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Machine learning Optimization strategy for the inelastic buckling modelling of un-corroded and corroded reinforcing plain bars

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ABSTRACT: Many concrete structures and infrastructure reinforced with plain steel reinforcement were designed in the 1960s and 1970s. Such structures are deteriorating due to corrosion, which has exposed reinforced concrete (RC) components to the spalling of the concrete cover and the subsequent inelastic buckling of steel longitudinal rebars. This paper presents an optimization strategy based on genetic algorithms to simulate the cyclic response of steel plain bars. A refined finite element model of the steel bar is adopted for the numerical analysis. Thus, the genetic algorithm optimizes the main parameters of the most adopted constitutive model for steel rebars. The optimization procedure compares the available experimental tests with the numerical results by reducing a pre-defined objective function. Regression analyses are then performed for each calibrated model parameter. Therefore, taking advantage of the comprehensive numerical procedure, a parametric analysis is conducted to include the effects of corrosion on the inelastic buckling of plain rebars. The parametric study aims to develop accurate and adequate constitutive models for steel reinforcing bars in robust seismic analyses for RC structures. A case study of a typical old RC column with longitudinal plain bars under cyclic loading is presented.

1 INTRODUCTION

Corrosion is one of the most detrimental causes of the damage, durability, and premature degradation of reinforced concrete (RC) structures. To date, there is an extensive portfolio of existing concrete structures and infrastructure reinforced with an old type of steel reinforcement named ″plain‶ or ″smooth‶ rebars [Arani et al., (2014); De Risi et al., (2017)]. Such steel reinforcement bars are obsolete and no longer available by international technical standards. Mostly adopted between the 1960s and the early 1980s, plain steel bars suffer from extreme conditions due to harsh and highly corrosive environments, i.e., chlorides [Di Sarno and Pugliese (2020)].

Plain concrete has low tensile strength and is vulnerable to cracking under minor loading conditions. Outer and inner cracking allows substances (i.e., chlorides) to penetrate the concrete and activate physical and chemical processes. Such substances de-passivate the layer of film protecting the steel rebars, thus, affecting its mechanical and geometrical properties, i.e., decrease of the yield and the ultimate stresses, decrease of the ultimate strain (ductility), and reduction of the steel diameter. The concrete cover spalling is an imminent consequence of the cracking expansion in RC components, which exposes the longitudinal rebars to inelastic buckling. Such a nonlinear instability affects the post-yielding compressive response of plain rebars.

Furthermore, the corrosion effects reduce the onset of the buckling and the softening branch and, thus, the mode shape of the buckling itself. There is currently an extensive and comprehensive state-of-art for the buckling effects on the compressive response of ribbed reinforcing bars, with and without corrosion [Bae et al., (2005); Kashani et al. (2013); Akkaya et al., (2019)]. However, few studies were carried out for such nonlinear effects on sound plain rebars [Cosenza and Prota, (2006), Prota et al. (2009)], and there is no evidence, to the best of authors' knowledge, of inelastic buckling of corroded plain bars. Therefore, this study presents a nonlinear optimization strategy, through the evolutionary algorithm named genetic algorithm, to investigate and optimize the model parameters of the most adopted constitutive material for smooth steel bars, named Menegotto-Pinto model [Menegotto and Pinto, (1973)]. This latter constitutive model is mainly used to simulate the monotonic and cyclic response of ribbed rebars, and it can be overused for plain bars. As a result, an accurate analysis is carried out to investigate whether or not the default model parameters are suitable for reproducing the response of smooth rebars. An advanced nonlinear Finite Element (FE) model is adopted for simulating the inelastic buckling. Then, the genetic algorithm is performed to match the numerical model results with the available experimental tests. Relationships of the most critical parameters from the numerical analysis are presented as a function of the stirrups spacing-to-diameter of longitudinal bars (hereafter named slenderness ratio and denoted by L/D) using the regression analysis method. Hence, taking advantage of the comprehensive numerical study, corrosion is applied to reproduce its effects on the inelastic buckling of smooth rebars as a sort of virtual laboratory testing. The results of such parametric study are utilized in an advanced software platform for robust seismic analyses. A case study of a typical RC column, designed according to obsolete technical codes, with un-corroded and corroded plain reinforcing bars is presented, and the results are discussed.

