SBUF

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ARC-PROGRAM

PROGRAM FOR ASSESSING ANCHORAGE IN CORRODED REINFORCED CONCRETE STRUCTURES

Verktyg för bedömning av korroderade betongkonstruktioners tillstånd och livslängd

Per Kettil, Skanska

2018-09-15

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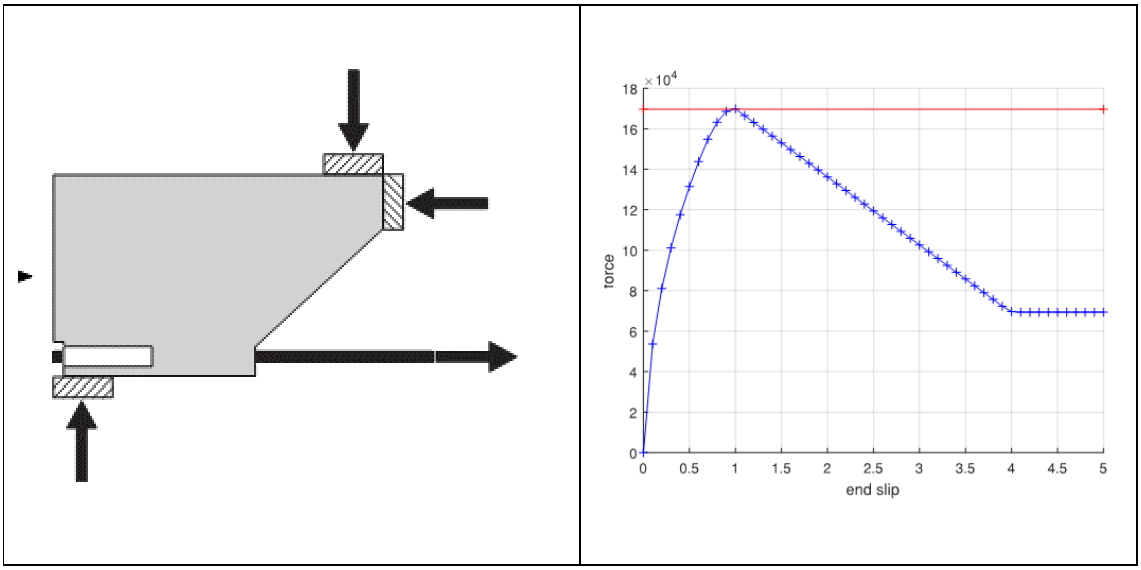
ARC-program



Program for assessing anchorage in corroded reinforced concrete structures

Program description

Version 1.0

2018-08-02

Preface

The program development was initiated by work presented in [1]. The program was developed for practical use within the project “Verktyg för bedömning av korroderade betongkonstruktioners tillstånd och livslängd” (“Tool for assessment of corroding reinforced concrete structures”), by the project group:

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Summary

Corrosion of reinforcement affects the bond mechanism between reinforcement and concrete, and thus the anchorage. The ARC-program contains a model that describes the bond-slip response of corroded reinforcement, which can be used in the assessment of the anchorage capacity in corrosion-damaged structures. The program files together with a number of example files may be downloaded from www.sbuf.se or www.chalmers.se.

Sammanfattning (summary in Swedish)

Armeringskorrosion påverkar vidhäftnings-/förankringskapaciteten mellan betong och armering och därmed konstruktionens bärförmåga. Datorprogrammet ARC (förkortningen betyder översatt till svenska ”bedömning av förankringskapacitet i korroderade armerade betongkonstruktioner) innehåller en beräkningsmodell som beskriver sambandet mellan vidhäftning och glidning mellan betong och armering, och kan användas för att bestämma förankringskapaciteten även för korroderad armering. Programfiler och exempelfiler kan laddas ned från www.sbuf.se eller www.chalmers.se.

Limitations

Note that the program is developed to be used for assessment of existing structures, not for design of new structures. For example, the partial safety factors in section 2.4 were calculated for the target reliability index of 3.7, which is recommended for assessment of existing structures; in design of new structures, typically a larger value of reliability index is required.

Disclaimer

The program is based on scientific research and been developed by best practice. But the authors can not take any responsibility for the use of the program. It is the user’s full responsibility to verify the correctness and interpretation of results.

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1 Introduction

Corrosion of reinforcement affects the bond mechanism between reinforcement and concrete, and thus the anchorage. This program contains a model that describes the bond-slip response of corroded reinforcement, which can be used in the assessment of the anchorage capacity in corrosion-damaged structures.

2 Theory

2.1 Overview

The program contains a model that describes the bond-slip response of corroded reinforcement. The model is an extension of the bond-slip model given in the CEB-FIP (*fib*) Model Code 2010 to account for the effect of corrosion. In the following the theory behind the program and the selection of relevant model parameters (input data) for actual applications is presented.

2.2 Mathematical model

2.2.1 Differential equation

The mathematical model is based on the differential equation if equilibrium of a bar, see [1], [3] and Figure 2.1:

$$A_s \cdot \frac{d\sigma_s}{dx} - \pi \cdot \phi_m \cdot \tau_b = 0 \qquad (1)$$

where As is the cross-sectional area of the bar and ϕ_m is the bar diameter, σ_s is the stress in the bar and τ_b is the bond stress.

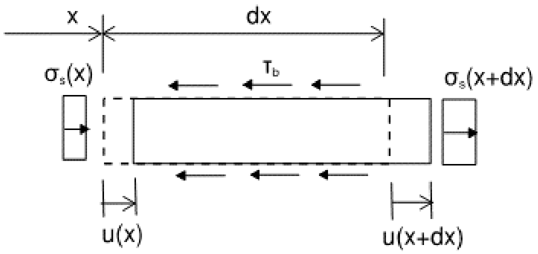


Figure 2.1 Illustration of stresses acting on a bar segment with length dx and the resulting deformation.

The reinforcement bar within the anchorage length is assumed to be in the elastic range, thus:

$$\sigma_s = E_s \varepsilon_s, \quad \varepsilon_s = \frac{du}{dx} \qquad (2, 3)$$

E_s is the elastic modulus, ε_s is the strain and u denotes the displacement of the bar at point x. If the deformation of the surrounding concrete is neglected, the slip s between the reinforcement bar and the surrounding concrete equals the displacement of the bar:

$$u = s \tag{4}$$

When considering pull-out of a reinforcement bar with embedment length l_b and prescribed displacement the boundary conditions are:

$$\sigma_s(0) = 0, \quad u(l_b) = u_{l_b} \tag{5, 6}$$

where u_{l_b}, is the displacement at the end of the bar where the pulling force is applied. The corresponding pulling force F_{l_b}, can be obtained as:

$$F_{l_b} = A_s \sigma_s(l_b) \tag{7}$$

where A_s is the area of the bar, and $\sigma_s(l_b)$ is the stress at the pulled end.

2.2.2 Bond-slip model

For monotonic loading, the bond stress can be calculated as a function of the slip, for example using the following equations from Model Code 2010 [4], see also [3]:

$$\tau_b = \tau_{bmax}(s/s_1)^{\alpha} \qquad \text{for } 0 \le s \le s_1 \tag{8}$$

$$\tau_b = \tau_{bmax} \qquad \text{for } s_1 \le s \le s_2 \tag{9}$$

$$\tau_b = \tau_{bmax} - (\tau_{bmax} - \tau_{res})\,(s - s_2)/(s_3 - s_2) \quad \text{for } s_2 \le s \le s_3 \tag{10}$$

$$\tau_b = \tau_{res} \qquad \text{for } s_3 \le s \tag{11}$$

where the parameters depends on the mode of failure, i.e. pull-out or splitting failure, see tables below.

Table 2-1. Bond-slip parameters

	Pull-out (MC 2010)	
	“Good”	**“All other”**
$\boldsymbol{\tau_{bmax}}$	$2.5\sqrt{f_{cm}}$	$1.25\sqrt{f_{cm}}$
$\boldsymbol{s_1}$	$1.0\ mm$	$1.8\ mm$
$\boldsymbol{s_2}$	$2.0\ mm$	$3.6\ mm$
$\boldsymbol{s_3}$	$c_{clear}{}^{\star}$	$c_{clear}{}^{\star}$
$\boldsymbol{\alpha}$	0.4	0.4
$\boldsymbol{\tau_{res}}$	$0.4\tau_{bmax}$	$0.4\tau_{bmax}$

* c_{clear} is the clear distance between ribs.

Table 2-2. Bond-slip parameters

	Splitting (MC 2010)			
	“Good”		**“All other”**	
	Unconfined	**Stirrups**	**Unconfined**	**Stirrups**
$\boldsymbol{\tau_{bmax}}$	$2.5\sqrt{f_{cm}}$	$2.5\sqrt{f_{cm}}$	$1.25\sqrt{f_{cm}}$	$1.25\sqrt{f_{cm}}$
$\boldsymbol{\tau_{bu,split}}$	Eq. 12	Eq. 12	Eq. 12	Eq. 12
$\boldsymbol{s_1}$	$s(\tau_{bu,split})$	$s(\tau_{bu,split})$	$s(\tau_{bu,split})$	$s(\tau_{bu,split})$
$\boldsymbol{s_2}$	s_1	s_1	s_1	s_1
$\boldsymbol{s_3}$	$1.2s_1$	$0.5c_{clear}{}^{\star}$	$1.2s_1$	$0.5c_{clear}{}^{\star}$
$\boldsymbol{a}$	0.4	0.4	0.4	0.4
$\boldsymbol{\tau_{res}}$	$0^{\dagger}$	$0.4\tau_{bu,split}{}^{\dagger}$	$0^{\dagger}$	$0.4\tau_{bu,split}{}^{\dagger}$

* c_{clear} is the clear distance between ribs.

† residual capacity modified in the proposed model, ARC2010.

To differ between the two modes of failure, the splitting strength is given in Model Code 2010 as:

$$\tau_{bu,split} = \eta_2 \cdot 6.5 \cdot \left(\frac{f_{cm}}{25}\right)^{0.25} \cdot \left(\frac{25}{\phi_m}\right)^{0.2} \left[\left(\frac{c_{min}}{\phi_m}\right)^{0.25} \left(\frac{c_{max}}{c_{min}}\right)^{0.1} + k_m \cdot K_{tr}\right] \qquad (12)$$

where η_2 is 1.0 and 0.7 for “good” and “all other” bond conditions respectively, f_{cm} is the mean cylinder compressive strength in MPa, ϕ_m is the diameter of the anchored bar in mm, and c_{min} and c_{max} are defined as

$$c_{min} = \min(c_s/2\,, c_x, c_y) \qquad (13)$$

$$c_{max} = \max(c_s/2\,, c_x) \qquad (14)$$

where c_s is the clear spacing between main bars, c_x is the cover in x-direction and c_y is the cover in y-direction. k_m and K_{tr} are the confinement coefficient and the amount of the transverse reinforcement, respectively, defined as

$k_m = 12$ for bars located within $5\phi_m \leq 125$ mm from a stirrup corner
$k_m = 6$ if $c_s \geq 8c_y$
$k_m = 0$ if $c_s < 8c_y$, or if a crack can propagate to the concrete surface without crossing transverse reinforcement

The transverse reinforcement is quantified as:

$$K_{tr} = n_t A_{st}/(n_b \phi_m s_t) \leq 0.05 \qquad (15)$$

where n_t the number of legs of confining reinforcement crossing a potential splitting-failure surface at a section, A_{st} is the cross-sectional area of one leg of a transverse bar, s_t is the longitudinal spacing of confining reinforcement and n_b is the number of anchored bars or pairs of lapped bars in the potential splitting surface.

