THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Corrosion of steel bars in fibre reinforced concrete: Corrosion mechanisms and structural performance

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Cover:

Failure section of a RC beam revealing crack bridging fibres and ruptured reinforcement bars

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To Maria, Marcos

& my mother

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Abstract

The viability of employing fibre reinforcement to improve the durability performance of RC structures by delaying and/or reducing rebar corrosion and by mitigating the structural impact of corrosion-induced damage have been investigated. Given the enhanced crack control of FRC, it could be advantageous to use fibres in civil engineering structures to decrease the ingress of corrosion-initiation substances. However, the combined use of both types of reinforcement in chloride environments raises questions regarding the potential influence that fibres may have on the corrosion process of conventional rebar.

Long-term experiments were carried out featuring naturally corroded RC elements subjected to different loading conditions and varying crack widths. Complementary short-term experiments were carried out to isolate the influence of fibres on individual parameters governing the process of reinforcement corrosion, such as chloride diffusion, internal cracking and electrical resistivity, as well as on corrosion-induced damage, such as cracking and spalling of the cover.

From the experiments it was found that the ingress of chloride ions into concrete, assessed through migration and bulk diffusion tests, was not significantly affected by the presence of fibres. The internal crack pattern of conventionally RC beams subjected to bending loads revealed a tendency for crack branching and increased tortuosity when fibres were present, which can potentially decrease the permeation of concrete and promote crack self-healing. The time to corrosion initiation, evaluated through half-cell potential monitoring, for fibre reinforced beams were similar or longer than the plain concrete ones. However, the effect of fibres was minor compared to the difference between cracked and uncracked specimens, thus highlighting the importance of cracks for the initiation of corrosion. The DC resistivity was found to be unaffected by steel fibres, indicating that they do not pose a risk for increased corrosion rates. Gravimetric steel loss measurements showed that the corrosion level of reinforcement bars embedded in FRC beams was similar or even lower than for plain concrete beams. Moreover, the examination of the corrosion patterns and a detailed analysis of individual corrosion pits revealed a tendency for more distributed corrosion with reduced cross-sectional loss in FRC. Corrosion-induced cracking of the cover was somewhat delayed by fibre reinforcement, particularly for small cover thicknesses, which was attributed to the additional source of passive confinement provided by the fibres. Thereafter, corrosion-induced cracks were effectively arrested by fibres, which resulted in an enhanced bond behaviour of SFRC with no apparent loss of bond strength and high residual bond-stresses. Fibres also had a positive effect on the residual flexural capacity of corroded beams, which generally displayed a slightly increased load-carrying capacity and rotation capacity compared to plain concrete beams with corroded reinforcement.

The promising results obtained in this study indicate that FRC may be effectively used to extend the service life of civil engineering structures by delaying and reducing reinforcement corrosion as well as by mitigating the structural effects of corrosion-induced damage.

Key words: Fibre reinforced concrete, chloride-induced corrosion, durability, electrical resistivity, cracking, reinforcement bond, residual flexural capacity

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Sammanfattning

Möjligheten att använda fiberarmering för att förbättra beständigheten hos armerade betongkonstruktioner genom att fördröja och/eller reducera armeringskorrosion samt minska effekten av korrosionsinitierade skador på bärförmågan har undersökts. Då fiberarmering möjliggör en förbättrad kontroll av sprickbildning så torde det vara fördelaktigt att använda detta också i anläggningskonstruktioner för att minska inträngningen av korrosionsorsakande ämnen. Användningen av två armeringstyper och material i kloridhaltiga miljöer leder till frågeställningar kopplat till vilken inverkan fibrer kan ha på korrosionsprocessen hos konventionell armering.

Långtidsförsök med naturlig korrosion utfördes på armerade provkroppar med olika belastningsförhållanden och sprickvidd. Dessa försök kompletterades med korttidsförsök med avsikt att särskilja fibrernas inverkan på individuella parametrar som styr korrosionsprocessen, så som kloriddiffusion, inre sprickbildning och elektrisk resistivitet. Fibrers inverkan på sprickbildning orsakad av armeringskorrosion undersöktes också.

Resultaten från försöken visade att kloridinträngningen, både genom diffusion och migration, inte påverkades av fibrerna. Den inre sprickbildningen hos armerade balkar utsatta för böjning, visade att fibrer gav upphov till ökad sprickförgrening och -krokighet, något som potentiellt kan minska inträngningen och förbättra den självläkande förmågan. Tiden till korrosionsinitiering övervakades genom att mäta korrosionspotentialen med en halvcell, och från resultaten framgick att fiberarmerade provkroppar betedde sig likvärdigt eller bättre jämfört med de utan fibrer. Effekten var dock marginell i jämförelse med den effekt som sprickor hade (dvs skillnad mellan osprucka och spruckna provkroppar) vilket klargör vikten av sprickor på tiden till korrosionsinitiering. Tillsättning av stålfiber påverkade inte materialets likströmsresistivitet, vilket tyder på att de inte orsakar ökad korrosionshastighet. Gravimetrisk analys av viktförlusten hos armeringsstängerna visade att korrosionsgraden hos stänger ingjutna i fiberarmerad betong var likvärdig eller lägre än för de ingjutna i konventionell betong. Genom att undersöka korrosionsmönster och -former, samt genom att i detalj studera individuella gropfrätningar, avslöjades en tendens till en mer fördelad armeringskorrosion med minskad tvärsnittsförlust i fiberarmerade provkroppar. Korrosionsinitierad uppsprickning av täckskiktet fördröjdes av fiberarmeringen, särskilt vid små täckskikt, vilket förklaras av den passiva omslutningseffekt som fibrerna bidrar med. Efter sprickinitiering kunde fibrerna effektivt förhindra ökad spricktillväxt vilket resulterade i förbättrade vidhäftningsegenskaper för armeringen. Vidare innebar fibrer ingen märkbar förlust av vidhäftningspåkänningen och en betydligt högre restvidhäftningspåkänning erhölls. Fibrer hade också en positiv effekt på restmomentkapaciteten och hos korroderade balkar, vilka uppvisade en något högre bärförmåga och rotationskapacitet jämfört med de utan fibrer.