2 FINITE ELEMENT MODEL FOR THE INELASTIC BUCKLING

The force-based element with distributed plasticity is utilized to simulate the nonlinear behavior of the steel bar. Such an element is characterized by various integration points that include the cross-section fibers of the reinforcing rebar. The constitutive material named STEEL02 (refers to Menegotto and Pinto model) in OpenSees [MKenna et al. (2000)] is employed in each cross-section fibers.

Since the linear transformation is inadequate to solve large inelastic displacement-small strain problems, the so-called co-rotational formulation is used for large displacements while remaining small deformations along the element [Souza, (2000)].

A symmetric buckling shape is assumed for the transversal deformation of longitudinal rebars, whereas the maximum inflection in the middle is used for the displacement recordings. A geometrical imperfection was applied in the middle of the steel bar to ensure the inelastic buckling occurred in the nonlinear finite element model (Figure 1).

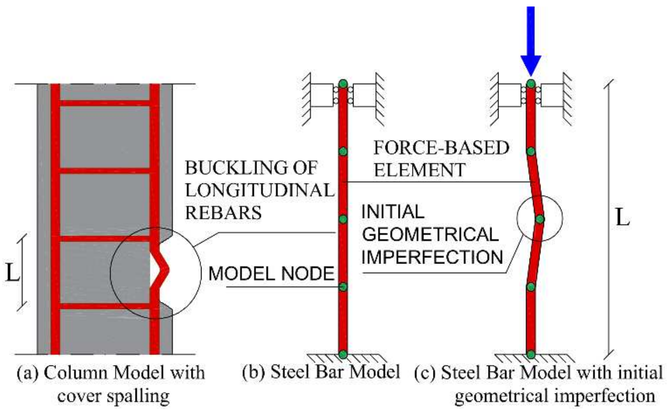


Figure 1. Finite Element Model of the inelastic buckling

Such an imperfection was equal to L/1000 according to ASTM A6/A6M (2019). As to the boundary conditions, one end is fixed, and the other end is free to move along the longitudinal axis of the steel bar. Moreover, the steel bar is modeled using six force-based elements to maintain a realistic aspect ratio of the steel bar during buckling.

3 OPTIMIZATION PROCEDURE

3.1 *Genetic Algorithm*

Genetic Algorithm (hereafter referred to as GA) is used to calibrate some of the parameters of the Steel02 constitutive material. Such an optimization approach, typically grouped in the machine learning techniques, is based on minimizing a properly chosen objective function. Pre-defined intervals for the model parameters (lower and upper values) input the plausible random values to generate the Matlab code for the numerical model in OpenSees to run.

In this specific case, the model parameters for Steel02 are f_y, E_s, b, cR_0, cR_1, cR_2, a_1, a_2, a_3 and a_4. Such variables represent: f_y is the yielding stress, E_s is the elastic modulus, b is the hardening ratio, cR_0 - cR_1 - cR_2 are the three parameters defining the Menegotto-Pinto backbone curve, a_1 - a_2 - a_3 - a_4 are the isotropic parameters in tension and compression. The parameters to be calibrated are b, cR_1, cR_2, a_1 and a_3. Such parameters are adequately chosen for different reasons: b does affect the post-elastic response and could be significant when buckling occurs, cR_1 - cR_2 are the parameters governing the curved transition from the elastic to the plastic branch, a_1 and a_3 characterize the energy dissipated for each cycle in tension and compression and depend upon a_2 and a_4 ($a_1/(a_3)^{0.8}$ and $a_2/(a_4)^{0.8}$), which are set to unity.

The experimental evidence and the results from the numerical model are then employed in the objective function to minimize. Such an objective function is computed as follows:

$$error = \frac{\sqrt{\sum_{j=1}^{m}\left(F_{exp,i} - F_{num,i}\right)^2}}{\sqrt{\sum_{j=1}^{m}\left(F_{exp,i}\right)^2}} \quad (1)$$

where m is the total number of recorded experimental points and, F_{exp} and F_{num} are the forces from the experimental and the numerical results, respectively. The GA stops when the specified criteria are met.

