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Numerical Study of the Bond Strength Evolution of Corroded Reinforcement in Concrete in Pull-Out Tests

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Featured Application: Authors are encouraged to provide a concise description of the specific application or a potential application of the work. This section is not mandatory.

Abstract: The corrosion of rebars in reinforced concrete structures impacts their geometry (diameter and ribs) and mass, damages the concrete at the interface between the two materials, deteriorates the bond strength, and causes the cracking of the concrete cover. In the following study, a 2D numerical model of the pull-out test is presented in order to study the impact of corrosion on the bond strength. Several parameters are investigated: the embedment depth, the rebar's diameter, and the width of the concrete cover. The model reproduces the slip of the rebar and the failure through the splitting of concrete. It integrates an interface between the two materials and a concrete damage model that simulate the deterioration of concrete in compression and tension. The results obtained are validated with experimental data from the literature. Moreover, a parametric study is carried out to determine the impact of the embedment depth, the diameter of the rebar, and the concrete cover on the bond strength. The present study confirms that a greater embedment depth increases the pulling load. The study also confirms that the rebar's diameter impacts highly the loss of bond between the rebar and the concrete cover. Lastly, the final main result of this paper is that the width of the concrete cover slows the loss of bond strength between the two materials.

Keywords: reinforced concrete; corrosion; finite element method; pull-out capacity; bond behavior; damage plasticity

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1. Introduction

Corrosion of rebars is the most common way of damaging reinforced concrete structures. Corrosion leads to the mass loss of the rebar and reduces its diameter, the damage of the concrete interface and the bond between the two materials, and finally the cracking of concrete cover [1]. This is because the corrosion of the reinforcement causes their volume expansion due to the apparition of rust [1]. This expansion exerts pressure on the concrete at the interface and generates tensile stresses in the concrete cover [2]. Since concrete is a quasi-brittle material, this leads to the development of tensile cracks [2].

The corrosion is caused mainly by the aggressiveness of the environment, particularly the structures close to the sea or water such as bridges. This increases greatly the cost of

repair and maintenance of these structures and reduces their life-expectancy. It is then of great importance to develop a numerical model that can simulate the corrosion process and assess the deterioration of these RC structures in order to help predict their behavior. The investigation of the bond deterioration due to corrosion has been widely investigated experimentally in the literature through pull-out tests in Fang et al. [1], Lee et al. [2], AlSulaimani et al. [3], and Almusallam et al. [4]. The corrosion process was performed artificially by immersing the specimens in a sodium chloride solution and applying a voltage between an electrode and the rebar. The corrosion was assumed to be uniform along the reinforcement, and the corrosion degree was controlled and varied for the different specimens. A pull-out test was then performed, and the evolution of the bond stress between the rebar and the concrete as a function of this corrosion degree was reported. Analytical models have also been proposed in the literature (Chung et al. [5], Coccia et al. [6], Cabrera et al. [7]) that express the evolution of the bond stress and that are validated by experimental results. Zhu et al. [8] proposed a different experimental protocol to study the impact of the non-uniform corrosion on the bond between concrete and the rebar. They partially coated the reinforcement with epoxy resin before they were casted in concrete and before performing the accelerated corrosion, ensuring that the rebar wasn't totally corroded. The impact of stirrups reinforcements has been studied by Lin et al. [9], where they found that they were extremely corroded compared to the rebars and that they prevented failure by splitting the concrete cover in the pull-out tests they carried. A 3D numerical model of the pull-out test with corroded rebars has also been proposed by Ozbolt et al. [10] where they mainly investigated the damaging of the concrete cover. Another 3D numerical model has been proposed by Amleh et al. [11] to investigate the effect of corrosion on the bond strength through a numerical pull-out test carried out in the software ABAQUS. However, the numerical pull-out test models in the literature investigate either the evolution of the bond stress by manually adding the damage to the bond model or the damaging of the concrete cover by studying the evolution, length, and width of the tensile cracks. Moreover, there is no model in the literature that combine these two aspects to study the impact of corrosion on the bond strength of RC structures.

In this paper, we propose a complete numerical study of a 2D model of the pull-out test with corroded rebars. The numerical model can simulate the evolution and deterioration of the bond stress, and also the damaging of the concrete cover using two damaging mechanisms (tensile and compressive damage) and an interface that models tangential and normal contact. In Section 1, the various aspects of our numerical model are presented and detailed. In Section 2, these results are validated through experimental data in the literature. Finally, in Section 3, to further validate our model, a parametric study where we investigate the impact of the rebar diameter, the embedment depth, and the concrete cover size on the bond stress is presented.

2. Model Presentation

2.1. Model Geometry

The studied model is a 2D axisymmetric model composed of a plain reinforcement rebar embedded in a block of concrete. The diameter of the rebar is 12 mm in this model, and the embedment depth is 100 mm. The concrete part is a 150 mm $\times$ 150 mm block of concrete with a cover of 69 mm. The Figure 1 represents the detailed geometry of the model.

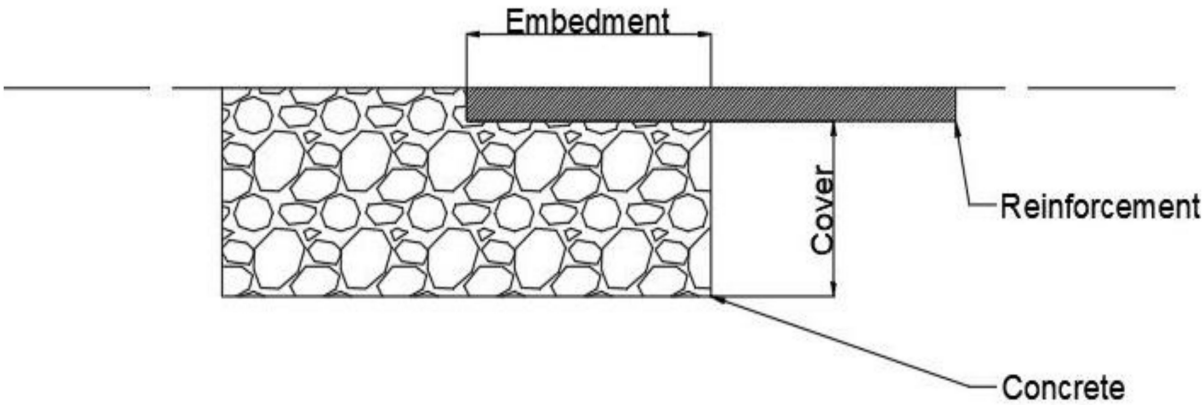

Figure 1. Representation of the geometry of the pull-out model.