De lovande resultat som har framkommit av denna undersökning indikerar att fiberarmerad betong konstruktivt och produktivt kan användas för att förlänga livslängden hos anläggningskonstruktioner genom att fördröja armeringskorrosion och minska den strukturella effekten av skador orsakade av armeringskorrosion.

Nyckelord: fiberarmerad betong, kloridinitierad armeringskorrosion, beständighet, elektrisk resistivitet, sprickbildning, vidhäftning, restbärförmåga

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Preface

The work presented in this doctoral thesis represents the fourth of a series of industrial PhD projects carried out in collaboration between Chalmers University of Technology and Thomas Concrete Group AB, preceded by the works of Ingemar Löfgren, Oskar Esping and Anette Jansson. The present work was carried out between December 2012 and August 2017 in the research group of Concrete Structures within the Division of Structural Engineering at Chalmers University of Technology. The project was financed by Thomas Concrete Group AB.

First of all, I would like to express my most sincere gratitude to my supervisors, Prof. Karin Lundgren and Adj. Prof. Ingemar Löfgren. Throughout my PhD, they have shared their vast knowledge and experience, providing valuable discussion, advice and insights yet they have always given me the freedom to conduct my own research, allowing me to evolve as a researcher. Given their level of commitment to the project, their understanding and their thorough review of my work, I cannot think of anyone better to have as supervisors.

I want to convey my appreciation to the members of the reference group, Elisabeth Helsing, Anders Lindvall, Per-Ola Svahn, Mikael Westerholm, Arvid Hejll and David Fall for showing their interest in my work and taking the time to get involved and share their valuable thoughts and comments. Prof. Luping Tang is specially thanked for assisting me throughout the different stages of this work and having his door always open to share his vast knowledge in chloride ingress and corrosion of steel in concrete.

I would also like to thank all my colleagues, former and present, at the Division of Structural Engineering for creating such a nice working environment. Special thanks go to my fellow PhD students in the research group of Concrete Structures, particularly to Mattias Blomfors for his kindness and friendship. I also want to thank visiting PhD student Ismael Vieito for his valuable help and interesting discussions. Dr. Ignasi Fernandez is gratefully acknowledged for his valuable assistance in many parts of the project. I am also grateful to the technical staff at Chalmers, former technician Lars Wahlström and current technicians Marek Machowski and, particularly, Sebastian Almfeldt, for their help in executing all the experimental work.

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I would like to express my gratitude to Thomas Concrete Group AB for making this project possible through financial support. Furthermore, I would like to acknowledge MaxFrank, Cementa Research and CBI Borås, for their generous contribution to the project.

I would also like to convey my appreciation to my former colleagues and friends at Universitat Politècnica de Catalunya, Prof. Ángel Aparicio, Prof. Joan Ramon Casas and Prof. Gonzalo Ramos as well as Marta Sarmiento, Maria del Mar Casanovas, Giorgio Anitori, Miriam Soriano and Raquel Juan. Special thanks go to my close friends, Jacinto and Eduardo Jimenez for their encouragement and moral support and Eduard Mondéjar and his wife Xènia for inspiring discussions and their contribution to the cover of this thesis. Above all, I want to thank them all for their true friendship throughout the years in spite of the distance between us.

I am deeply grateful to my dear mother, Carmen Berrocal, who taught me the value of hard work and that a bad person can never be a good professional. She has always been my role

model in life and has supported me in all my decisions. The reason why I chose to use my second last name “Berrocal” in my academic career is because if I have been able to come this far, it is thanks to her. Muchas gracias por todo mamá.

Finally, I want to direct my special thanks to my lovely family, Maria and Marcos, who have been very understanding and patient during my PhD, specially during all my trips to courses and conferences. Their love and affection have been indispensable in this journey and none of this would have been possible without their unconditional support. For all that and much more, thank you.

Carlos Gil Berrocal

Gothenburg, August 2017

List of publications

This thesis consists of an extended summary and the following appended publications:

Journal Papers

I. C.G. Berrocal, K. Lundgren, I. Löfgren, Corrosion of steel bars embedded in fibre reinforced concrete under chloride attack: State of the art, Cem. Concr. Res. 80 (2016) 69–85. doi:10.1016/j.cemconres.2015.10.006.

II. C.G. Berrocal, I. Löfgren, K. Lundgren, L. Tang, Corrosion initiation in cracked fibre reinforced concrete: Influence of crack width, fibre type and loading conditions, Corros. Sci. 98 (2015) 128–139. doi:10.1016/j.corsci.2015.05.021.

III. C.G. Berrocal, I. Löfgren, K. Lundgren, N. Görander, C. Halldén, Characterisation of bending cracks in R/FRC using image analysis, Cem. Concr. Res. (2016). doi:10.1016/j.cemconres.2016.09.016.

