Cathodic Protection of Steel in Reinforced Concrete

Introduction

Cathodic protection (CP) is a common strategy for retarding the corrosion of reinforcing steel in concrete structures, such as bridges and parking garages. By the use of CP the potential of the corroding surface is lowered, thereby decreasing the rate of undesired anodic corrosion reaction.

This example models the cathodic protection of a steel reinforcing bar (rebar) in concrete. The corrosion cell consists of a zinc anode, the concrete, acting as electrolyte, and the steel surface. Iron oxidation, water reduction (hydrogen evolution) and oxygen reduction are considered on the steel surface, whereas oxygen and charge transport are accounted for in the concrete electrolyte.

The anode and the steel surface are connected electrically via a potentiostat that controls the cell voltage.

Concrete is a porous material, and an effect of this is that its transport properties for ions and gases vary with the moisture content. Therefore the electrolyte conductivity and oxygen diffusion coefficient are modeled to vary with the concrete pore saturation level using empirical data.

The corrosion rate for various moisture contents is investigated.

The model example is based on a paper by Muehlenkamp and others (Ref. 1).

For a more detailed description for how to build this model, including screen shots, see the *Introduction to the Corrosion Module*.

Model Definition

GEOMETRY

Figure 1 shows the model geometry. The geometry modeled represents a two dimensional cross section of a repeating unit cell in a larger structure where three symmetry planes (top, bottom and right) have been used in order to reduce the model geometry. The zinc anode has been coated onto the concrete by thermal spraying and is assumed to be permeable to air.
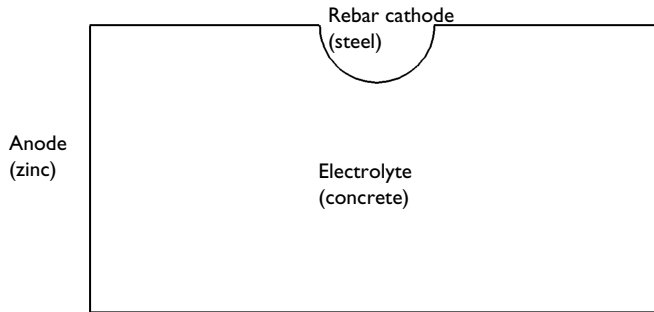
Figure 1: Model geometry. One electrolyte domain and two electrode surfaces.

CONCRETE DOMAIN EQUATIONS

Use a Tertiary Current Distribution Nernst Planck interface to model the electrochemical currents. The electrolyte conductivity depends on the pore saturation level according to Figure 2.
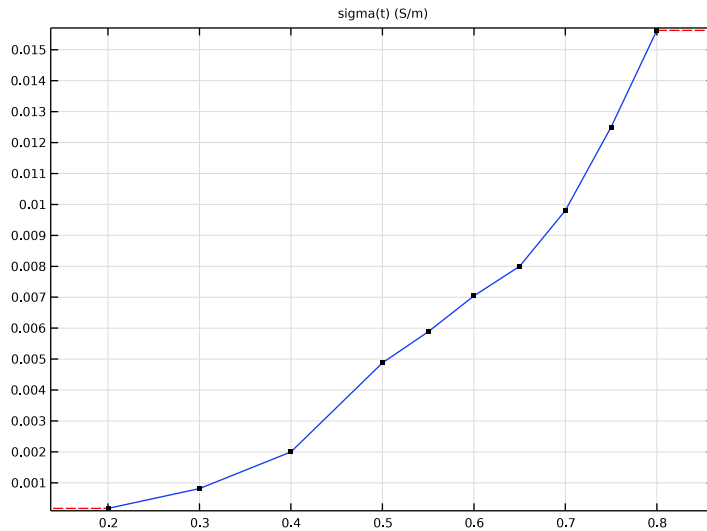

Figure 2: Electrolyte conductivity (S/m) as function of the concrete pore saturation level.