2.2.3 Influence of corrosion

It has been observed that the local bond stress-slip curve of corroded reinforcement can be approximated by shifting the uncorroded curve in the slip direction [1], see Figure 2.2.

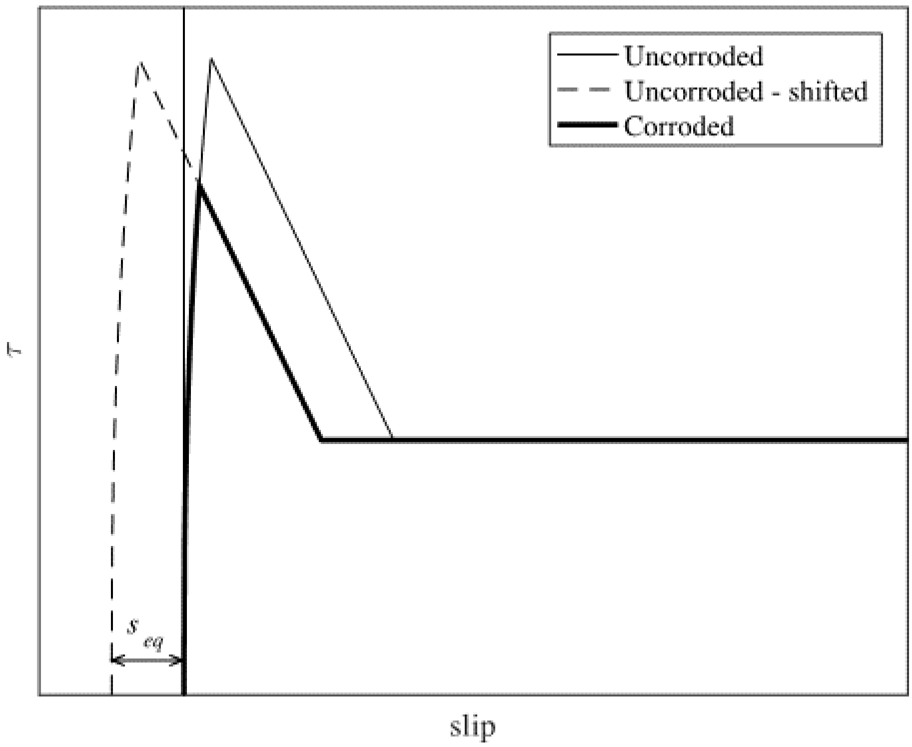


Figure 2.2 Illustration of the equivalent slip, s_{eq}, *to account for the effect of corrosion in a sample bond stress-slip curve, where splitting strength governs the maximum bond stress.*

This can be expressed as:

$$s_{eff} = s + s_{eq} \tag{16}$$

where s_{eff} is the effective slip, s is the mechanical slip and s_{eq} is the equivalent slip to account for the effect of corrosion. The equivalent slip can be estimated as [3]:

$$s_{eq,nostir} = 2.9W_c \qquad \text{without stirrups} \tag{17}$$

$$s_{eq,stir} = 13.6W_c \qquad \text{with stirrups} \tag{18}$$

where W_{c} is the corrosion level (weight loss) in decimals and the equivalent slip is output in mm. For cases without stirrups there is data up to around 15% corrosion, and for cases with stirrups up to approximately 20% corrosion. Therefore, the domains for Equation 17 and 18 are 0-15% and 0-20% corrosion weight loss, respectively.

Increasing corrosion levels will ultimately crack the concrete cover. The corrosion penetration leading to cracking can be estimated as [3]:

$$x_{cr} = 11 \cdot \left(\frac{f_{cm}}{40}\right)^{0.8} \cdot \left(\frac{c}{\phi_m}\right)^{1.5} \cdot \left(\frac{\phi_m}{16}\right)^{0.5} \tag{19}$$

where f_{cm} is the mean cylinder compressive strength in MPa, ϕ_m is the diameter of the anchored bar in mm, and c is the concrete cover. The influence of corrosion on cracking of the cover is accounted for by using the reduced splitting strength [3]:

$$\tau_{bu,split,red} = \eta_2 \cdot 6.5 \cdot \left(\frac{f_{cm}}{25}\right)^{0.25} \cdot \left(\frac{25}{\phi_m}\right)^{0.2} (1 + k_m \cdot K_{tr}) \tag{20}$$

where η_2 is 1.0 and 0.7 for “good” and “all other” bond conditions respectively, f_{cm} is the mean cylinder compressive strength in MPa, ϕ_m is the diameter of the anchored bar in mm, and k_m and K_{tr} are the confinement coefficient and the amount of the transverse reinforcement, respectively, defined in the previous section.

A modified expression of the residual bond capacity for specimens with low stirrup content is proposed for both the corroded and uncorroded cases [3]:

$$\tau_{res,mod}(K_{tr}) = \begin{cases} (0.16 + 12K_{tr}) \cdot \tau_{bu,split,red} & \text{for } 0 \leq K_{tr} \leq 0.02 \\ 0.4 \cdot \tau_{bu,split,red} & \text{for } 0.02 < K_{tr} \end{cases} \tag{21}$$

2.3 Model parameters

2.3.1 Summary of model parameters

Reinforcement bar:

ϕ_m = bar diameter
E_s = elastic modulus

Concrete:

f_{cm} = mean cylinder compressive strength in MPa

Bond:

s_{eq} = equivalent slip, only dependent on
W_c = corrosion level (weight loss) in percent

τ_{bmax} defined by table and is only dependent on f_{cm}

$\tau_{bu,split}$ for uncorroded and and $\tau_{bu,split,red}$ for corroded bars are defined by Equation 12 and 20 respectively, and are dependent on:

η_2 = 1.0 and 0.7 for “good” and “all other” bond conditions
c_{min} and c_{max} according to equation, defined by:
  c_{s} = the clear spacing between main bars
  c_{x} = cover in x-direction
  c_{y} = cover in y-direction

k_{m} = confinement coefficient, depends on distance from stirrup corner

c_{s} = clear spacing between main bars

K_{tr} = coefficient amount of transverse reinforcement, as given by Equation 15, depends on:
  n_{t} = number of legs of confining reinforcement
  A_{st} = cross-sectional area of one leg of a transverse bar
  s_{t} = longitudinal spacing of confining reinforcement
  n_{b} = the number of anchored bars

$\tau_{\mathrm{res,mod}}$ = residual strength, as given by Equation 21, and depends on
  $\tau_{\mathrm{bu,split,red}}$ = see above
  K_{tr} = see above

2.3.2 Determination and selection of parameters

Reinforcement bar:

ϕ_{m} = bar diameter (original/uncorroded), obtained from drawing or measured on site
E_{s} = elastic modulus of rebar steel, may be set to 200 GPa

Concrete:

f_{cm} = mean cylinder compressive strength, obtained from drawing or measured by e.g. compression test on drilled cores

Bond:

η_2 = 0.7 - 1.0 dependent on bond conditions
$c_{\mathrm{s}} = c_{\mathrm{x}} = c_{\mathrm{y}}$ = measured on site, see Figure 2.3. If cover has spalled a reduced splitting strength is used see, Equation 20.

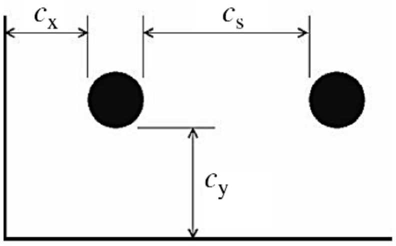


Figure 2.3 Notations for bar spacing and cover [4]

Corrosion level:

W_c = corrosion level, weight loss in principle measured at one section of the bar)
$W_c = (A_s\text{-}A_{s,corr})/A_s$ corrosion level, weight loss (in principle measured at one section of the bar)
A_s = Area of uncorroded reinforcement, $\pi\phi_m^2/4$
A_{corr} = Area of corroded reinforcement, $\pi(\phi_m - 2x)^2/4$ if x is corrosion penetration

For cases without stirrups there is data up to around 15% corrosion, and for cases with stirrups up to approximately 20% corrosion. Bond strength is not significantly influenced by a varied corrosion distribution around a bar.

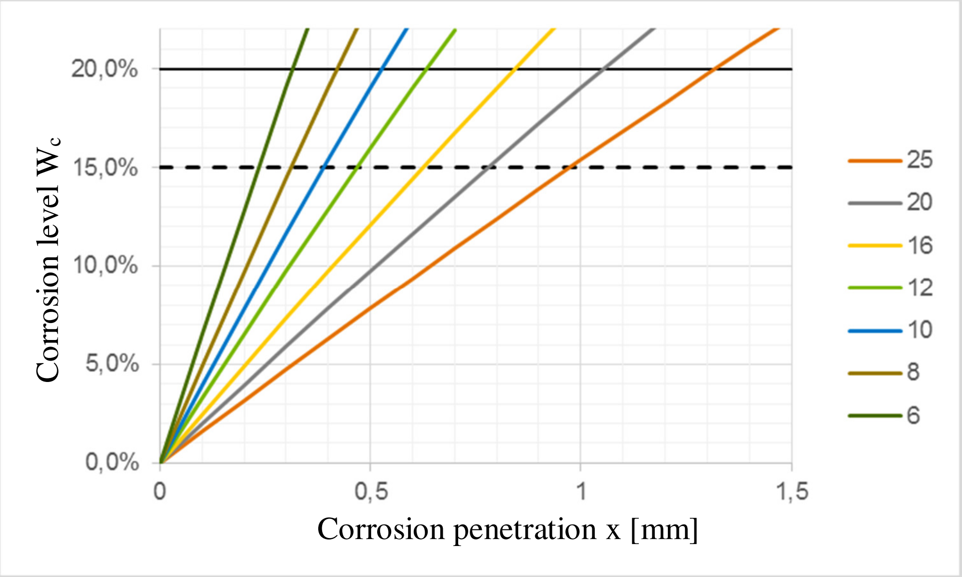


Figure 2.4 Corrosion x [mm] versus corrosion level W_c [%] for reinforcement bars $\phi 6$ to $\phi 25$

Confinement: Corrosion level W_c

k_m = 12 for bars located within $5\phi_m \leq 125$ mm from a stirrup corner

$k_m = 6$ if $c_s \geq 8c_y$
$k_m = 0$ if $c_s < 8c_y$, or if a crack can propagate to the concrete surface without crossing transverse reinforcement
n_t, A_{st}, s_t, n_b = regarding transverse reinforcement, obtained from drawing or measured on site

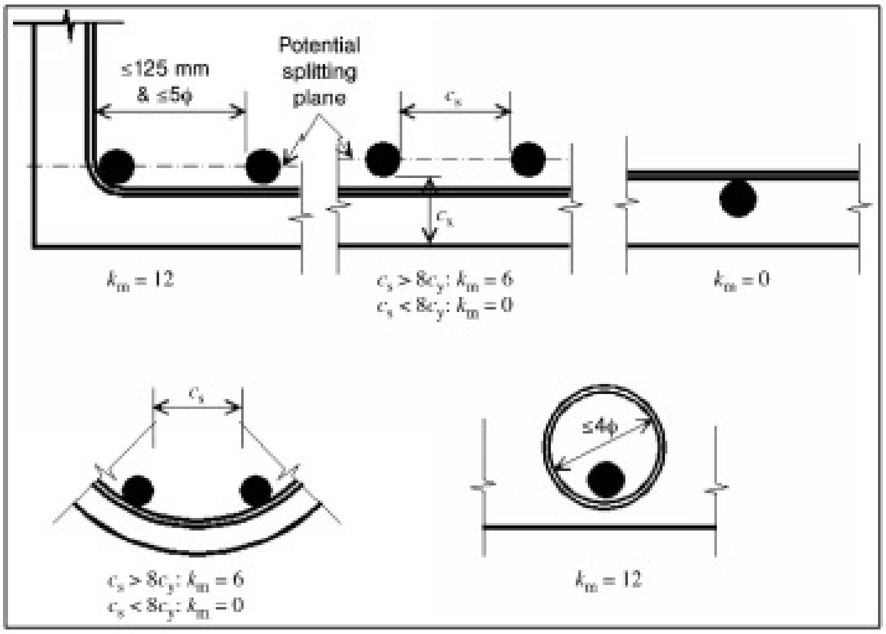


Figure 2.5 Confinement coefficients for transverse reinforcement [4]

The influence of corroded stirrups on the bond capacity is not explicitly included in the model. However, based on the corrosion level of the stirrups their effective area can be used as input to ARC2010. When corrosion of the stirrups has caused the concrete cover to crack or spall off, this can be treated by using a reduced splitting strength as presented in Section 2.3.2 see, Equation 20.