IV. C.G. Berrocal, I. Fernandez, K. Lundgren, I. Löfgren, Corrosion-induced cracking and bond behaviour of corroded reinforcement bars in SFRC, Compos. Part B Eng. (2017). doi:10.1016/j.compositesb.2017.01.020.

V. C.G. Berrocal, K. Hornbostel, M. Geiker, I. Löfgren, K. Lundgren, D. Bekas, Electrical resistivity measurements in steel fibre reinforced cementitious materials, Submitted to: Cem. Concr. Compos.

VI. C.G. Berrocal, I. Löfgren, K. Lundgren, The effect of fibres on steel bar corrosion and flexural behaviour of corroded RC beams, Submitted to: Engineering Structures.

AUTHOR'S CONTRIBUTION TO JOINTLY PUBLISHED PAPERS

The appended papers were prepared in collaboration with the co-authors. In the following, the contribution by the author of this doctoral thesis to the appended papers is described.

In **Paper I** the author participated in the planning of the paper, made the literature study, contributed to the discussion of the results and took the major responsibility for the writing of the paper. The co-authors assisted in the discussion of data and writing of the paper.

In **Paper II**, the author made the literature study, participated in the planning and execution of the experimental programme, carried out the analysis of the data, led the discussion of the results and took responsibility for the planning and writing of the paper. The co-authors participated in the planning of experiments, contributed in evaluating and discussing the results and assisted in writing the paper.

In **Paper III**, the author planned the experiments together with Löfgren, carried out the analysis of the data, led the discussion of the results and took responsibility for the writing of the paper. The experimental work was carried out by Görander and Halldén. All co-authors contributed in the discussion of results and assisted in writing the paper.

In **Paper IV**, the author made the literature study, planned and executed the experimental programme together with Fernandez, carried out most of the data analysis and numerical modelling, led the discussion of the results and took the responsibility for the planning and writing of the paper. The co-authors contributed in evaluating the experimental data, discussing the implementation and results from the numerical modelling and they assisted in writing the paper.

In **Paper V**, the author made the literature study, planned and executed the experiments, carried out the analysis and evaluation of the data, prepared the discussion of the results and took the lead for the planning and writing of the paper. The co-authors contributed in planning the experiments, evaluating and discussing the data, and assisted in writing the paper.

In **Paper VI**, the author participated in the planning and led the execution of the experiments, including the long-term monitoring of corrosion, carried out the analysis of the data, led the discussion of the results and took responsibility for the planning and writing of the paper. The co-authors participated in the planning of experiments, contributed in evaluating and discussing the results and assisted in writing the paper.

OTHER PUBLICATIONS RELATED TO THIS THESIS:

In addition to the appended papers, the author of this thesis has also contributed to the following publications.

Licentiate Thesis

Berrocal, C. G. (2015). *Chloride Induced Corrosion of Steel Bars in Fibre Reinforced Concrete*. Chalmers University of Technology, Licentiate Thesis, Gothenburg, ISSN 1652-9146.

Conference Papers

C-I. C.G. Berrocal, L. Karin, L. Ingemar, Influence of Steel Fibres on Corrosion of Reinforcement in Concrete in Chloride Environments: A Review, in: A. Kohouyjova (Ed.), 7th Int. Conf. Fibre Concr. 2013, Prague, Czech Republic, 2013: pp. 1–10.

C-II. C.G. Berrocal, I. Löfgren, K. Lundgren, Experimental Investigation on Rebar Corrosion in Combination with Fibres, in: The Nordic Concrete Federation (Ed.), Proc. XXII Nord. Concr. Res. Symp., Norsk Betongforening, Reykjavik, Iceland, 2014: pp. 223–226.

C-III. C.G. Berrocal, I. Fernandez, K. Lundgren, I. Löfgren, Influence of fibre reinforcement on the initiation of corrosion-induced cracks, in: Mater. Syst. Struct. Civ. Engieering, 21-24 Aug 2016, Lyngby, Denmark, 2016.

C-IV. C.G. Berrocal, K. Lundgren, I. Löfgren, Investigation on the influence of fibre reinforcement on chloride induced corrosion of RC structures, in: 11th Fib Int. PhD Symp. Civ. Eng., 29-31 Aug 2016, Tokyo, Japan, 2016.

C-V. C.G. Berrocal, I. Löfgren, K. Lundgren, Effect of fibre reinforcement on the crack width profile and internal crack pattern of conventionally reinforced concrete beams, in: 9th Rilem Int. Symp. Fiber Reinf. Concr. - BEFIB 2016, 19-21 Sept 2016, Vancouver, Canada, 2016.

C-VI. C.G. Berrocal, I. Fernandez, I. Lofgren & Karin Lundgren, Corrosion- induced cracking and bond behaviour of corroding reinforcement bars in SFRC, in: the Nordic Concrete Federation (Ed.), Proc. XXIII Nord. Concr. Res. Symp., Norsk Betongforening, Aalborg, Denmark, 2017.

1 Introduction

1.1 Background

Reinforced concrete (RC) is nowadays present in a large part of the infrastructure all over the world. The high compressive strength of concrete combined with the tensile properties of steel makes it a competitive and versatile material suitable for a multitude of applications. Existing structures made of RC include, for instance, bridges, tunnels, harbours, dams or off-shore platforms, as well as a wide range of buildings. It is precisely due to this broad variety of applications that reinforced concrete structures are often exposed to extremely severe conditions, e.g., marine environment, freeze-thaw cycles, carbon dioxide, chemical and biological attack, etc.

