IOP Conference Series: Materials Science and Engineering

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To cite this article: S Imperatore and M Kioumarsi 2019 *IOP Conf. Ser.: Mater. Sci. Eng.* **652** 012032

ICCEMS 2019 IOP Publishing
IOP Conf. Series: Materials Science and Engineering **652** (2019) 012032 doi:10.1088/1757-899X/652/1/012032

Lateral displacement capacity of reinforced concrete elements damaged by corrosion

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Abstract. The aim of this work is to evaluate the influence of corrosion on the lateral displacement capacity and on the global ductility of reinforced concrete (RC) elements, using finite element (FE) analysis. The corrosive phenomenon is simulated accounting for its consequences on the reinforcing bars (variation of the steel geometry and mechanical properties), on the concrete (cracking) and at the interface (variation of the bond-slip behaviour). The parametric analysis, using numerical models, highlights how corrosion significantly changes the structural performance of the element in terms of deformability.

1. Introduction

The corrosion is the most important degradation phenomenon in reinforced concrete (RC) structures. Although several researchers studied the degradation phenomena due to corrosion effect, more efforts are needed to optimize the costs of maintenance and restoration of the deteriorated structures [1]-[4]. In a RC element, the macroscopic effects of the corrosion are the concrete cover cracking, splitting and the reduction of the reinforcement cross-section. Rebar cross-section reduction can be uniform or localized depending on the corrosion typology: in the case of carbonation, uniform corrosion usually occurs; elements deteriorated by chloride attack, instead, are typically characterized by pitting corrosion. In any case, the degraded element experiences a drastic reduction in strength and ductility, as well as a consequent expected variation of the rotational capacity, dissipation capacity and failure mode. All these aspects are also related to a change in the bond-slip behaviour after corrosion.

In order to evaluate the safety of the structure and to optimize any rehabilitation measurements, the influence of the corrosion, affecting the structural performance of a RC element, should be adequately investigated. At international level, the issue has been tackled in both the scientific and regulatory levels. Since the beginning of the century, the International Federation for Structural Concrete (fib) produced the Service Life Model Code in 2006 and the new Model Code in 2010. In both the cases, the specific aspects related to the reinforcement corrosion are described and the criteria for assessing the service life of degraded structural elements are defined.

In the scientific field, technical literature deals with the topic mainly from the static point of view. In this context, a wide state of the art is available. The reduction of the steel cross-section is accompanied by a mechanical properties decay both in the cyclic and monotonic behaviours, both in tension and in compression [5]-[11]. At the same time, as a result of corrosion, the steel cross-section reduction is accompanied by the formation of corrosion products, cracking and spalling of the concrete cover and changing the bond-slip behaviour [12]-[18]. Only taking into account the degradation of the mechanical properties of reinforcement, the sectional capacity of any RC element appears significantly reduced in the time [19]-[26]. This aspect, may significantly affect the seismic behaviour of the structures [27]. Obviously, the decay may become more significant if also bond and cracking are considered.

In the present work, basing on the numerical FE models, a parametric analysis is performed in order to investigate the lateral displacement capacity of RC elements damaged by corrosion.

2. Decay laws to account for the corrosion: bond-slip behaviour and reinforcements

The reinforcement cross-section reduction is the first consequence of corrosion degradation. Since the production process of the steel rebars induces a multilayer microstructures able to satisfy the regulatory mechanical performances, the corrosive attack also changes in the reinforcement constitutive law. The variation of the mechanical characteristics of reinforcing bars can be statistically represented with a linear regression of the strength and an exponential regression of the ultimate strain [11].

With specific reference to the uniform corrosion, the degradation laws are analytically expressed by the following formulations, which define the mechanical features for a given percentage of corrosion.

$$\sigma_{y,ad} = 1\text{-}0.0143453 \cdot M_{loss}\,[\%] \tag{1}$$

$$\sigma_{uad} = 1\text{-}0.0125301 \cdot M_{loss}\,[\%] \tag{2}$$

$$\varepsilon_{u,ad} = e^{-0.0204983 \cdot Mloss\,[\%]} \tag{3}$$

where $\sigma_{y,ad}$ and $\sigma_{u,ad}$ are respectively the yielding and ultimate nominal strength of the corroded reinforcement, adimensionalized respect to the initial un-corroded nominal strength; $\varepsilon_{u,ad}$ is the fracture strain of the corroded reinforcement, adimensionalized respect to the un-corroded one; M_{loss} is the percentage of mass loss due to the corrosion degradation.

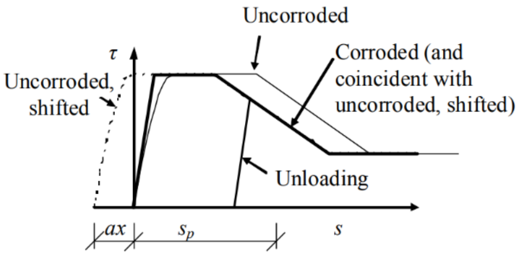

Figure 1. Local bond-slip law model before and after corrosion, from [28].