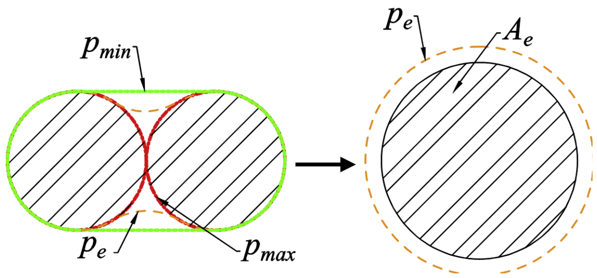
Bundled reinforcement: For bundled reinforcement the area and perimeter are decoupled, see Figure 2.6 and the table below.

A corrosion level is applied and the cross sectional area is reduced. The equivalent area and perimeter after corrosion is:

$$A_{corr} = W_c \cdot A_e,\ A_{e,corr} = (1 - W_c) \cdot A_e$$

$$\phi^{e}_{m,corr} = \sqrt{\frac{4A_{e,corr}}{\pi}}$$

$$p_{e,corr} = p_e(\phi_{corr}), \text{ where } \phi_{corr} = \sqrt{\phi^2 \cdot (1 - W_c)}$$



$A_s = A_e$ = equivalent area of bundled bars
p_e = bond perimeter of bundled bars, average value of upper bound p_{max} and lower bound p_{min}

Figure 2.6 Scheme of the minimum, maximum and average perimeters and the equivalent area and perimeter for the bundled reinforcement bars.

Table 2-3. Equivalent diameter and perimeter

Uncorroded case (2 bars):	Uncorroded case (3 bars):	Uncorroded case (4 bars):
$A_e = 2 \cdot \pi \cdot \frac{\phi^2}{4}$ $\phi_m^e = \sqrt{\frac{4A_e}{\pi}}$ $p_e = \phi\left(1 + \frac{3\pi}{2}\right)$	$A_e = 3 \cdot \pi \cdot \frac{\phi^2}{4}$ $\phi_m^e = \sqrt{\frac{4A_e}{\pi}}$ $p_e = \phi\left(\frac{3}{2} + \frac{7\pi}{4}\right)$	$A_e = 4 \cdot \pi \cdot \frac{\phi^2}{4}$ $\phi_m^e = \sqrt{\frac{4A_e}{\pi}}$ $p_e = \phi(2 + 2\pi)$

Multi-layer reinforcement:
Investigations has shown that the second (and higher) layer of reinforcement (seen from the bottom) has equal or greater capacity than the lower layer. This is also in accordance with Eurocode EN 1992-1-1, which does not differentiate capacity for one or several layers. Hence, calculations can be performed for the bottom layer, and then the anchorage capacity for the second (and higher) layers can be set equal to the capacity of the first layer.

2.4 Evaluation of results

The design resistance for the anchored force R_d should be calculated as

$$R_\mathrm{d} = \frac{R_\mathrm{ARC}(f_\mathrm{ck}, f_\mathrm{yk}, x_\mathrm{nom})}{\gamma_\mathrm{M}},$$

where R_{ARC} is the force calculated by the ARC model using characteristic values (95%) for strength parameters, and nominal (average) values for the rest of the parameters, and γ_M is a partial safety factor with proposed values according to the table below.

Table 2-4. Proposed values for partial safety factor γ_M

Corrosion level W_c	Without stirrups	With stirrups
0%	2.0	1.9
5%	-	4.7
10%	-	4.9
15%	3.4	5.2-6.4*
20%	-	5.2-7.6*

*For cases where n_b is 1-5, intermediate cases can be interpolated.

Remark: Due to high uncertainties associated with corrosion levels of 5 and 10% in case of no stirrups, it was chosen to not differentiate between different levels of corrosion for the partial factors. The partial factors are instead derived for an uncorroded case and a corroded case. For the corroded case 15% corrosion should be used as input to the ARC model.

Background for partial safety factors:
The target reliability index is $\beta_t = 3.7$ (one-year reference period) according to recommendations by the Joint Committee on Structural Safety. It should be noted that this β_t may not be used for new designs. When verifying the partial factors normal and Gumbel distributions were used for the permanent and variable loads respectively, with characteristic levels of 50 and 98%. For a detailed description of the derivation of the partial factors, see [7].

Design anchorage length L_d is theoretically the anchorage length that fulfill the equality

$$R_{\mathrm{ARC}}(f_{\mathrm{ck}}, f_{\mathrm{yk}}, \boldsymbol{x}_{\mathrm{nom}}, L_d) = (F_{\mathrm{yk}}/\gamma_{\mathrm{s}}) * \gamma_{\mathrm{M}}$$

where F_{yk} is the rebar yield force for the actual level of corrosion. One should note that the force $F_{\mathrm{yk}}/\gamma_{\mathrm{s}} * \gamma_{\mathrm{M}}$ usually substantially exceeds the rebar yield force, which make the formula somewhat theoretical and not possible verify by experiment, and results from the ARC-program may become unstable. Therefore, the formula is replaced by the following formula based on approximation by linearization:

$$R_{\mathrm{ARC}}(f_{\mathrm{ck}}, f_{\mathrm{yk}}, \boldsymbol{x}_{\mathrm{nom}}, L_k) = F_{\mathrm{yk}}$$

$$L_d = L_{\mathrm{k}} * (\gamma_{\mathrm{M}}/\gamma_{\mathrm{s}})$$

Note that the approximation corresponds to the commonly used assumption/approximation of uniform bond stress along the anchorage length.

Lap lengths may be assumed equal to anchorage lengths. For several layers of reinforcement, it is assumed that maximum 50% of the reinforcement is spliced at the same position, otherwise a special investigation must be performed.

Warning messages: The program uses a Matlab ODE solver to solve the differential equation. For some cases (typically cases without stirrups and/or long anchorage lengths) the solver will issue warnings that tolerance criteria not have been met while the maximum number of mesh points has been used. For most cases the accuracy is enough despite the warning. This can be checked allowing a larger number of mesh points in input data solparam, see Section 3.3.2.

3 User manual

3.1 Download

The ARC-program consists of a number of function files written in the Matlab [8] programming language. The program files together with a number of example files may be downloaded from:

www.sbuf.se
www.chalmers.se

The files should be saved in a directory on the C-drive, for example with the following address (the address may be chosen is arbitrarily, this is just an example):

```
C:\user\matprog \ARC2010
```

3.2 Overview

Input data, computations and result printing with the ARC-program is defined in a Matlab [8] command file. The user writes a command file for each specific application, usually by copying and adapting a file from a previous application or example file.

The content of the command file is structured in the following manner (where each step is described in detail in the next sections):

0. Initiation of the program
1. Definition of model parameters (input data)
2. Calls to the ARC-functions to perform calculations and result presentation

When the command file is completed, the program is executed in the Matlab environment.

3.3 Command file (main program)

3.3.1 Initiation

Firstly, the Matlab ”memory” should be cleared from previously performed calculations by the following commands:

```
clear all; close all
```

Then the address (“path”) should be set to the directory that contains the ARC-program functions, e.g. according to the following (where the program has been put in the directory ”C:\user\matprog \ARC2010”):

```
dir='C:\user\matprog\ARC2010';
addpath(dir);
```

3.3.2 Input data

Input data to be specified in the command file (numerical values used are indicative and is to be replaced with actual values):

```
%------------------------------------------------------------------------------
% Main rebar geometry and corrosion data:
%------------------------------------------------------------------------------

 fi_main = 16;      % Main bar diameter [mm]
                    % A second value can be added to indicate number of bars in a
                    % bundle use 1,2,3 or 4, e.g.  fi_main = [16, 1]

 cclear = 6.5;           % Clear spacing between ribs [mm]
                         % (if empty calculated by the program as 0.39*fi_main)
 L = 70;                 % Embedment length [mm]
 cx = 64;                % Concrete cover x-dir [mm]
 cy = 64;                % Concrete cover y-dir [mm]
 cs_mb = 200;            % Clear span to closest main bar [mm]
 w_corr = 2.8e-2;        % Corrosion level for main bar [-]

%------------------------------------------------------------------------------
% Stirrup (transverse reinforcement) geometry:
%------------------------------------------------------------------------------

 fi_stir=0;              % Stirrup diameter (0 if no stirrups) [mm]
 s_stir=1;               % Stirrup spacing (1 if no stirrups) [mm]

%------------------------------------------------------------------------------
% Material data for rebar and concrete
%------------------------------------------------------------------------------

 Es = 200e3;       % Young's modulus of reinforcement [MPa]
 fy = 500;         % Characteristic yield strength of main reinforcement [MPa]
 fcm = 56;         % Mean compressive strength (cylinder) fccm [MPa]
                   % and tensile strength fctm [MPa], e.g. fcm = [fccm, fctm].
                   % If fctm is not given the program will be compute it from fccm
%------------------------------------------------------------------------------
% Bond model data:
%------------------------------------------------------------------------------
 eta2 = 1.0;       % = 1.0 for "good bond cond."
                   % = 0.7 for "all other bond cond."
 km = 0;           % = 12: if distance from stirrup is < 125mm & < 5phi
                   % = 6: if clear span to closest main bar > 8cy
                   % = 0: if clear span to closest main bar < 8cy
                   % = 0: if transverse reinforcement inside main bar
```

```
  nb = 1;           % Number of anchored bars or pairs of lapped bars in
                    % the potential splitting surface
  nt = 0;           % Number of legs of confining reinforcement crossing a
                    % potential splitting failure surface at a section
  alpha = 0.4;      % Shape factor for ascending part of bond-slip curve
  ptr = 0;          % Transverse stresses (pressure negative) [MPa],
                    % mean stress in concrete (orthogonal to bar axis)
                    % averaged over a volume around the bar with a diameter
                    % of 3 main bar diameters
  wcr = 0;          % Longitudinal pre-cracking, crack width [mm], if zero no pre-crack

%-----------------------------------------------------------------------------
% Analysis and output request data:
%-----------------------------------------------------------------------------

  run_option = 1;          % =0: Compute force-slip response.
                           % =1: Compute anchorage length

  plot_option = 'full';    % Output selection, choose "full" or force or "off"

  slip = [0:0.1:5];        % Slips for result presentation

  solparam = [1e-2, 1000];    % Relative tolerance, max number of iterations for ODE
                              % solver if not given default values will be used.
```

3.3.3 Call to subroutine ”runARC2010”

After the input data is specified, the ARC-program is executed by a call to the subroutine ”runARC2010”, see further Section 3.4.1.