2.2. Corrosion Model

The corrosion of the reinforcement not only affects the geometrical properties of the rebar, but also the mechanical properties of the RC structure. It leads to the mass loss of steel of the rebar and generates rust that takes more volume due to its composition (mostly water [12]). The corrosion degree is a percentage of mass loss expressed as follows:

$$X = \frac{M_i - M_f}{M_i}, \tag{1}$$

where X is the corrosion degree, M_i the initial mass of the rebar and M_f the final mass of the corroded rebar. The volume expansion of the rebar is also characterized with a ratio between the volume of steel lost and the volume of rust. According to [13,14], this ratio can be up to 6.5, which means that the volume of rust can be 6.5 times higher than the lost volume of steel in the corroded areas and depends on the composition of the corrosion product [13]. This parameter has been determined experimentally and analytically in previous studies [6,8,13] for uniform and artificial corrosion, and was set to $\alpha_{r/s}$ = 3.75. Since the aim of our model is to reproduce artificial uniform corrosion, the rust-steel ratio is also set in our study to $\alpha_{r/s}$ = 3.75.

The distribution of the corrosion is usually irregular and depends on various parameters such as the aggressiveness of the environment. It is usually taken as uniform when performed experimentally [6,14–16]; this is because the structure studied is fully immersed in the solution and the current is applied all along the rebar uniformly. A uniform corrosion is also considered in our model. Equation (1) can be rewritten using the cross sections as in [9] as follows:

$$X = \frac{A_i - A_f}{A_i}, \tag{2}$$

where A_i is the initial cross section of the rebar and A_f the residual cross section of the rebar. We first need to determine A_f by setting the corrosion degree X in the following equation:

$$A_f = A_i(1 - X), \tag{3}$$

Assuming that the corrosion is uniform along the rebar, we can determine the residual diameter of the rebar (the diameter of the rebar after removing the corrosion material) and the difference between the initial and residual diameter of the reinforcement as follows:

$$L = \phi_i - \phi_f, \tag{4}$$

with ϕ_i and ϕ_f being the initial and residual diameters of the rebar. We can now determine using $\alpha_{r/s}$ that we have set earlier, the expansion of the rebar, expressed in 2D as a displacement:

$$D_f = L(\alpha_{r/s} - 1), \tag{5}$$

where D_f is the final imposed displacement that depends directly on the corrosion degree and the diameter of the rebar.

2.3. Material Model

2.3.1. Concrete

To model the internal cracking of concrete due to tensile stresses and the crushing of the interface due to the volume expansion of concrete, the Concrete Damage Plasticity (CDP) model in the commercial software ABAQUS is used. The CDP model allows us to model concrete as an elastic and homogenous material with the two main damage mechanisms that are the tension cracking and compression crushing of concrete. This means that the material follows a quasi-elastic law until reaching the failure stresses (both in compression and tension) [17]; a softening of the strain-stress law is considered to model the appearance of micro-cracks.

A damage variable is considered in the CDP to model the degradation of the of the elastic modulus [17] as follows:

$$E = E_0(1 - d), \tag{6}$$

where E_0 the initial and undamaged elastic modulus of the concrete, d the damage variable that is a function depending on the stress field, and the two damage variables are d_c and d_t. The damage variable d ranges from 0 (undamaged material) and 1 (totally damaged material).

In our work, the Concrete Damage Plasticity parameters are those gathered experimentally by Jankowiak et al. [18]. These parameters, presented in Table 1, are ψ the dilatation angle, ϵ the flow potential eccentricity, σ_{b0}/σ_{c0} the ratio between the initial equibiaxial and uniaxial compressive yield stress, and K_c the ratio of the second stress invariant on the tensile meridian to the compressive meridian [19].

Table 1. Parameters of the CDP model of the concrete.

E(GPa)	ν	ψ (○)	ϵ	σ_{b0}/σ_{c0}	K_c
19.7	0.19	38	1	1.12	0.666

Figure 2 represents the tension stiffening and concrete crushing laws proposed in [18] and used in our work to model the failure behaviors of concrete.

2.3.2. Reinforcement

The reinforcement is modeled independently of the concrete cover and not as an embedded element. This allows us to study the interactions between the concrete and the rebar, as well as the damage to the interface due to corrosion in our numerical pull-out test. The rebar is modeled as an elastic element with an elastic modulus and a Poisson coefficient, as presented in Table 2.

Table 2. Rebar elasticity parameters.

E (GPa)	ν
210	0.2

The rust material is not modeled due to the uncertainties regarding its mechanical properties [6,20,21]. Its elastic modulus is considered equal to the rebar's elastic modulus [6,8,13,14], and the volume expansion of the reinforcement is directly applied on the rebar part. Moreover, the behavior of the rust is taken into account with the rust/steel ratio $\alpha_{r/s}$.

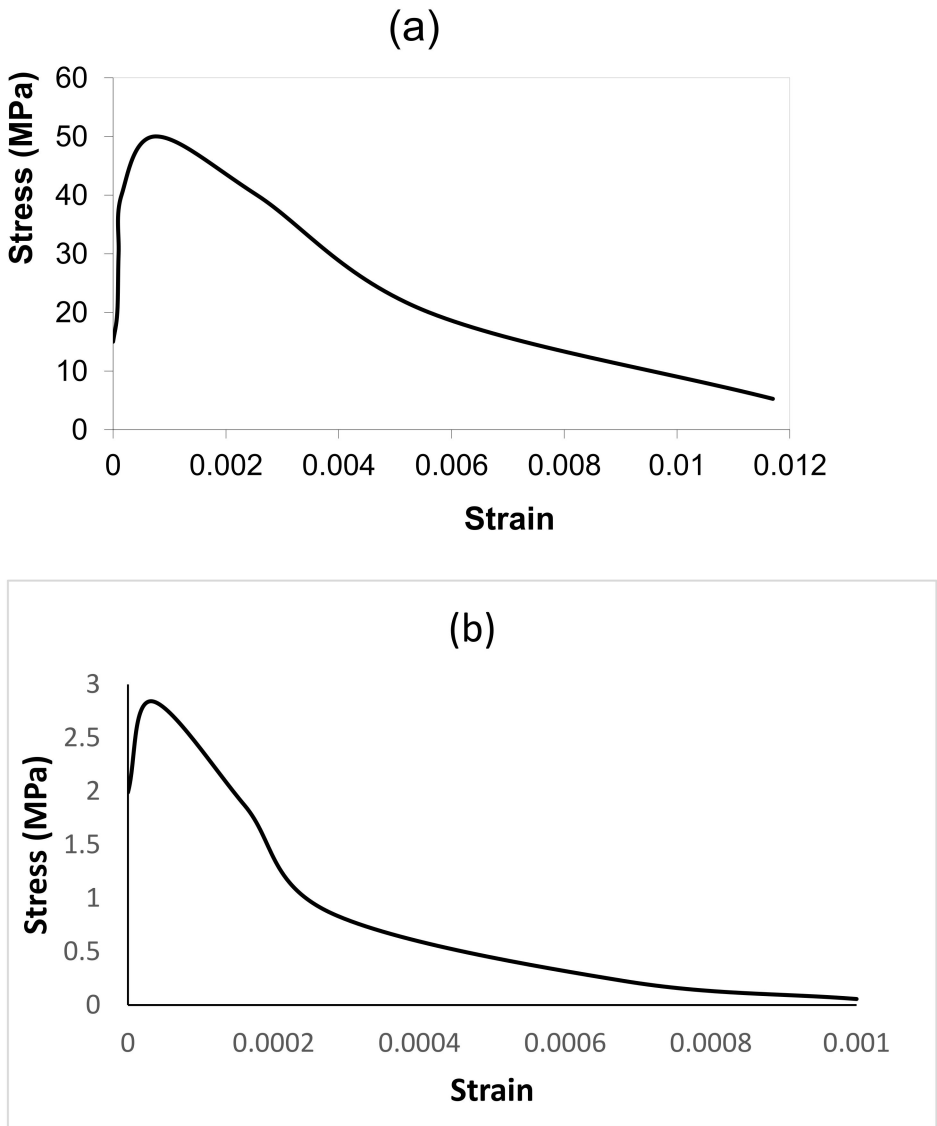

Figure 2. Uniaxial stress-strain curve with damage in compression (**a**) and traction (**b**) [18].