4 CYCLIC RESPONSE OF SMOOTH REBARS UNDER INELASTIC BUCKLING

4.1 *Steel02*

One of the most adopted constitutive materials for steel reinforcing bars is the model proposed by

Menegotto and Pinto (1973). Such a model represents the best trade-off between simplicity in the formulation and efficiency in the implementation. Furthermore, it is widely used as it does not often lead to convergence issues in complex and advanced three-dimensional FE models. Its normalized formulation is given by:

$$\sigma^* = b\varepsilon^* + \frac{(1-b)\varepsilon^*}{(1+|\varepsilon^*|^R)^{\frac{1}{R}}} \quad (2)$$

where σ^* is the normalized stress, ε^* is the normalized strain, R governs the smooth transition between two asymptotes (elastic and plastic asymptotes) and depends on cR_0, cR_1, and cR_2. Employing the default values in Stee02, the comparison between the numerical and experimental results are graphically depicted in Figure 2.

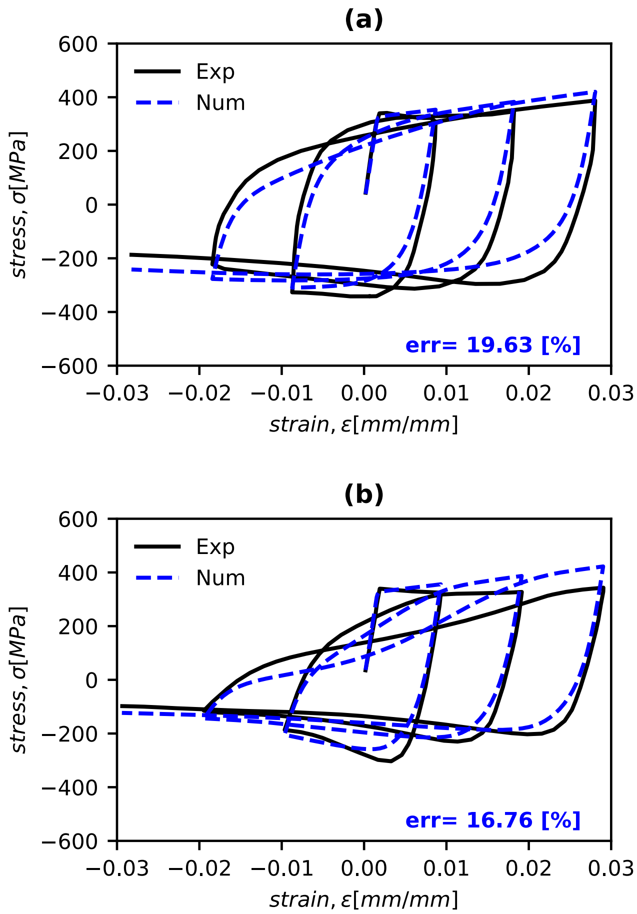


Figure 2. Effects of default parameters on the inelastic buckling using the FEM approach. (a) L/D = 10 and (b) L/D = 15

The matching between the numerical and the experimental outcomes illustrates that the FE model underestimates the dissipated energy for each half cycle when using the default parameters. Nevertheless, such an observation is more related to constitutive material parameters rather than the incapability of the numerical model to reproduce the complete hysteretic response. This latter suggests that parametric optimization is deemed necessary. The optimization procedure results through the GA are presented in Figure 3. It can be observed that the proposed approach (GA plus FE model) can adequately and accurately predict the cyclic response of smooth rebars with various slenderness ratios. The dissipated hysteretic energy for each half cycle, which is a crucial component during earthquake events, is reasonably predicted.