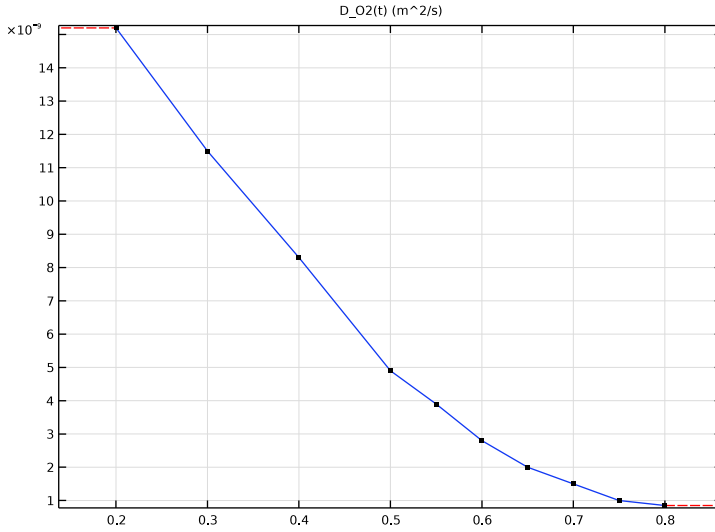The oxygen diffusivity depends on the pore saturation level according to Figure 3.

Figure 3: Oxygen diffusivity (m^2/s) in the concrete as function of pore saturation.

BOUNDARY CONDITIONS

Choose the electrical potential of the Zn anode as ground for the system. By assuming the kinetics of the Zn anode to be very fast the polarization is neglected in the model, setting the electrolyte potential to

$$\phi_{l, Zn} = -E_{eq, Zn} + \phi_{s, Zn} = -E_{eq, Zn}$$

Set the concentration of oxygen at the Zn anode to atmospheric conditions according to

$$c_{O_2, Zn} = c_{O_2, ref}$$

Consider three different electrode reactions on the steel rebar boundary: iron oxidation, oxygen reduction, and hydrogen evolution:

$$Fe \rightarrow Fe^{2+} + 2e^-$$

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$$

$$2H_2O + 2e^- \rightarrow H_2 + 2OH^-$$
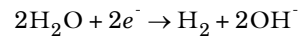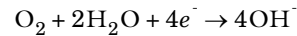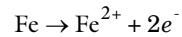
Model the reaction kinetics for these reactions with an Electrode Surface node in the Tertiary Current Distribution, Nernst Planck interface, on which the external electric potential of the steel bar, $\phi_{s,\,\mathrm{steel}}$, is set to the applied cell potential of -1 V.

The electrode kinetics of the steel bar reactions are described by Tafel expressions according to

$$i_{\mathrm{Fe}} = i_{0,\,\mathrm{Fe}} \cdot 10^{\frac{\eta_{\mathrm{Fe}}}{A_{\mathrm{Fe}}}}$$

$$i_{\mathrm{O_2}} = -\frac{c_{\mathrm{O_2}}}{c_{\mathrm{O_2,\,ref}}} i_{0,\,\mathrm{O_2}} \cdot 10^{\frac{\eta_{\mathrm{O_2}}}{A_{\mathrm{O_2}}}}$$

$$i_{\mathrm{H_2}} = -i_{0,\,\mathrm{H_2}} \cdot 10^{\frac{\eta_{\mathrm{H_2}}}{A_{\mathrm{H_2}}}}$$

using the parameters shown in Table 1, where the overpotential for each reaction is calculated as

$$\eta = \phi_{s,\,\mathrm{steel}} - \phi_l - E_{\mathrm{eq}}$$

TABLE 1: ELECTRODE REACTION PARAMETERS.

PARAMETER	UNIT	Zn	Fe	O_2	H_2
Equilibrium potential, E_{eq}	V	-0.68	-0.76	0.189	-1.03
Exchange current density, i_0	A/m^2	-	$7.1 \cdot 10^{-5}$	$7.7 \cdot 10^{-7}$	$1.1 \cdot 10^{-2}$
Tafel slope, A	V/decade	-	0.41	-0.18	-0.15

The oxygen reduction reaction causes a flux of oxygen at the steel surface according to Faraday's law.

Use atmospheric concentration as initial value for the oxygen concentration variable.

STUDY

Solve the model using a parametric sweep over a stationary study step, solving for a range of pore saturation values from 0.2 to 0.8.