Subroutine ”runARC2010” performs calculation of force-slip response and if requested also required anchorage length, and returns result data and graphs.

3.3.4 Result presentation

Subroutine ”runARC2010” performs basic result presentation. Additional result presentation can be obtained by using built-in Matlab functions, e.g.:

plot, xlswrite etc.

If the user wishes, additional result presentation can be obtained by using built-in Matlab functions, e.g. “plot” (plots graphs), “xlswrite” (write data to excel), etc. See further the Matlab user manual [8].

3.3.5 Program execution

The program is executed in the Matlab environment by issuing the command file name (which may be chosen almost arbitrarily, for limitations see Matlab user manual [7]), here assumed to be “filename” at the Matlab command prompt:

```
>> filename
```

and then press the enter key on the keyboard.

3.4 ARC-functions

3.4.1 Subroutine ”runARC2010”

Subroutine ”runARC2010” is called from command file (main program), to run the ARC-program and obtain results.

```
[Fs,x,u,sig,tau,s,t,fn,bondmat,tau_bu_split,tau_bu_res,tau_bu_max,Fy]=
runARC2010(     fi_main,cx,cy,cs_mb,L,fi_stir,s_stir,fcm,w_corr,Es,...
fy,eta2,km,nt,nb,alpha,cclear,ptr,wcr,slip,plot_option,run_option,solparam);
```

where input data (fi_main, cx, cy …) are as defined in the previous section, and output data are as follows:

Fs = Fs(s) = vector with pulling force corresponding to end slip s
x = vector with coordinates x along anchorage length
u = u(s,x) = matrix with displacements for different end slips s and coordinates x along the anchorage length
sig = sig(s,x) = matrix with rebar stress for different end slips s and coordinates x along the anchorage length
tau = tau(s,x) = matrix with bond stress for different end slips s and coordinates x along the anchorage length
s = vector with end slips s
t = bond stress for the slips s, e.g. the bond-slip curve
fn = current plot number
bondmat = structure with bond material data
tau_bu_split = splitting bond stress
tau_bu_res = residual bond stress
tau_bu_max = maximum bond strengh
Fy = rebar yield force

3.4.2 Subroutine ”bond”

Subroutine ”bond” is called repeatedly from ”runARC2010” to calculate the anchorage force for different end slips.

```
[Fs,x,u,sig,tau,s,t]=bond(slip,dims,L,Es,bondmat)
```

where input data is

- slip = end slip for which the pulling force should be computed
- dims = rebar data:
  - if length(dims)==1: dims = fi = rebar diameter
  - if length(dims)==2: dims = [om, A] = rebar perimeter and area
- L = anchorage length
- Es = rebar elastic modulus
- bondmat = structure with bond material data, containing:
  - .type = bond-slip curve type umber:
    - = 0: Elastic
    - = 1: Elasto-plastic
    - = 2: CEB/FIP model code 1990
    - = 3: User defined by table
    - = 4: CEB/FIP model code 2010
  - .data = bond material data, depends on type:
    - type = 0:
    - = G = bond shear modulus
    - type = 1:
    - = [G,f] = bond shear modulus and bond yield strength
    - type = 2:
    - = [s1,s2,s3,alpha,tmax,tf] = bond parameters according to CEB/FIP model code 1990, c.f. MC2010 below
    - type = 3:
    - = [s; t] = table with slip s versus bond stress t
    - type = 4:
    - = [s; t] = table with slip s versus bond stress t
    - = [s1,s2,s3,alpha,tmax,tslpit,tf] = bond parameters according to CEB/FIP Model Code 2010:
    - [alpha, s1, s2, s3] = [α, s_1, s_2, s_3], see Section 2.2.2
    - [tmax, tspilt, tf] = [τ_{bmax}, τ_{res}, $\tau_{bu,split}$], see Section 2.2.2
  - .red = [Optr, Ocr], Optr = reduction factor for transverse pressure and
    Ocr = reduction factor for longitudinal cracking
  - .corrpar = corrosion data (only for type = 4, and only needed if bar is
    corroded) = [xc, k], xc = corrosion penetration, k = s_eq/xc, where
    seq = corrosion equavilent slip
  - .option = not currently used

and output data are as follows:

- Fs = pulling force corresponding to end slip s
- x = vector with coordinates x along anchorage length
- u = u(x) = vector with displacements for end slip s and coordinates x along the anchorage length
- sig = sig(x) = vector with rebar stress for end slip s and coordinates x along the anchorage length

tau = tau(x) = vector with bond stress for end slip s and
coordinates x along the anchorage length
s = end slips s
t = bond stress tau for the slips s, e.g. the bond-slip curve

The force Fs for given end slip s is calculated by solving the differential equation described in Section 2.2 using the matlab solver “bvp4c”.

3.4.3 Subroutine ”bondode”

Subroutine that defines the differential equation described in Section 2.2, and is repeatedly called by the Matlab solver “bvp4c”.

[f]=bondode(x,y,EP,MP,WP,bc,bcval)

where input data is

x = vector with coordinates x along anchorage length
y = [u; sig], u = current displacement, sig = current rebar stress
EP = [om, A] = rebar perimeter and area
MP = Es = rebar elastic modulus
WP = bondmat, see previous section
bc = not entered by this subroutine
bcval = not entered by this subroutine

and output data are as follows:

f = [es; fb]
es = sig/Es = rebar strain,
fb = om*tau/A = bond force normalised by rebar area

“bondode” calls subroutine “bondstress” to obtain the bond stress corresponding to current slip s = u.

3.4.4 Subroutine ”bondbc”

Subroutine that defines the boundary conditions to the differential equation described in Section 2.2, and is repeatedly called by the Matlab solver “bvp4c”.

[r]=bondbc(ya,yb,EP,MP,WP,bc,bcval)

where input data is

ya = [u, sig] displacement and stress at bar end a
yb = [u, sig] displacement and stress at bar end b
EP, MP, WP = see previous section, not entered by this subroutine

bc = [ba, bb], boundary condition index as defined by the use of "bvp4c" at the ends of the bar, here set to ba = 2, bb = 3 corresponding to prescribed stress and prescribed displacement respectively
bcval = [bva, bvb] prescribed values at both ends of the bar, here set to
bva = end stress = 0, bvb = end slip

and output data are as follows:

r = y(bc) – bcval, where y = [ya, yb], bc and bcval as defined by input above

3.4.5 Subroutine "bondstress"

Subroutine that defines the different bond-slip models described in Section 2.2, and is repeatedly called by the subroutine "bondode". The user may also wish to call the function to obtain bond stress for a given displacement/slip.

```
[tau]=bondstress(u,mtrl)
```

where input data is

u = displacement u = slip s at a point
mtrl = bond material data = bondmat, see section above

and output data are as follows:

tau = bond stress corresponding to given u = s

The advanced user may implement their own bond-slip model into this subroutine.

3.4.6 Subroutines "bondstress_MC1990", "bondstress_MC2010"

Subroutines that defines the bond-slip models according to CEB/FIP model code 1990 and 2010, repectively, which called by "bondstress". Input and output syntax

```
[tau]=bondstress_MC1990(u,data,opt)
```

```
[tau]=bondstress_MC2010(u,data,opt)
```

Input and output data compare subroutine "bondstress".

4 Verification examples

4.1 Bond-slip

The local bond stress-slip relationships obtained from the ARC2010 model are compared with relationships obtained from experiments [3]; pull-out tests without transverse reinforcement and beam test with stirrups spacing 100 mm and 150 mm respectively.

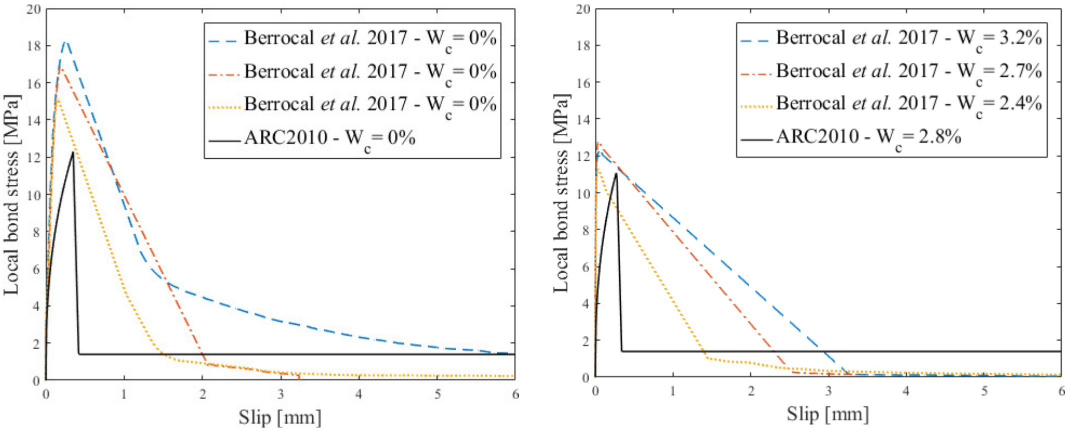
4.1.1 Case with plain concrete (no stirrups)

The pull-out tests with plain concrete performed by Berrocal *et al.* 2017 [5] serves as comparison for cases without stirrups. Geometrical data of the test specimens and the input parameters for the ARC2010 model are presented in Table 4-1. As the embedment length in the tests was shorter than five times the diameter, a constant bond stress along the embedment length was assumed when the local bond stress from the tests was calculated. The bond stress-slip relationship were compared for uncorroded as well as for moderate corroded reinforcement respectively, see Figure 4.1 for the results.

It can be seen that the maximum local bond stress agrees reasonably well between the experiments and the model, especially for the case with corrosion. The descending branch just after peak stress (between approximately 0.5-2 mm slip) might seem to be more ductile in the tests compared to the model. However, the reason is that in the tests no values were recorded in that interval, so the test curve is just a straight line between two points and gives no information about the shape of the descending branch. The "residual strength" at larger slips (>2 mm) is however over-estimated by the model. This is expected since very limited confinement if present after the concrete cover of the circular pull-out test specimens are cracked. The ARC2010 is however calibrated to have a residual bond stress as is common in more real situations such as bars in beams or slabs.

Table 4-1: Input data for pull-out test specimens and model parameters used in ARC2010 model.

