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Effect of time dependent corrosion rate on residual capacity of corroded RC beam

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Abstract. Corrosion is the most commonly severe defect in reinforced concrete (RC) structures and it mainly causes reduced rebar cross-section. The corrosion rate is the determining parameter of the progress of corrosion-induced damage. The present work is focused on the application of finite element (FE) analysis, using DIANA, to predict the residual capacity of reinforced concrete beam with different degree of corrosion. To this aim, existing experimental data is used to develop a FE model of corroded beams and to investigate their behaviour. This model is validated to predict the impact of time and current rate of corrosion on the residual load carrying capacity of corroded RC beams.

1. Introduction

Corrosion of steel rebar embedded in reinforced concrete (RC) members is one of the major causes of deterioration of these structures [1-3]. Rebar corrosion is a chemical process, which has physical consequences such as decreased ultimate strength and serviceability of structures [1]. The infrastructures today are therefore facing a new challenge that governments, industry and research need to address. The early research in the field of reinforcement steel corrosion, focused on the causes and mechanisms through which steel transforms to rust [4]. However, in recent years, the research focus have moved towards more practical oriented topics. These topics include the assessment of risk, reliability and residual load carrying capacity of corroded concrete elements [2, 4-14].

Early investigations have shown that corrosion is a chemical process that stems from the attack to reinforced concrete by compounds present in the environment. Ingress of chloride ions into concrete affect rebars, causing depassivation of steel and beginning of the corrosion problems [15]. The loss of steel cross section is one of the main physical effects of corrosion [16]. Furthermore, concrete cracking due to stresses exerted by corrosion products as well as loss of bond between concrete and rebars are the other consequences of corrosion of the reinforcement [3, 4, 10, 17]. As a result, serviceability and ultimate strength of reinforced concrete elements may be reduced [2, 7, 10, 18, 19].

Collecting experimental data of corroded concrete elements is challenging, as it means having to analyse reinforcement from old structures [20], or undertake long laboratory experiments with induced corrosion [1, 5, 21]. Thus, much effort has been directed to modelling the corrosion and developing simulation tools that enable investigating residual capacity of corroded concrete elements [10, 22-24].

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Accelerated corrosion test is another way to assess corroded RC members. However, in the accelerated experimental test, corrosion rate is one of the most important input parameters, which could affect residual capacity of the RC structures [25].
In this paper, existing experimental data by Rodriguez et al. [21] is used to develop a finite element (FE) model of corroded beams and to investigate their mechanical behaviour. This model is validated and used to predict the impact of time and current rate of corrosion on the load carrying capacity of corroded beams.

2. Finite element simulation of corroded beams

2.1 Experimental setup
The beams for numerical simulations were selected from experimental tests by Rodriguez et al. [21]. Thirty-one beams were tested to investigate the effect of different variables such as details of reinforcement, and a range of corrosion percentages on the corroded beams. In the current study, three of the beams were selected for the numerical simulation. An un-corroded reference beam (no.1), slightly corroded beam (no.2) and severely corroded beam (no.3) were addressed to mainly account for the effect of reinforcement corrosion on RC beams loaded in a four-point bending. Geometry dimensions and rebar arrangement of the selected simply supported beams are shown in Figure 1. The tensile, compressive and stirrups rebars with diameter of 10mm, 8mm and 6mm are constructed in the tested beams, respectively.
The compressive strength of the reference beam is reduced to 34 MPa (from 50 MPa) by adding calcium chloride solvent (3 percent by weight of cement) to accelerate the corrosion process in the test data from [21]. The beams were cured for 28 days in wet conditions. By this way, an accelerated corrosion procedure was established to achieve the required level of corrosion. The reinforcement was subjected to a constant corrosion current rate of 1 μA/cm2. However, due to the presence of stirrups, the corrosion is not distributed uniformly along the bar [21]. In present study, the authors are intending to test the residual capacity of beam for different corrosion rates of 1, 2, 3 and 4 μA/cm2. For this purpose, the corroded beam no. 2 was studied in the deterioration interval time of 50 years. More details are presented in Section 3.