Results and Discussion

Figure 4 shows the electrolyte potential for a pore saturation level of 0.8. The electrolyte potentials is lower toward the back (the right side) of the rebar.
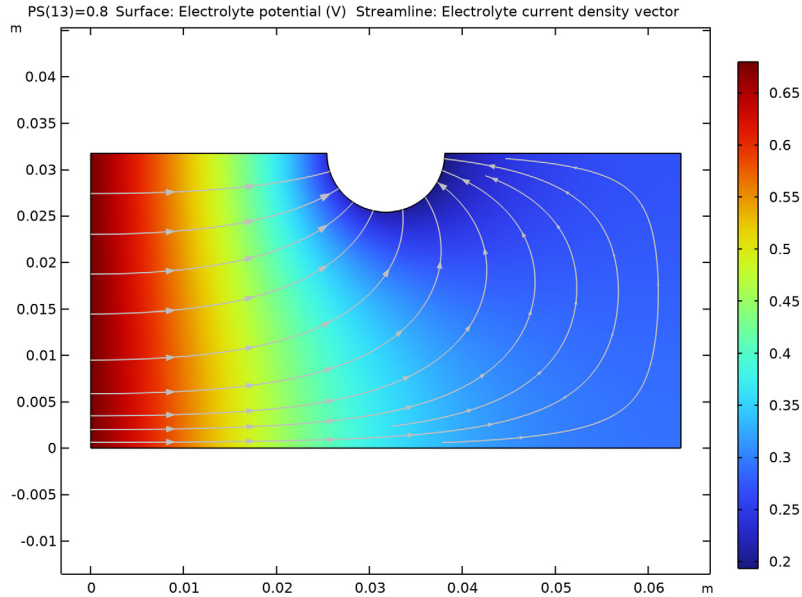

Figure 4: Electrolyte potential for a pore saturation (moisture) level of 0.8.

Figure 5 shows the oxygen concentration in the electrolyte for a pore saturation level of 0.8. The concentration is very low close to the rebar, indicating that the oxygen reduction kinetics should be mass transport limited for this pore saturation level. The concentration is lower toward the back of the rebar.
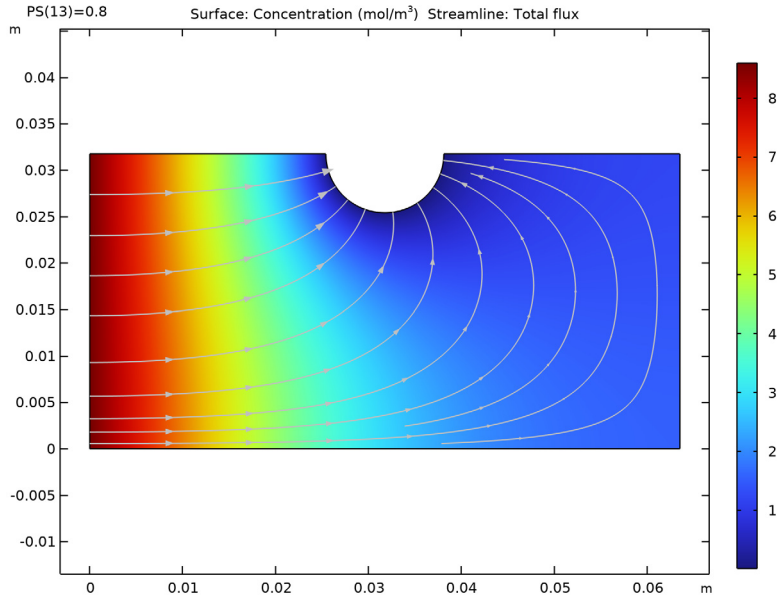
Figure 5: Oxygen concentration for a pore saturation (moisture) level of 0.8.

An important factor for the corrosion rate of the rebar is the operating electrode potential, which is the difference between the electric potential (here the potential applied by the potentiostat) and the electrolyte potential. Figure 6 shows the operating electrode potential for various pore saturation levels for three different points (front, middle and