Parameter	**Value**
Embedment length [mm]	70
Main bar diameter ϕ_m [mm]	16
Cover x-dir c_x [mm]	64
Cover y-dir c_y [mm]	64
Concrete compressive strength f_{cm} [MPa]	56
Young's modulus E_s [GPa]	200
Yield strength main bars f_y [MPa]	500
Alpha factor α [-]	0.4
c_{clear} [mm]	6.5
Bond conditions η_2 [mm]	1



(a) uncorroded *(b) moderate corrosion level*

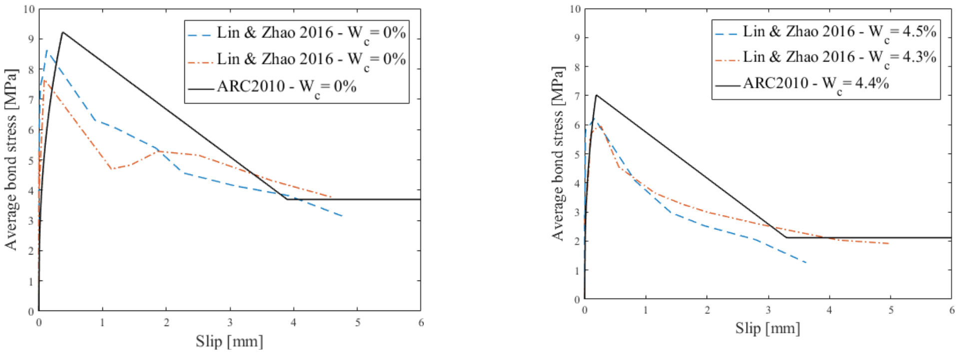
Figure 4.1: Comparison between ARC2010 and experiments without stirrups.

4.1.2 Case with stirrups

Beam tests from Lin and Zhao 2016 [6] were used for comparison for cases with stirrups. The beams had stirrups with spacing of either 100 mm or 150 mm. The geometrical and model input parameters are given in Table 4-2. As the embedment length in these tests were longer than five times the diameter, the average bond stress from experiments and the ARC2010 model were compared for varying levels of corrosion; uncorroded, moderate corrosion level and high corrosion level. Resulting bond-slip curves are presented in Figure 4.2 and Figure 4.3.

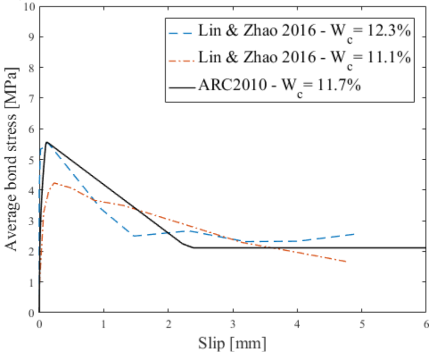
Table 4-2: Input data for beam test specimens and model parameters used in ARC2010 model.

Parameter	**Value**
Embedment length [mm]	150
Main bar diameter ϕ_m [mm]	20
Cover x-dir c_x [mm]	40
Cover y-dir c_y [mm]	65
Concrete compressive strength f_{cm} [MPa]	30
Young's modulus E_s [GPa]	200
Yield strength main bars f_y [MPa]	540
Stirrup diameter ϕ_s [mm]	6
c-c stirrups s_t [mm]	100/150
Efficiency of stirrups k_m	12
Alpha factor α [-]	0.4
c_{clear} [mm]	$0.39\phi_m$
Bond conditions η_2 [mm]	1



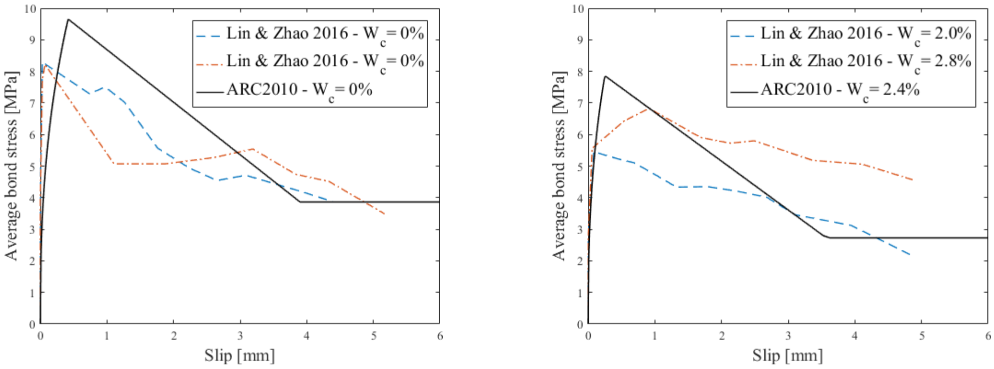
a) uncorroded

b) moderate corrosion level



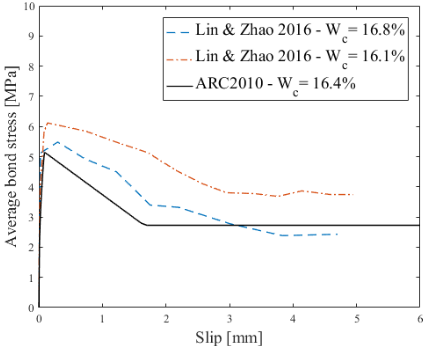
c) high corrosion level

Figure 4.2: Comparison between ARC2010 and experimental results for cases with 150 mm stirrup spacing.



a) uncorroded

b) moderate corrosion level



c) high corrosion level

Figure 4.3: Comparison between ARC2010 and experimental results for cases with 100 mm stirrup spacing.

As can be seen, the model is able to represent the average bonds stress-slip relationships rather well, in terms of both the peak bond stress as well as the residual bond strength. For the uncorroded cases the ARC2010model, that is the original Model Code 2010, is shown to overestimate the peak bond stress slightly. With increasing corrosion level this overestimation becomes smaller.

4.2 Anchorage length

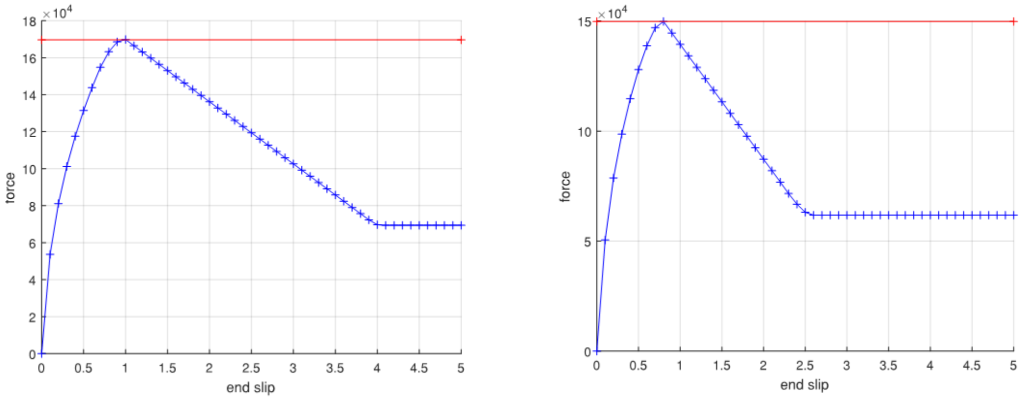
The required anchorage length of the rebar is computed for the same data as in the examples in Section 4.1. The anchorage length (note, no partial safety factor applied – verification example) is defined as the required embedment length to anchor the yield force of the bar. Note that for corroded bars the yield force is lower than for the uncorroded bar, since the bar area is reduced by corrosion.

For input data se Section 4.1. The results are presented in Table 4-3, Figure 4.4 and Figure 4.5.

Table 4-3. Computed anchorage lengths.

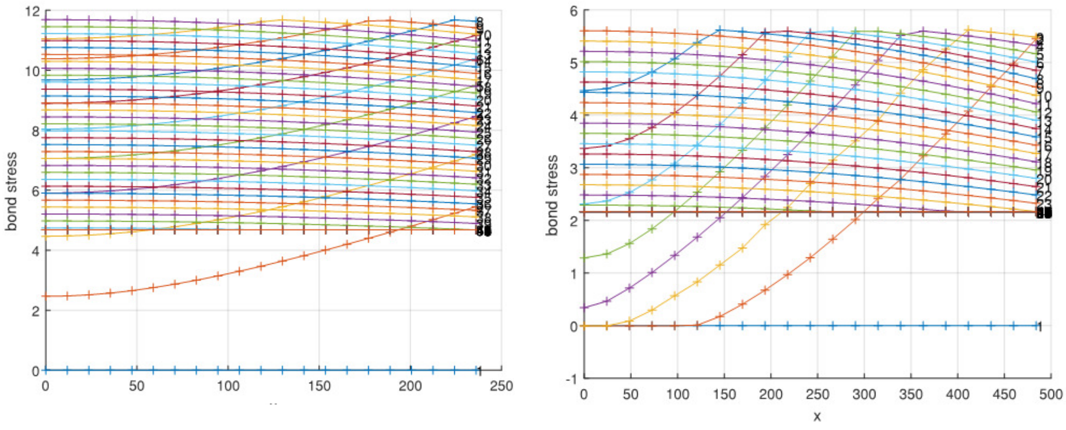
Input data	**Corrosion Level W_c**	**Yield force F_y [kN]**	**Anchorage length L [mm]**	**Average bond stress [MPa]**
See Table 4-1	0%	100	186	10.7
See Table 4-1	2.8%	98	225	8.74
See Table 4-1	5%	96	1226	1.59
See Table 4-2, s=150 mm	0%	170	236	11.4
See Table 4-2, s=150 mm	4.4%	162	388	6.80
See Table 4-2, s=150 mm	11.7%	150	484	5.24
See Table 4-2, s=150 mm	25%*	127	762	3.07
See Table 4-2, s=100 mm	0%	170	226	11.9
See Table 4-2, s=100 mm	2.4%	165	347	7.69
See Table 4-2, s=100 mm	16.4%	142	518	4.77
See Table 4-2, s=100 mm	25%*	127	767	3.05

*) Note: Outside the region of verified data for the model/program $\leq$ 20%.



a) b)

Figure 4.4 Force-slip response with data from Table 4-2 units [N] and [mm]. a) s=150 mm, Wc=0% with L = 226 mm and b) s=150 mm, Wc=11.7% with L =484 mm.



a) b)

Figure 4.5 Bond stress along bar for different load levels with data from Table 4-2, units [MPa] and [mm]. a) s = 150 mm, Wc = 0% with L = 226 mm and b) s = 150 mm, Wc = 11.7% with L = 484 mm.

Figure 4.4 shows force – slip diagram (slip at the pulled end of the bar). Figure 4.5 shows bond stress along the bar for different load levels, where x=0 is at the free end of the bar, and x = L is at the end where the pulling force is applied. For low load levels, the maximum bond stress arise at the pulled end of the bar, while the bond stress is lower at the free end of the bar, due to the deformation in the rebar. For higher load levels the bond stress get more uniformly distributed along the bar, because the deformation in the bar get less significant compared to the slip.

5 Examples of application

5.1 Beam example

A simply supported beam according to the figure below is loaded by uniform design load q_d (including self-weight). The load is assumed to act along the theoretical span 6 m.