Corrosion, due to chlorides present in sea water and in most of the de-icing salts used to remove ice and snow from the roads, is today regarded as one of the biggest problems affecting the durability of RC structures [1]. Corrosion of reinforcing steel is avoided in the first place because it entails the appearance of surface cracks and rust stains giving a bad aesthetic impression. However, if corrosion proceeds, it may lead to a serious loss of the local cross-sectional area of the reinforcing bars and a reduction of the bond between the concrete and the steel, both of which affect the structural behaviour of the RC element and which may eventually compromise the stability and safety of the structure. During the last century a number of structural failures have occurred the causes of which have been mainly attributed to corrosion problems [2].

The problems associated with corrosion are not merely structural. Most existing civil engineering structures have been designed for a total life-span ranging from 50 to 120 years. Yet it is not unusual to find structures that have incurred severe damage after only 15 to 20 years from the start of their service life. Therefore, traffic administrations from countries where structures suffer from corrosion damage are putting a great deal of effort into repairs, retrofitting and replacements of these structures to avoid additional incidents. Unfortunately, all these actions represent a huge economical cost to society in order to maintain an adequate state of serviceability in the current civil engineering infrastructure.

The increased awareness of the problems and costs that can be directly attributed to the corrosion of reinforcement has spurred research into new methods to try to delay, reduce or even prevent corrosion. Current methods are very diverse in nature and focus on different aspects of the corrosion process to mitigate its effects. Corrosion inhibitors, for instance, are chemical compounds which can be added to the concrete mixture or applied onto the surface of hardened concrete to disrupt the anodic and cathodic partial reactions occurring at the rebar surface. Cathodic protection, provided by the supply of an external current, or the use of sacrificial anodes can be also used. Steel reinforcement bars with a surface treatment, e.g. epoxy coated or galvanized, also represent a common way to mitigate corrosion. Even the use of alternative reinforcing materials with improved corrosion resistance, e.g. stainless steel or non-corroding materials, such as Fibre Reinforced Polymer, have been investigated [3].

However, the use of any of the aforementioned preventive methods, irrespective of the method chosen, often leads to the rise of secondary problems, such as chemical incompatibilities with the concrete, the need for additional equipment, a loss of mechanical properties or prohibitive costs. Nevertheless, whether these methods could in practice mitigate the effects of corrosion on reinforced concrete structures in an effective way, they all share the common feature of being very specific to the problem, i.e. no beneficial effects are gained other than improved corrosion resistance. An ideal method would not only mitigate corrosion effectively, but would also provide mechanisms to improve its structural behaviour [4].

The degradation process of reinforced concrete is governed by transport mechanisms that allow the ingress of detrimental substances found in the environment towards the inner zones of concrete where the reinforcement is located. Therefore, preventive methods should never be used as substitutes for good quality, well-executed and well-cured concrete [5]. Large concrete covers are also a desirable parameter to slow down the ingress of deleterious agents and thus obtain more durable structures. On the other hand, the use of large concrete covers implies that cracks formed at the concrete surface can develop without impediments until they reach the reinforcement, resulting in large surface crack widths. Cracks are regarded as potentially harmful to the corrosion process, as they provide preferential paths for external agents to penetrate into concrete. Current structural codes, such as Eurocode 2, fib Model Code and ACI 318 [6–8], specify crack width limitations which may be fulfilled using small bar diameters and placing additional amounts of secondary reinforcement with narrow spacing. This practice, though, tends to cause congested reinforcement layouts which complicate the casting and vibrating procedure of concrete structures, leading to potential defects that may ultimately impair the durability of a structure.

Fibre reinforced concrete (FRC) offers an enhanced toughness and more ductile behaviour compared to plain concrete due to an improved control of the fracture process of the material caused by fibre-bridging of discrete cracks. In combination with conventional rebar, one of the main advantages of using fibres is a significant reduction of the crack width. FRC has been successfully employed to replace conventional reinforcement, either partially or entirely, in different structural applications and with different purposes, such as: in industrial floors and slabs on grade to arrest cracking, mostly due to plastic and drying shrinkage [9]; in tunnels as sprayed concrete [10,11] or precast segmental linings [12] to increase efficiency and reduce costs compared to conventional reinforcement systems; to improve the water tightness in containment structures [13]; and in thin shells or complex shape structures where conventional rebar systems are not suitable [14]. In Sweden, the combined use of steel fibres and conventional reinforcement in structures exposed to a marine environment or de-icing salts has been restricted by the Swedish Traffic Administration. However, it is argued that fibres could also be used in civil engineering structures like bridges or harbour piers, where their crack limiting effects are of interest, to decrease the ingress of detrimental agents, thus delaying or even preventing corrosion of reinforcement. Furthermore, the use of fibres could be beneficial to mitigate the structural impact of damage originating from corrosion of reinforcement, thereby extending the service life of RC structures.

1.2 Aim and objectives

Within the present project, the following research question was formulated: *Can fibre reinforcement be used to extend the service life of RC structures suffering from chloride-induced corrosion of reinforcement?* The research question can be divided into the potential effect of fibres to improve the durability performance of RC structures by delaying and/or reducing corrosion and by mitigating the structural impact of corrosion-induced damage. Accordingly, the general aim of this work is to better understand whether and how fibres may affect the corrosion process and structural performance of conventionally reinforced concrete elements exposed to chloride environments. To reach the general aim, the following specific objectives have been defined:

- To investigate how fibres influence the ingress of chloride ions into concrete, both uncracked and cracked.
- To assess how fibres influence the development of cracks within the concrete cover, particularly at the reinforcement level.
- To identify the effect of fibres on the corrosion initiation and propagation of conventional steel reinforcement.
- To better understand how different loading conditions and varying crack widths influence the reinforcement corrosion process.
- To determine how conductive fibres, such as steel fibres, affect the resistivity and resistivity measurements of cement-based materials and whether they might pose a risk of increased corrosion rates in steel reinforcement due to a decreased resistivity of the concrete.
- To assess the effectiveness of fibre reinforcement to arrest the development of corrosion-induced cracks in conventionally reinforced concrete elements.
- To evaluate the impact of fibres on the structural performance of reinforced concrete elements with corroding reinforcement.

