software, on an RC plane frame. It has been part of an existent structure, that was built in 70's in the Messina strait (Italy) area.

The general structural conditions of building are good, except for a diffused corrosion of beams and columns. In particular, as regards foundation and structural elements exposed to the atmospheric events are interested by corrosion-damage. Then, a lateral RC frame has been choose for the analysis.

The non-linear static analyses has been performed by implementing the numerical plastic rotation – bending moment relationships for each beams and columns of RC frame.

Two different scenarios were assumed: the non-corroded plane frame, and the plane frame interested by a 15% corrosion degree. The empirical model suggested before to predict the detrimental effect of corrosion on material mechanical properties has allowed to model all plastic hinges in the RC frame.

The Figure 4 shows the push-over analysis results of non-corroded and corroded frame. As can be observed the distribution of plastic hinge is quite the same. In the non-corroded frame, a lower number of plastic hinges than corroded frame has been observed. Furthermore, the average exploitation level of plastic hinges was higher, as expected.
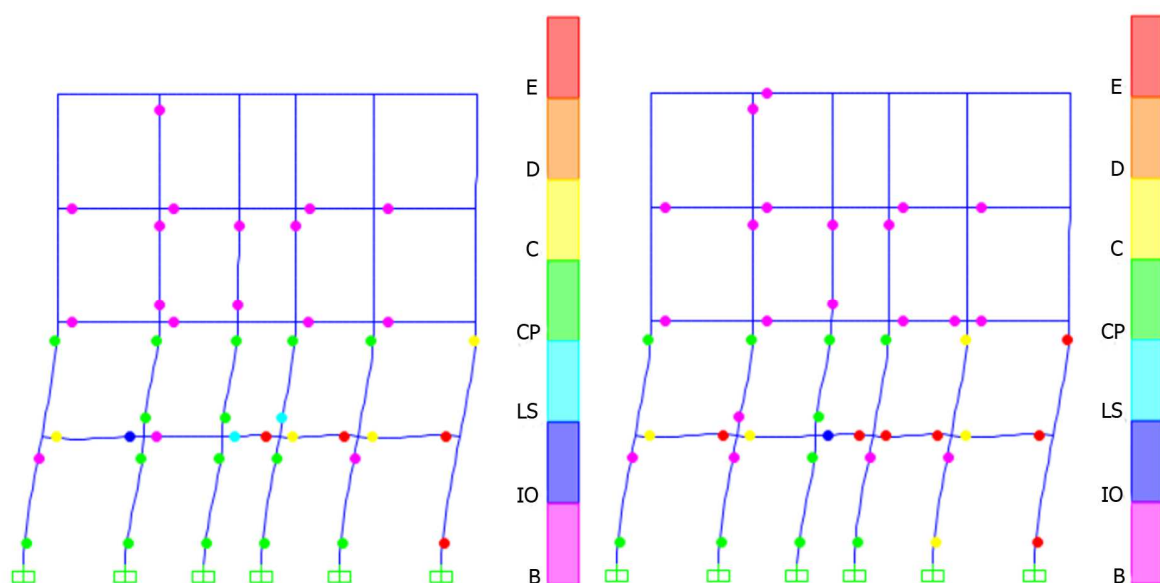

Figure 4. Last step of push-over analyses of: a) non-corroded; and b) corroded RC frame.

In Figure 5, the push-over curves for plain and corroded frame, respectively, are plotted.
These curves highlight the corrosion effects influence on the base shear-behaviour of RC frame. The corroded RC frame has been less ductile than not-corroded one, by tracing the less strength and ductility of materials involved. The area under the δ-V curve is small for the corroded RC frame, as consequence of the reduced dissipation capacity.
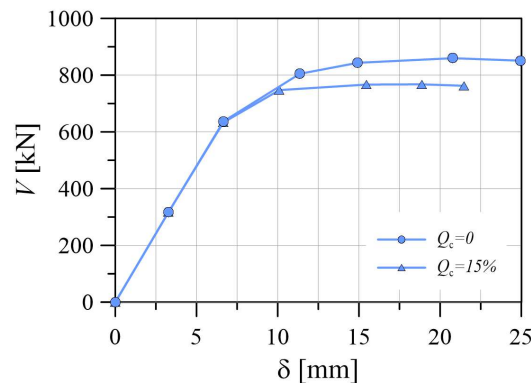

Figure 5. Displacement – Total base shear curve.

6. Conclusions

In this paper, the corrosion effects in the push-over response of RC frames have been analysed.
First, a database of test on corroded rebar has been collected, thus the corrosion-damage on mechanical properties of steel rebar has been investigated.
By examining these data, a simple equation for the decay prediction of material mechanical properties, as function of the degree of corrosion and the rebar diameter, has been provided. The consistency of this linear relationship has been discussed and validated, highlighting the need of further investigations with the aim of better reproducing the ductile behaviour of corroded RC cross-section.
Some numerical analysis have been carried out to evaluate the curvature - bending moment relationships of RC cross-sections, characterized by corrosion phenomena. They show that the corrosion drastically degreases the ductility and ultimate strength of RC cross-section.
Finally, the non-linear static behaviour of an existing RC frame, which is part of a real structure characterized by corrosion, has been evaluated.
The distribution of the plastic hinges remain quite the same as the non-corroded case. By contrast, the corrosion effects on the global behaviour of the RC frame lead to less ductility and strength, confirming the need to further investigate this issue with the aim to propose more refined models.

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