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Article

Ultimate flexural capacity of reinforced concrete elements damaged by corrosion

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Abstract: Worldwide the steel corrosion is one of the greatest deterioration problems for reinforced concrete structures. Comparing some literature experimental results with a complex FEM model, the present paper points out the principal aspects those characterize the static behavior of RC elements damaged by corrosion. Moreover, the non-dimensional abaci defined for some specific case studies finalized to the evaluation of the residual flexural strength of corroded elements highlight the dangerousness of the corrosion degradation if the failure of the element is governed by the steel.

Keywords: corrosion, fem model, degradation abaci, flexural strength.

1. Introduction

The increased aggressiveness and environmental pollution have highlighted the issue of the deterioration in reinforced concrete (RC), previously considered long life unalterable and non-degradable material. During last decades, the corrosion degradation has occurred on reinforced concrete structures, causing loss of load-bearing capacity, both in the service and in ultimate limit state. The first evidence of corrosion degradation is the formation of rust stains on the surface of the artifact; then, the concrete cracks [1] and the steel-concrete interaction is actually lost, corrosion rate increases and reinforcement section is reduced. If not properly countered, depending on environmental aggressiveness, the ductility and the flexural strength can be drastically reduced and consequently the service life drop down [2].

The evaluation of the behavior of structural elements subjected to corrosive phenomena cannot disregard the study of the degradation process and its implications on both the materials and the sectional geometry (Fig. 1). To estimate the static behavior of RC elements damaged by corrosion, the first aspect to consider is related to the steel reinforcement degradation. Previous literature's studies have demonstrated that the reduction of the steel cross-section is accompanied by a decay in the material mechanical properties both in tension and in compression, both in the monotonic and in the cyclic behavior [3-11]. Since the steel consumption is accompanied by the formation of corrosion products (characterized by a density lower than the original material) the cracking and the cover spalling of the concrete also occur [12-17]. Consequently, the bond interaction between the concrete and the steel is significantly modified [18-25].

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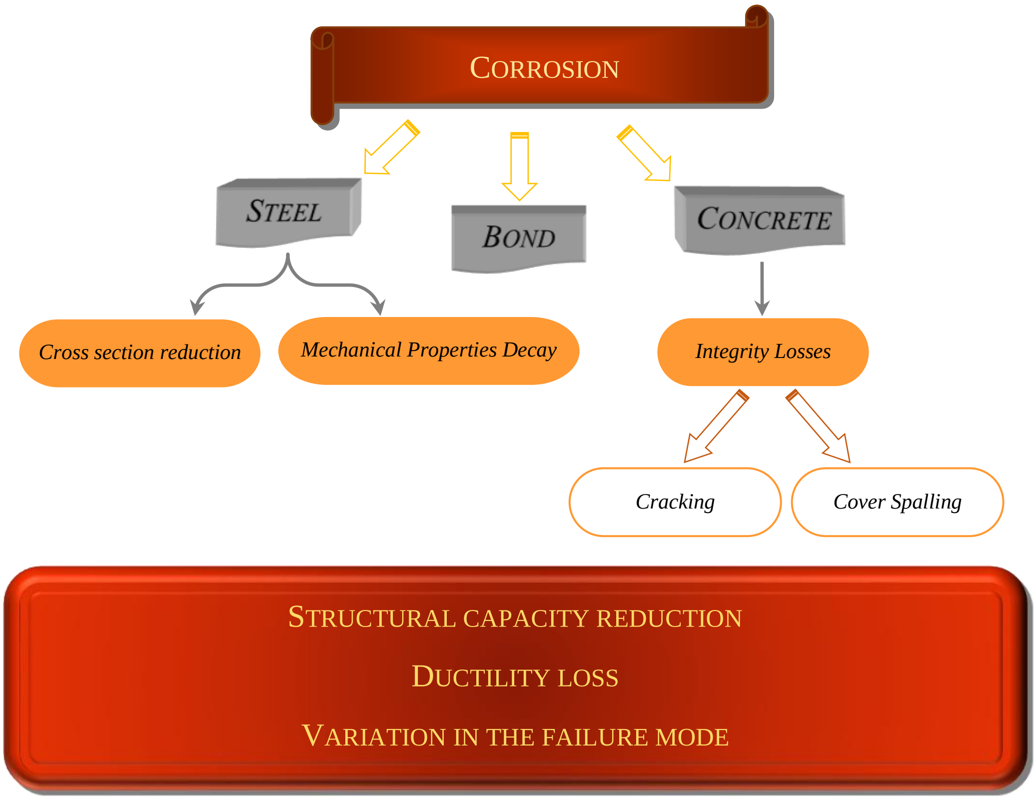

Figure 1. Corrosion influence on the behavior of a structural element.