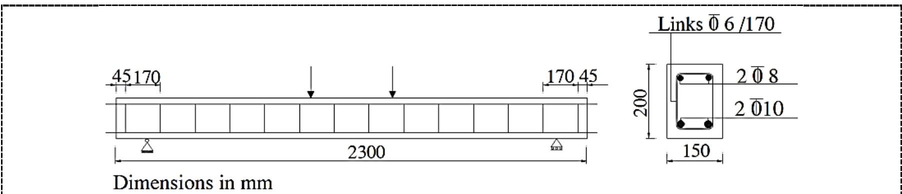

Figure 1. Geometry of beams investigated by Rodriguez et al. [21].

2.2 Finite Element Analyses
The FE method is a suitable numerical technique to investigate the global behaviour of the corroded reinforced concrete structures and the impact of corrosion on the bond strength between the corroded reinforcement and the surrounding concrete [16]. Many research studies were carried out by using different commercial FE programs or in-house developed codes to assess the corrosion impact on the concrete structure [3, 4, 7, 16, 26]. In this study, two-dimensional nonlinear FE analysis were carried out using DIANA. Due to the symmetry condition, only half part of the geometry is simulated. An axial displacement with a constant rate is imposed to the loading point of the beam. To solve the nonlinear problem, the Newton-Raphson (NR) approach was applied in the solver. It should be mentioned that the uniform corrosion assumption is taken into account in the current model in which the initial diameter of the reinforced bars is gradually reduced due to the uniform corrosion attack. The residual cross section area of the tensile reinforcement, which is induced by the uniform corrosion, is calculated by:

$$A_{res} = \frac{\pi.\varphi_R^2}{4} = \frac{\pi.(\varphi_0 - \alpha x)^2}{4} \quad (1)$$

where φ_0 is the initial (nominal) diameter, φ_R is the residual bar diameter, α is coefficient depending on the type of attack and *x* is corrosion penetration.

2.2.1. Material properties of concrete and steel. The concrete was modelled using four-node quadrilateral plane stress elements Q8MEM. In addition, a constitutive model based on nonlinear fracture mechanics using a smeared rotating crack model based on total strain was used to model the concrete. The constitutive model for concrete in tension is shown in Figure 2.

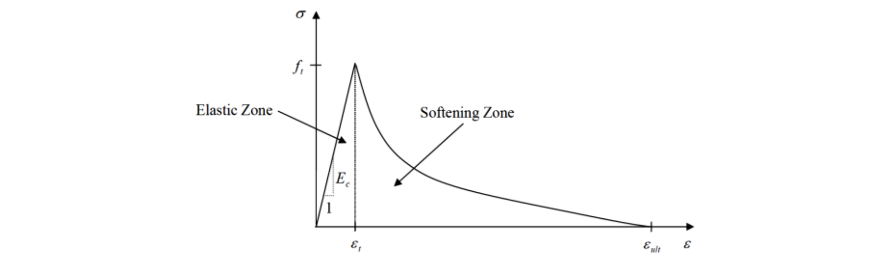

Figure 2. Stress-strain curves for concrete in tension.

The Summary of material properties used in numerical simulation of concrete beams are illustrated in Table 1. It should be noted that the compressive strength of the corroded beams were only about 70% of the strength of the reference [21].

Table 1. Material properties of concrete.

Concrete Properties	Symbol	Reference beam (no.1)	Corroded beams (no.2 & 3)
Compressive strength	f_{cc}	50 MPa	34 MPa
Tensile strength	f_{ct}	3.5 MPa	2.8 MPa
Young's modulus	E_c	32200 MPa	28000 MPa
Tensile fracture energy	G_F	0.12 N/m	0.09 N/m
Crack band width	h	10 mm	10 mm
Poisson's ratio	ϑ	0.2	0.2

The reinforcement was modelled by two-node straight truss elements L2TRU. The constitutive behaviour of the reinforcing steel was assumed to follow that of a standard elastic-ideally plastic with hardening. The yield strength f_{sy}, the ultimate strength f_{su} and the elastic modulus E_s for the steel reinforcement are given in Table 2.

Table 2. Steel strength for corroded and non-corroded models, data from [21].