back) of the rebar surface. The potential drops considerably at a pore saturation level of **0.65**.
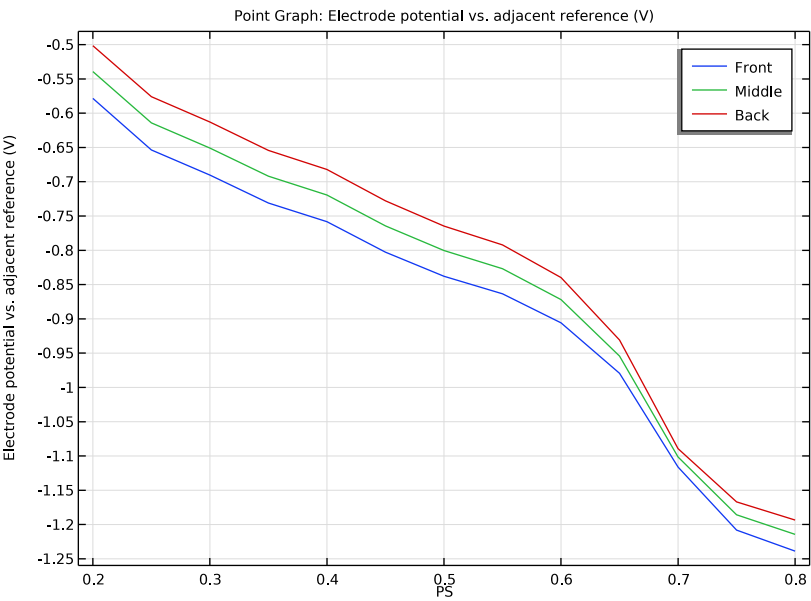

Figure 6: Operating electrode potential for three points at the rebar-concrete interface.

Figure 7 shows the local oxygen concentration at the rebar for various pore saturation levels. The concentration drops significantly toward higher saturation levels. This is an effect of the decreasing diffusivity of oxygen in the concrete for higher saturation levels.
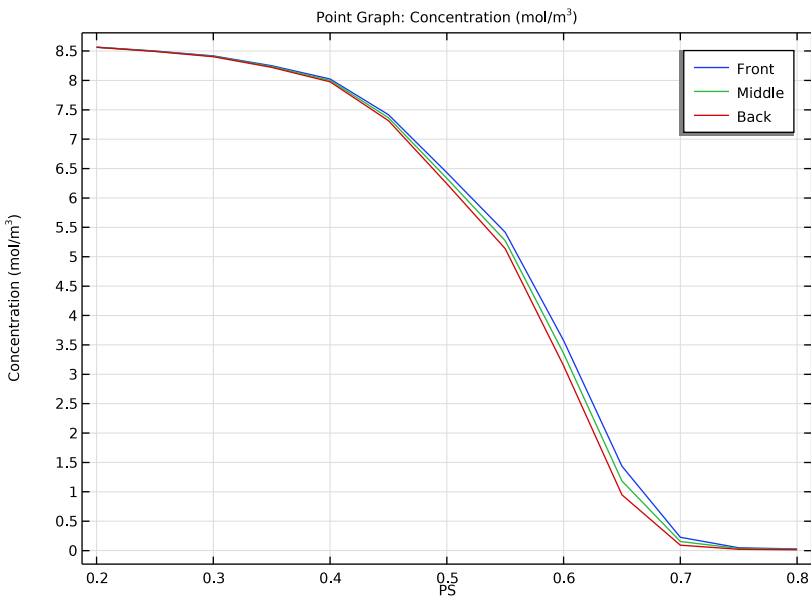

Figure 7: Local oxygen concentration at the rebar-concrete interface.

The local oxygen reduction current densities at the rebar are shown in Figure 8. The magnitude of the oxygen reduction current density is highest around a pore saturation level of $0.6 - 0.65$. Up to this point the current densities are increasing due to increased

electrolyte conductivity, but for higher pore saturation levels the current densities decrease due to decreased oxygen diffusivity.
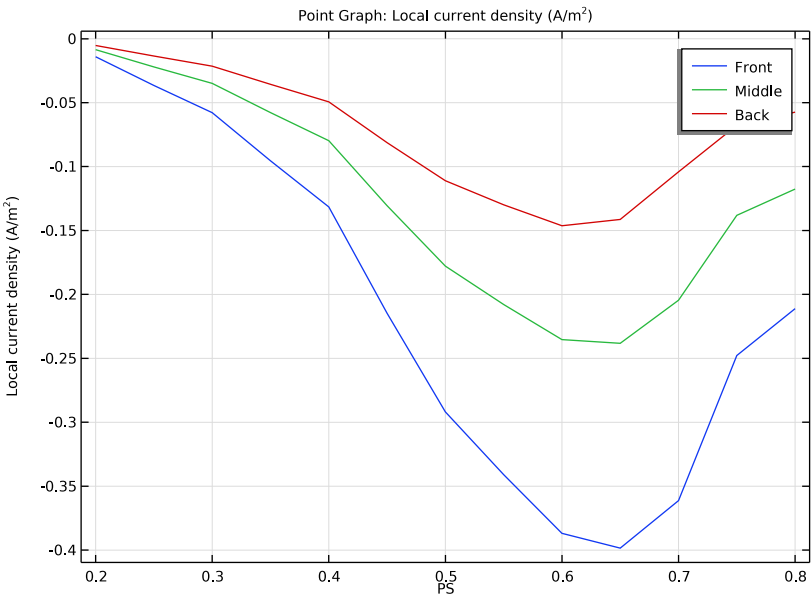

Figure 8: Local oxygen reduction current densities at the rebar-concrete interface.