2.4. Boundary Conditions

In this section, the boundary conditions and the interface model used in our pull-out test model are detailed.

The modeling of the pull-out test is performed in two phases implemented in the software ABAQUS as steps. In the first one, the "Corrosion Step" the corrosion of the rebar is modeled. In the second phase, the "Pull-out Step", the pulling-out of the reinforcement is modeled to simulate the pull-out test. This is detailed in the following subsection.

2.4.1. Concrete Boundary Conditions

To avoid any movement in the Corrosion Step or in the Pull-out Step, the bottom of the concrete part is clamped throughout the whole simulation. The top of the concrete part is also blocked in the y direction ($U_y = 0$) in order to follow the axisymmetric conditions.

2.4.2. Rebar Boundary Conditions

In the Corrosion Step, an imposed displacement is imposed in the y direction at the bottom part of the rebar that is in contact with the concrete to model the volume expansion of the reinforcement due to corrosion. The corrosion is considered uniform along the rebar, which means that the imposed displacement is uniform along the rebar.

The top of the rebar is blocked in both x and y direction ($U_x = 0$ and $U_y = 0$). The first condition ($U_y = 0$) is for the axisymmetric conditions. The second condition ($U_x = 0$) is set to avoid any displacements in the x direction that can be caused by the imposed displacement of the volume expansion of the rebar. This condition is relaxed in the Pull-out Step to allow the rebar to move.

There is only one boundary condition set in the second step, an imposed displacement in the x direction at the free end of the rebar to simulate the pull-out test. No boundary condition is set at the other end of the reinforcement. The boundary conditions applied on the rebar are presented in Figure 3.

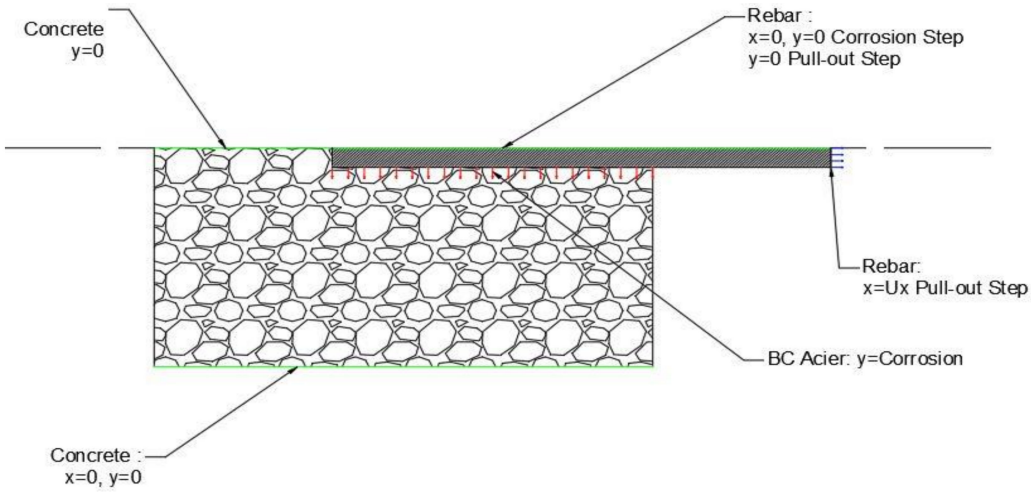

Figure 3. Boundary conditions of the pull-out model.

2.4.3. Concrete-Rebar Interface

A surface to surface interface is modeled with ABAQUS. This module uses a master-slave contact algorithm. The master surface is assigned to the stiffer material, in our case the concrete part [11].

A normal contact is modeled that follows the Kuhn–Tucker optimality conditions that are as follows:

$$\begin{matrix} t_n \geq 0 \\ g \leq 0 \\ t_n \cdot g = 0 \end{matrix} , \tag{7}$$

with t_n as the contact pressure and g the clearance. The first two equations ensure that there is a compressive contact between the two parts, and that there is no penetrability between the two materials. The third equation, the complementary condition, ensures that we can have contact pressure only if we have contact and that there is no contact pressure where there is a gap between the two materials. The Kuhn–Tucker optimality conditions are presented in Figure 4.

To enforce the normal contact, we used the Augmented Lagrange Method, which is a combination of the penalty, and the Lagrange method, which enables an exact resolution of the contact equations while using the penalty terms to simplify the iterations [22].

In order to study the evolution of bond stress as a function of the corrosion degree, a tangential contact needs to be modeled. In ABAQUS, the friction law related to the tangential contact behavior follows the Coulomb model. In this model, the two surfaces stick until reaching a shear critical stress $T = \mu t_n$, where sliding between the two surfaces starts. The friction coefficient μ is in our present work set to 0.45, according to Raous et al. [23], where they found that this value fits their experimental results. To enforce the tangential contact, the penalty method is used.