1.3 Methodology and scientific approach

An extensive literature study was conducted giving special attention to two particular aspects. Firstly, experimental data available in the literature regarding the influence of fibres on the corrosion of rebar in concrete as well as on other concrete properties governing the corrosion process, e.g. cracking, water permeation, chloride diffusion and electrical resistivity, were compared and evaluated. The review of experimental studies provided a state-of-the-art knowledge of the subject to be investigated. Secondly, knowledge gaps around the general aim, i.e. research topics that have been explicitly stated to need further research, that constitute a subject of debate among researchers or that have been scarcely investigated in the literature, were identified. These knowledge gaps became the basis on which the specific objectives were defined.

Based on the information obtained from the literature study, a series of experiments were designed to meet the specific objectives. The experiments can be classified into two large groups: long-term corrosion experiments and short-term specific experiments. The former, the main experiments, aimed at reproducing, as far as possible, the conditions to which real structures are subjected (loading, exposure, etc.) in order to obtain meaningful results. The latter consisted of separate experiments that were carried out to either investigate a phenomenon that could not be captured in the main experiments or isolate the influence of fibre reinforcement on individual parameters thereby providing additional information for the correct interpretation of the main experiment results. The analysis of data and interpretation of results from both long and short-term experiments, together with the use of analytical and numerical models in certain parts of the work, provided valuable information that will contribute to a better understanding of the possibilities and challenges of combining fibre reinforcement and traditional rebar in concrete structures exposed to corrosive environments.

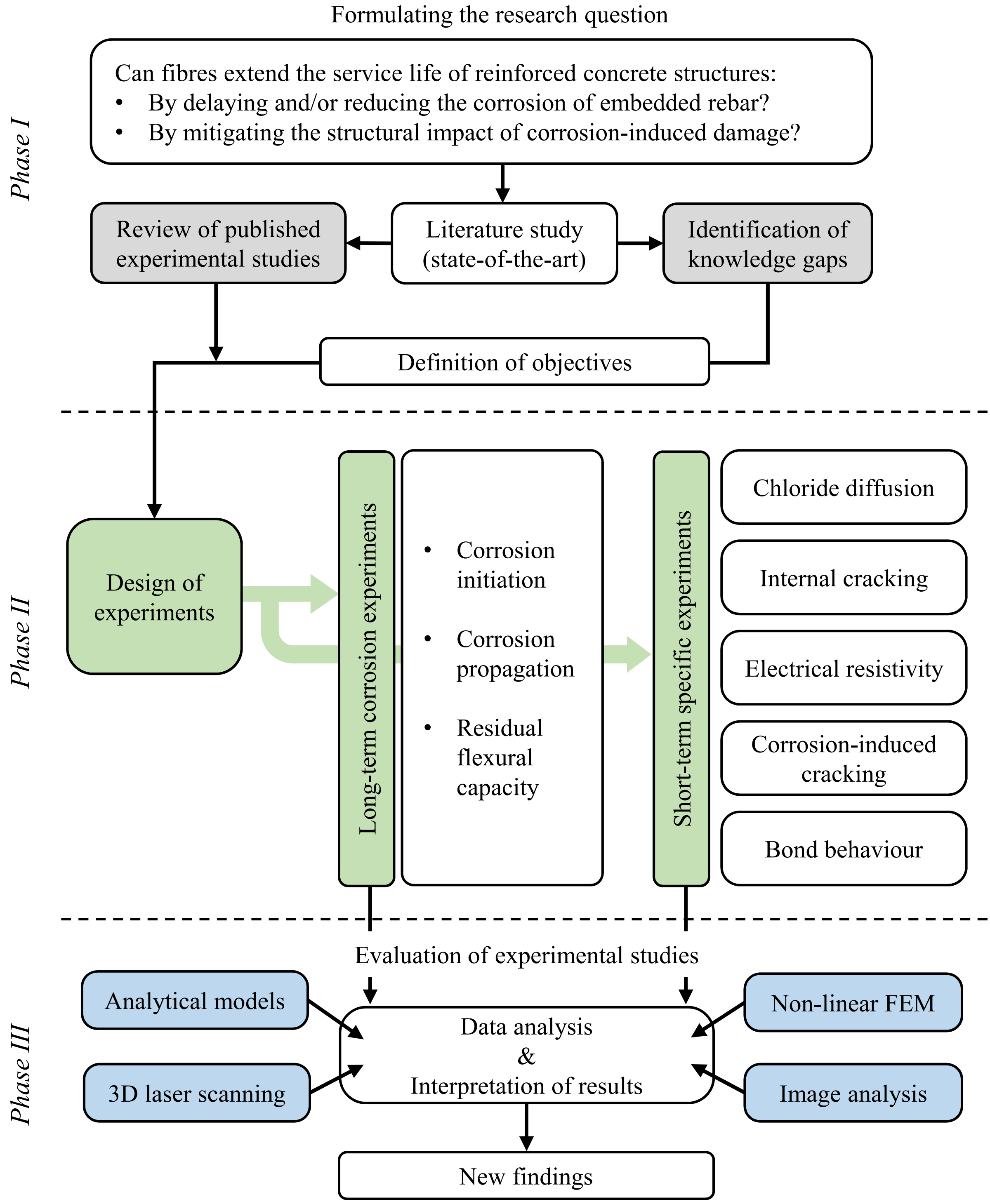


Figure 1.1 Schematic illustration of the methodology followed in the present study