The hydrogen evolution current densities are shown in Figure 9. Hydrogen evolution is very limited below a PS level of 0.65, which is the saturation level at which the electrode potential gets below the equilibrium potential (1.03 V) for the hydrogen evolution reaction, see Figure 6.
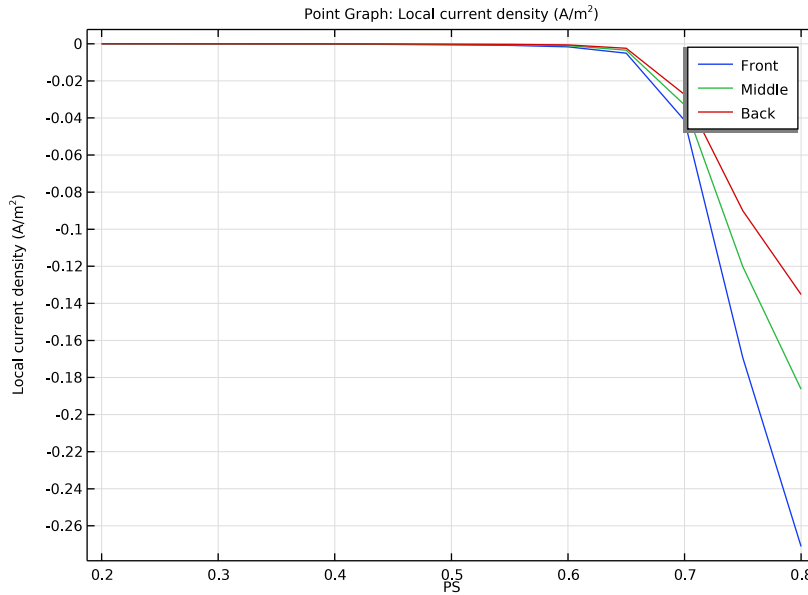
Figure 9: Local hydrogen evolution current densities at the rebar-concrete interface.

Finally, the iron oxidation current densities are shown in Figure 10. Corrosion current densities are higher for low PS levels, which is in line with the higher electrode potential for low PS levels (Figure 6). It should be noted that the magnitude of iron oxidation current density is considerably smaller than oxygen reduction and hydrogen evolution current densities at the steel rebar indicating the effectiveness of zinc coating onto the concrete in protecting the steel rebar from corrosion.
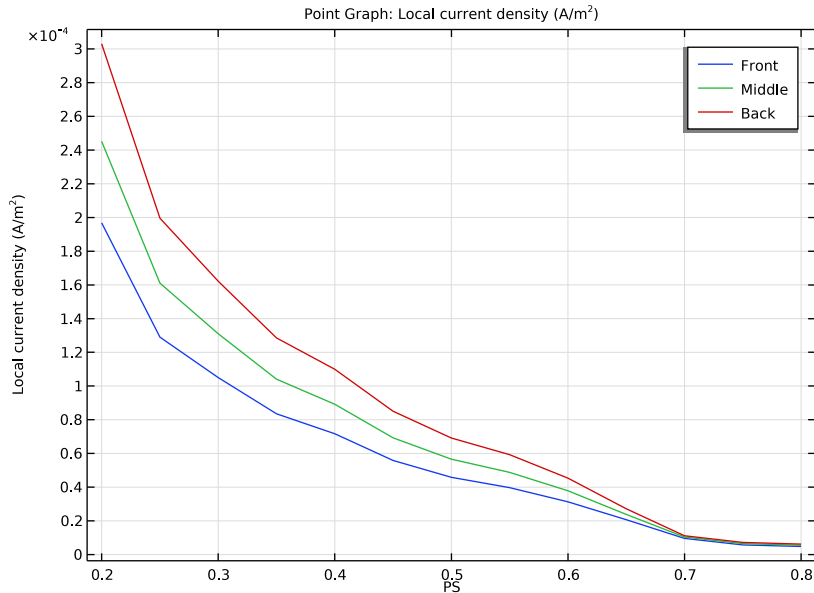
Figure 10: Iron corrosion current densities at the rebar-concrete interface.