Another aspect that significantly compromised by corrosion is the bond-slip performance. Due to the electro-chemical reactions, iron oxides form at the steel-concrete interface and exert a radial pressure on the concrete cover and modify the bond condition. Typically, three different stages occur:

- In the so-called pre-cracking, an improvement of the bond strength is detected. In fact, the corrosion products exert a pressure able to promote the concrete confinement.
- In the second stage, cracking stage, a crack forms and then the bond capacity returns to be similar to the initial un-corroded specimen.
- In the third stage, defined of post-cracking, the cracks spread in the concrete cover and enlarge. The confinement effect is loosen and a sharp reduction of the bond conditions are observed.

In this paper, to consider the bond-slip behaviour due to the corrosion in FE model, the plasticity model proposed in [28] has been adopted. In model is shown in Figure 1, where τ represent the bond strength, s the slip of the reinforcement, s_p the plastic slip of the un-corroded bar, and ax is a parameter introduced to account for the corrosion effects. According to model, the degradation is accounted for shifting the CEB-FIP bond-slip formulation [29] along the slip axis of a quantity ax, where a is a constant parameter fixed equal to 8.1 and x is the actual corrosion penetration.

3. Parametric analyses

Effects of corrosion on the lateral displacement capacity of RC elements is evaluated using FE analysis, performed by ATENA 2D software. In particular, a wall-plate joint has been considered to be studied, see Figure 2. The wall-plate joint has been modelled using the plane stress idealization and has been designed to evaluate the bond-slip capacity of anchoring bars according to [30], and it is here modified to account for the corrosion effects. Aim of this study is, in fact, to understand how the bond-slip capacity of corroded reinforcement affects the lateral displacement capacity of the element.

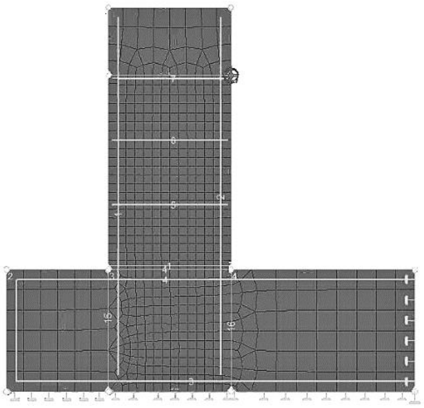

Figure 2. FE model adopted for the parametric analysis.

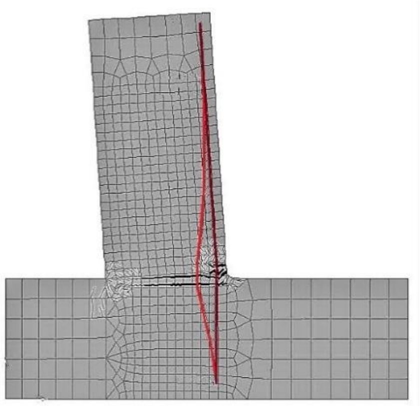

Figure 3. Collapse configuration and stress distribution in the un-corroded element.

The wall has 30 cm depth and is characterized by a height of 120cm; the wall consists of seven bars of 12mm diameter on each side and presents a cover of 30mm, the stirrups have a diameter of 8mm and a spacing of 30cm. The plate has a width of 120cm and a depth of 35cm, the transversal reinforcement consists in 10mm diameter stirrups with a spacing of 20cm; the lower reinforcements consist of seven bars of 12mm diameter, while the upper reinforcements are 13 bars of 16mm diameter. In this way, the failure of the element is localized on the wall-plate interface. The concrete has a cylindrical characteristic strength of 25MPa and is modelled with a nonlinear constitutive law both in tension and in compression. The reinforcements are characterized by a yielding characteristic strength of 450MPa and are modelled with a trilinear constitutive law. The loading scheme involves in an eventual axial load of 3500kN (to investigate the full structural capacity) and in a horizontal displacement, monotonically increasing, and acting 20cm under the top of the element. The collapse configuration of the un-corroded reference element, with the stress distribution on the tensed reinforcement, is represented in Figure 3.

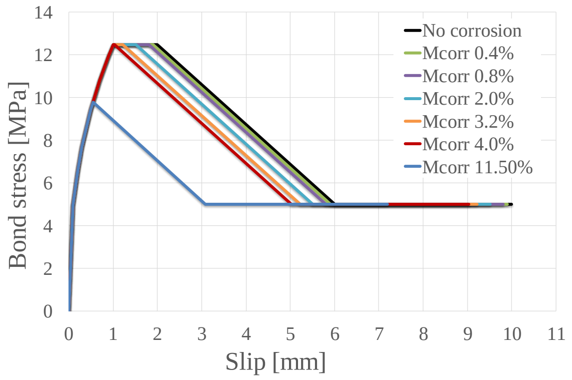

Figure 4. Bond-slip curves employed in the numerical simulation, according to [28].

To investigate the structural degradation, when the corrosion does not still cause a significant reduction in the reinforcement mechanical characteristics (i.e., the below the regulatory limits), the parametric analysis has been carried out considering corrosion levels up to the 11.5% in terms of mass loss. Moreover, the case of the uniform corrosion is chosen, since it seems strongly affects the bond-slip behaviour. The bond-slip curves considered in the parametric analysis are reported in Figure 4.