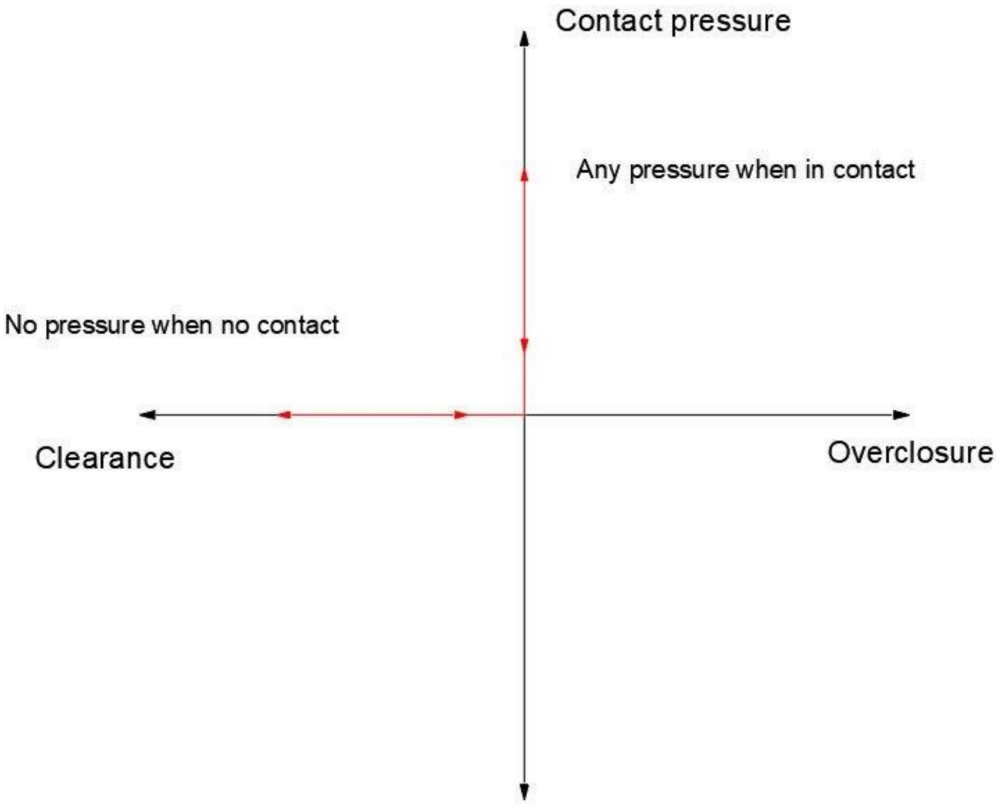

Figure 4. Representation of the Kuhn–Tucker contact conditions.

2.5. Mesh

When using the Concrete Damage Plasticity model, the results of the concrete part can be heavily influenced by its meshing. Quadrilateral elements are used to mesh the concrete cover and two regions are set. The first region, around the rebar with a refined and structured mesh and an element size of 2 mm × 2 mm, and the second region, near the concrete part edges, meshed freely, also with quadrilateral elements, with an average element size of 4 mm × 4 mm.

The rebar part is meshed with a refined and structured mesh with an element size of also 2 mm × 2 mm all along. Coincident nodes at the concrete-rebar interface region are set. Finally, 195 elements are present in the reinforcement and 1795 elements in the concrete cover (Figure 5).

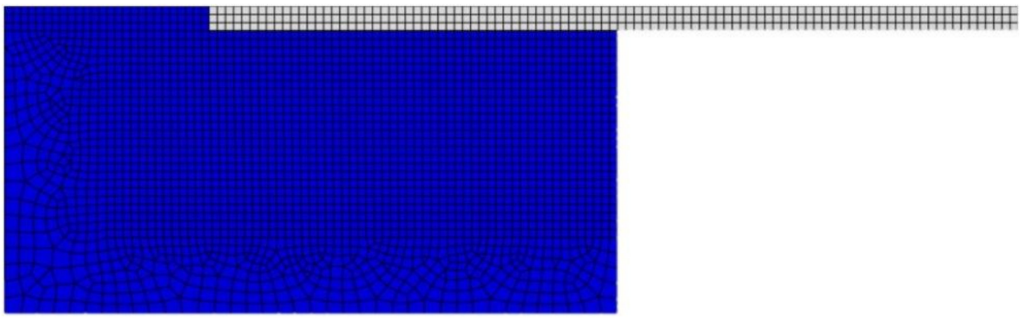

Figure 5. Final mesh of the numerical model.

3. Model Validation

The nature of the bond between the concrete and the rebar is three-fold: chemical adhesion, friction, and mechanical (especially with deformed rebar with the mechanical interlock of its ribs). Of the three, the chemical adhesion is the least significant and it is broken after only some slight movement [6,24]. Concerning the mechanical bond,

since the rebars ribs have not been modeled, the bond strength will mainly depend on the friction. However, corrosion deteriorates the rib's geometry of the deformed bar, leading to a significant decrease of the lug height [11]. The impact of the mechanical bond of corroded deformed bars becomes less important in comparison with non-corroded deformed bars [6,11,16].

Overall, three failure modes are possible in a pull-out test: the pull-out failure mode when there is a perfect slip of the rebar, the cover splitting mode characterized by the splitting of a cone of concrete, and the reinforcement failure with the rebar yielding. In our model, only the first two modes are considered, and only the first one is studied. The second one is detected in our simulations as convergence problems due to the extreme damaging of the concrete cover, since it is impossible to model the splitting of concrete.

As explained previously, after applying the volume expansion on the rebar, a displacement is imposed at its free end. This allows us to determine the necessary load to pull the rebar for the various degrees of corrosion studied, as presented in Figure 6. As we can see in this same figure, the load necessary to remove the rebar decreases greatly after some slight movements. We can also notice that this same load increases for small degrees of corrosion before it drops for larger degrees. This is due to the fact that, at lower degrees of corrosion, the concrete at the interface region is still not damaged, and the volume expansion only leads to a better adherence between the reinforcement and the concrete cover. The volume expansion of the rebar increases the radial forces applied on the concrete interface which enhances the holding capacity of the concrete cover. Experimentally, this increase is also observed in [14,16,24]; it was explained due to the rough nature of the rust material in contact with concrete. Here, we can conclude that this increase in the pulling load of the corroded rebar in lower degrees of corrosion is more significant in reality since it takes these two behaviors into account.