Reference

1. E.B. Muehlenkamp, M.D. Koretsky, and J.C. Westall, "Effect of Moisture on the Spatial Uniformity of Cathodic Protection of Steel in Reinforced Concrete," *Corrosion*, vol. 61, no. 6, pp. 519–533, 2012.

Application Library path: `Corrosion_Module/Cathodic_Protection/` `cathodic_protection_in_concrete`

Modeling Instructions

From the **File** menu, choose **New**.

N E W

In the **New** window, click ◈ **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **2D**.

2 In the **Select Physics** tree, select **Electrochemistry>Tertiary Current Distribution, Nernst-Planck>Tertiary, Supporting Electrolyte (tcd)**.

3 Click **Add**.

4 In the **Number of species** text field, type 1.

5 In the **Concentrations (mol/m³)** table, enter the following settings:

c

6 Click **Study**.

7 In the **Select Study** tree, select **General Studies>Stationary**.

8 Click **Done**.

GLOBAL DEFINITIONS

Load the model parameters from a text file.

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 Click **Load from File**.

4 Browse to the model's Application Libraries folder and double-click the file cathodic_protection_in_concrete_parameters.txt.

DEFINITIONS

Create interpolation functions for the electrolyte conductivity and oxygen diffusivity as functions of the pore saturation level. Load the data from text files.

Interpolation 1 (int1)

1 In the **Home** toolbar, click f(x) **Functions** and choose **Local>Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **File**.

4 Click **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file cathodic_protection_in_concrete_sigma.txt.

6 Click **Import**.

7 In the **Function name** text field, type sigma.

8 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
sigma	S/m

9 Click ▣ **Plot**.

The plot should look like Figure 2.

Interpolation 2 (int2)

1 In the **Home** toolbar, click f(X) **Functions** and choose **Local>Interpolation**.

2 In the **Settings** window for **Interpolation**, locate the **Definition** section.

3 From the **Data source** list, choose **File**.

4 Click 📁 **Browse**.

5 Browse to the model's Application Libraries folder and double-click the file
  `cathodic_protection_in_concrete_D_O2.txt`.

6 Click ▣ **Import**.

7 In the **Function name** text field, type D_O2.

8 Locate the **Units** section. In the **Function** table, enter the following settings:

Function	Unit
D_O2	m^2/s

9 Click ▣ **Plot**.

The plot should look like Figure 3.

GEOMETRY 1

Now create the geometry by using a rectangle and a circle.

Rectangle 1 (r1)

1 In the **Geometry** toolbar, click ▢ **Rectangle**.

2 In the **Settings** window for **Rectangle**, locate the **Size and Shape** section.

3 In the **Width** text field, type W.

4 In the **Height** text field, type L.

5 Click ▣ **Build Selected**.

6 Click the ⊹ **Zoom Extents** button in the **Graphics** toolbar.

Circle 1 (c1)

1 In the **Geometry** toolbar, click ⊙ **Circle**.

2 In the **Settings** window for **Circle**, locate the **Size and Shape** section.

3 In the **Radius** text field, type R_rebar.

4 Locate the **Position** section. In the **x** text field, type S+R_rebar.

5 In the **y** text field, type L.

6 Click ▦ **Build Selected**.

Difference 1 (dif1)

1 In the **Geometry** toolbar, click ▰ **Booleans and Partitions** and choose **Difference**.

2 Select the object **r1** only.

3 In the **Settings** window for **Difference**, locate the **Difference** section.

4 Click to select the ▭ **Activate Selection** toggle button for **Objects to subtract**.

5 Select the object **c1** only.

6 In the **Geometry** toolbar, click ▦ **Build All**.

TERTIARY CURRENT DISTRIBUTION, NERNST-PLANCK (TCD)

Now set up the physics for the tertiary current distribution. Start with the domain transport properties.

Electrolyte 1

1 In the **Model Builder** window, under **Component 1 (comp1)>Tertiary Current Distribution, Nernst-Planck (tcd)** click **Electrolyte 1**.