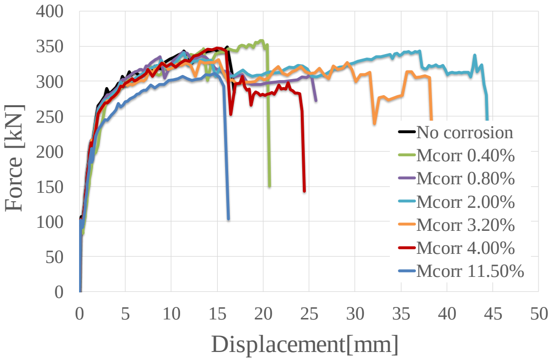

Figure 5. Pushover curves for different corrosion levels: pure bending.

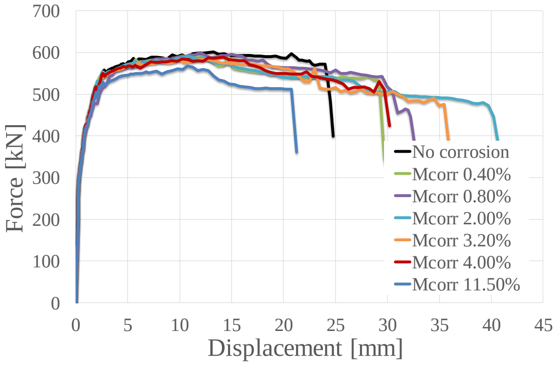

Figure 6. Pushover curves for different corrosion levels: flexure and axial load.

The obtained results are represented in Figure 5 in the case of the pure bending, while the axial load is also considered in Figure 6. Whether or not the axial load is considered, the lateral displacement capacity of the element it is significantly influenced by corrosion. In particular, for a mass loss up to the 2%, the global ductility increases from 7.15 to 19.35 if the pure bending action is considered, while it varies from 7.87 to 13.02 if an axial load of 3500kN is superimposed. Instead, corrosion levels higher that the 2% induce a progressive reduction of the lateral displacement capacity, which returns similar to that obtained for the un-corroded case in both the load cases, when the 11.5% mass loss is considered. Moreover, it is worth to note that the latter corrosion level is the only issue characterized also by a slight strength reduction, due to the greater impact of the mechanical properties degradation of reinforcement.

4. Conclusions

In this paper, a wall-plate joint into the in-plane-stress idealization has been considered in order to evaluate as the bond-slip capacity of corroded reinforcement affects the lateral displacement capacity of the element. The variation of the bond-slip law due to the corrosion has been modelled according to [28]. Moreover, a decay of the reinforcement mechanical properties for the considered degradation level has been introduced. Two different load cases are analysed: the pure bending and the combined compressive and bending stress, the latter considers an axial load level comparable to the point of maximum in the ultimate strength domain. The effects of corrosion on the lateral displacement capacity is evaluated analysing the response of the element in terms of pushover curves, crack pattern, stresses distribution. For sake of brevity, only the load-displacement curves are shown in the present work. The following conclusions can be drawn:

The obtained results clearly remark the influence of corrosion on the lateral displacement capacity of a RC element. In both the load cases the global ductility significantly increases for corrosion level up the 2%. It is worth noting that this degradation level can be achieved in few years from the casting of the reinforced concrete element, depending on the environmental aggressiveness. Higher corrosion levels are instead characterized by a progressive reduction of the lateral displacement capacity. This effect is related only to the variation in the bond-slip law. In fact, for the considered corrosion levels, the reinforcement mechanical properties decay appears negligible and then does not affect the response of the element. In this optic, the effects of the influence of corrosion on the steel-to-concrete interaction and on the reinforcement can be disregarded and the key factor of the study become the

influence of the bond-slip behavior for degradation levels up to 10% in mass loss. Moreover, the obtained results show that the lateral displacement capacity is lower than the initial un-corroded accompanied by a slight strength reduction for an 11.5% corrosion level in the both considered load cases. This means that the most common corrosion levels, characterized by mass losses greater 10%, modify the structural behaviour in terms of both strength and lateral displacement capacity. Consequently, both the degradation of mechanical properties of reinforcement and the influence of the corrosion on the bond-slip behaviour should be considered in the numerical simulation of deteriorated structures. It is worth observing that corrosion modify also the crack pattern, due to the progressive reduction of the bond strength capacity. In particular, a reduction of the number of crack and an increase of their width is detected by increasing the corrosion level.
In conclusion, the corrosion can significantly influence the performance of a reinforced concrete element in terms of strength and, above all, of ductility. The correct simulation of the degradation, then, appears the key point to effectively catch the performance modifications and collapse configurations.

Acknowledgments

This paper is part of the research convention “Effect of the corrosion on the steel-to-concrete interaction” between Niccolò Cusano University and Oslo Metropolitan University. We would like to show our gratitude to the Oslo Metropolitan University for the financial support of this project.

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