MODELLING OF THE STRUCTURAL EFFECTS OF CORROSION DETERIORATION IN REINFORCED CONCRETE BEAMS

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Abstract

Since the steel corrosion is the most recurrent type of deterioration of reinforced concrete structures, it is necessary that its study evolves into solutions that can help by simulating this kind of problem as realistically as possible. This work was being developed based on this statement and in order to deepen the theme. Topics such as the most common causes of corrosion, the consequences on a reinforced concrete structure, the various types of approaches that can be taken during computational analysis, the ways of introducing corrosion as well as the bond slip models of heterogeneous structures (concrete-steel), are addressed in this work. In addition, some concepts and theories necessary for the development of the computer program in use as well as it's adaptation to the intended purpose are taken into account. Four scenarios of possible deterioration were tested: corrosion at the continuity support, at the middle sections of the span, at the end supports and, last, in all extension of the inferior reinforcement. Additional scenarios are taken into account, in which the absence or presence of confinement is considered through the addition of stirrups, approximating the behaviour of a slab in the former case.

Keywords: Corrosion; Cracking; Bond-slip; Embedded crack; Finite elements.

1 Introduction

Since corrosion is the most recurrent type of deterioration in reinforced concrete structures, it's study and simulation becomes one of the focal points for the development of better strengthening and rehabilitation solutions. In the same way, the possibility of modelling the structural behaviour makes it possible to comprehend the damage caused by deterioration and the critical failure areas.

In this way, will be studied the effects caused by corrosion and its expansive products on a regular size beam, used in common constructions, which will present deterioration on the steel-concrete connection interfaces and lead to cracking of the concrete beam. Besides, whit this study will be possible to prove the theories of bond-slip and embedded cracks, which will be used in the simulations ahead.

To provide a complete work, it will be explained the computational program used, the theories assumed to develop the simulation, the examples in study as well, and at the end, a careful analysis of the obtained results and conclusions.

2 State of Art

2.1 Corrosion

There are several mechanisms that can lead to the deterioration of a reinforced concrete structure being the most significant and most recurrent the corrosion of the reinforcement bars. This type of anomaly causes a significant loss of the resistant capacity of the structure caused not only by the loss of section, but also by the loss of bond between steel bars and concrete [1] thus causing a structural fragility that can be fatal for its safety.

There are several concepts that describe corrosion, however, it can be understood as the destructive interaction of a material, in this case reinforced concrete, with the environment as a result of harmful reactions of chemical or electrochemical nature. This process is spontaneous and originates from the need for the material to reach its lowest energy state [2].

Due to the contact with the environment, the concrete gradually loses its initial characteristics. There are two major factors that indicate the beginning of the corrosion process, the first is the pH value of the concrete, at the time of the decrease to values in the range of 10 to 11 [1][3] mainly by the action of atmospheric carbon dioxide [4] and the second results from the moment when the chloride content exceeds the critical value. When one of these two cases occur, the passive reinforcement protection film is destroyed, leaving this element in direct contact with the concrete [4].

The water in the concrete pores will originate OH- which will come into contact with the anode. This compound together with oxygen and iron (Fe), present in the steel, will produce corrosion products such as iron oxide (Fe2O3), commonly called rust, and electrons. These electrons will be consumed in the cathode. *Figure 1* presents an example scheme of this process.

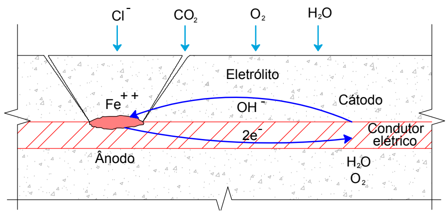
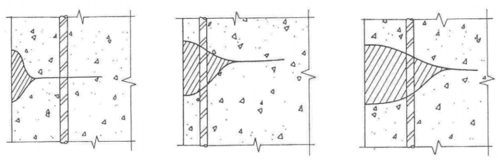


Figure 1.- Corrosion reactions on a reinforcement concrete element (adapted from [5]).

There are a number of aspects that can lead to early corrosion, which makes it unsafe for a structure to be designed to last a given lifetime. The most important and significant, which deserve to be highlighted, are the design/conception defects and the exposure environments, the latter being, to a certain extent, related to the former.