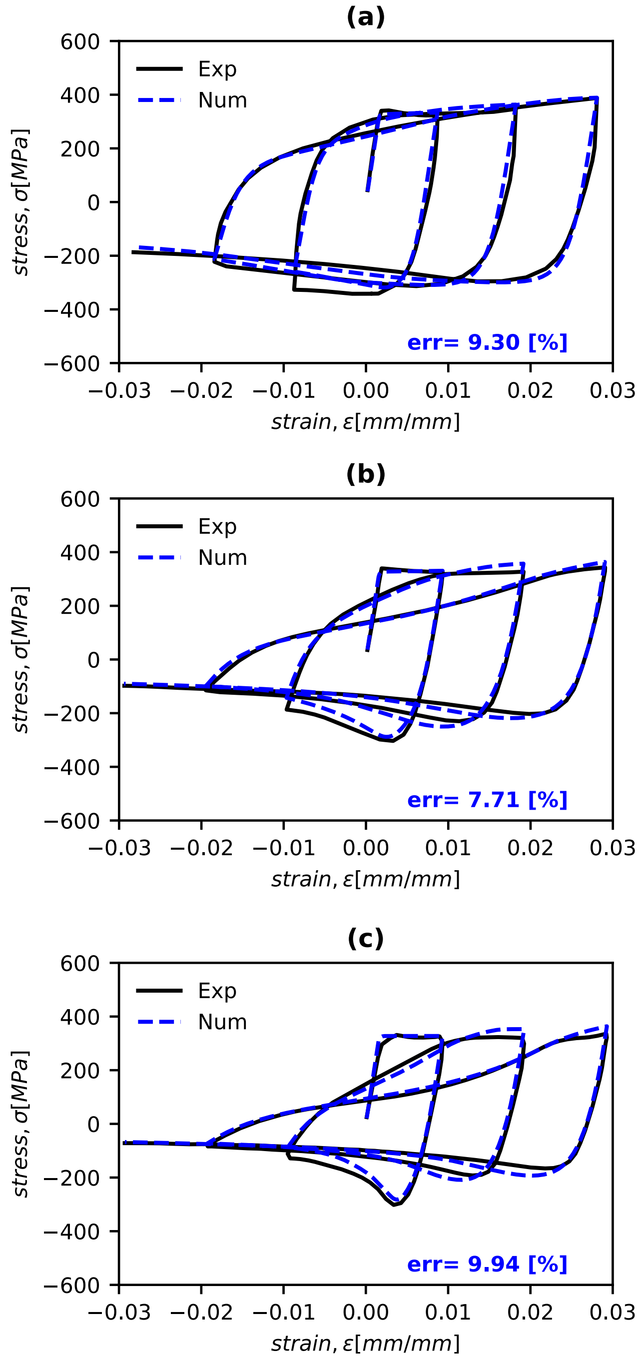


Figure 3.Results from the GA and the FE model. (a) L/D = 10, (b) L/D = 15 and (c) L/D = 20

The total error between the experimental and the numerical results is reduced by almost half compared with the one obtained by using the default parameters. Specifically, for L/D equal to 10, the error is now 9.30% compared with 19.63% and reduced at 7.71% and 9.94% (originally 16.76% and 19.77%) for L/D equal to 15 and 20, respectively. Besides, the shape of the curves produced by the FE model follows the ones obtained from the experimental tests. Such numerical results are significant for obtaining more reliable constitutive materials for robust and accurate seismic risk analyses when dealing with existing RC structures with smooth reinforcing bars.