Type of bar	Strength (MPa)	Ref. beam (no. 1)	Corroded beam (no. 2)	Corroded beam (no. 3)
Stirrups (ϕ6)	Yield, Ultimate	626, 760	506, 610	451, 550
Compressive (ϕ8)	Yield, Ultimate	615, 673	615, 673	615, 673
Tensile (ϕ10)	Yield, Ultimate	575, 655	569, 648	552, 626

While the uniform corrosion may considerably changes the mechanical properties of reinforcement [1], reduction of yield and ultimate strength of corroded rebar is calculated based on the following equations [1]:

$$f_y^D = (1 - \alpha_y(\frac{A_{cor}}{A_0})100)f_{y0} \quad (2)$$

$$f_u^D = (1 - \alpha_u(\frac{A_{cor}}{A_0})100)f_{u0} \quad (3)$$

where f^D and f_0 are the residual and initial strength respectively, A_{cor} is the pit area, A_0 is the cross-sectional area of the non-corroded rebar, α_y = 0.005, and α_u = 0.005 [1]. As a result of uniform corrosion, the rebar diameter is reduced. The sum of uniform corrosion area was subtracted from the original steel cross-section.

2.2.2. Bond slip model. The mechanical behaviour of reinforced concrete structures are mainly controlled by the bond strength and bond-slip between the concrete and reinforcing steel. This behaviour is drastically affected by corrosion in the studied structures. The relative displacements of the reinforcement bars should be measured to investigate the bond slip between the reinforcement steel and the concrete [20]. For this purpose, the CEB-FIP 2010 model code is slightly modified here to describe the impact of corrosion on bond between the reinforcement steel and the concrete. The bond slip behaviour was changed based on the amount of the uniform corrosion and kept constant along the tensile rebar [1]. Moreover, the bond strength is calculated using Equation 4 [27], which describes the effect of concrete and steel stirrup confinement on bond strength.

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

In which 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 f_{yt} are the stirrups cross-section and the stirrup yield strength respectively, S_S is the stirrup spacing, R is a factor which is function of the amount and rate of corrosion [27]. Bond slip behaviour of simulated beams with/without corrosion are indicated in Figure 3.

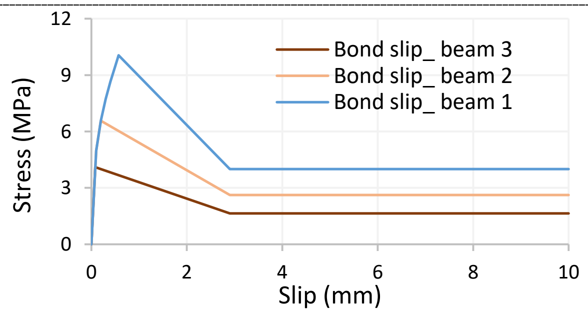

Figure 3. Bond slip behaviour of the reference beam (no.1) and the corroded beams (no.2 and 3).

3. Results and discussion

3.1 Comparison between FE results and the experimental data

The load-displacements at the mid-span of the three different simulated beams were compared with the three corresponding experimental results (see Figure 4). The results of numerical solution are in agreement with the test data. In the experimental investigation, the reference beam no.1 had a low ratio of tensile reinforcement and failed due to yielding of tensile reinforcement bars. The same failure type was observed in the FE simulation. In addition, a good correlation is obtained between the two curves in the yield loads as well as the ultimate loads. Similar to beam no.1, the simulation results for slightly corroded beam no.2 and severely corroded beam no.3 are in alignment with the experimental results. However, a higher difference between experimental and numerical results was observed in the severely corroded beam no.3 compared to slightly corroded beam no.2. Moreover, before the first crack, in all of the simulated beams, the initial stiffness is higher than the experimental results. This difference might be due to micro cracking in the experimental condition, which can result in lower initial stiffness compared to numerical analysis. Based on results from experimental and numerical investigations, notable reduction is clear on the load carrying capacity of corroded beam by increasing the level of corrosion. Since steel bar corrosion affects serviceability as well as ultimate capacity, both the Serviceability Limit State (SLS) and the Ultimate Limit State (ULS) should be taken into account. Serviceability limit state is defined based on deflection L/500 (L is length of the beam), according to ACI code.

In FE analyses, corrosion leads to reduction of SLS load up to 7% for beam no.2. This percentage for beam no.3 is 38%. As it can be seen in Figure 4, obtained SLS loads from the FE analyses of beams no. 1 and 2 are in good agreement with the experimental specimens results, while a deviation between FE and experimental results for severely corroded beam (no.3) for SLS load is seen (around 20%). Long corroding period for beam no.3 (compared to no.2) may have caused stiffness reduction and increased crack width, which could be the reason of this deviation.