When it comes to design errors or defects, it mostly refers to the inadequate choice of the type of concrete to be used for a given environment and the incorrect calculation of the required coating. Among the numerous design errors that can occur, the most significant for the subject under analysis are the poor execution of concrete (water/cement ratio, vibration, curing, among others) and the inadequate positioning of reinforcement, not respecting the established overlay.



a) b) c)

Figure 2.- Corrosion behaviour in relation to concrete quality versus coating thickness (adapted from [5]).

a) High coating thickness and high concrete quality;
b) Low coating thickness and good concrete quality;
c) High coating thickness and low concrete quality.

In summary, the aggressiveness of the corrosion mechanisms depends, in large part, on the properties of the surface layers of concrete [4], i.e., on the coating of the reinforcement.

As mentioned above, corrosion can cause harmful and irreversible effects to any element of a reinforced concrete structure. It is known that, when the corrosion process occurs, the reinforcement progressively loses section area, which results in a decrease of the reinforcement area and, in turn, a reduction of the applicable load.

The loss of section is a consequence of the consumption of iron ions and can thus be associated with the increase in volume caused by corrosion products. This relationship is crucial for the modelling of the effects of corrosion in a piece because it will influence the results, this subject will be addressed later on at the point of modelling. With the reduction of the section of the bars, a reduction of the ductility of the piece is also a side effect and the steel-concrete bond is compromised [5].

The formation of corrosion products, produces an increase of 2 to 6 times [3] the consumed volume of the rod, this significant increase causes tensile forces in the concrete will result in a crack opening which aggravates the effects of corrosion.

2.2 Fracture mechanics

Fracture mechanics consists in the study of the behaviour of materials in the proximity of a crack [3][6].

The beginning of cracking occurs when and where the tensile strength in concrete is reached (f_t) [7][8]. As the cracking evolves, the stress does not drop abruptly to zero, but decreases due to the increase in crack opening (ω) [7], which will depend both on the conditions of environmental exposure as well as the imposed load [9]. For this reason, the behaviour of the cracked zone is described by a relation stress - crack opening (t - ω), *figure 3.a)*, instead of a relation stress - strain (σ - ε) used in the continuous environment, *figure 3.b)*.

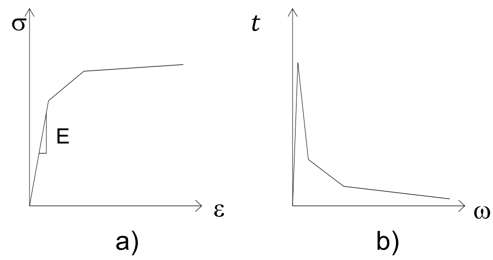


Figure 3.- tension-deformation diagram; tension-crack opening diagram.

An important concept to describe the behaviour of microcracking is the fictitious crack. This concept was introduced by Hillerborg [7] based on the fact that the decrease in stress in the neighbourhood of microcracking is not abrupt; instead it is progressive, as can be seen in figure 3.b) [6][7][8][9][10].

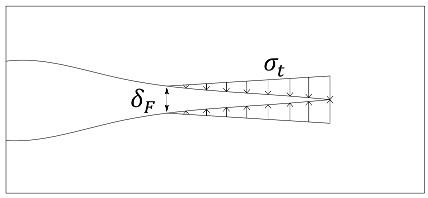


Figure 4.- Fictitious crack and resulting stresses.

3 Numerical Considerations

3.1 Computer Program

The program in use is a non-commercial 2D program, developed in the scientific area of structural mechanics and structures of the *Instituto Superior Técnico* [3][11][12.

There are some basic concepts behind the program already implemented before the development of this work that have been used or improved and that due to their importance in the results analysed later. It will be mentioned the non-linear and iterative model, the total approach and embedded gaps, which are the key concepts for the present work.

3.2 Non-linear and non-iterative model

The tests, object of the simulations described here, are subject to two types of non-proportional loading: i) the application of vertical loads and ii) the application of imposed strains equivalent to the corrosion effect.

The influence of nonlinearity in the domain does not significantly affect the behaviour of the microcracked zone at the end of the crack [6]. However, the behaviour in the cracked zone, characterized by softening, gives rise to numerical difficulties, leading to the loss of uniqueness of the solution. In addition to cracking, there are other important nonlinear behaviours, such as compression crushing, slipping of the steel-concrete interface and elastic-plastic behaviour of steel. Due to these nonlinearities, namely softening, lead to the loss of the positiveness of the stiffness matrix, making iterative methods more complex, time consuming and without assured convergence. In particular, the localisation of cracking in a reinforced concrete structure often leads to the non-convergence of conventional iterative methods, such as the Newton-Raphson method and the arc length. For this reason, this paper adopts a non-iterative method that is associated with a damage model.