1.4 Limitations

A summary of the main limitations globally applicable to the present work, including this thesis and the appended papers, is described in the following:

- Although the reduction of pH within the concrete cover due to carbonation is also a cause of corrosion initiation in steel reinforcement, only chloride-induced corrosion was investigated. Furthermore, in the experiments, corrosion was promoted by exposure to sodium chloride (NaCl) solution, which can satisfactorily reproduce the conditions of structures subjected to de-icing salts, but might differ from marine exposure due to the chemical reaction of other ions present in the sea water, e.g. Mg^{2+}, SO_4^{2-}.
- In the different studies where cracking was investigated, only mechanically-induced cracks introduced through bending loading were considered. Cracks originating from direct tensile loads or restraint cracking, which may give rise to different crack morphologies and therefore have a different impact on the corrosion of conventional reinforcement, were not investigated.
- Among the vast variety of commercially available fibres, including different materials, sizes, shapes and cross-sections, only three types of fibre were employed in the present work: a 35 mm long end-hooked low carbon steel fibre and straight Polyvinyl-Alcohol (PVA) fibres presented in two different size, namely 30 and 18 mm long. Special emphasis was placed on the study of steel fibres. As conventional reinforcement, only B500B steel rebar was used. The rest of materials (cement, aggregates, etc.) were restricted by the available resources.
- Only one concrete mix composition was used in the different experimental studies, featuring a self-compacting mix with a water-cement ratio of 0.47, maximum aggregate size of 16 mm, and low fibre contents (<1% vol.). The influence of varying those parameters is outside the scope of this work.

1.5 Original features

The original features of the present work are summarized as follows:

- The corrosion of reinforced concrete beams made of plain and fibre reinforced concrete has been experimentally investigated for naturally corroded beams subjected to different loading conditions. The study comprises the entire corrosion process including the initiation phase, the propagation phase and the residual flexural capacity of the beams.
- Combining an innovative test setup and image analysis, the internal crack morphology and the relation between the crack width at the reinforcement and at the surface of reinforced concrete beams made of plain and fibre reinforced concrete was investigated and quantified.
- The present study has revealed valuable information regarding the electrical behaviour of cementitious composites reinforced with steel fibres which may be fundamental for a generalized deployment of SFRC in civil engineering structures prone to suffer reinforcement corrosion. In particular, the present work suggests a modification of the methods currently used to measure the resistivity of plain concrete for their correct application on SFRC. Moreover, the unsuitability for SFRC of certain methods based on the application of DC voltages, has been highlighted.

1.6 Outline of the thesis

This thesis consists of an introductory part and two appended papers.

Chapter 1 provides the background, aim and objectives of the work together with the scope and limitations and a general description of the scientific methods and original contributions of this thesis.

Chapter 2 introduces the fundamental knowledge necessary to establish the theoretical framework on which this project has been developed. In **Paper I**, this knowledge is extended through a literature review on how the corrosion of reinforcement may be influenced by using steel fibres in conventionally reinforced concrete structures exposed to chloride environments.

Chapter 3 presents an overview of the experimental programme and a compilation of the individual experiments carried out in this project which includes a summary of the background motivating the need for the experiments, a brief description of the experiments and a collection of the main findings. Further details are available in **Papers II-VI**.

Chapter 4 includes a summary and discussion of the most important findings of the project, presented in the order of the different phases of reinforcement corrosion.

Chapter 5 contains the main conclusion drawn from this study and suggestions for future research.

2 Theoretical background

2.1 Corrosion of steel in concrete

The phenomenon of corrosion is an electrochemical process [15] which can be understood as two half-cell reactions, anodic and cathodic, occurring on the surface of a metal in contact with an aqueous solution containing oxygen. In the case of steel reinforcement, these reactions can be described by Eq. 2.1 and Eq. 2.2, which represent the anodic oxidation of iron and the cathodic reduction of oxygen. Both of these reactions occur simultaneously and are necessary for the continuation of the corrosion process.

$Fe \rightarrow Fe^{2+} + 2e^-$ Iron dissolution (anodic reaction) (2.1)

$H_2O + \frac{1}{2}O_2 + 2e^- \rightarrow 2OH^-$ Oxygen reduction (cathodic reaction) (2.2)

A Pourbaix diagram [16] is a graphical representation of the thermodynamically stable regions of an aqueous electrochemical system for different potential and pH combinations according to the Nernst's equation. Fig. 2.1 illustrates the Pourbaix diagram for iron, *Fe*, in which three different thermodynamic corrosion regions can be identified: an immunity region, a passivity region and an active corrosion region.