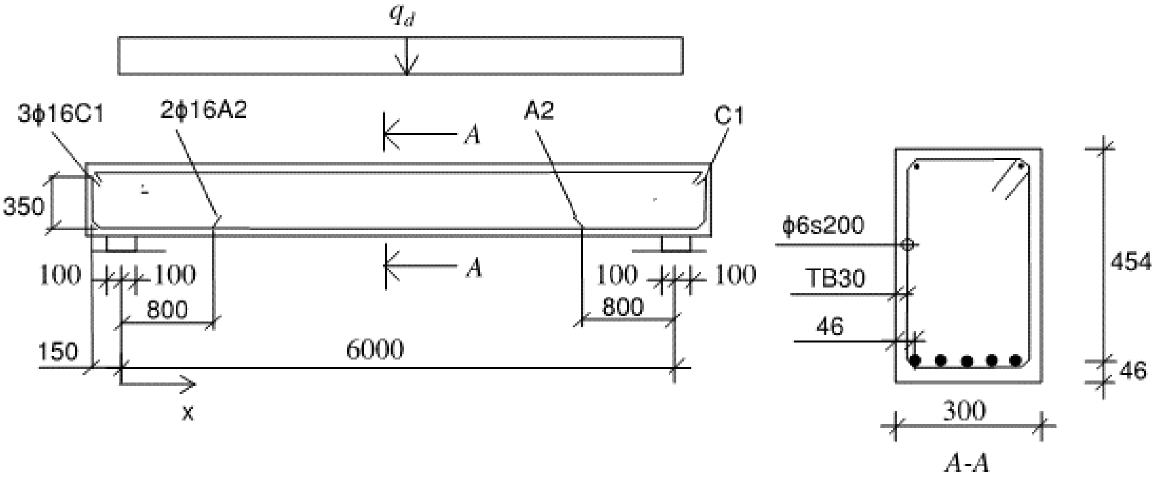


Figure 5.1 Beam example

The beam is reinforced by 3+2ϕ16 at the bottom, and by stirrups ϕ6s200. The anchorage length of the C1 bars behind the centre of the support is 150+350 = 500 mm. Reinforcement grade K500B. Concrete grade C30/37.

The design load bearing capacity q_{rd} is to be determined for different levels of reinforcement corrosion penetration 0, 0.2 and 0.4 mm on both the main rebars and the stirrups, corresponding to 0, 5 and 10% corrosion weight loss for the main ϕ16 bars. Also determine which corrosion penetration that corresponds to a required load capacity of 20 kN/m.

Start with assuming an arbitrary value of design load q_{da}, then determine utilisation ratios w.r.t. to moment, shear and bond failure, and finally establish correct values of q_{rd}.

The shear force and moment are:

```
qda = 35                        % assumed value
x = [0:0.5:3]
V = qda*(3.0-x)
M = qda*3.0*x - 35*x.^2/2
```

The shear capacity is:

d = 0.454 % [m]
A_{sv} = [28, 24, 21]*1e-6*2 % for 0, 0.2 and 0.4 mm corrosion [m2]
s = 0.200 % [m]
f_{sv} = 435e3 % design value = 500/1.15, [kN/m2]
cot = 2.5 % shear crack inclination cotθ

V_{sr} = A_{sv}*f_{sv}*0.9*d/s*cot = [124, 106, 93] kN

The utilisation ratio in shear is:

nyv = V(1)./Vsr*100 = [84, 98, 112] % for 0, 0.2 and 0.4 mm corrosion, [%]

The moment capacity is:

d = 0.454 % [m]
A_{sl} = 5*[201, 191, 181]*1e-6; % for 0, 0.2 and 0.4 mm corrosion, [m2]
f_{sl} = 435e3 % design value = 500/1.15, [kN/m2]

M_r =0.9*d*A_{sl}*f_{sl} = [178, 169, 160] kNm

The utilisation ratio for maximum moment is:

nym = M(end)./Mr*100 = [88, 93, 98] % for 0, 0.2 and 0.4 mm corrosion, [%]

The total force in the main rebars due to bending moment and due to inclined cracking by shear is:

z = 0.9*d
Fsm = M/z % Due to bending
Fsv(1,:) = V.^2*s./(2*z*f_{sv}*A_{sv}(1)) % Due to shear, for no corrosion
Fsv(2,:) = V.^2*s./(2*z*f_{sv}*A_{sv}(2)) % Due to shear, for 0.2 mm corrosion
Fsv(3,:) = V.^2*s./(2*z*f_{sv}*A_{sv}(3)) % Due to shear, for 0.4 mm corrosion

Plot total force:

```
figure(1); clf; hold on
plot(x,Fsm+Fsv(1,:),'b-')
plot(x,Fsm+Fsv(2,:),'m-')
plot(x,Fsm+Fsv(3,:),'r-')
```

The following input data is used to compute the anchored force by the ARC2010 program:

ϕ =16 mm
cclear = 6.4 mm
c_x = c_y = 43-16/2 = 35 mm

c_s = (300-43*2)/4-16 = 37 mm
$\phi_{stirrups}$ = [6, 5.6, 5.2] mm % for 0, 0.2 and 0.4 mm corrosion
$s_{stirrups}$ = 200 mm

f_{ck} = 30 MPa
E_s = 200 GPa
f_{yk} = 500 MPa

$\eta 2$ = 1.0
k_m = 6 (12 for corner bars, 6 for the other bars, use 6 on safe side)
n_b = 5, n_t = 1, α = 0.4
ptr = 0 (bearing pressure neglected on safe side)
w_{cr} = 0 (longitudinal pre-cracking is not likely)

W_c = [0, 5, 10] % for 0, 0.2 and 0.4 mm corrosion

Partial safety factors of 1.9, 4.7 and 4.9 are applied for the cases with 0, 0.2 and 0.4 mm corrosion respectively, according to Section 2.4. The tables below shows the computed anchorage lengths.

Table 5-1. Computed design anchorage length for different corrosion levels.

Corrosion [mm]	**Corrosion Level W_c**	**Anchorage length L_{bk} [mm]**	**Design anchorage length L_{bd} [mm]**	**Rebar design yield force [kN]**
0	0%	246	246*(1.9/1.15) = **410**	201*435e-3 = 87.4
0.2	5%	330	330*(4.7/1.15) = **1350**	191*435e-3 = 83.1
0.4	10%	416	416*(4.9/1.15) = **1780**	181*435e-3 = 78.7

Plot total force resistance of main bars, and compute utilisation:

```
Lb = 0.410
Fsr = 87.4
xr = [-0.5,-0.5+Lb, 0.8, 0.8+Lb, 3]
Fsr = [0,3,3,5,5]*Fsr
plot(xr,Fsr,'b-')
xi = [0:0.01:3]
ny = interp1(x, Fsm+Fsv(1,:),xi) ./interp1(xr,Fsr,xi)
max(ny) %= 90 %

Lb = 1.350
Fsr = 83.1
xr = [-0.5,-0.5+Lb, -0.5+Lb*2, 3]
```

```
Fsr = [0,3,5,5]*Fsr
plot(xr,Fsr,'m-')
xi = [0:0.01:3]
ny = interp1(x, Fsm+Fsv(2,:),xi) ./interp1(xr,Fsr,xi)
max(ny) %= 140 %

Lb = 1.780
Fsr = 78.7
xr = [-0.5,-0.5+Lb, -0.5+Lb*2]
Fsr = [0,3,5]*Fsr
plot(xr,Fsr,'r-')
xi = [0:0.01:3]
ny = interp1(x, Fsm+Fsv(3,:),xi) ./interp1(xr,Fsr,xi)
max(ny) %= 222 %

xlabel('Coordinate x [m]')
ylabel('Total force in main bars [kN]')
title('Force and resistance main bars')
grid on
```

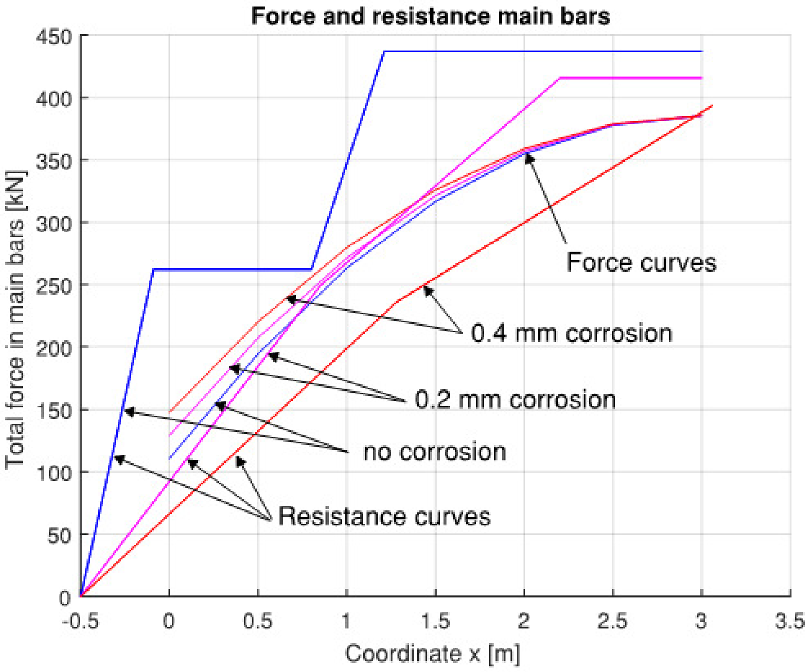


Figure 5.2 Force and resistance for the main bars, for an assumed design load qd = 35 kN/m

The utilisation ratio w.r.t. anchorage is:

nya = [90, 140, 222] % for 0, 0.2 and 0.4 mm corrosion, [%]

The utilisation ratio w.r.t. all modes of failure is:

```
ny =max([nyv;  nym; nya]) = [90, 140, 222] % for 0, 0.2 and 0.4 mm corrosion
```

The example shows that the anchorage of the bars at the support is clearly most critical w.r.t. to corrosion. Shear and moment capacity due to area reduction of the corroded bars is less affected.

The design load bearing capacity is:

```
qrd =  qda*1./(ny/100) = [38, 25, 15] % 0, 0.2 and 0.4 mm corrosion, [kN/m]
```

Plot design load versus corrosion:

```
figure(2); clf; hold on
plot([0, 0.2, 0.4],qrd,'b+-'),     plot([0, 0.4], [20,20],'r+-')
axis([0, 0.4, 0, 40])

xlabel('Corrosion [mm]')
ylabel('Load bearing capacity qd [kN/m]')
title('Beam design load bearing capacity w.r.t. corrosion')
grid on
```