Among the main contributions analyzing the flexural behavior of corroded beams, the works of Rodriquez et al. [26-30] must firstly mentioned. The experimental results show that the collapse is caused by the steel failure accompanied by a significant concrete cracking for low reinforcement amount, while high reinforcement amount the is due to concrete crushing and buckling accompanied by a considerable ductility reduction. Capozucca [31] observes a 45% strength reduction for a 13% diameter reduction, while Mangat and Elgarf [32] state a 25% strength reduction for a 9.5% corrosion level, a reduction in terms of ultimate displacement and stiffness and a variation of the failure mode. Analyzing the global behavior of naturally corroded beams, Castel [33] highlights significant increasing of the maximum displacement and stiffness and ductility reduction. Moreover: Torres-Acosta [34] shows that the 20% corrosion level causes about the 60% flexural strength decay; Azad [35] confirms the increasing of deformation as a consequence of the corrosion; Zhang [36] relates the pitting corrosion development with the ultimate capacity and the bending stiffness reduction, that is the more sensitive parameter due to the steel–concrete bond loss. According to the latter, Du [37] experimentally finds that under the same loads, the time-dependent deflections of corroded beams increased more rapidly than those of non-corroded beam, and reached their limiting deflections prematurely. Other researches [38-40] evaluate the flexural strength degradation on reinforced concrete beams subjected to various different levels of chloride-induced reinforcing corrosion, finding that the failure mode can change from ductile to brittle when corrosion occurs.

The brief review of the works proposed in the scientific literature shows that a reliable procedure to estimate the residual life of a reinforced concrete structure subjected to corrosion is not yet well defined, due to a widespread uncertainty on the experimental results, often influenced by not controlled corrosion distribution. For this reason, at the scientific and regulatory level, a reliable methodology for simulating the flexural behavior of corrosion-damaged reinforced concrete elements has not yet been proposed. Only taking into account the degradation of the reinforcement mechanical properties, the sectional capacity of any RC element appears significantly reduced in the time [40-48]. This aspect, may significantly affect the seismic behavior of the structures [49-51]. Obviously, the decay may become more significant if also the bond and cracking are considered.

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Aim of the present paper is to highlight all these aspects by mean a numerical model in which one of the beams tested by Rodriguez [30] is simulated. Once that the comparison between the numerical and experimental results confirmed the reliability of the degradation model proposed by one the authors [11], non-dimensional abaci are defined to estimate the residual strength of a corroded beam. The obtained results clearly show decay in the flexural strength with the corrosion level as a function of the sectional reinforcement amount.

2. The corroded element with flexure: numerical modeling.

In order to predict the mechanical behavior of a corroded RC beam, an experimental case is selected to be simulated and analyzed using nonlinear finite element (NLFE) method.

2.1. Selected experimental case study

Rodriguez [30] investigated the effect of reinforcement corrosion on residual capacity of corroded and un-corroded RC beams under four-point bending test. In these experimental tests, many beams with various types of failure were investigated. In order to assess the applicability of the decay laws proposed by one the authors [11], a beam for a numerical simulation was chosen from [30]. Specifically, the mechanical properties of the reinforcement have been modified according the Eqs. (1-3) for the yielding strength, the ultimate strength, and the ultimate strain respectively.

$$\frac{\sigma_{y,corr}}{\sigma_{y,uncorr}} = 1 - 0.143453 \cdot M_{corr}[\%] \tag{1}$$

$$\frac{\sigma_{u,corr}}{\sigma_{u,uncorr}} = 1 - 0.125301 \cdot M_{corr}[\%] \tag{2}$$

$$\frac{\varepsilon_{u,corr}}{\varepsilon_{u,uncorr}} = e^{-0.024983 \cdot M_{corr}[\%]} \tag{3}$$

where σ_y and σ_u are respectively the yielding and ultimate stress of the reinforcement, M_{corr} is the percentage of mass loss due to the corrosion and ε_u is the ultimate strain. It is assumed that the yielding strain can be directly derived by the σ_y since the elastic modulus of the reinforcement does not significantly change after the corrosion degradation.
Geometry dimensions and rebar detailing of the selected simply supported beam are shown in fig. 2. In the chosen beam, the amount of the uniform corrosion on the tensile reinforcement was 14% steel cross section reduction and the uniaxial compressive strength of concrete is 34 MPa. In the present study, reduction of the mechanical properties of corroded reinforcement was considered using Eqs. (1-3).

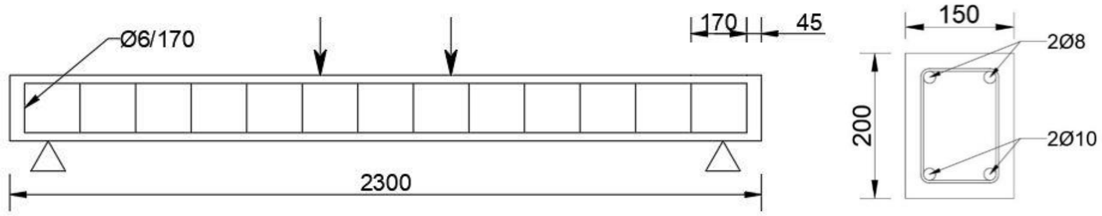

Figure 2. Geometry of simulated corroded RC beams investigated by Rodriguez et al. [30] in mm.

2.2. FE Analysis and Material Properties

The two-dimensional (2D) NLFE analysis was performed in DIANA [52] by incorporating the material models. Only half of the beams was modelled to take advantage of the symmetry in geometry, supports and loading conditions. It is assumed that the corrosion is uniformly distributed

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along the tensile reinforcements. A vertical stepwise incremental displacement was applied at the loading point in the model (see fig. 3). In addition, the nonlinear problems were solved using Modified Newton-Raphson approach.