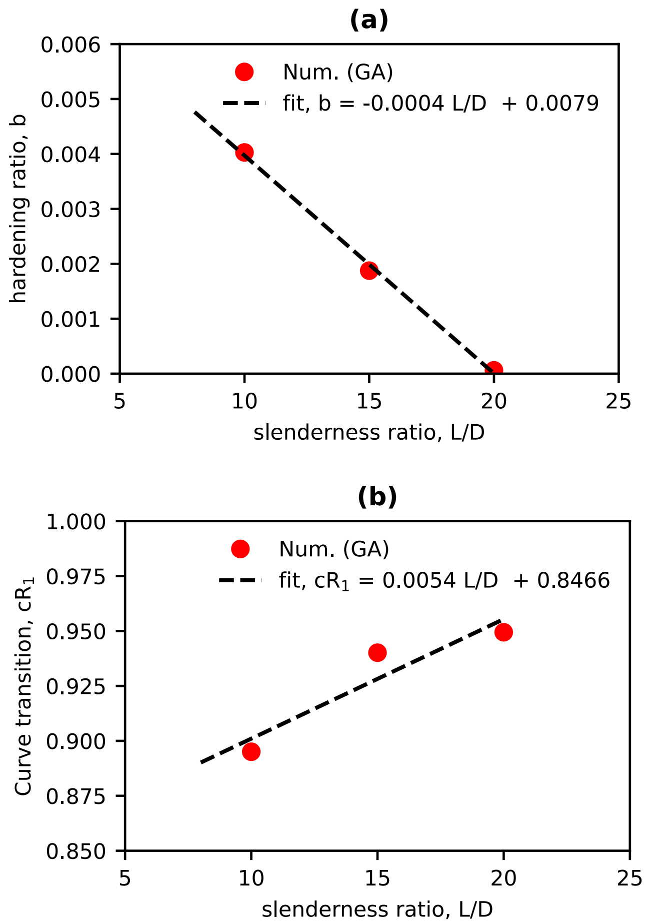
5 REGRESSION ANALYSIS

The results of the GA are illustrated in Table 1.

Table 1. Numerical results of the GA for the calibrated parameters

	Optimized Parameters				
L/D	*b*	cR_1	cR_2	a_1	a_3
10	0.00403	0.89505	0.43545	0.01502	0.01922
15	0.00187	0.94012	0.28502	0.02868	0.02656
20	0.00006	0.94943	0.31705	0.06421	0.03967

Table 1 shows that the hardening ratio values (b) decrease with the slenderness ratio (L/D) increase. Conversely, the curve transition parameter (cR_1) and the isotropic parameters (a_1 and a_3) increase with the increased effects of the inelastic buckling. Instead, a slightly different trend can be observed for cR2, with a decrease from L/D of 10 to 15, and an increase from 15 to 20. Regression analysis is then carried out to accurately describe the correlation between the calibrated parameters and the slenderness ratio. The results of the regression analysis are presented in Figure 4.