3.3 Total Approach

In the total approach, the positive secant stiffness matrix is used [3]. In this type of approach, it is allowed to unload the structure up to the initial point, in order to perform a change in stiffness caused by the increase in damage and the structure is recharged again until a critical point is reached.

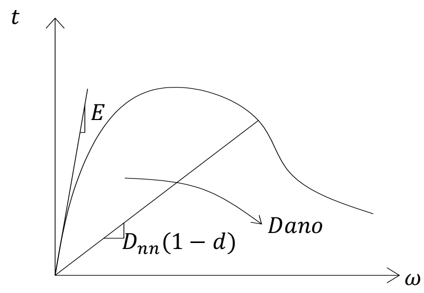


Figure 5.- Damage model.

Given the non-proportional nature of the load, the application of this method, with total unload, does not correspond to the real situation, and may give rise to stress states very different from those verified in the structure. For this reason, a variant of the non-original method is adopted in which, in each step, a value close to the loads obtained in the previous step is initially introduced. Next, the solution is increased incrementally, for the current loading phase, in order to reach again at least one critical point in the material [13]. This method allows to obtain a response always close to that corresponding to that obtained in the previous step, without significant changes in the state of stress in the structure resulting from the action of the various non-proportional loads.

3.4 Embedded Crack

With the creation of a crack embedded in the concrete, two new nodes are introduced in the element in question, as can be seen in *figure 6*, thus increasing progressively the number of degrees of freedom of the system as the crack progresses.

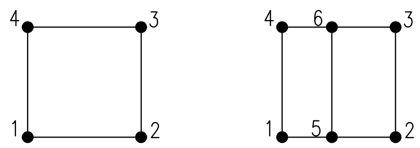
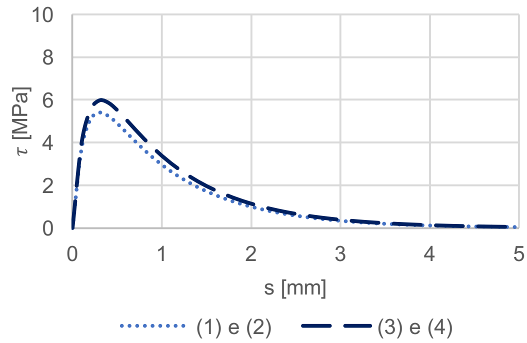


Figure 6.- Development of an embedded crack in a reinforcement concrete structure.

It is admitted that the propagation of cracks is done in such a way that a new embedded discontinuity always crosses entirely a finite element, having always knots of beginning and end in the same element. The discontinuities are straight and the corresponding direction is defined perpendicular to the direction of the main voltage (σ_I) which is obtained at the central integration point of the element in question [14]. In the case of the opening of the crack propagated so far, the criteria must be checked at the tip of the gap [6][14].

3.5 Bond-slip Model

It is necessary to define a specific model suitable to the conditions of interface between the concrete and the reinforcement bars, knowing beforehand that corrosion introduces some additional uncertainties in the determination of the bond-slip relationships [15]. Thus, the model adopted by Jiang et al. [16] based on the work developed by Wu and Zhao [17] is used, from which proven satisfactory results are obtained [3]. Whit this method is possible to obtain the graphs corresponding to the behaviour of this interfaces for the different sections of the beam. The *graph 1* represent the implementation of the equations for a degree of corrosion null, meaning 1 as the continuity support on the superior bar, 2 as the half beam on the superior bar, 3 as the continuity support on the inferior bar and 4 as the half beam on the inferior bar.



Graph 1.- Bond-slip curve for null corrosion.

3.6 Corrosion Model

it is necessary to assume an adequate methodology that translates the variation of the steel volume in relation to the temperature variation in direction y. It was thus followed, as in previous studies, the methodology proposed by Fang et al. [18] which admits a parameter that reflects the degree of corrosion in which the state of the structure is observed (η).

This methodology translates into a relationship between the variation of the radio of the bar section and the variation of the temperature that it is exposed. For the application of these formulas it is necessary to enter into consideration with a non-dimensional parameter that translates the relationship between the reduction of the radius of the steel bar and that resulting from the expansion of the corrosion products, assumed as $\beta = 2$.