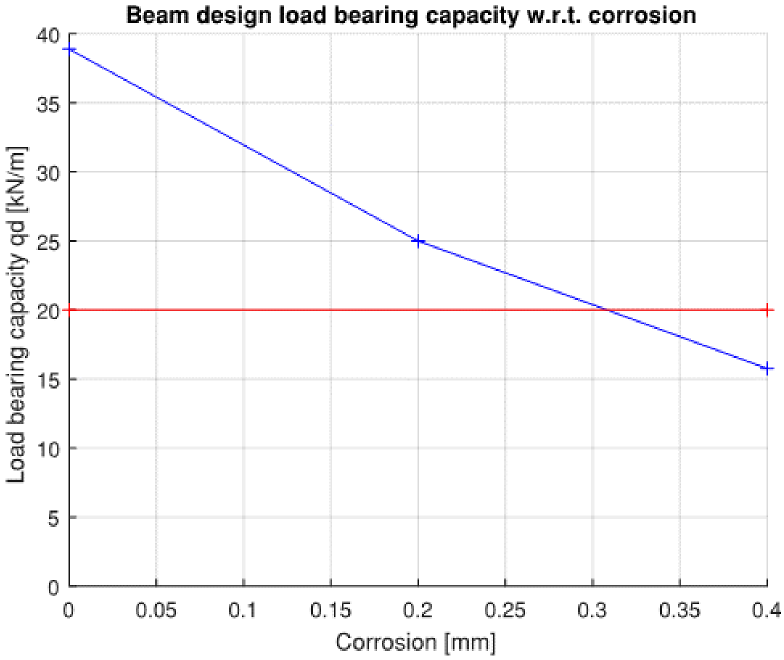
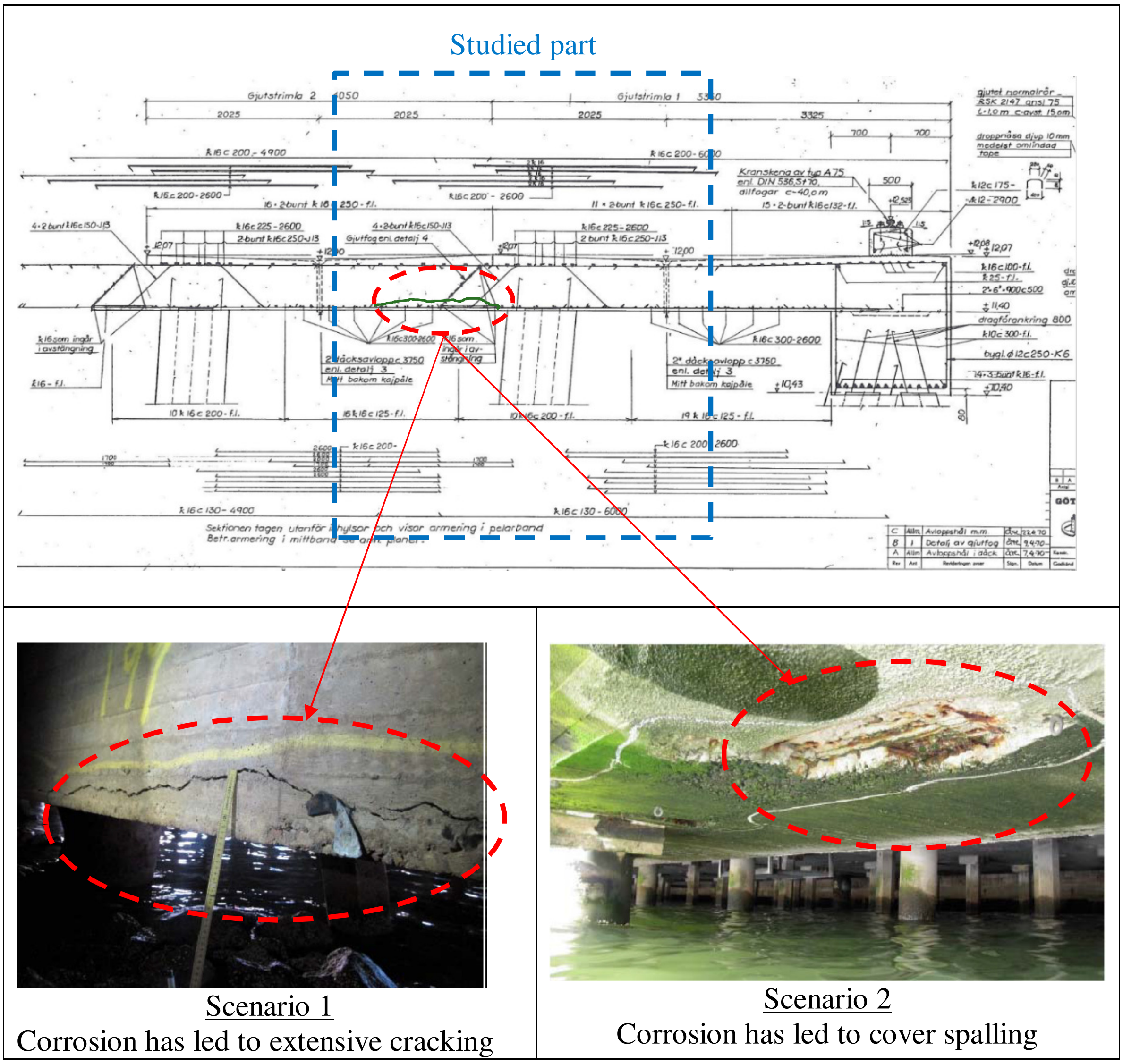


Figure 5.3 Load bearing capacity versus corrosion penetration for the beam

The diagram shows that the required load level of 20 kN/m can be sustained up to approximately 0.3 mm of corrosion.

5.2 Two-way slab, an example from a quay structure

Reinforced concrete (RC) slabs are among the most exposed parts in quay structures and the reinforcing bars maybe subjected to corrosion damage since they are often within the splash zone of see water. Bending and punching shear are usually governing failure modes at the ultimate limit state for RC slabs subjected to concentrated loads. However, anchorage capacity may become critical, for instance at the curtailment and splicing region at the casting joints, if the reinforcing bars are subjected to extensive corrosion. While provisions in EC2 and Model Code can be used to calculate bending and punching shear capacities, calculation methods to estimate anchorage capacity, or the required anchorage length to prevent anchorage failure, of corroded RC slabs are not given in design codes. This example aims to demonstrate the application of the ARC program for the estimation of the anchorage capacity in corroded RC slabs.



Scenario 1
Corrosion has led to extensive cracking

Scenario 2
Corrosion has led to cover spalling

Figure 5.4 An example quay structure in Gothenburg harbour with two damage scenarios (shown in red circle).

In this example, two scenarios are studied, see Figure 5.3, in which corrosion of bottom reinforcement in the RC slab has led to extensive cracking (scenario 1), and cover spalling (scenario 2). The geometry of the RC slab is summarised in Figure 5.4, and the dimensions, reinforcement amounts and material properties are given in Table 5-2.

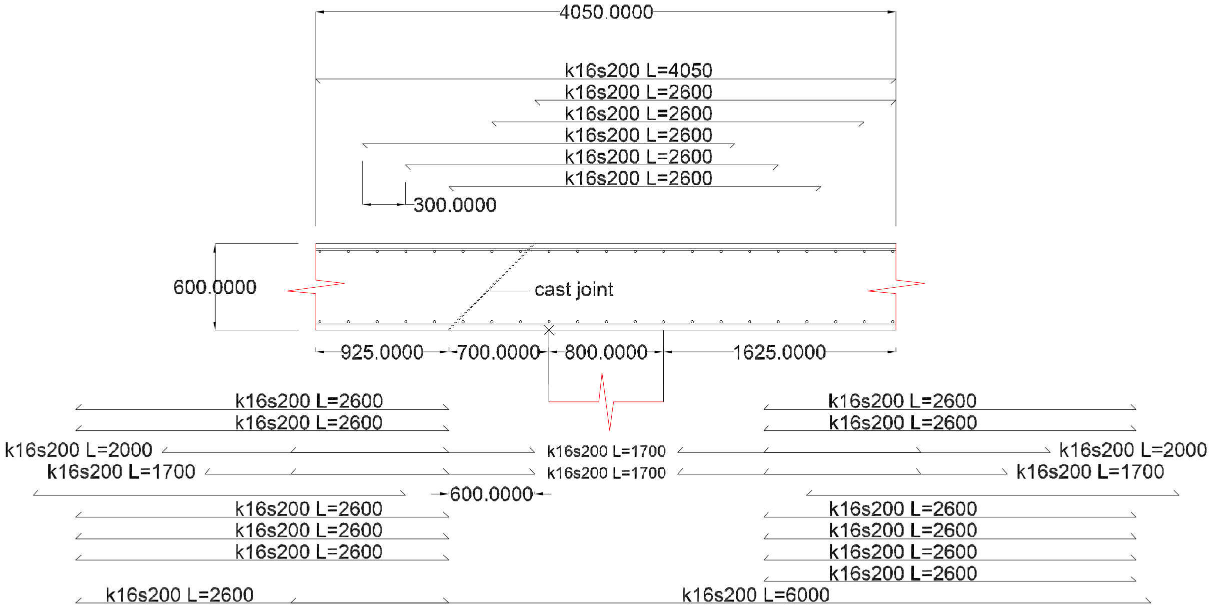


Figure 5.5 The dimensions and rebar layout of the studied slab (inspired by a quay structure from Gothenburg harbour); all dimensions are in mm.

Table 5-2. Dimensions, reinforcement amounts and the assumed material properties. d is effective height; fc is the compressive strength of concrete; dg is aggregate size; fy and fu are yield and ultimate strength of reinforcement steel.

Slab dimension [mm] B×B×h	Concrete			Reinforcing steel		
	TB [mm]	f_c [MPa]	d_g [mm]	reinforcement	f_y [MPa]	f_u [MPa]
4050×4050×600	40	30	16	Ø16 s200	400	450

The design load in ULS is 100 kN/m2, with 25% permanent load and 75% variable load.

The utilisation ratios and load capacity w.r.t. to moment*, shear and bond failure is to be determined for different levels of reinforcement corrosion penetration 0 and 0.6 mm, corresponding to 0 and 15% corrosion weight loss for the main ϕ16 bars.

> *) The study is here limited to study of moment capacity w.r.t. to the bottom reinforcement, which is most critical w.r.t corrosion. The top reinforcement and punching shear capacities has not been checked.

The shear force and maximum sagging moment are:

```
q = [25, 75]           % Dead and live load [kN/m2]
L = 4                  % Span length
x = [0:0.5:L/2]

V = sum(q)*(L/2-x)

M(1,:) = q(1)*L/2*x - q(1)*x.^2/2
M(1,:) = -M(1,end)*2/3+M(1,:)
M(2,:) = q(2)*L/2*x - q(2)*x.^2/2
M(2,:) = -M(2,end)*1/3+M(2,:)

M = M(1,:)+M(2,:)
```

The shear capacity is:

d = 0.55 % [m]
f_v = 0.45e3 % estimated value, [kN/m2]
V_{cr} = d*fv = 247 kN/m

The utilisation ratio in shear is (checked at support, $x \approx 0.8/2$ m):

```
ny = V(2)./Vcr*100 = 61 %
```

The moment capacity is:

d = 0.55 % [m]
A_{sl} = 5*[201, 170]*1e-6 % for 0 and 0.6 mm corrosion [m2]
f_{sl} = 400e3/1.15 % design value, [kN/m2]

M_r =0.9*d*A_{sl}*f_{sl} = [173, 146] kNm

The utilisation ratio for maximum moment is:

```
ny = M(end)./Mr*100 = [67, 80]   % for 0 and 0.6 mm corrosion, [%]
```

The total force in the main rebars due to bending moment and due to inclined cracking by shear is:

```
z = 0.9*d
Fsm = M/z          % Due to bending
Fsv = V/2          % Due to shear
Fsd = Fsm + Fsv
Fsd = min(Fsd,Fsm(end)*ones(1,5))
```

Plot total force:

```
figure(1); clf; hold on
plot(x,Fsd,'b-')
axis([0,2, 0,400])
```

The following input data is used to compute the required anchorage length by the ARC2010 program:

ϕ =16 mm
cclear = 6.4 mm
c_y = 40 mm
c_s = 200-16 = 184 mm
c_x = 184/2 = 92 mm

f_{ck} = 30 MPa
E_s = 200 GPa, f_{yk} = 400 MPa

$\eta 2$ = 1.0
k_m = 0, n_b = 1, n_t = 1, α = 0.4, ptr = 0, w_{cr} = 0

W_c = 15%

Partial safety factors of 2.0 and 3.4 are applied for the cases with 0 and 0.6 mm corrosion respectively, according to Section 2.4. The table below shows the computed anchorage lengths.

Table 5-3. Computed design anchorage length for different corrosion levels.