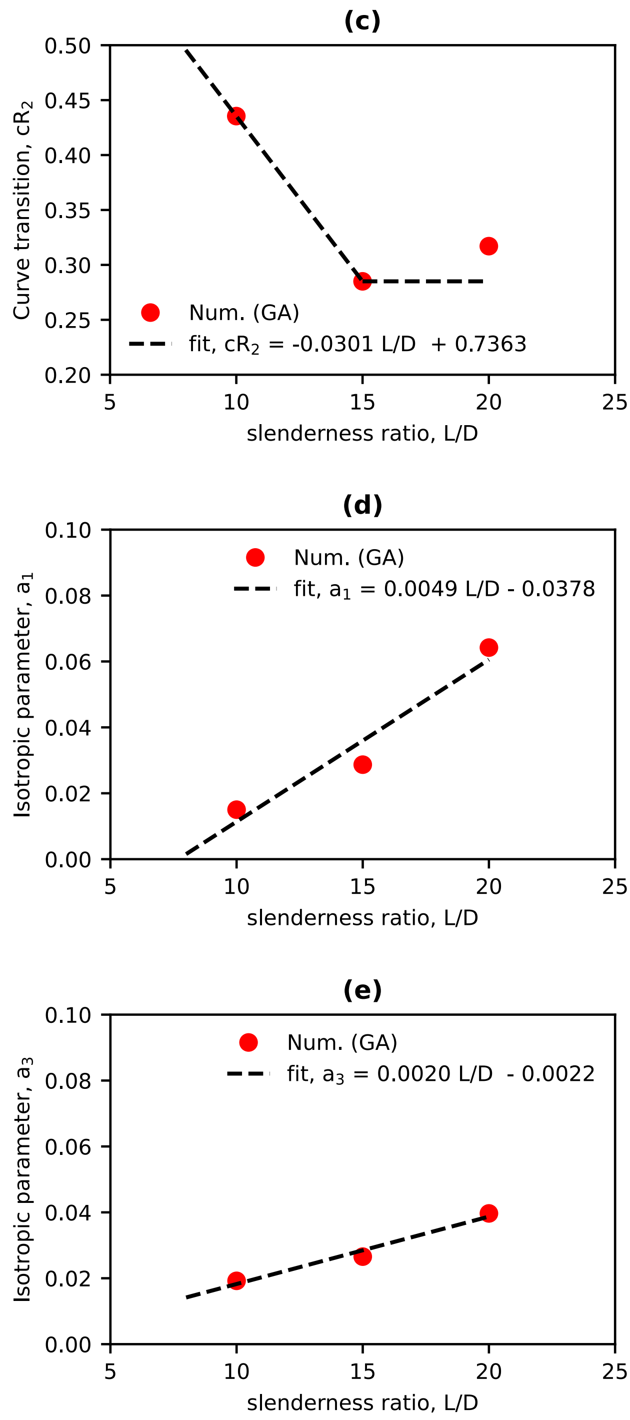


Figure 4. Relationships of the calibrated parameters as a function of the slenderness ratio. (a) Hardening ratio, (b) and (c) curve transition parameters, (d) and (e) isotropic parameters.

Primarily, linear interpolations represent the correlation between the optimized parameters and the slenderness ratio. Conversely, the curve transition parameter cR_2 varies with a linear trend until L/D is equal to 15 and then it is kept constant.

6 CASE STUDY

A case study of a typical RC column reinforced with plain rebars is herein investigated. The experimental test results of RC columns under cycling loading from Di Ludovico et al. (2014) are used. They performed monotonic and cyclic tests on eight full-scale concrete columns (square and rectangular) reinforced with plain bars and designed according to provisions and construction materials enforced from 1940 to 1970. The mean cylindrical compressive strength of the concrete was equal to 18.85 MPa, and the yield and ultimate tensile strength of steel rebars were 330 MPa and 445 MPa, respectively. The slenderness ratio (L/D) for the inelastic buckling model was 12.5. The FE model used for this case study is similar to the one presented in Pugliese and Di Sarno (2022). It consists of: (a) one displacement-based element with a length equal to the maximum of the cross-section geometrical dimensions that include the inelastic buckling calculated according to the FE above-presented and an elastic beam element for the remaining length, (b) a nonlinear zero-length spring to simulate the strain penetration between the column and the foundation, (c) a zero-length spring to account for shear failure eventually.

Taking advantage of the FE model of the steel bar and the comprehensive regression analysis for the optimized model parameters, the buckling response with the slenderness ratio equal to 12.5 is simulated, including the effects of corrosion (corrosion rate, CR, equal to 0%, 10%, and 20%). The results are presented in Figure 5.

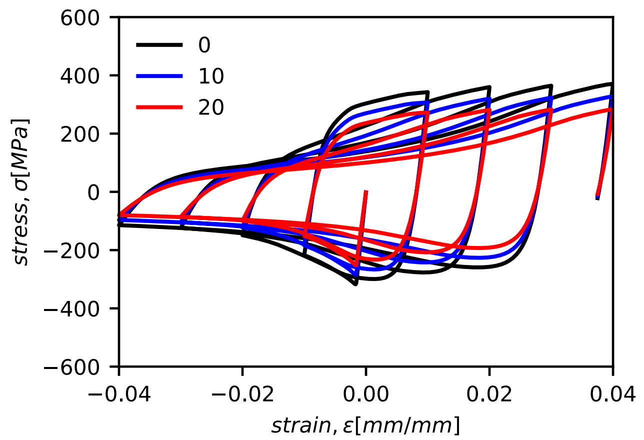


Figure 5. Parametric study of the inelastic buckling considering the corrosion effects

It can be observed that corrosion affects the nonlinear behavior of the smooth rebars reducing the yielding and the ultimate stress, the onset of buckling, and increasing the pinching effects during the reloading from compression to tension. A hysteretic material available in OpenSees is used to simulate the inelastic buckling according to the numerical simulation presented in Figure 5. Such material consists of some parameters representing the mechanical properties of the steel bar plus two parameters for the pinching along the two axes, x and y. Therefore, the GA is used in the FE model of the un-corroded RC column with smooth rebars to calibrate those pinching parameters and the length for the displacement-based element to match the experimental results.

The outcomes of the GA are shown in Figure 6.