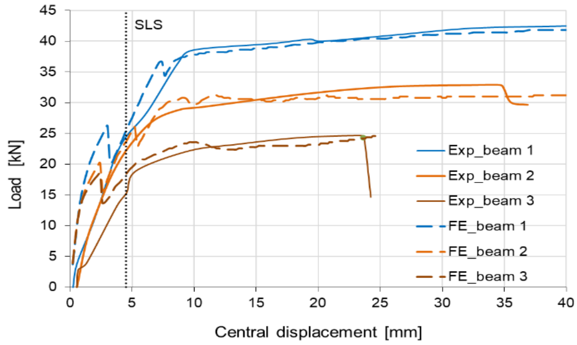

Figure 4. Load-displacement curve of the reference beam (no.1) and the corroded beams (no.2 and 3), after [28].

3.2 Current rate and time of corrosion

Notable reduction of the ultimate capacity is directly associated with the level of corrosion in the reinforced concrete structure. In fact, the level of corrosion is a time dependent quantity, which significantly increases by the evolution of time. Another key quantity, which induces severe deterioration in RC structures, is corrosion rate, which mainly corresponds to loss of rebar cross section area per unit of time. A model for the time dependent loss of steel cross-sectional area as a function of corrosion rate can be derived using the relation for mass loss of reinforcing steel based on Faraday's low, which is described in details by Baingo et al. [26].

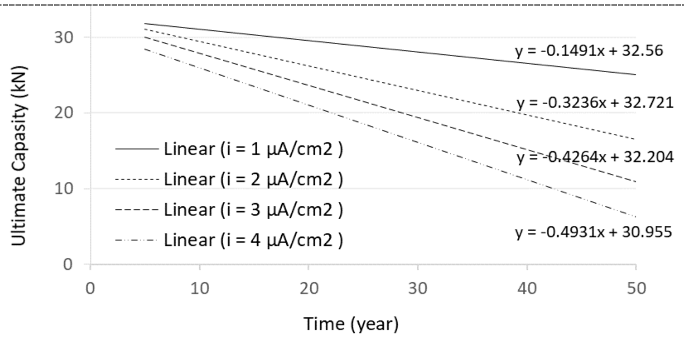

Figure 5. Trendlines of ultimate capacity vs time for the corroded RC beam with different current rates of corrosion: a) i =1 $\mu A/cm^2$, b) i =2 $\mu A/cm^2$, c) i =3 $\mu A/cm^2$ and d) i =4 $\mu A/cm^2$.

A corrosion rate can be expressed as a current density (current per unit surface area), a rate of weight loss or a rate of section loss, which induces the reduction of structural safety and reliability. In this study, the corrosion rate of 1 μA/cm^2 is implemented in the analyses and it is increased up to 4μA/cm^2. The beam with the moderate corrosion (beam no.2) is addressed for this investigation and the ultimate capacity is studied as a function of evolution time and current corrosion rate. The results of numerical studies represent the impact of moderate to high corrosion rate on the residual capacity of reinforced concrete structure during the service lifetime of 50 years. As illustrated in the Figure 5, by increasing the time of corrosion, ultimate capacity will decrease and the failure occurs at earlier stage of the corrosion. By increasing the current rate from 1 to 4 μA/cm^2, the 5-year-old corroded beams, show 4% capacity reduction. However, this reduction is about 65% for the 50-year-old corroded beams. The general behaviours of capacity reduction are derived by the linear equations presented in Figure 5. It is indicated that up to 80% of loading capacity is lost at higher current rates of corrosion (4 μA/cm^2), while at lower rate (1 μA/cm^2) residual capacity is decreased up to 20% compare to the no corrosion case.

4. Conclusions

The objective of the present work was to develop a nonlinear FE analysis to simulate the mechanical behaviour of reinforced concrete structures while affected by the time-dependent corrosion rate over the interval time of 50 years. This validated FE models are implemented to predict the impact of time and current rate of corrosion on the load carrying capacity of corroded beams. Results show that in the 5-year-old corroded beam, increasing current rates of corrosion has less effect on capacity reduction in comparison with the 50-year-old corroded beam. By increasing the time of corrosion form 5 to 50 years, ultimate capacity will decrease with a linear trend. For the beam with corrosion rate of 4μA/cm^2, loading capacity is reduced up to 80%, while at 1 μA/cm^2, residual capacity is decreased up to 20% compare to the no corrosion case.

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