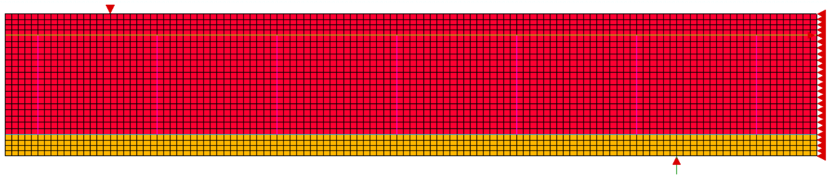

Figure 3. Mesh size and finite element model of one half of the beam.

The concrete was modelled using four-node quadrilateral plane stress elements. The tensile and compressive behaviors of concrete were represented through a smeared rotating crack model with Hordijk and elastic-ideally plastic models, respectively. Details of these models are described in [52]. It is reported that the compressive strength of concrete in compression zone, which is subjected to cracks due to the corrosion, might be reduced in comparison with undamaged concrete [53-56]. In this study, the reduced value of compressive strength is assigned to the concrete elements of the top cover for 2D FEM using a proposed equation by Coronelli and Gambarova [42].

2.3. Bond-Slip model

In FE model, one dimensional interface layer was modelled along the tensile rebars to consider the effect of bond-slip behavior. Interaction between the reinforcement and the concrete was modelled with 2+2 node line interface elements in 2D models. For the simulated corroded beam, bond slip behavior based on fib 2010 Model Code [57], which is confined with steel stirrups, was adopted. In this study, the bond slip behavior was modified based on the amount of the uniform corrosion and kept constant along the tensile rebar. In addition, the bond strength was calculated according to [43], as a function of the concrete strength, the cover-to-diameter ratio and stirrup confinement:

$$U_{\max}^{D} = R\cdot\left[0.55+0.24\left(c/d_0\right)\right]\cdot\sqrt{f_c}+0.191\left(\frac{A_{sw}\cdot\sigma_{yt}}{s_s\cdot d_0}\right) \tag{4}$$

where, $U_{\max}^{D}$ is the reduced bond strength, c is the thickness of concrete cover, d_0 is the diameter of the anchored rebar, f_c is the concrete compressive strength, A_{sw} and σ_{yt} are the stirrups cross section and the stirrup yield strength respectively, ss is the stirrup spacing, and R is a coefficient that depends on the corrosion and is equal to 1 for the selected case study.

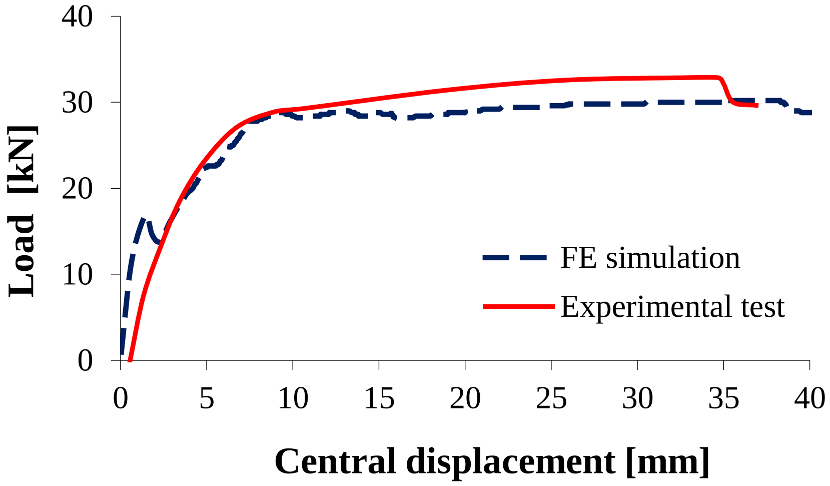

Figure 4. Comparison of load displacement curves at mid-span for 2D FE analysis and experimental results of a corroded RC beam no. 115; experimental data from [30].

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2.4. Comparison between the numerical and the experimental results

The obtained load-displacement curve at mid-span of corroded beam from nonlinear FE analysis (fig. 4) indicates good agreement with experimental observation at ultimate limit state (ULS) and serviceability limit state (SLS). The results of FE simulation prove the accuracy and applicability of the proposed decay laws (Eqs. 1-4) to modify the mechanical properties of corroded reinforcements.

3. Non Dimensional Abaci for the residual flexural strength of corroded rectangular sections.

The results proposed in the previous section highlight the feasibility of the decay laws in the estimation of the behavior of a corroded element under bending moment. As well known, the flexural strength of a reinforced concrete elements, is characterized by the mechanical properties of the constituent materials, while its deformation is related to the interaction between the steel and the concrete and then by the sectional curvature. The latter, of course, influences both the strains and the tensional levels of the constituent materials and then it has also relapses on the strength of the section itself. In reinforced concrete elements, the perfect bond condition is usually assumed and the full compatibility between the concrete and the reinforcement strains is then considered. When this hypothesis decay, for high load level and when the cracking occurs, with the decreasing of the bond the steel stress increases, reaching its maximum values on the crack. Then, assuming that a slip between the materials may occurs, the effective flexural strength of the element is slightly greater than the one evaluated in the classical hypothesis of perfect bond, which then can be regarded as conservative in terms of strength.
The application of decay laws for the steel to the classical models of the structural engineering, allows the definition of abaci to estimate the residual flexural strength of corroded element. The proposed relationships in the present paper are developed for the most typical pattern of exposed reinforced concrete beams in ordinary structures: the formed beam and the flat beam. For each kind of beam, the geometrical percentage of the tension reinforcement is varied in the range [1.3‰Ac; 4%Ac], as proposed by the EuroCode 2 [58]. For the compression reinforcement, a minimum quantity of 2ϕ14 diameter is imposed and increased until the tensile reinforcement amount.
According to the section 9.2 of the EuroCode 2 [58], the minimum tension steel content should be:

$$A_{s,\min} = 0.26 \cdot \frac{f_{ctm}}{\sigma_y} \cdot b \cdot d \tag{5}$$

where f_{ctm} represent the mean tensile concrete strength, σ_y the reinforcement yielding strength and b and d represent the section width and effective height, respectively. Remembering that the mechanical reinforcement percentage is defined as:

$$\omega = \rho \cdot \frac{\sigma_y}{f_{ck}} \cdot \tag{6}$$

Being ρ the geometrical reinforcement percentage and f_{ck} the concrete compressive strength, a minimum mechanical reinforcement percentage, $\omega_{s,min}$, may be defined as:

$$\omega_{s,\min} = 0.08 \cdot \frac{1}{\sqrt[3]{f_{ck}}} \tag{7}$$

Then, assuming a (cubic) compressive strength of 35 MPa for the concrete and reinforcements with a yielding strength of 450 MPa, the previous positions (Eqs. 5-7) indicate a minimum tension reinforcement of 2ϕ14 for both a (30x60) cm^2 formed beam section and a (70x25) cm^2 flat beam section. Parametric analyses have been performed considering three different corrosion scenarios: (i) section corroded all around its perimeter; corrosion of steel in tension; the steel in compression is corroded half of bars in tension in terms of mass loss. For each degradation condition, both the pitting corrosion pattern is considered by applying to the reinforcements the aforementioned decay laws to a classic uniaxial stress-plastic strain curve constitutive law. According to the EuroCode2 [58], the ultimate strength of the steel is assumed equal to 540 MPa, while the characteristic strains are assumed equal

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to 0.655‰ for the hardening initiation and it is equal to 10% for the collapse. The concrete is conventionally modelled the conventional relationship of Mander [59] assuming the presence of stirrups ϕ8/30 to account for the confinement.

Table 1 Compression and tension reinforcement in the formed beam.

Tension reinforcements	Compression reinforcements		
2ϕ14	2ϕ14		
3ϕ16	3ϕ16		
3ϕ20	3ϕ16	3ϕ20	
3ϕ24	2ϕ14	3ϕ16	3ϕ20

Table 2. Compression and tension reinforcement in the flat beam.

Tension reinforcements	Compression reinforcements		
6ϕ14	4ϕ14		
6ϕ16	4ϕ16		
6ϕ20	4ϕ20		
6ϕ24	4ϕ24		
8ϕ24	4ϕ24	6ϕ24	8ϕ24

The parametric analysis results are generalized by introducing the non-dimensional ultimate bending moment after corrosion ($m_{u,corr}$), defined as the ratio between the ultimate bending moment of the corroded section and the ultimate bending moment of the sound section. The reinforcement adopted for both the formed and the flat beams are reported in the tables 1 and 2, respectively. Since ω_{corr} depends only on the tensile reinforcement, the mechanical reinforcement percentage reduces linearly with the corrosion level (fig. 5).

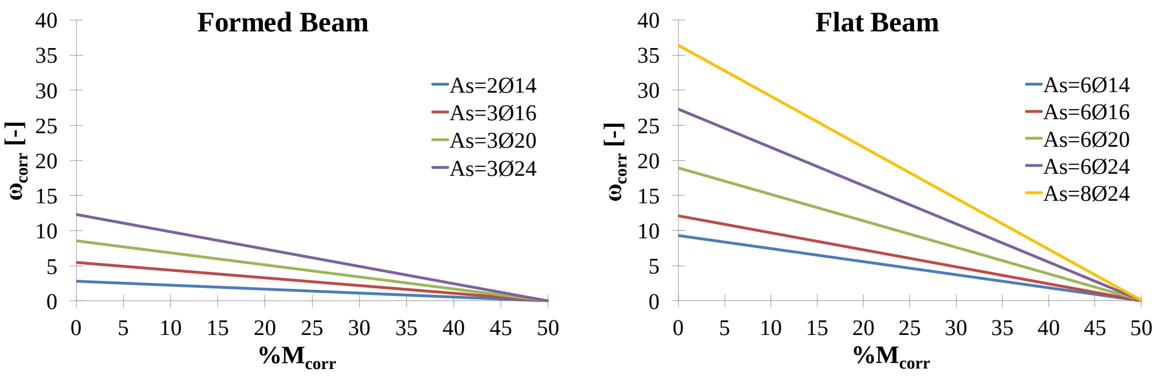

Figure 5. Decay of the mechanical reinforcement percentage with the corrosion levels.