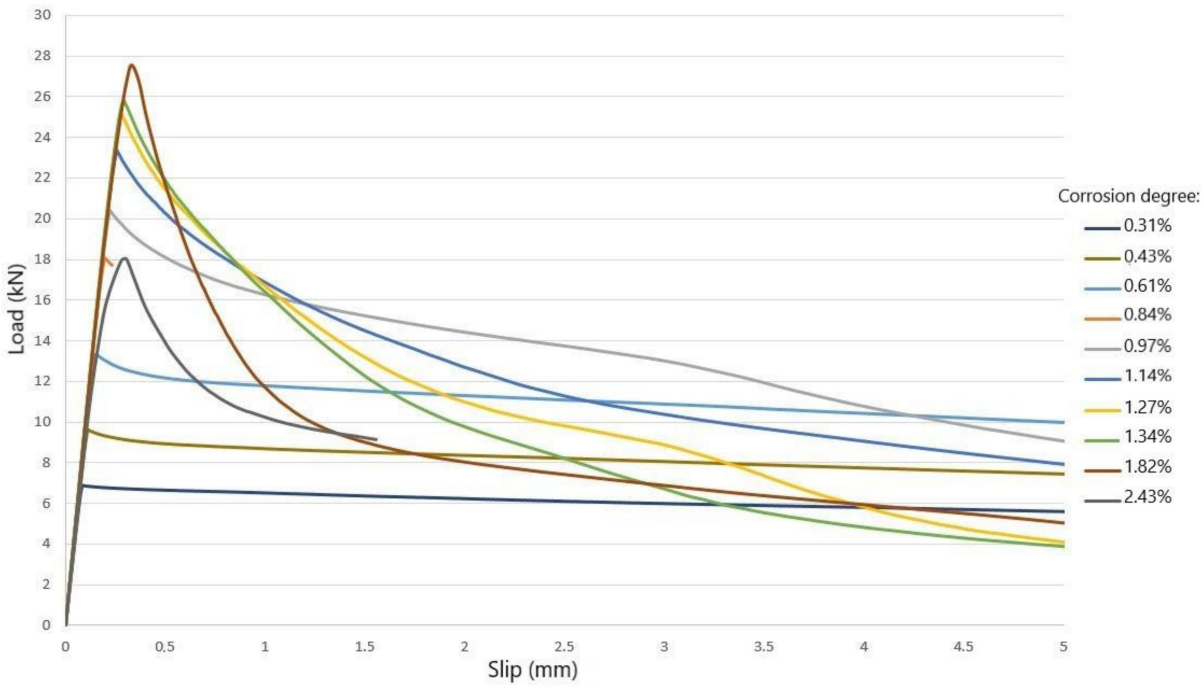

Figure 6. Load-slip pull-out curves for different corrosion degrees.

When the degree of corrosion starts to grow, the rust damages the concrete at the interface. Cracks start to appear due to the tensile stresses inside the concrete cover, generated by the volume expansion of the rebar, and due to the quasi-brittle nature of the concrete. It is at this moment that the pulling load starts to decrease, as we can see

in Figure 6. The evolution of the bond stress as a function of the corrosion degree is also investigated (Figure 7), using the following formula [6,19,25,26]:

$$\tau = \frac{N_{\max}}{\pi h_{\mathrm{ef}} d}, \tag{8}$$

where τ is the bond stress, $N_{\max}$ the maximum load of the pull-out simulation, d the diameter of the rebar, and h_{ef} the embedment depth of the rebar.

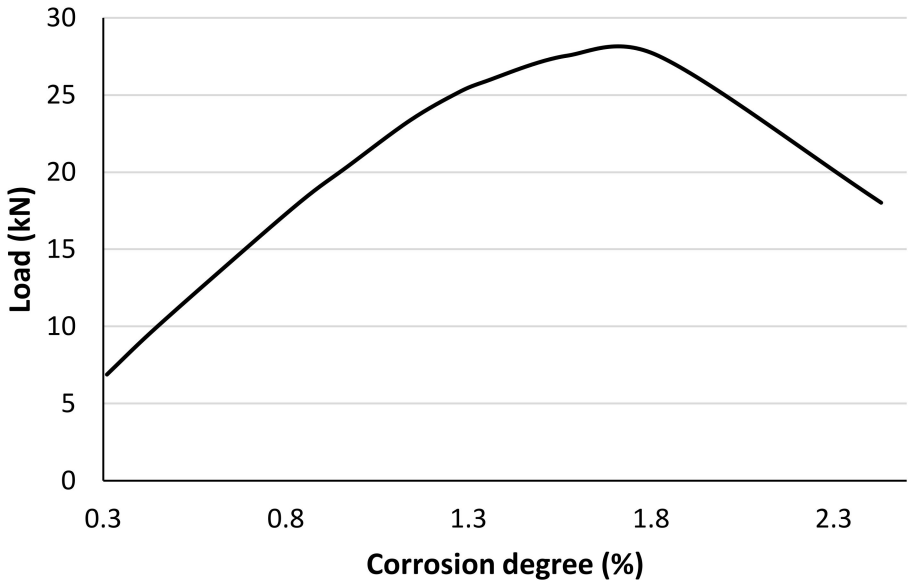

Figure 7. Evolution of the maximum pull-out load as a function of the corrosion degree.

To validate our model, only experimental data from the literature were used. The bond stresses reported in the literature are very scattered, and there is a clear difference in term of magnitudes [14,24]. This can be explained with the sensitive nature of concrete, the types of reinforcement used or the conditions of the experimental program.

The results of Jin et al. [16] are plotted in Figure 8. They worked on the effect of corrosion on the bond stress of plain and deformed rebar. They carried out pull-out tests on cubic concrete specimens of 100 × 100 × 100 mm with a 12 mm diameter plain and deformed corroded rebar and with an embedment depth of 80 mm. The corrosion was simulated artificially, and was considered uniform all along the rebar. We can notice that the results they obtained are similar to our numerical model, especially the results with the plain rebars. As for the deformed rebars, we can highlight that the bond stress is significantly higher at very low degrees of corrosion compared to the bond stress of the plain specimens and compared to our models. This is because, with plain rebars, there is no mechanical contact between the reinforcement and the concrete cover, and at lower degrees of corrosion, the ribs of the deformed rebars are still not enough damaged.

The results of Lin et al. [9], where they carried out pull-out test on corroded concrete blocs with also only one deformed rebar, are also plotted in Figure 8. The top concrete cover varied between 25 mm and 35 mm and a fixed lateral concrete cover of 65 mm. The embedment depths were of 300 mm with only 200 mm of contact between the rebar and the concrete. The specimens had either two or four stirrups. They conducted artificial corrosion on the specimens before pulling-out the rebars. They noticed that stirrups were the more corroded than the rebars. The results they obtained are quite similar the ones with our numerical model; we notice the same tendency with small differences in term magnitudes for the bond stresses. This can be explained by the presence of the stirrups and also because the rebar is deformed.