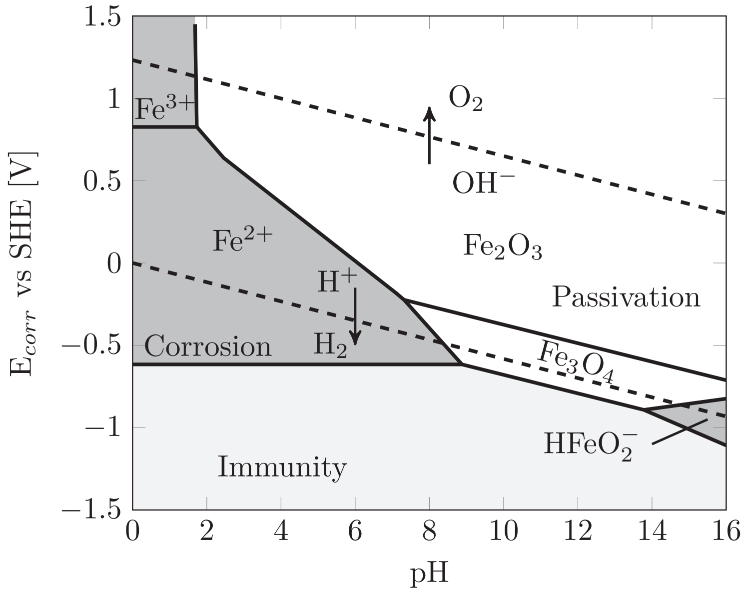


Figure 2.1. Simplified Pourbaix diagram for iron in water at 25°C (ion activity 10^{-6} mol/l) [16]

From this diagram it can be observed that at very low potentials, the steel is in the immunity region, which means that corrosion is not thermodynamically favoured. When potentials increase, for very high pH values, as is the case with the pore solution of concrete, the steel is in the passivity region. This means that under high alkalinity conditions, a very thin, dense and stable iron-oxide film is formed on the surface of the steel [17]. This film, often referred to as the passive layer, greatly reduces the ion mobility between the steel and surrounding concrete; thus, the rate of corrosion drastically drops and becomes negligible. Therefore, under most conditions, well designed and executed reinforced concrete structures will present good durability as the concrete provides protection against corrosion of the reinforcing steel.

Nevertheless, corrosion remains one of the major problems affecting reinforced concrete structures. According to Tuutti's model [18], the service life of a reinforced concrete structure can schematically be divided, from the perspective of reinforcement corrosion, into two time periods: initiation and propagation, which is graphically illustrated in Fig. 2.2. The initiation period is considered to be the time required for external agents to penetrate into the concrete and cause depassivation of the reinforcing steel, whereas the propagation period is characterized by active corrosion, with associated iron dissolution in the anodic regions.

The most common depassivating substances causing corrosion of reinforcement are: (i) the carbon dioxide present in the atmosphere, which decreases the alkalinity of the pore solution of the concrete leading to the dissolution of the passive layer; and (ii) chlorides, from marine environments, de-icing salts or other sources, which tend to cause a localized breakdown of the passive film, provided enough moisture and oxygen are available at the reinforcement.

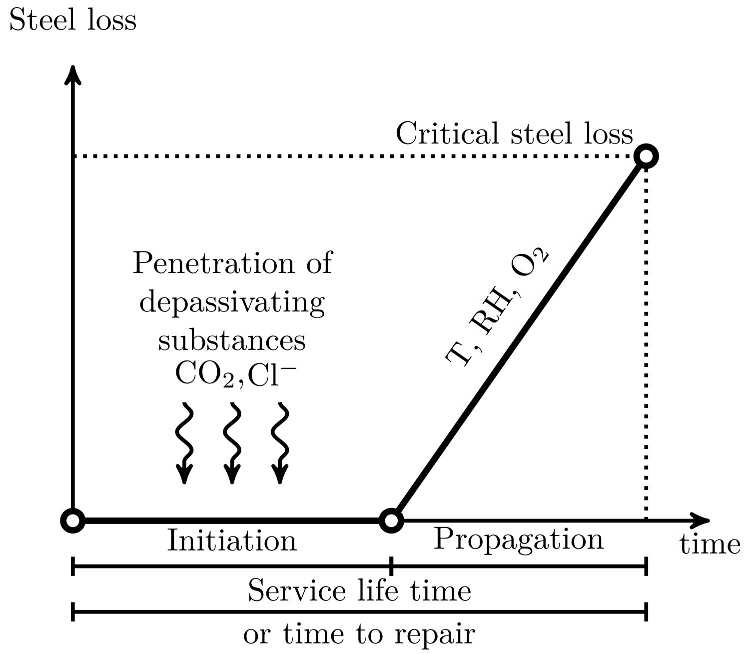


Figure 2.2. Tuutti's model for reinforcement corrosion, modified from [18]

In the case of chloride-induced corrosion, the concentration of chlorides in the concrete needs to reach a certain value before breakdown of the passive layer occurs. This value, commonly referred to as *the chloride threshold value* or *the critical chloride content*, is generally expressed in terms of total chloride by weight of binder or [Cl^-]/[OH^-] ratio [19]. However, this parameter is known to be dependent on multiple factors and, consequently, a large scatter can be found among different values reported in the literature. A recent review on the subject by Angst et al. [20] revealed values of the critical chloride content ranging from 0.04 to 8.34% total chloride by weight of cement. Some of the factors that are regarded as having a greater impact on the critical chloride content are the pH of the pore solution, the oxygen availability and the characteristics of the steel-concrete interface, including the type of hydration products formed and presence of defects [2,21,22].