For the considered sections, the non-dimensional ultimate bending moment after corrosion ($m_{u,corr}$) is plotted as a function of the mass loss of the reinforcement in tension. Both in the case of the flat and the formed beams, the uniform corrosion cause a linear decay of the flexural capacity with the increasing of the corrosion level (figs. 6-7). The reduction is accompanied by a depth reduction of the neutral axis with the consequent increase of the curvature. Then, the work rate of the reinforcements in tension increases ì as the deformability.

Similar results are obtained for all considered scenarios and reinforcement amount and configurations, also in the case of the pitting corrosion (figs. 8-9). This means that the behavior of a corroded reinforced concrete member can be easily studied applying decay laws to the reinforcements mechanical properties [11] and assuming the same corrosion level on the different steel layers. However, it is important point out the dangerousness of the pitting corrosion morphology, which induces a quasi-parabolic decrease of the flexural capacity of the element.

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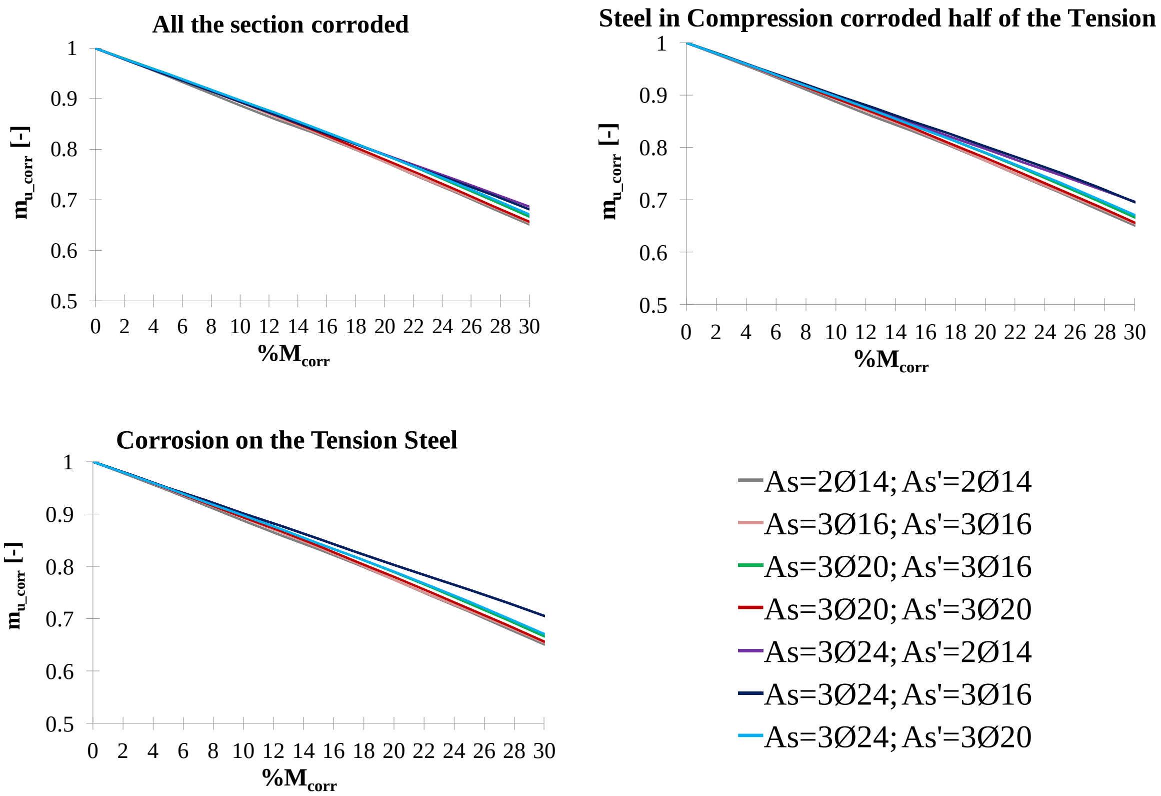

Figure 6. Non-dimensional ultimate bending moment for different corrosion scenarios - Formed Beam, uniform corrosion.

