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Nonlinear numerical analysis of a concrete frame under corrosion due to carbonatation

Chiara P. Teodoro[1], Adrielle N. Marques[1], Rogério Carrazedo[1]

[1]*Dept. of Structural Engineering, São Carlos School of Engineering, University of São Paulo*
Av. Trabalhador São Carlense, 400, 13566-590, São Carlos, SP, Brazil
chiarapteodoro@usp.br, adriellenascimento@usp.br, rogcarrazedo@sc.usp.br

Abstract. Reinforced concrete structures are used worldwide due to their durability, resistance and flexibility to conform to different geometries. However, exposure to weather causes degradation, and pathological manifestations may appear. One of the most common is corrosion, their be generated by chloride ingress and carbonation. In the initiation stage, the corrosion agents cause depassivation of the rebar. Afterwards, the propagation stage begins, where the structures suffer loss of rebar area, cracks, strength loss and, in the end, collapse. In this paper, the displacements evaluation of a structure under carbonation was accomplished by implementing the loss of rebar area. Through the coupling of the reduction of the stiffness of the structure in the propagation stage with the Finite Element Method based on Positions code dedicated to the analysis of laminated frames, developed in FORTRAN programming language, that naturally considers geometric nonlinearities, allowing high displacements and rotations, and using Saint-Venant-Kirchhoff's constitutive law. FEM based on Positions uses total Lagrangian formulation and its degrees of freedom for frame elements are given by nodal positions and generalized vectors which may express the variation of section heigh and rotations. The physical nonlinearity of concrete was considered by implementing Mazars damage model. The results have shown that the numerical model is efficient to simulate the degradation of structures under uniform corrosion.

Keywords: FEM, reinforced concrete, corrosion, Mazars damage model.

1 Introduction

Reinforced concrete structures are used worldwide and one of the main reasons for their degradation is corrosion (Apostolopoulos and Papadakis, [1]; Rodrigues et al. [2]). This issue affects not only the structure, but the world economy, considering that every year it is spending 2.5 trillion dollars worldwide accordingly to World Corrosion Organization[1], and, also, the population due to the possibility of the collapse of the structure caused by the severe problems produced by the products of corrosion.

Corrosion can be described as a type of deterioration from a chemical or electrochemical reaction. In reinforced concrete, the rebar is protected by the high level of alkalinity of the surrounding and from the physical barrier of the concrete. But the entrance of aggressive agents such as chloride or concrete carbonation causes depassivation, i.e., the material loses the passive layer, established as the thin boundary made by oxides and hydroxides that acted as a protection (Coelho [3]).

Carbonation of the concrete causes uniform corrosion in the rebar by the reaction of the components of concrete with the carbon dioxide present in the environment. This degradation occurs in two phases accordingly to Tutti[4]. Firstly, in the initiation phase, the reinforced concrete suffers depassivation. After, in propagation stage appears both simple pathological manifestation as stains and more problematic ones like loss of stiffness, reduction of the area of the rebar, change in the bond of steel- concrete interface, cracks and lastly the collapse of the structure (Rodrigues et al. [2]).

Nowadays the study of structures became more related to geometric nonlinearity because of the current need

[1] Available in: < https://corrosion.org/>. Accessed in september 10, 2021.

for the use of space, which motivates the construction of more flexible and slender structures. The corrosion increases this problem as the result of the loss of the stiffness caused by corrosion, that provokes higher deflection. This nonlinearity is related to the equilibrium in the deformed position of the structure and that is considered naturally by using the numerical formulation of positional-based Finit Element Method (FEM). In the positional method, the nodal positions are used as variables, differently from the conventional FEM that uses displacements. Positional-based FEM method is based on the principle of minimum potential energy and in this work, we will use the total Lagrangian formulation that fixes the reference as the initial position of the body (Coda and Greco [5]; Liberati [6]).

Towards the objective of this paper is to analyze the comportment of a reinforced concrete structure under corrosion, a numerical formulation was made in FORTRAN language using positional-based FEM and a laminated frame element to contemplate the heterogeneity of the transversal section. Mazars damage model was implemented to consider the physical nonlinearity of the concrete. The corrosion was coupled by decreasing the rebar area, caused by the corrosion products, reducing the stiffness of the structure and consequently the young modulus of the materials. The results obtained were compared with the literature for a maximum displacement of the structure in different degrees of corrosion.

2 Corrosion

According to Helene [7], it is possible to describe corrosion as the results of chemical or electrochemical destructive reactions caused by the relation between the material and the environment, that can be coupled or not with a mechanical or physical action of degradation. In reinforced concrete structures the high alkalinity of the concrete keeps the passive layer stabilized and under this condition the rebar corrosion is almost imperceptible. However, some mechanisms, such as the presence of chloride and concrete carbonation, can promote the destabilization of this layer and complete the initial phase of corrosion.