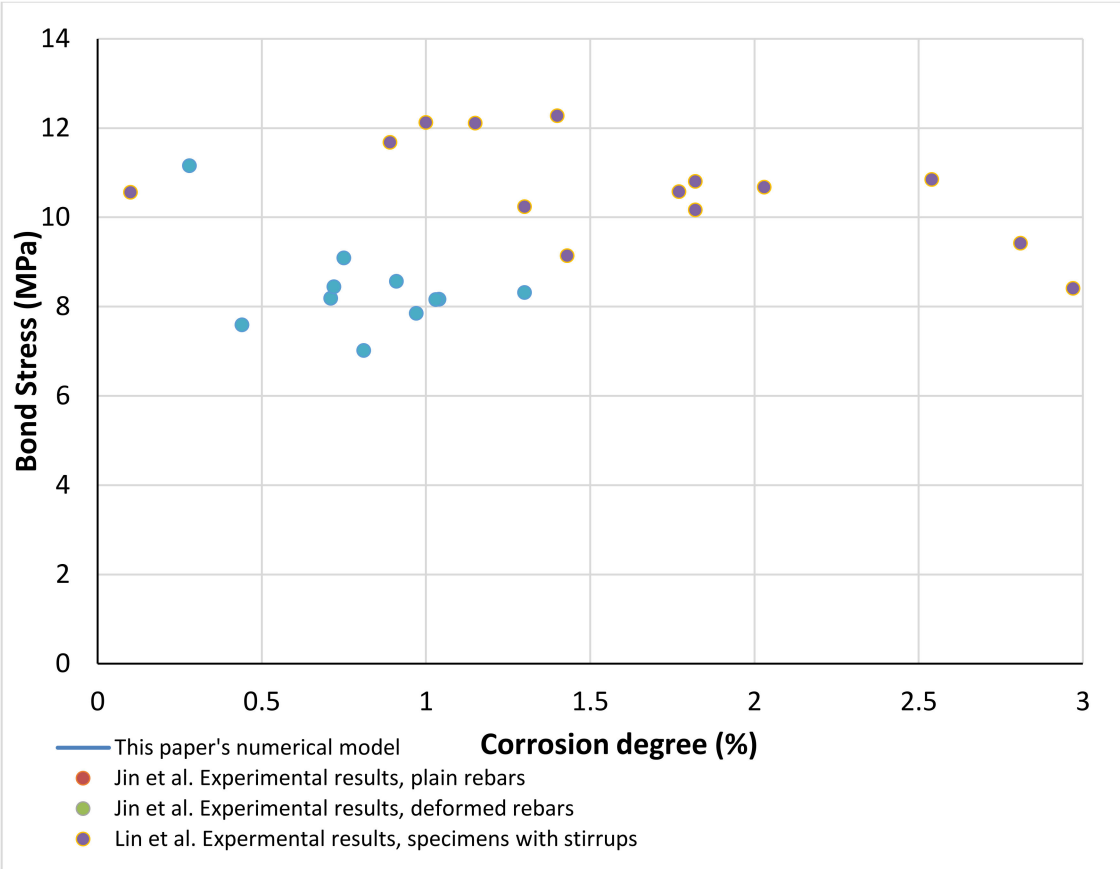

Figure 8. Numerical results: bond stress-corrosion degree with comparison with the literature.

Finally, we also plotted in Figure 8 the results of tested naturally corroded specimens from Horrigmoe et al. [26] from their report delivered to the Integrated Research Project "Sustainable Bridges-Assessment for Future Traffic Demands and Longer Lives", funded by the European Commission. The main objective of the report was to study the impact of corrosion on the structural strength of RC structure. They collected cubic pieces of concrete from the Ullasund Bridge in Norway to test them. The specimens were exposed to the natural environment of the area for approximately 30 years and were corroded naturally. The size of the specimens tested was about 150mm × 150mm × 150mm with a single 25 mm diameter deformed rebar. These specimens were then cast in concrete cylinders of 320 mm diameter. They assessed the corrosion degree of the specimens after carrying out the pull-out test.

Overall, we notice that the results from our numerical model and the experimental results from the literature and plotted in Figure 8 exhibit the same tendency, with some discrepancies in term of magnitudes. There is an increase in the bond stress, and after reaching a certain degree of corrosion (around 1.5% in our model), the bond stress drops significantly. As explained earlier, this is due to the damaging of the concrete at the interface and the cracking of the concrete cover. As for the corrosion degree where the drop occurs, the results in the literature are very scattered. Al Sulaimani et al. [3] noticed an increase of bond stress until reaching a corrosion degree of 1%, the bond stress drops after. Almusallam et al. [4] found that the corrosion degree where a drop in the bond stress was noted was about 5%. Coccia et al. [6] found that the reduction of bond stress happens at a corrosion degree of approximately 0.5%. As mentioned before, there is a wide variety in term of results in the literature, and this had been outlined in [14,24]; furthermore the results show the same trend across the literature.

Pull-out failure can be one of the three failure modes presented before. The second mode that our model is able to simulate is the cone failure of the concrete cover, as can

be seen in Figure 9. This failure mode happens when the stress generated by the pull-out of the rebar exceeds the tensile strength of the concrete. We can see the failure cone marked out by the damaged zone in tension of the concrete cover in Figure 9. Since the damaging of the concrete is modeled using a finite element model that cannot simulate discontinuities in matter, when the failure cone is fully determined, the model stops running due to convergence issues. This phenomenon happens when the degree of corrosion is approximately 1%, depending on the diameter of the rebar. This has been confirmed in Zhu et al. [8], who also noticed that over a corrosion degree of 1%, the specimens started failing through splitting of the concrete.

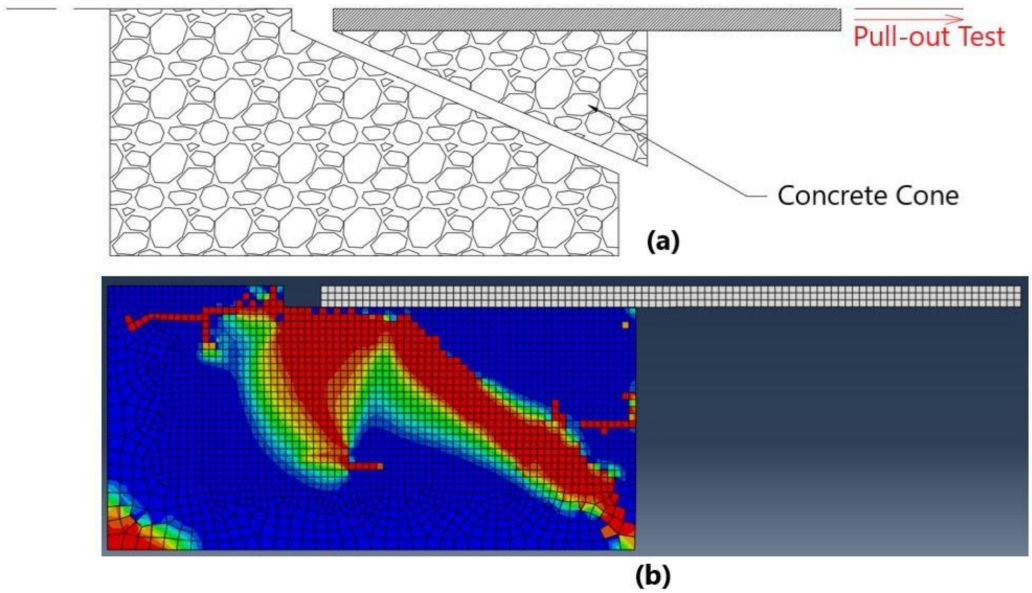

Figure 9. Representation of the concrete cone failure in the numerical pull-out test (**a**), tensile damage in the numerical model (**b**).

4. Parametric Study

To further validate our model, a parametric study is presented, where the impact of the embedment depth, the diameter of the rebar, and the concrete cover on the mechanical parameters of our numerical model are investigated.

The results of the evolution of the bond stress and the maximum pull-out load at the concrete-rebar interface as a function of the corrosion degree are presented in the following subsection.

4.1. Effect of the Embedment Depth

In this section, the impact of the embedment depth on the mechanical properties of our model is studied. In total, three embedment depths are considered: 50 mm, 70 mm, and the initial embedment presented in the previous section of 100 mm. For each model, the same degrees of corrosion were considered, and the evolution of the maximum pull-out load for each simulation as a function of the corrosion degree for the three embedment depths studied is presented in Figure 10.