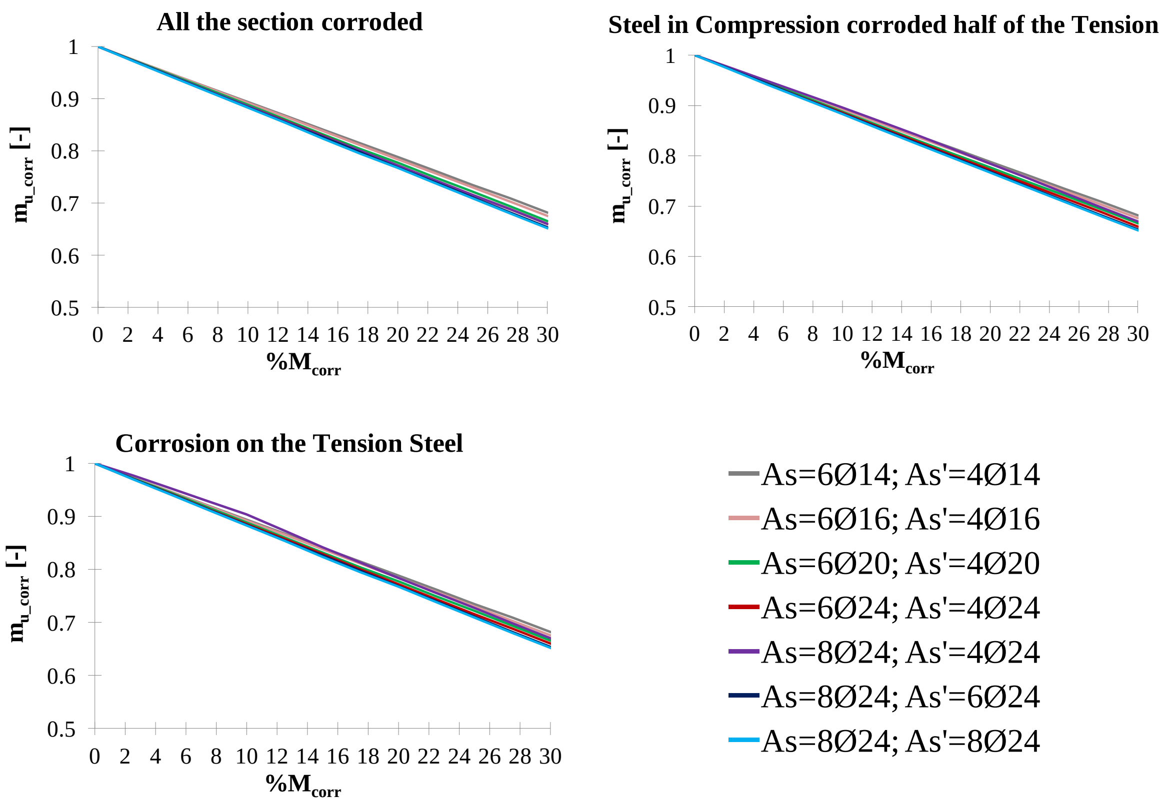

Figure 7. Non-dimensional ultimate bending moment for different corrosion scenarios - Formed Beam, uniform corrosion.

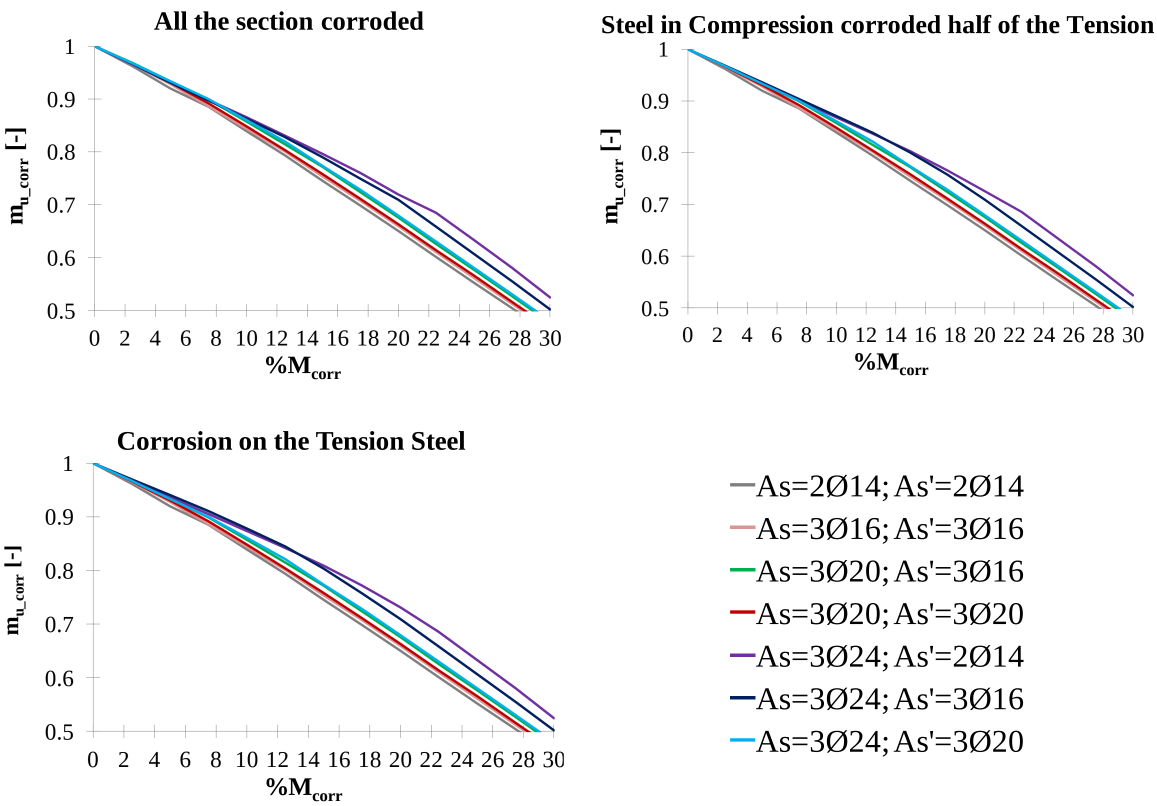

Figure 8. Non-dimensional ultimate bending moment for different corrosion scenarios - Formed Beam, pitting corrosion.