The corrosion by chloride occurs from the migration and accumulation of chloride ions ($Cl-$) and is localized, also can cause sudden collapse (Coelho [3]). The corrosion by carbonation can be described in the Eq. 1, when the calcium hydroxide ($\mathrm{Ca(OH)_2}$) present in the cement hydration reacts with carbon dioxide ($\mathrm{CO_2}$) from the environment and result in calcium carbonate ($\mathrm{CaCO_3}$). The $\mathrm{CaCO_3}$ decreases the alkalinity in the rebar surroundings and at a certain temperature can destabilize the passive layer and occurs the depassivation, as shown in Fig. 1. It is influenced mainly by the factors presented in Fig.2 , accordingly to Felix [8], Helene [7], Pellizzer [9] and Possan [10]. These components can increase the carbonation velocity and the diffusion of CO_2 in the reinforced concrete structure.

$$\mathrm{Ca(OH)_2} + \mathrm{CO_2} \rightarrow \mathrm{H_2O} + \mathrm{CaCO_3}\,. \quad (1)$$

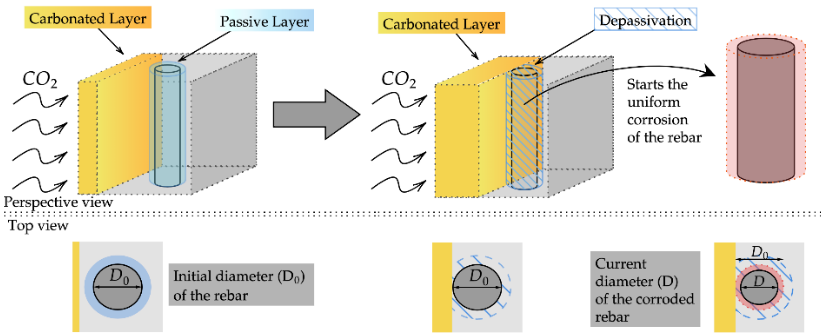


Figure 1. Basic mechanism of corrosion by carbonation

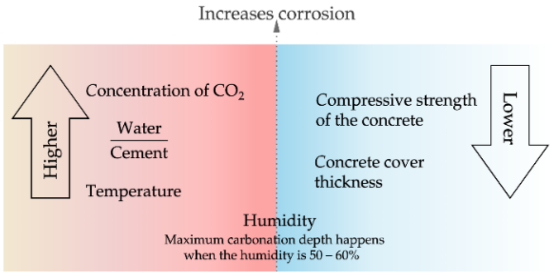


Figure 2 . Main factors that increase corrosion by carbonation

Hereafter these factors will contribute even more to carbonation: according to Stewart et al. [11], in Australia the risks generated by carbonation corrosion, due to the augment of the concentration of CO_2 in the atmosphere, will increase by 400% in 2100, and Bastidas-Arteaga et al. [12] concluded that from the influence of global warming the time of failure of a structure will reduce in 31% or the useful life of the structure will decrease in 15 years for moderate levels of corrosion.

Tutti [4] defined two phases for corrosion. The first one, the initiation phase, happens from the conclusion of the building to when the aggressive agent reaches the rebar. For carbonation corrosion, in this phase occurs: the penetration of CO_2, concrete decalcification, a decrease of the pH in the pores near the rebar and finally the depassivation. After starts the propagation stage with the depassivation and goes thru all the lifetime of the structure. In this process happens the deleterious effects in the concrete and steel thus the formation of expansive corrosion products originated by the chemical reaction which creates tensile stress in the concrete higher than the material can support that triggers the formation of cracks, reduces the rebar area, stains in the surface, change in the adherence between concrete and steel, reduction of yield stress. All these damages make the structure lose stiffness and can deform until collapses (Coelho [3], Rodrigues et al. [2] and Helene [7])

The propagation stage causes more damage to the structures and many studies were made to understand their effects. Some of them relates to how the corrosion affects the proprieties of the reinforced concrete or how these changes in the proprieties cause a reduction in the lifetime of the structure or loss of stiffness. The Fig. 3 summarizes these studies in literature through time in three types of models: reduction of rebar area, given damage on the concrete (cracks, reduction of compressive strength, applied damage model, etc.) and change in the bond at steel-concrete interface.