4 Case Study

4.1 Structural Piece

In order to approximate as much as possible to a real case, but trying to maintain a simple character for programming and analysis, a section of usual dimensions was defined. For that question, a hyperstatic beam with two symmetrical spans of five meters each (5 m) was chosen, with a height of fifty centimetres and a width of thirty centimetres (0.50x0.30 m^2). Thinking on the structural behaviour it has been dimensioned whit a regular reinforce counting whit longitudinal bars and stirrups.

4.2 Materials

To characterize the beam is also necessary the complete definition of all the materials used, as well as all the necessary parameters for the modelling of the beam, for that matter in continuation it will be present the chosen materials.

The selected concrete was a C30/37, a current used concrete in today constructions and the steel used for reinforcement was an A500 NR.

4.3 Finite Element Mesh

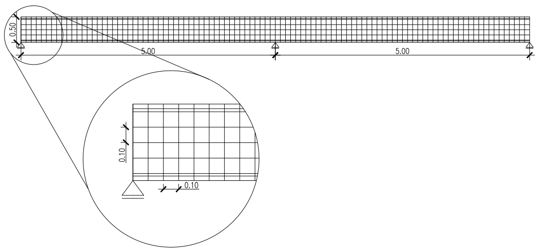


Figure 7.- Finite Element Mesh.

One of the most influential aspects of the results obtained in the modelling of the beam behaviour is the definition of the finite element mesh. Obtain a balance between detail of the results and complexity of the calculations is not often an easy issue. With this in mind it was ben chose a simple mesh with elements of 10 by 10 mm as can be seen on *figure 7*.

4.4 Applied Charges

The load for the tests in question was given in three phases, each one defined by a data file where all the characteristics of the test as well as the admitted commands and control parameters are established.

In the first data file, all parameters relating to the mesh, support conditions, materials used, bond-slip ratios as well as the established service load of 40 kN/m are defined. For the second load, the temperature increases corresponding to the chosen degree of corrosion for the experiments (10% and 20%) is introduced.

the third load file includes an increment of the load applied in the first load case until failure is obtained.

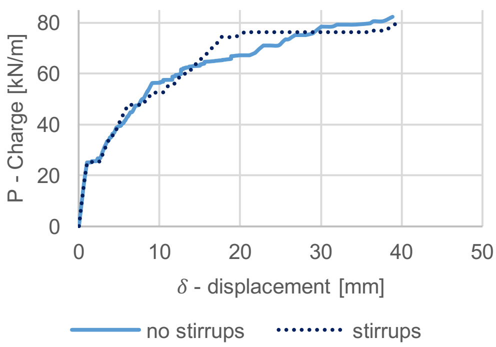
4.5 Tests and Trials

A series of tests was developed in order to test different types of corrosion making possible the analysis of the structure’s behaviour with diverse degrees of corrosion on different sections of the beam. The tested sections are: i) in the continuity support, ii) in the mid span of the beam, iii) in the end support and iv) in the total extension of the entire lower beam.

Besides of this series of tests the presence of confinement was also analysed in the present work.

5 Analysis of Results

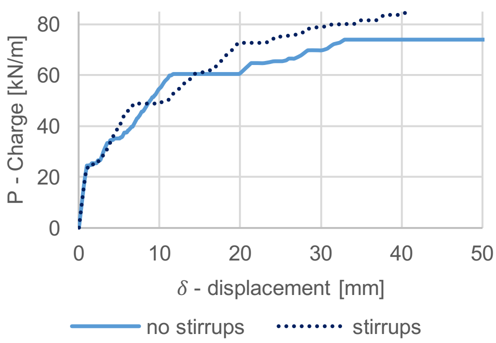
5.1 10% of Corrosion on the Continuity Support



Graph 2.- Charge-displacement diagram for test 1.

Due to the opening of cracks and the deterioration of the steel-concrete connection interface, the structure presents a progressive stiffness change, being for the stirrups case less severe and occurring later.

5.2 20% of Corrosion on the Continuity Support



Graph 3.- Charge-displacement diagram of test 2.

For the case of a 20% degree of corrosion an early deterioration of the interfaces can be observed, thus resulting in a behaviour with less capacity than the previous case. It is thus possible to analyse the yielding levels at an earlier stage and that the confined case has advantages over the unconfined one.

5.3 10% of Corrosion on the Half Beam

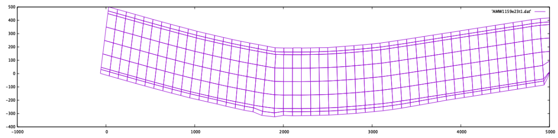


Figure 8.- Deformed at collapse test 3 stirrups.