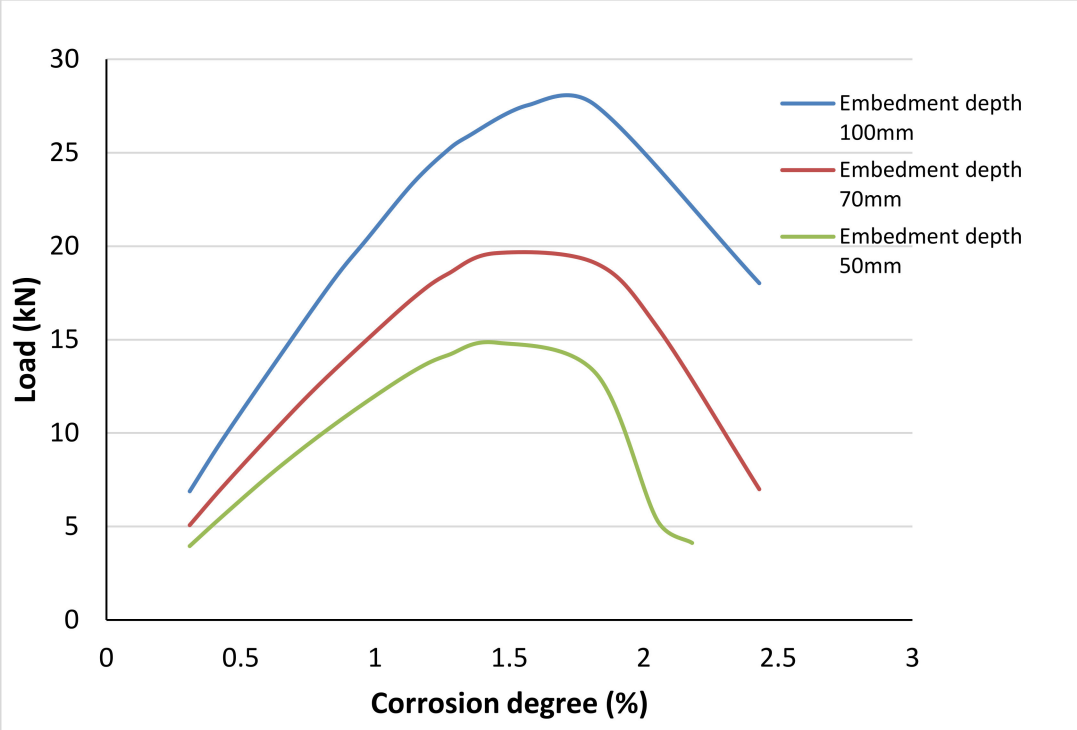

Figure 10. Evolution of the maximum pull-out load as a function of the corrosion degree for different embedment depths.

We can notice in Figure 10 that the greater the embedment depth is, the greater the pulling-out load is. This result has been reported in the literature [19,27], and can be explained as follows: the embedment depth is directly linked to the size of the surface in contact with the concrete. This means that there is more friction as the embedment depth is increased, which makes it harder to pull-out the reinforcement, even if it is corroded, as can be seen in Figure 10. We can notice that the pulling load is twice as bigger for an embedment depth of 100 mm than for an embedment depth of 50 mm. Finally, we can also note that there is an increase in the maximum pulling load for lower degrees of corrosion and a significant drop after about 1.5% corrosion, and that this drop happens at around the same corrosion degree for the three models. We can conclude that the embedment depth only affects the load necessary to pull-out the rebar.

4.2. Effect of the Diameter of the Rebar

In this section, the impact of the rebar diameter on the pull-out load and the bond stress of the model is studied. In total, four diameters are considered: 10 mm, 12 mm, 14 mm, and 16 mm. The evolution of the maximum pull-out load for each simulation for the four diameters at the same corrosion degrees is plotted in Figure 11.

We can see that the greater the diameter of the rebar is, the greater the pull-out load is. The impact of the diameter on the adherence between the rebar and the concrete has been studied, and the results in the literature are scattered. It has been reported in [28] that a greater diameter of the rebar improves the adherence. This can be explained by the fact that when we increase the diameter of the rebar, we also increase the surface in contact with concrete, meaning that the bond stress increases as we increase the diameter of the rebar, for the same corrosion degrees. This can be observed in Figure 12, where we plotted the bond stress as a function of the rebar diameter for the three diameters studied.

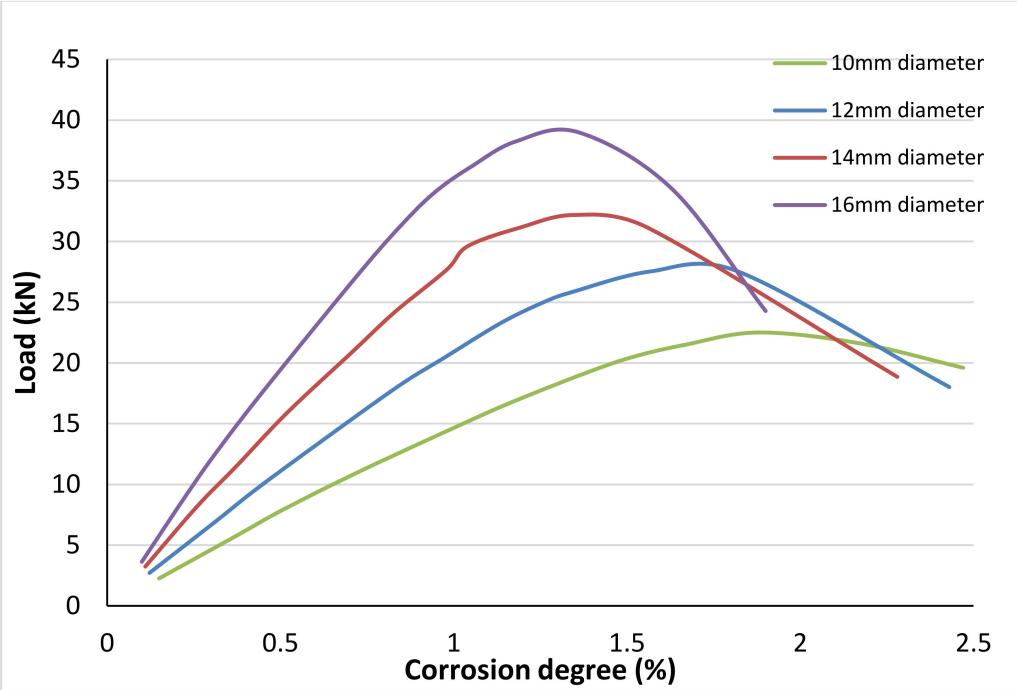

Figure 11. Evolution of the maximum pull-out load as a function of the corrosion degree for different rebar diameters.