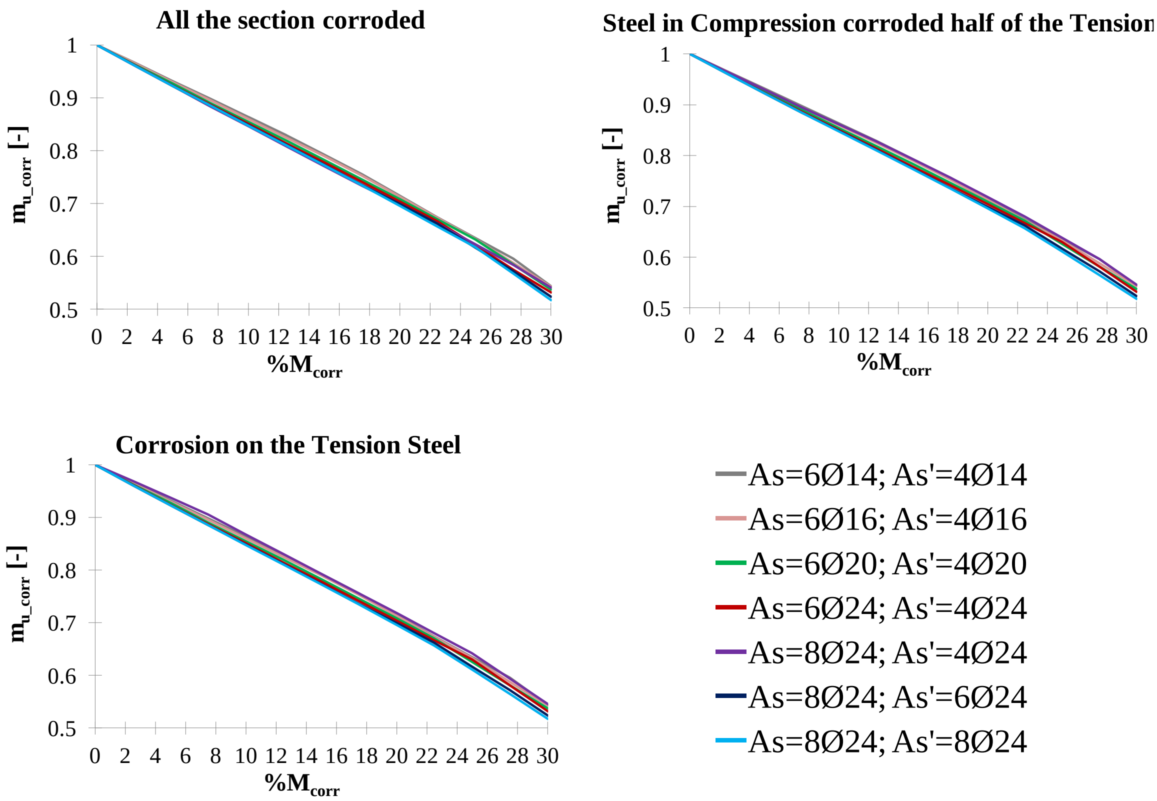

Figure 9. Non-dimensional ultimate bending moment for different corrosion scenarios - Flat Beam, pitting corrosion.

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The analysis of the ultimate curvature of the two beam typologies appears very interesting (fig. 10). In the case of the formed beams, both the corrosion level and the decay of the reinforcement mechanical properties modify the collapse mode of the section: in case of corrosion losses up to 5% in mass loss, the sectional collapse is governed by the reinforcement and not anymore by the concrete. Then, when the pitting corrosion damages a formed beam, the residual flexural strength of the elements strongly depends on the amount of longitudinal reinforcements. Differently, in the case of the flat beam, corrosion modifies the collapse mode only for higher mass losses and the dependence of the flexural decay law on the longitudinal reinforcements amount appears quite negligible.

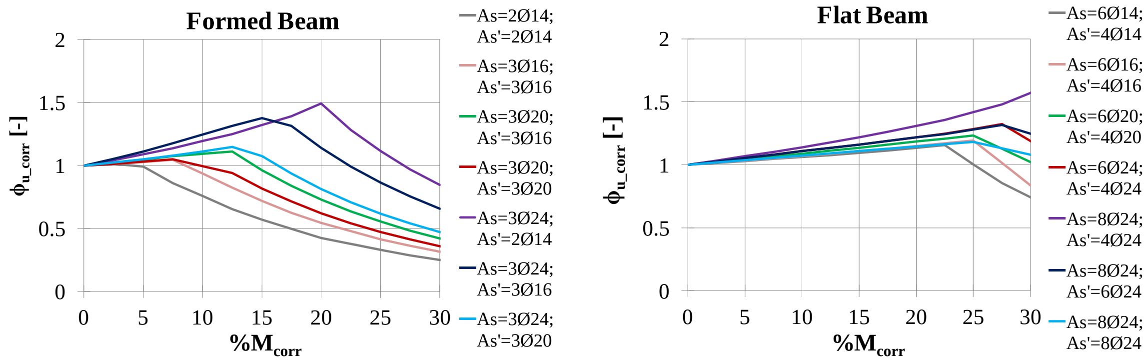

Figure 10. Non-dimensional ultimate curvature after the pitting corrosion: differences between the flat and the formed beams.