2 In the **Settings** window for **Electrolyte**, locate the **Diffusion** section.

3 In the D_c text field, type D_O2(PS).

4 Locate the **Solvent** section. From the σ_l list, choose **User defined**. In the associated text field, type sigma(PS).

Initial Values 1

1 In the **Model Builder** window, click **Initial Values 1**.

2 In the **Settings** window for **Initial Values**, locate the **Initial Values** section.

3 In the c text field, type C_O2_ref.

Electrode Surface 1

1 In the **Physics** toolbar, click ⬭ **Boundaries** and choose **Electrode Surface**.

2 Select Boundary 1 only.

Zinc oxidation

To implement a fast reaction kinetics assumption, a constant potential is set at the anode surface. To achieve this, set a constant value for the equilibrium potential and use the Primary Condition (Thermodynamic Equilibrium) type of electrode kinetics at the Electrode Reaction child node.

1 In the **Model Builder** window, under **Component 1 (comp1)>Tertiary Current Distribution, Nernst-Planck (tcd)>Electrode Surface 1** click **Electrode Reaction 1**.

2 In the **Settings** window for **Electrode Reaction**, type Zinc oxidation in the **Label** text field.

3 Locate the **Equilibrium Potential** section. From the E_{eq} list, choose **User defined**. In the associated text field, type Eeq_Zn.

4 Locate the **Electrode Kinetics** section. From the **Kinetics expression type** list, choose **Thermodynamic equilibrium**.

Electrode Surface 2

1 In the **Physics** toolbar, click ⬭ **Boundaries** and choose **Electrode Surface**.

2 Select Boundaries 6 and 7 only.

3 In the **Settings** window for **Electrode Surface**, locate the **Electrode Phase Potential Condition** section.

4 In the $\phi_{s,ext}$ text field, type E_app.

Oxygen reduction

Three different reactions occur at this electrode surface: oxygen reduction, iron oxidation and hydrogen evolution.

1 In the **Model Builder** window, under **Component 1 (comp1)>Tertiary Current Distribution, Nernst-Planck (tcd)>Electrode Surface 2** click **Electrode Reaction 1**.

2 In the **Settings** window for **Electrode Reaction**, type Oxygen reduction in the **Label** text field.

3 Locate the **Stoichiometric Coefficients** section. In the n text field, type 4.

4 In the ν_c text field, type -1.

5 Locate the **Equilibrium Potential** section. From the E_{eq} list, choose **User defined**. In the associated text field, type Eeq_O2.

6 Locate the **Electrode Kinetics** section. From the **Kinetics expression type** list, choose **Cathodic Tafel equation**.

7 In the i_0 text field, type c/C_O2_ref*i0_O2.

8 In the A_c text field, type A_O2.

Electrode Surface 2
In the **Model Builder** window, click **Electrode Surface 2**.

Iron oxidation
1 In the **Physics** toolbar, click ⚙ **Attributes** and choose **Electrode Reaction**.

2 In the **Settings** window for **Electrode Reaction**, type Iron oxidation in the **Label** text field.

3 Locate the **Equilibrium Potential** section. From the E_{eq} list, choose **User defined**. In the associated text field, type Eeq_Fe.

4 Locate the **Electrode Kinetics** section. In the i_0 text field, type i0_Fe.

5 From the **Kinetics expression type** list, choose **Anodic Tafel equation**.

6 In the A_a text field, type A_Fe.

Electrode Surface 2
In the **Model Builder** window, click **Electrode Surface 2**.

Hydrogen evolution
1 In the **Physics** toolbar, click ⚙ **Attributes** and choose **Electrode Reaction**.

2 In the **Settings** window for **Electrode Reaction**, type Hydrogen evolution in the **Label** text field.

3 Locate the **Equilibrium Potential** section. From the E_{eq} list, choose **User defined**. In the associated text field, type Eeq_H2.

4 Locate the **Electrode Kinetics** section. In the i_0 text field, type i0_H2.

5 From the **Kinetics expression type** list, choose **Cathodic Tafel equation**.

6 In the A_c text field, type A_H2.

Concentration 1
The concrete is in contact with air at the left, and the concentration is therefore constant at this boundary.