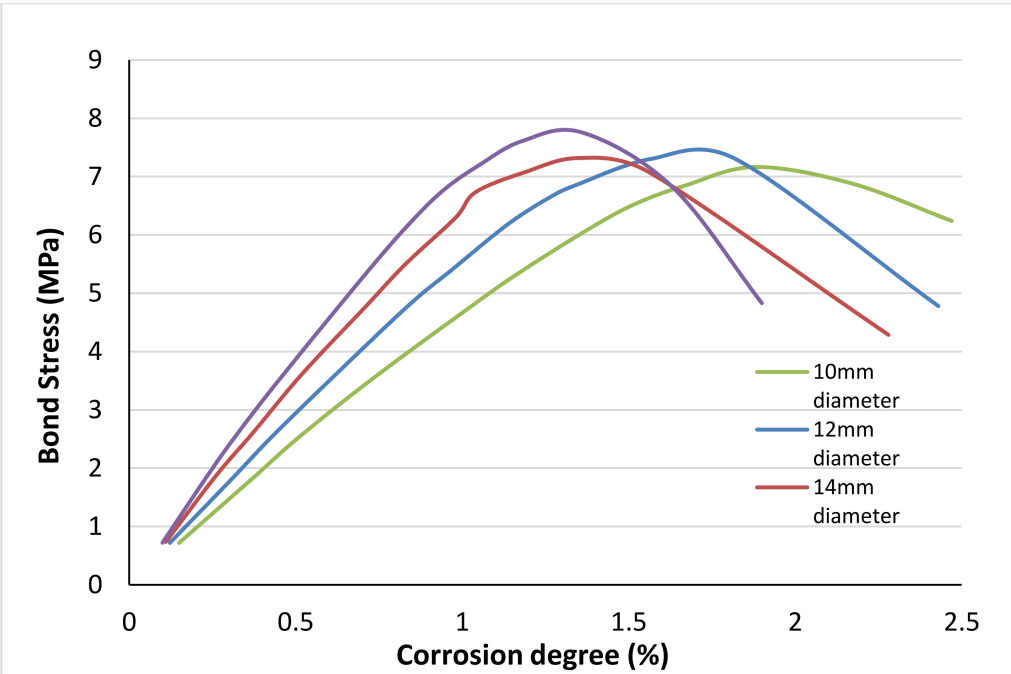

Figure 12. Evolution of the bond stress as a function of the corrosion degree for different rebar diameters.

We can also see in Figure 12 that the bond stress is greater for larger rebar for low degrees of corrosion and when the drop of the bond stress happens, this trend is reversed. We note that the corrosion degree where this drop of the bond stress occurs is smaller as we increase the diameter of the rebar. This is because the corrosion degree of a rebar depends mainly on its volume and mass. This means that for the same corrosion degree, the volume expansion of rebar of a diameter of 14 mm damages the interface more significantly than a

rebar of a diameter of 10 mm. We can conclude that the diameter of the rebar impacts not only the maximum pulling load of the corroded rebar, but also the bond stress.

4.3. Effect of the Concrete Cover

In this section, the impact of the concrete cover on the mechanical properties of our model is investigated. A total of three concrete cover sizes are considered: 50 mm, 70 mm, and 100 mm. In Figure 13, the evolution of the bond stress as a function of the corrosion degree for the three concrete covers we chose to work with is presented.

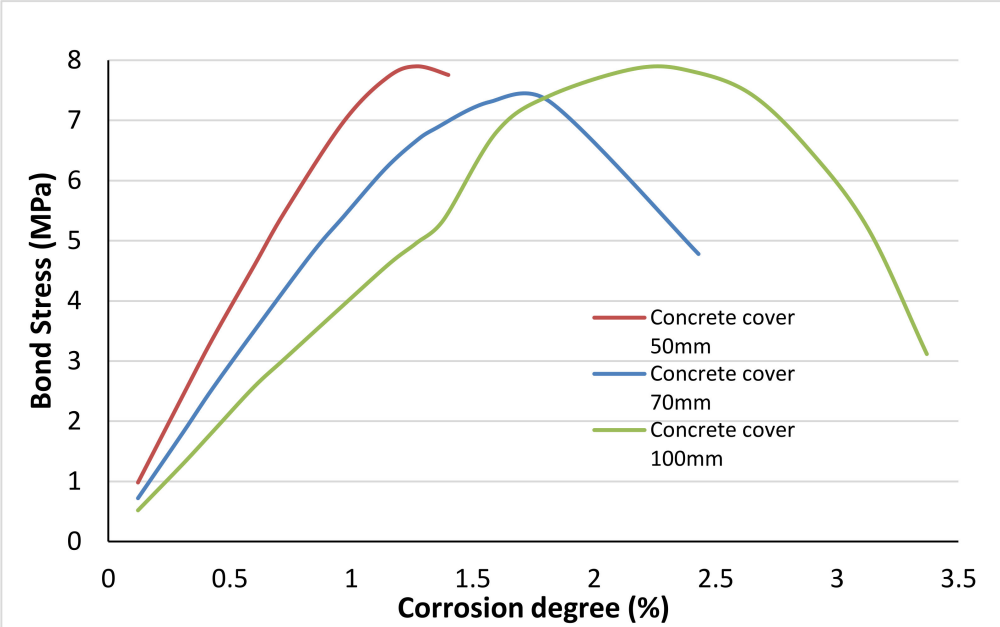

Figure 13. Evolution of the bond stress as a function of the corrosion degree for different concrete cover sizes.

We can clearly note that the concrete cover affects highly the bond stress in our numerical model. We can also see that the concrete cover doesn't affect the evolution of the bond stress significantly, but the interface is more easily damaged. For a concrete cover of 50 mm, we can see that at a corrosion degree of around 1%, the interface is sufficiently damaged to affect the bond stress between the reinforce and the concrete, whereas with a concrete cover of 100 mm, the interface is damaged at a corrosion degree of around 2.5%.

We can clearly see that a sufficient concrete cover helps to prevent the early damaging of the bond stress between the two materials. This has been observed in [3,11]. We can also note that with a small concrete cover, 50 mm in our case, the numerical model has significant issues of convergence past the 1.2% corrosion degree. This is due to its extreme state of damaging.

5. Conclusions

In the present paper, a 2D numerical model of the pull-out test for RC structures with corroded reinforcement was presented. The modeling approach was based on the use of Concrete Damage Plasticity model, which can model the damaging in compression and tension and on modeling of an interface that can model normal and tangential contact. The obtained results were then compared to experimental data in the literature. The following conclusions can be drawn:

- At lower degrees of corrosion, approximately 1.5% in our model, the bond stress increases because the concrete at the interface is not yet sufficiently damaged;
- After a certain degree of corrosion, the bond stress significantly drops due to the damaging and deterioration of the concrete cover;

- Failure by splitting of concrete happens more often in our numerical model when the corrosion degree is greater than 1%;
- Increasing the embedment depth of the rebar increases the maximum pull-out load of each simulation for the same corrosion degree;
- Increasing the rebar diameter increases the bond stress and the maximum pull-out load for the same corrosion degree;
- The larger the rebar diameter is, the sooner the bond stress is affected and the concrete at the interface is damaged;
- Increasing the size of the concrete cover delays significantly the drop of the bond stress and the deterioration of the concrete cover.

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