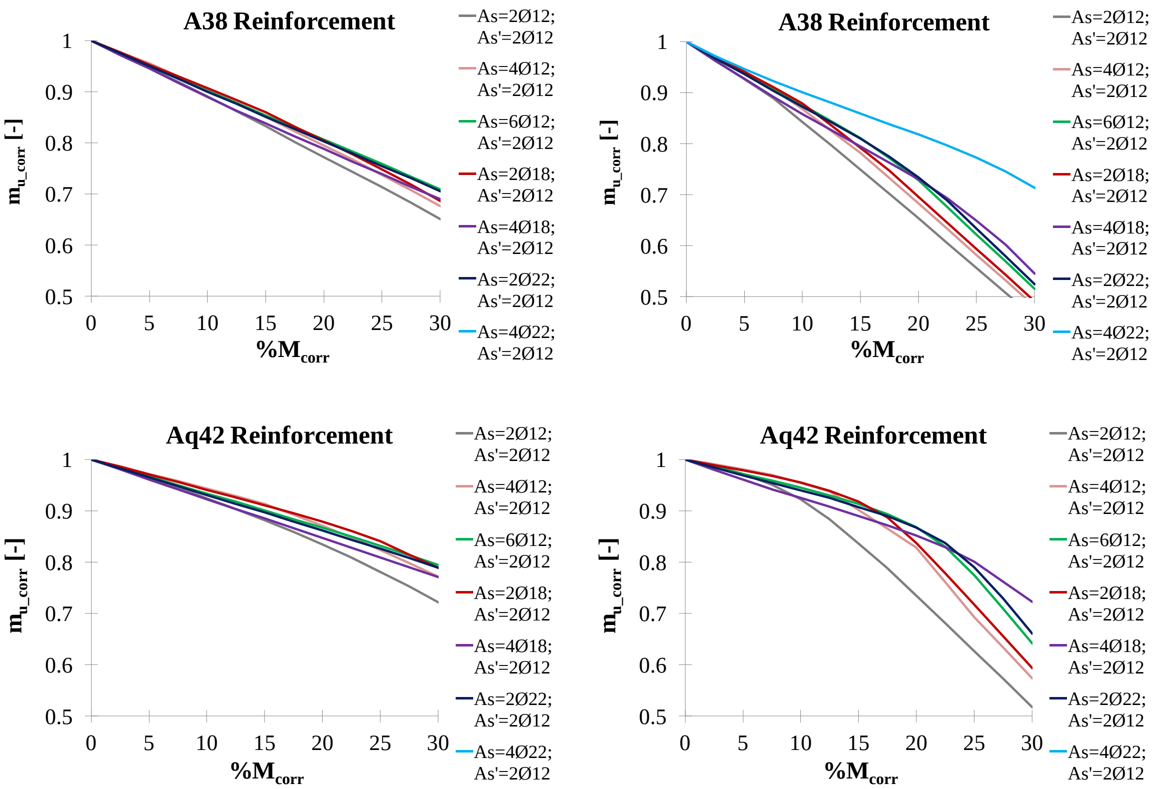

Figure 11. Non-dimensional ultimate bending moment for existing formed beams: on the left the case of the uniform corrosion, on the right the pitting corrosion.

The abaci previously reported are defined considering beams whom dimensions and reinforcement comply with the principles of current codes; the geometrical reinforcement percentage, in fact, is between 0.18% and 0.80% for the formed beams and between 1.75% and 2.35% for the flat beams.

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Code limitations, of course, may not be satisfied by existing structures. For instance in Italy, during 70s, the usual employed concrete had by a mean (cubic) compressive strength of 20 MPa, while the reinforcements were belonged to the steels so-called A38 (σ_y = 380 MPa; σ_u = 460 MPa; ε_u = 14%) or AQ42 (σ_y = 230 MPa; σ_u = 420 MPa; ε_u = 20%). A (30x50) cm^2 cross-section with a concrete cover of thickness equal to 2 cm, typically characterized the formed beams. Moreover, the beams were designed to sustain only the gravitational loads and according to simplified formulations belonging with band criteria. Specifically, in compression only two 12 mm diameter rebars were applied, with the merely function to support the stirrups, while in tension from 2 to 6 bars with a diameter in the range from 12 mm to 22 mm were provided, depending on the effective load level. Some examples of abaci obtained for this typical condition are reported in fig. 11. The obtained results show once again the dangerousness of the pitting corrosion and the quasi-parabolic shape of the decay laws those are strictly related to the initial reinforcement mechanical properties.

4. Conclusion

Corrosion degradation can occur on reinforced concrete structures, causing loss of load-bearing capacity both in the service and in ultimate limit state. To estimate the residual life of a reinforced concrete structure subjected to corrosion a reliable procedure not yet exist, even if it is now well known, that first aspects to consider are related to the reinforcement degradation, the decay in the bond interaction between the concrete and the steel, the concrete cracking and the cover spalling.

In order to predict the mechanical behavior of a corroded RC beam, an experimental case is selected and analyzed by mean nonlinear finite element method. The obtained results indicates good agreement with experimental observation at ultimate and serviceability limit state, proving the accuracy and applicability of the adopted decay laws (eqs. 1-4). Moreover, the application of decay laws for the steel to the classical models of the structural engineering, allows the definition of abaci to estimate the residual flexural strength of corroded element (figs. 6-11), those once again highlight the dangerousness of the corrosion degradation.

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Conflicts of Interest: The authors declare no conflict of interest.

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