1 In the **Physics** toolbar, click ⬭ **Boundaries** and choose **Concentration**.

2 Select Boundary 1 only.

3 In the **Settings** window for **Concentration**, locate the **Concentration** section.

4 Select the **Species c** check box.

5 In the $c_{0,c}$ text field, type C_O2_ref.

MESH 1

Use the physics-controlled mesh settings, with an extra fine mesh size.

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Mesh 1**.

2 In the **Settings** window for **Mesh**, locate the **Physics-Controlled Mesh** section.

3 From the **Element size** list, choose **Extra fine**.

STUDY 1

Set up an auxiliary continuation sweep for the 'PS' parameter.

Step 1: Stationary

1 In the **Model Builder** window, under **Study 1** click **Step 1: Stationary**.

2 In the **Settings** window for **Stationary**, click to expand the **Study Extensions** section.

3 Select the **Auxiliary sweep** check box.

4 Click ✛ **Add**.

5 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
PS (Pore saturation)	range(0.2, 0.05, 0.8)	

6 In the **Home** toolbar, click ▬ **Compute**.

RESULTS

The model is now solved. Follow the remaining steps below to reproduce the plots from the Results and Discussion section.

Rebar Potential

1 In the **Home** toolbar, click 🔳 **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type Rebar Potential in the **Label** text field.

Point Graph 1

1 Right-click **Rebar Potential** and choose **Point Graph**.

2 Select Points 3–5 only.

3 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)> Tertiary Current Distribution, Nernst-Planck>tcd.Evsref - Electrode potential vs. adjacent reference - V**.

4 Click to expand the **Legends** section. Select the **Show legends** check box.

5 From the **Legends** list, choose **Manual**.

6 In the table, enter the following settings:

Legends
Front
Middle
Back

7 In the **Rebar Potential** toolbar, click ⊙ **Plot**.

Rebar Potential

In the **Model Builder** window, right-click **Rebar Potential** and choose **Duplicate**.

Oxygen Concentration

1 In the **Model Builder** window, under **Results** click **Rebar Potential 1**.

2 In the **Settings** window for **1D Plot Group**, type Oxygen Concentration in the **Label** text field.

Point Graph 1

1 In the **Model Builder** window, expand the **Oxygen Concentration** node, then click **Point Graph 1**.

2 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)> Tertiary Current Distribution, Nernst-Planck>Species c>c - Concentration - mol/m³**.

Oxygen Concentration

In the **Model Builder** window, right-click **Oxygen Concentration** and choose **Duplicate**.

Oxygen Reduction Current Density

1 In the **Model Builder** window, under **Results** click **Oxygen Concentration 1**.

2 In the **Settings** window for **1D Plot Group**, type Oxygen Reduction Current Density in the **Label** text field.

Point Graph 1

1 In the **Model Builder** window, expand the **Oxygen Reduction Current Density** node, then click **Point Graph 1**.

2 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)> Tertiary Current Distribution, Nernst-Planck>Electrode kinetics>tcd.iloc_er1 - Local current density - A/m²**.

Oxygen Reduction Current Density

In the **Model Builder** window, right-click **Oxygen Reduction Current Density** and choose **Duplicate**.

Iron Oxidation Current Density

1 In the **Model Builder** window, under **Results** click **Oxygen Reduction Current Density 1**.

2 In the **Settings** window for **ID Plot Group**, type Iron Oxidation Current Density in the **Label** text field.

Point Graph 1

1 In the **Model Builder** window, expand the **Iron Oxidation Current Density** node, then click **Point Graph 1**.

2 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)> Tertiary Current Distribution, Nernst-Planck>Electrode kinetics>tcd.iloc_er2 - Local current density - A/m²**.

3 In the **Iron Oxidation Current Density** toolbar, click **Plot**.

Iron Oxidation Current Density

In the **Model Builder** window, right-click **Iron Oxidation Current Density** and choose **Duplicate**.

Hydrogen Evolution Current Density

1 In the **Model Builder** window, under **Results** click **Iron Oxidation Current Density 1**.

2 In the **Settings** window for **ID Plot Group**, type Hydrogen Evolution Current Density in the **Label** text field.

Point Graph 1

1 In the **Model Builder** window, expand the **Hydrogen Evolution Current Density** node, then click **Point Graph 1**.

2 In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)> Tertiary Current Distribution, Nernst-Planck>Electrode kinetics>tcd.iloc_er3 - Local current density - A/m²**.

3 In the **Hydrogen Evolution Current Density** toolbar, click **Plot**.