Corrosion [mm]	**Corrosion Level W_c**	**Anchorage length L_{bk} [mm]**	**Design anchorage length L_{bd} [mm]**	**Rebar design yield force [kN]**
0	0%	174	160*(2.0/1.15) = **300**	200*347e-3 = 69.7
0.6	15% (1-20%)	1240	1240*(3.4/1.15) = **3700**	170*347e-3 = 59.0

Plot total force resistance of main bars, and compute utilisation:

No corrosion:

```
Lb = 0.3
Fsr = 69.7*5
xr=[0:0.1:2.0];

xr1 = [0, 2.0];
Fsr1= [1.0, 1.0]*0.5*Fsr;
Fsr1 = interp1(xr1, Fsr1,xr)

xr2 = [0, 0.4, 0.4+Lb, 2.0]
Fsr2 = [0, 0, 1.0, 1.0]*0.1*Fsr
Fsr2 = interp1(xr2, Fsr2,xr)

xr3 = [0, 0.7, 0.7+Lb, 2.0]
Fsr3 = [0, 0, 1.0, 1.0]*0.4*Fsr
Fsr3 = interp1(xr3, Fsr3,xr)

Fsr = Fsr1 + Fsr2 + Fsr3

plot(xr,Fsr,'b-')

xi = [0:0.01:1];
ny = interp1(x, Fsd,xi) ./interp1(xr,Fsr,xi)
max(ny) %= 60%
```

Corrosion 0.6 mm, for spans without laps:

```
Lb = 3.7
Fsr = 59.0*5
xr=[0:0.1:2.0];

xr1 = [0, 1.5, 2.0];
Fsr1= [1.0, 1.0, 1.0]*0.5*Fsr;
Fsr1 = interp1(xr1, Fsr1,xr)

xr2 = [0, 0.4, 0.4+Lb, 2.0]
Fsr2 = [0, 0, 1.0, 1.0]*0.1*Fsr
Fsr2 = interp1(xr2, Fsr2,xr)

xr3 = [0, 0.7, 0.7+Lb, 2.0]
Fsr3 = [0, 0, 1.0, 1.0]*0.4*Fsr
Fsr3 = interp1(xr3, Fsr3,xr)

Fsr = Fsr1 + Fsr2 + Fsr3
```

```
plot(xr,Fsr,'m-')

xi = [0:0.01:1];
ny = interp1(x, Fsd,xi) ./interp1(xr,Fsr,xi)
max(ny) %= 99%
```

Corrosion 0.6 mm, for spans with laps at mid-span:

```
Lb = 3.7
Fsr = 59.0*5
xr=[0:0.1:2.0];

xr1 = [0, 1.5, 2.0];
Fsr1= [2.5/3.7, 1.0/3.7, 2*0.5/3.7]*0.5*Fsr; % W.r.t. to the laps at midspan
Fsr1 = interp1(xr1, Fsr1,xr)

xr2 = [0, 0.4, 0.4+Lb, 2.0]
Fsr2 = [0, 0, 1.0, 1.0]*0.1*Fsr
Fsr2 = interp1(xr2, Fsr2,xr)

xr3 = [0, 0.7, 0.7+Lb, 2.0]
Fsr3 = [0, 0, 1.0, 1.0]*0.4*Fsr
Fsr3 = interp1(xr3, Fsr3,xr)

Fsr = Fsr1 + Fsr2 + Fsr3

plot(xr,Fsr,'r-')

xi = [0:0.01:1];
ny = interp1(x, Fsd,xi) ./interp1(xr,Fsr,xi)
max(ny) %= 188%

xlabel('Coordinate x [m]')
ylabel('Total force in main bars [kN]')
title('Force and resistance main bars')
grid on
```

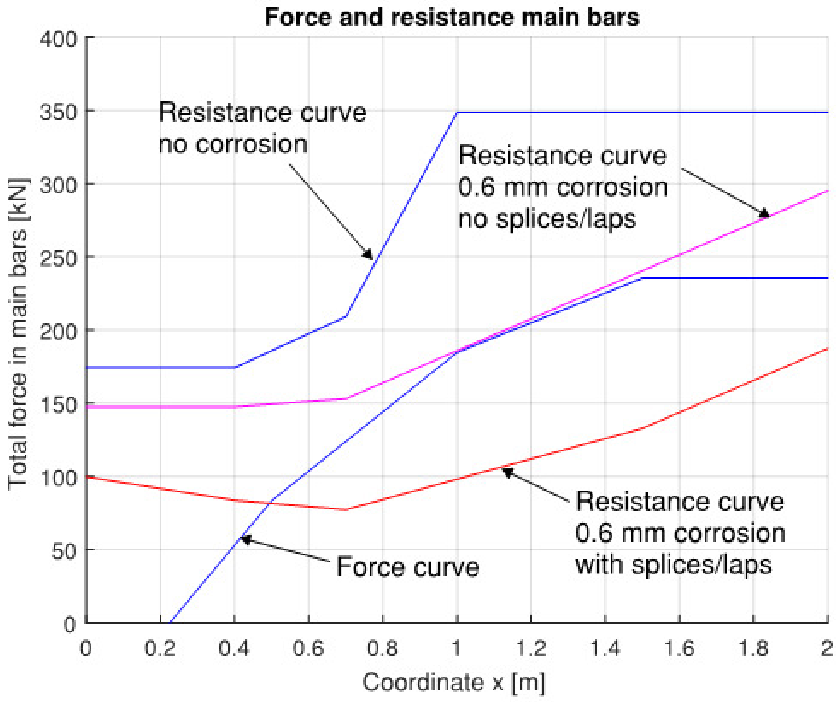


Figure 5.6 Force and resistance, main bars

The utilisation ratios and corresponding load capacities w.r.t. anchorage are:

ny = 60% for no corrosion
qrd ≥ 100 kN/m2

ny = 99% for 0.6 mm corrosion, for spans without reinforcement splices/laps
qrd = 100/0.99 ≈ 100 kN/m2

ny = 188% for 0.6 mm corrosion, for spans with reinforcement splices/laps
qrd = 100/1.88 ≈ 50 kN/m2

The example shows that the anchorage of the curtailed bars and reinforcement splices/laps are clearly most critical w.r.t. to corrosion.

In the example, the load capacity w.r.t. to the bottom reinforcement is 100 kN/m2 for up to 0.6 mm corrosion for spans having no laps. For spans with laps the load must be reduced to 50 kN/m2.

6 References

[1] Karin Lundgren, Per Kettil, Kamyab Zandi Hanjari, Hendrik Schlune and Armando Soto San Roman: “Analytical model for the bond-slip behaviour of corroded ribbed reinforcement”. Structure and Infrastructure Engineering, 8(2), 2009, pp.157–169.

[2] Mattias Blomfors: “Reliable assessments of concrete structures with corroded reinforcement: An engineering approach”, thesis for the degree of licentiate of engineering, Department of Civil and Environmental Engineering 2017:6, Chalmers University Of Technology, ISSN no. 1652-9146, Gothenburg, Sweden 2017.

[3] Blomfors M., Coronelli D., Lundgren K., Zandi K: “Engineering bond model for corroded reinforcement”. Submitted to Engineering Structures, 2017. Available in [1].

[4] CEB, 2013. CEB-FIP Model Code 2010. In fib “Model Code for Concrete Structures 2010”. Lausanne, Switzerland, pp. 152–189.

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[6] Lin H, Zhao Y. Effects of confinements on the bond strength between concrete and corroded steel bars. Constr Build Mater 2016;118:127–38.

[7] M. Blomfors, O. Larsson Ivanov, D. Honfi, M. Engen. “Partial safety factors for the anchorage capacity of corroded reinforcement bars in concrete”,. Submitted to Engineering Structures.

[8] Matlab, www.mathworks.com

7 Example command files

7.1 Bond-slip example in Section 4.1

```
%===================================================================
% Command file for ARC2010
%-------------------------------------------------------------------
% List of contents:
% ---------------------
% 0. Initiation of the program
% 1. Definition of model parameters (input data)
% 2. Call to the ARC-functions for calculations and result
%    presentation
% 3. User defined output data post-processing
%===================================================================

%===================================================================
% *** 0. Initiation of the program ***
%===================================================================

  clear all; close all

% Give path to directory with the ARC2010 program files

  dir='C:\kettil\skanska\147564 Korroderade btgkonstr
         SBUF\program\ARCmodel';
  addpath(dir);

%===================================================================
% *** 1. Definition of model parameters (input data)  ***
%===================================================================

%-------------------------------------------------------------------
% Main rebar geometry and corrosion data:
%-------------------------------------------------------------------

  fi_main = 16;               % Main bar diameter [mm]
  cclear = 6.5;               % Clear spacing between ribs [mm]
                              %(if empty calculated by program)
  L = 70;                     % Embedment length [mm]
  cx = 64;                    % Concrete cover x-dir [mm]
  cy = 64;                    % Concrete cover y-dir [mm]
  cs_mb = 200;                % Clear span to closest main bar [mm]
  w_corr = 2.8e-2 %5e-2;      % Corrosion level for main bar [-]

%-------------------------------------------------------------------
% Stirrup (transverse reinforcement) geometry:
%-------------------------------------------------------------------

  fi_stir=0;            % Stirrup diameter (0 if no stirrups) [mm]
  s_stir=1;             % Stirrup spacing (1 if no stirrups) [mm]

%-------------------------------------------------------------------
% Material data for rebar and concrete
%-------------------------------------------------------------------
```

```
  Es = 200e3;    % Youngs modulus of reinforcement [MPa]
  fy = 500;      % Yield strength of main reinforcement [MPa]
  fcm = 56;      % Mean compressive strength (cylinder) fccm [MPa]

%-------------------------------------------------------------------
% Bond model data:
%-------------------------------------------------------------------

  eta2 = 1.0;       % = 1.0 for "good bond cond."
                    % = 0.7 for "all other bond cond."
  km = 0;      % = 12: if distance from stirrup is < 125mm & < 5phi
               % = 6: if clear span to closest main bar > 8cy
               % = 0: if clear span to closest main bar < 8cy
               % = 0: if transverse reinforcement inside main bar
  nb = 1;      % Number of anchored bars or pairs of lapped bars in
               % the potential splitting surface
  nt = 0;      % Number of legs of confining reinforcement crossing
               % a potential splitting failure surface at a section
  alpha = 0.4; % Shape factor for ascending part of bond-slip curve
  ptr = 0;     % Transverse stresses (pressure negative) [MPa],
               % mean stress in concrete (orthogonal to bar axis)
               % averaged over a volume around the bar with a
               % diameter of 3 main bar diameters
  wcr = 0.0;   % Longitudinal pre-cracking, crack width [mm]

%-------------------------------------------------------------------
% Analysis and output request data:
%-------------------------------------------------------------------

  run_option = 1;           % =0: Compute force-slip response.
                            % =1: Compute anchorage length

  slip = [0:0.1:5];         % Slips for result presentation

  plot_option = 'full';     % Output selection, choose "full"
                            % or force or "off"

%===================================================================
% *** 2. Call to the ARC-functions for calculations and result
%        presentation  ***
%===================================================================

[Fs,x,u,sig,tau,s,t,fn,bondmat,tau_bu_split,tau_bu_res,tau_bu_max,Fy
,L,fir_main]=...
runARC2010(fi_main,cx,cy,cs_mb,L,fi_stir,s_stir,fcm,w_corr,Es,...
fy,eta2,km,nt,nb,alpha,cclear,ptr,wcr,slip,plot_option,run_option);

%===================================================================
% *** 3. User defined output data post-processing ***
%===================================================================
  L
  max(Fs)/1000
  Fy/1000
  Fy/(pi*fir_main*L)
```