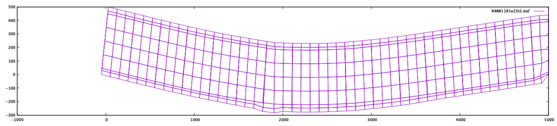


Figure 9.- Deformed at collapse test 3 no stirrups.

As the corrosion is introduced in the mid-span of the beam, it would be expected that this section becomes more critical than the continuity support. However, as it is possible to analyse by the results obtained, the critical section continues to be the continuity support, where the steel bars are plasticized, and the traction stress reaches ultimate values (500MPa).

5.4 20% of Corrosion on the Half Beam

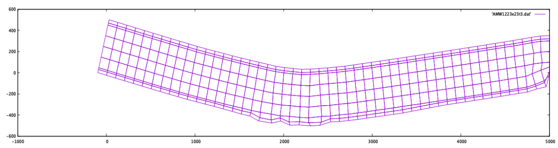


Figure 10.- Deformed at collapse test 4 stirrups.

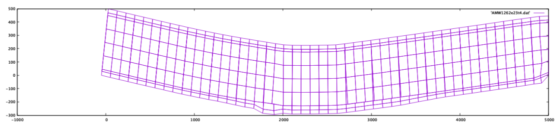
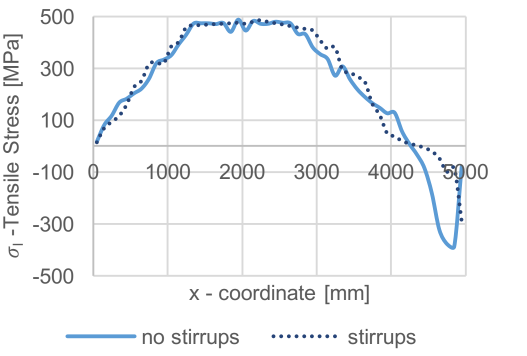


Figure 11.- Deformed at collapse test 4 no stirrups.

Like test 3, the beam finds it's critical section in the continuity support but at an early moment, presenting a smaller crack opening, but a much more pronounced degradation of the interfaces, resulting in a serious sliding of the interfaces in the lower bars in the midspan of the beam which causes collapse of the structure.

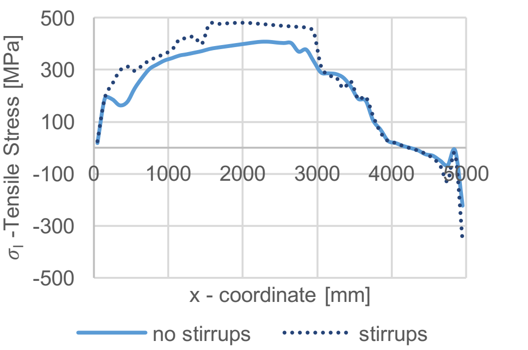
5.5 10% of Corrosion on the Extremity Support



Graph 4.- Tensile stress on inferior bars of test 5.

Applying a constant corrosion of two meters near the end support is expected the appearance of higher tensions in this section, on the inferior bars. For the degree of corrosion in question, such effect is not visible so it can be concluded that a degree of 10% is not enough to damage the structure.

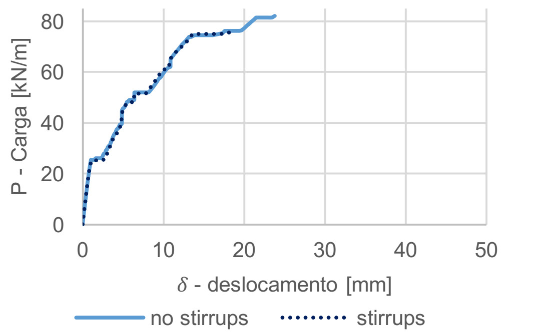
5.6 20% of Corrosion on the Extremity Support



Graph 5.- Tensile stress on inferior bars of test 6.

In contrast to the previous test, in test 6 it is possible to analyse an aggravated stress near the section of the end support being in coincidence with the expected in theory. Thus, it can be concluded that a 20 % degree of corrosion would cause a critical deterioration in the structure, conducing to the premature collapse before reaching que critical load.

5.7 10% of Corrosion on the Total Extension of Inferior Bars



Graph 6.- Charge-displacement diagram of test 7.