Model / Author	Reduction of rebar area	Given damage on concrete	Change in the bond at steel-concrete interface
Cabrera [13]	■	■	■
Ohtsu and Yosimura [14]		■	
Enright and Frangopol [15]	■		
Val, Stewart and Melchers [16]	■		■
Graeff [17]	■		■
Marsh and Frangopol [18]	■		
Peng and Stewart [19]	■		
Al-Harthy, Stewart and Mullard [20]		■	
Liberati, Leonel and Nogueira [21]	■		
Biondini and Vergani [22]	■	■	
Coelho [3]	■	■	
Felix *et. al.* [23]	■		
Sun et al. [24]		■	
Ramos and Carrazedo [25]	■	■	

Figure 3. Studies of different models to degrade the structure in carbonation corrosion

Biondini and Vergani [22] related that in experimental studies the main corrosion impact is the reduction of the cross-section area of the reinforcing steel bars and the Fig. 3 reinforces that importance by presenting the number of important studies made in this area associating corrosion and loss of rebar area. Due to its importance, the model applied to comprehend the behavior of the structure under corrosion in this study is the reduction of the rebar area. And that can be made experimentally or numerically, but according to Otieno [26] the numerical model gives the advantages of spending less money and time and the possibility of replicate different scenarios.

3 Positional-based FEM

Finite Element Method (FEM) is based on the division of the continuum integration domain into a pre-stablished and limited finite element (subdomains). It is a way to solve differential equation related to physical problems that contain complex geometry.

There are many approaches based on FEM to solve physical nonlinearity. One of them is Positional-based FEM with total Lagrangian reference that is based in mapping initial and current configuration. The nodal positions are determinate by the minimum potential energy principle (Eq. (2)). From the imposition of nullity of the first variation of the total energy functional, nonlinear equations appears, that can be solved by the iterative process of Newton-Raphson. The positional method uses Green strain which is an objective measure that can be apply to high displacements (Coda and Greco [5], Coda and Paccola [27]).

$$\begin{gathered} \Pi = \mathbb{P} + \mathbb{U}, \\ \frac{\partial \mathbb{U}}{\partial y} + \frac{\partial \mathbb{P}}{\partial y} = 0. \end{gathered} \tag{2}$$

This method for laminated frame elements is based in Coda and Greco [5], Coda and Paccola [27,28], Coda, Paccola and Carrazedo [29] and Bernardo [30].

The total function of change of the configuration of the element ($\vec{f}$) for each lamina is given by the Fig. 4, where the nodal positions and the generalized vectors ($\vec{V}$ and $\vec{G}$) are the variables of the problem. The generalized vectors represent the height and rotation of the node. The initial ($\vec{x}$) and actual ($\vec{y}$) nodal positions were represented by approximated curves by cubic approximation.

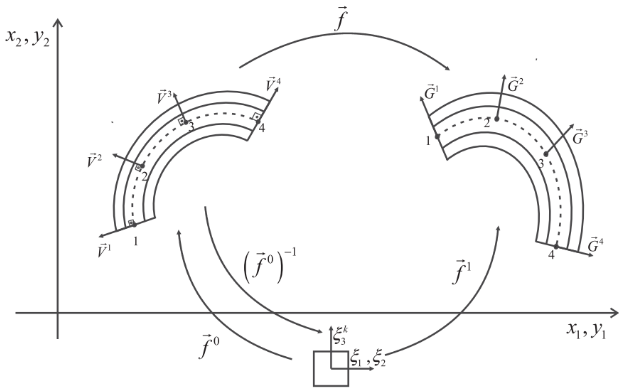


Figure 4. Finite element mapping. Reproduced from Coda, Paccola and Carrazedo [29].

Under many solutions for laminated elements available in the literature, this study uses the presence of Zig-Zag effect. The section using the zig-zag cinematic enrichment is made by line segments defined as layers that have continuity of the displacements in the interlaminar interfaces and, also, the permission to have discontinuity of the derivate of the transversal direction in those same points. The zig-zag effect includes the intensity of the Zig-Zag warping in the cross section as the five degrees of freedom in the problem. The first two degrees are the nodal positions, and the others are the height and rotation from the generalized vectors.

The uniform corrosion was coupled in the finite element program by reducing the young modulus of the materials and consequently the stiffness of the structure accordingly to the reduction of the area of the steel lamina caused by the products of corrosion. Along with the reduction of the young modulus was implemented the Mazars model of damage to change the internal forces developed in the concrete and finally analyze the true comportment of the concrete by considering the physical non-linearity.

4 Numerical Example

A numerical example was made to analyze the consistency of the methodology applied when compared to results in the literature for the augmentation of the displacement in a reinforced concrete structure suffering from uniform corrosion of the rebar.

Graeff [17] studied the structure from Fig. 5 in different percentages of corrosion and had the results of displacement in the mid-span for each stage of corrosion. The concrete used has elastic modulus of 25.93 GPa and compressive strength of 25 MPa and the steel has elastic modulus of 210 GPa. Graeff [17] made a numerical model in a finite element software based on the experimental model he did in the same configuration.