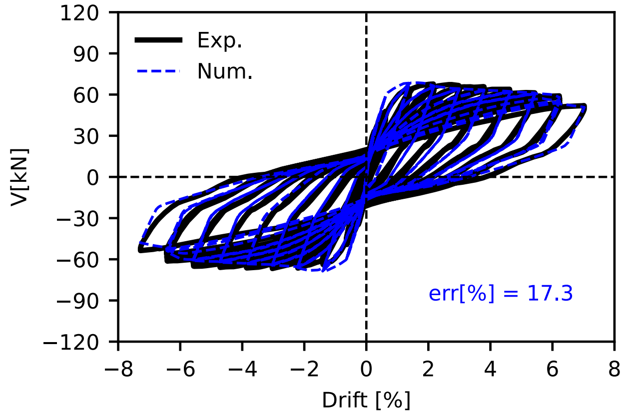


Figure 6. Experimental vs numerical results for the RC column with smooth rebars

The FE model can reasonably capture the cyclic response of the experiment with an error of 17.3%. In some cases, the values recorded during the experimental campaign presented the same displacements while changing for the stresses. The FE model cannot capture such an aspect, thus, increasing the error. The optimized values for the pinching of the hysteretic material are 0.5 and 0.8 along the x-axis and the y-axis, respectively; instead, the height of the displacement-based element, including the inelastic buckling, is equal to 450mm.

Applying the corrosion effects according to Pugliese et al. (2022) and using the calibrated parameters for pinching and the displacement-based element, the cyclic responses of the RC columns with aged smooth rebars are graphically illustrated in Figure 7.

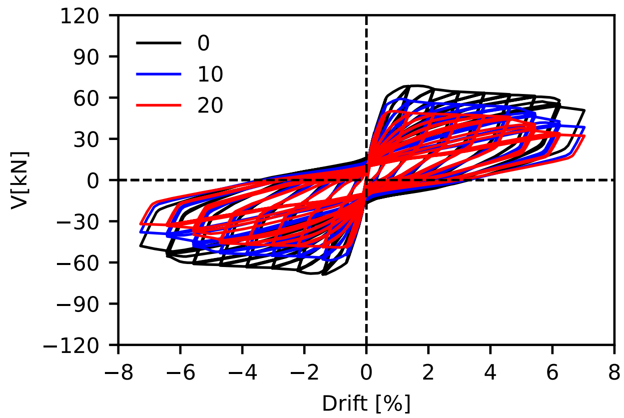


Figure 7. Cyclic response of the RC column with un-corroded and corroded smooth rebars

The numerical results in Figure 7 show a substantial reduction of the maximum lateral strength of the RC column in both directions, negative and positive. Specifically, the un-corroded RC column presents a positive and negative peak equal to 68.6kN and -68.7kN, compared with 59.1kN and -58.5kN for CR equal to 10%, and 50.1kN and -49.1kN for CR equal to 20%. Besides, the energy dissipated for each cycle appears to reduce because of the corrosion effects.

7 CONCLUSIONS

This study addresses the inelastic buckling response of smooth longitudinal rebars under cyclic loading using an optimization procedure based on a genetic algorithm and its application for a case study of an RC column with smooth rebars considering the effects of corrosion. The following conclusion can be drawn:

- The results of the FE model combined with the GA adequately minimize the objective function while matching the experimental tests. The errors calculated using the optimized parameters reduce substantially compared with the default parameters (e.g., from 19.6% to 9.3 for LD equal to 10, from 16.8% to 7.7% for LD equal to 15, and from 19.8% to 9.9% for LD equal to 20);
- The effects of corrosion are significant for the inelastic buckling of smooth rebars. Remarkably, there is a reduction in the onset of buckling and an increase in pinching effects when reloading from compression to tension;
- The application of the GA for the RC columns shows that the optimization procedure can allow for better predictions of the seismic response of RC components. The results in Figure 6 show an excellent match between the numerical and experimental results with an error of 17%;
- The effects of corrosion on RC columns can be detrimental over the lifetime of structural components. It can dramatically decrease the total lateral strength (e.g., from 68.6 to 50.1, for CR equal to 0% and 20%, respectively) and the energy dissipated for each cycle.

Future works should focus on the inelastic response of corroded smooth rebars as there is a lack of experimental tests on such a topic. Furthermore, more experimental campaigns should be considered for the effects of corrosion of nonconforming RC columns with corroded smooth rebars under cyclic loadings.

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