As can be seen in *graph 6*, there is an equality behaviour of the case with and without stirrups so it can be concluded that the effect of this, for the test, will not have an impact on the results. In turn, there is an early deterioration of the interfaces in the case without confinement, which will cause a slightly different crack map and a distorted deformed with more aggravated effect.

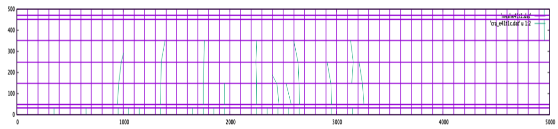


Figure 12.- Crack map of test 7 without stirrups.

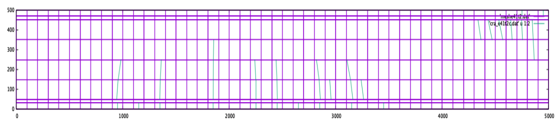


Figure 13.- Crack map of test 7 with stirrups.

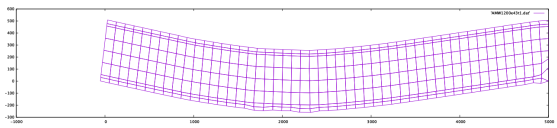


Figure 14.- Deformed at collapse of test 7 without stirrups.

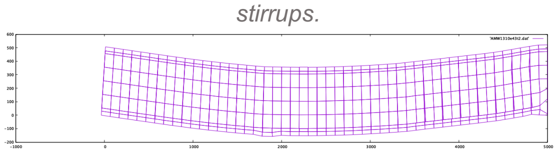
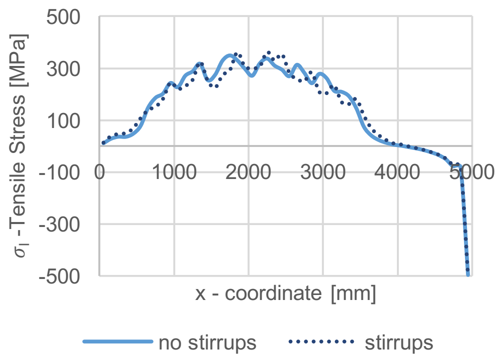
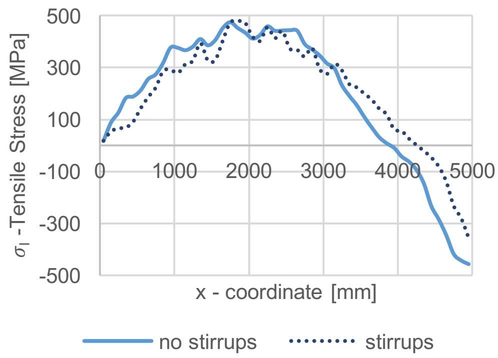


Figure 15.- Deformed at collapse of test 7 with stirrups.

The aforementioned effects can be analysed in the images presented above, where there is a crack opening with more than 0.2 mm more pronounced for the case without confinement and a more marked deformation with greater sliding of the steel-concrete contact interfaces as well as with a greater deflection by bending.



Graph 7.- Tensile stress on inferior bars of test 7 for yield strength.



Graph 8.- Tensile stress on inferior bars of test 7 for collapse.

The yielding occurs in the continuity support as it can be seen in *graph 7*, reaching plasticization of the bars in this zone however the collapse occurs by the half span section of the beam, *graph 8*.

This test represents a marked deterioration in the structure due to the extent of corrosion in the bars, which compromise the structure behaviour in great scale.

6 Conclusion

6.1 Final Conclusions

With this work, it is possible to gather a series of observations about the structural behaviour of a reinforced concrete beam, which are listed below:

1. A premature yielding is observed in the tests with a more aggravated corrosion degree.
2. Changes in the overall stiffness of the structure are directly associated with deteriorations of the steel-concrete interfaces or the plasticization of steel elements of the bars.
3. In terms of load capacity, it is not conclusive that the deterioration of the interfaces affects it substantially, and it is more likely that this happens due to the loss of section of the reinforcement bars.
4. It is possible to conclude that, for the presence of a higher degree of corrosion, the existence of confinement in the beam presents advantageous aspects.
5. At pre-break, the program does not allow conclusive results to be obtained, which in turn does not lead to a completely realistic response for the ultimate loads.

6.2 Recommendations for Future Works

the use of the reduction of the rod section area as the volume increases due to the corrosion products, this factor increases the difficulty in the numerical calculations due to the change of the stiffness matrix for each step, but it can be performed and provides a much more accurate and reliable analysis.

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