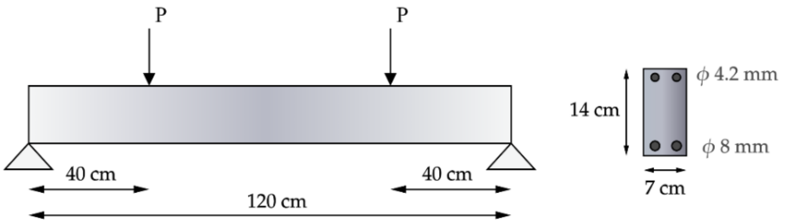
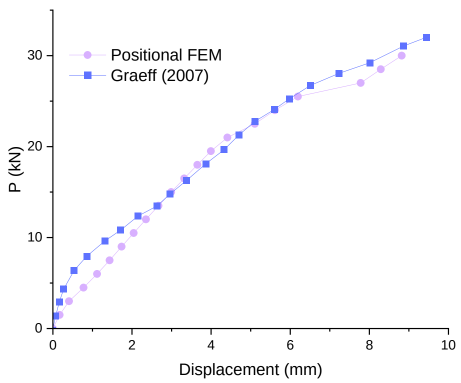


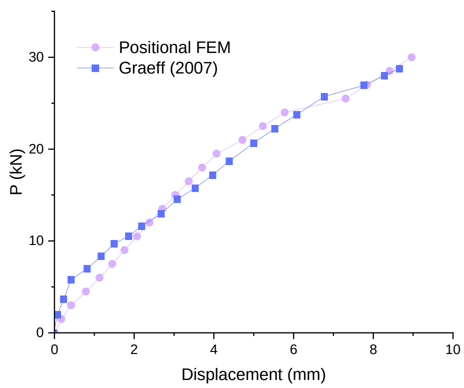
Figure 5. Scheme of the numerical example

In the numerical model of Graeff [17] was implemented changes in the properties of the concrete and steel for each corrosion degree. In 2% and 5 % of corrosion the rebar suffered, respectively, 3.71% and 7.41% of rebar area reduction. In 10% of corrosion the rebar area reduced 13.73% and decreased the adherence resistance in 11%. Finally, in 20% of corrosion, the rebar area, the adherence resistance, and the tensile strength diminished, respectively, 25.71%, 43% and 45 %.

In the positional based FEM program developed in FORTRAN language was applied the reduces of rebar area accordingly to Graeff [17] for each corrosion degree and, consequently, the decrease of stiffness and reduction of the young modulus of the steel and concrete. The value of the parameters A_c, B_c, A_t and B_t used for Mazars damage model were 1, 1000, 0.8 and 10000. The comparison of the results for displacement in the mid-span of the structure for 0% and 10% of corrosion are presented in Fig. 6.



a)



b)

Figure 6. Displacement at mid-span for a) 0% of corrosion and b) 10% of corrosion

As presented in Fig. 6 the results were compatible with the literature and the program made in FORTRAN using positional based FEM with laminated frame elements can be used to describe the reduction of rebar area caused by uniform corrosion. Even if he implemented the decreased of adherence resistance in 11% for 10% of corrosion, the model made only by reducing of the rebar area on FORTRAN could well represent the comportment of the structure. Proving the high importance of this effect on reinforced concrete structures under corrosion.

The Fig. 7 shows an expected outcome to proof a good functioning of the FORTRAN program. Such as the displacement augment as the corrosion increases, because causes loss of stiffness, and that is amplified when the structure is subjected to higher external forces that can be explained by the nonlinearity of the problem.

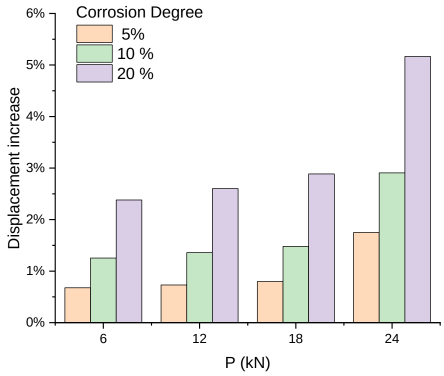


Figure 7. Displacement increase for each corrosion degree

The Fig. 6 and Fig. 7 represented the behavior of reinforced concrete beam under different corrosion stages and shown that this degradation causes problems for the structure even for low stages of corrosion, as an example, of increasing more than 5% of the displacement for corrosion of 20% of corrosion considering only the loss of the rebar.

5 Conclusion

Comprehending the structures' behavior under corrosion can solve and predict future problems not only for the reinforced concrete construction itself but also economically and socially. From this perspective this study proposed a numerical model made in Fortran language using positional-based FEM to solve the deformed shape of the structure during the effects of corrosion of loss of stiffness.

The program using just the reduction of the rebar area gave good results when compared to a numerical model in the literature built in a finite element software based in experimental results. Proving that corrosion augment the displacement for higher corrosion degrees and the importance of effect of decrease of the cross-section of the rebar in the structure for uniform corrosion. Contemplating, also, the physical and geometrically nonlinearity of the problem.

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