When the critical chloride content is reached and the passive layer breaks down, a pit is typically formed. Hence, the term used to describe this type of corrosion is *pitting corrosion*. After pitting has initiated, the diffusion of oxygen into the pit might be slower than its consumption through the cathodic reaction (Eq. (2.1)), thereby confining the reduction of oxygen to areas adjacent to the pit, while inside the pit, iron dissolution is the main reaction. Under those conditions, the environment inside the pit becomes particularly aggressive. This phenomenon is partly due to the local acidification of the anolyte inside the pit resulting from the hydrolysis of dissolved iron ions and partly due to an increased chloride content in the pit caused by the migration of chloride ions to balance the positive charge produced. Conversely, the removal of chloride ions from the cathodic areas and the production of hydroxyl ions resulting from the cathodic reaction of oxygen reduction, both tend to strengthen the protective film in the passive regions. Thus, the anodic and cathodic reactions are stabilized and the corrosion process can be sustained [23]. The overall process of chloride-induced pitting corrosion in concrete can be illustrated as shown in Fig. 2.3.

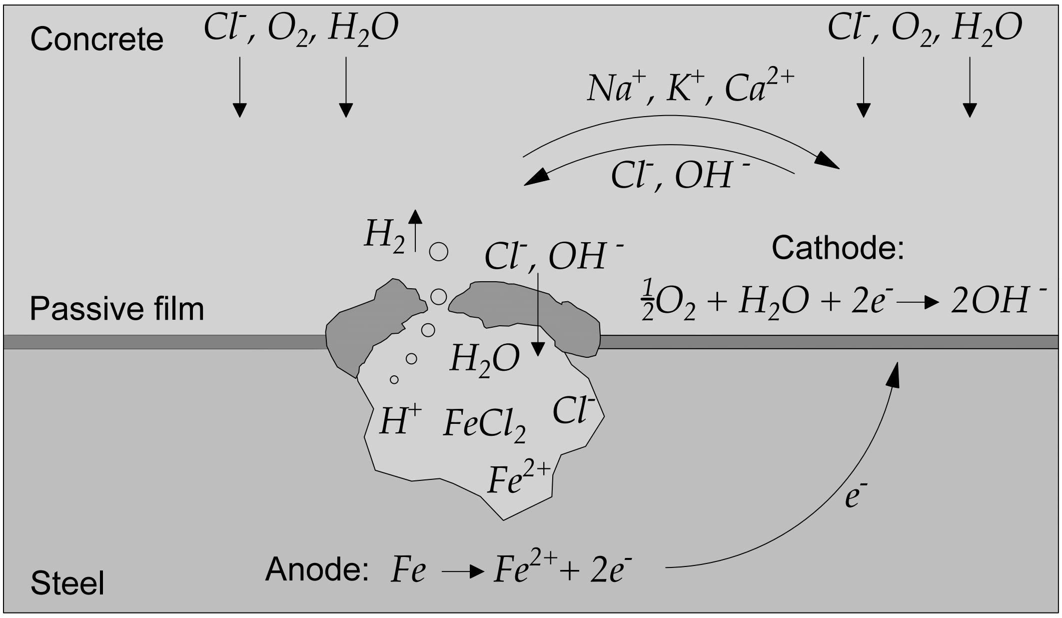


Figure 2.3. Schematic representation of the electrochemical process of chloride-induced pitting corrosion.

Once pitting corrosion has stabilized, an electrochemical circuit is formed involving four main steps (cf. Fig. 2.3): the anodic reaction of iron dissolution (Eq. 2.1), electron transfer through the reinforcement, the cathodic reaction of oxygen reduction (Eq. 2.2) and transport of ions through the concrete pore solution. The corrosion rate can be regarded as the current flowing through the circuit and is governed by the kinetics of the different reaction steps. With the exception of the electron transfer, which is never the limiting factor, the corrosion rate is controlled by the slowest of the remaining three processes. In submerged concrete, for instance, where oxygen depletion may occur, cathodic diffusion control is the most likely mechanism limiting the corrosion rate. In other cases, the ionic current flow between the anodic and cathodic sites might be the limiting reaction step, leading to ohmic control.

The electrical resistivity of concrete describes its ability to withstand the transfer of charge and it mainly depends on the moisture content, the pore structure and the chemistry of the pore solution [2]. Results from a vast amount of literature, see e.g. [24–29], indicate that an empirical inverse relation may exist between the concrete resistivity and the corrosion rate. An extensive review on the subject can be found in [30]. Whereas a high concrete resistivity might indicate pure ohmic control, as in dry concrete conditions, it has been postulated that under many other conditions the corrosion rate is controlled by a combination of the cathodic, anodic and ohmic partial processes [31].

The continuous dissolution of steel leads to a decrease of the cross-sectional area of the rebar. The ferrous ions released may combine with the hydroxyl ions in the solution to form solid products. These products are insoluble and often present a larger volume than that of the corresponding steel loss. The products are usually deposited on the rebar surface, in the surroundings of the anodic region, filling the pores adjacent to the interface between the concrete and the reinforcement bar [32]. The gradual accumulation of expansive corrosion products induces inner tensile stresses causing cracking and spalling of the concrete cover and a reduction of the bond between steel and concrete. Both the loss of the rebar section and steel-concrete bond lead to a decrease in structural safety.

2.2 Influence of cracking on corrosion

The phenomena causing degradation of reinforcement in concrete structures are largely dependent on the mechanisms that allow the ingress of water, oxygen and detrimental agents, such as chloride ions or CO_2, as well as mechanisms that allow the transfer of electrical current, to mention a few.

The transport mechanisms in concrete can be roughly divided into transport in the bulk material vs. transport in micro- and macro-cracks. Transport in the bulk material can be further classified into four basic mechanisms: *capillary suction* caused by capillary forces, sometimes also referred to as *absorption*; *permeation* driven by a pressure gradient; *diffusion* driven by a concentration gradient; and *migration* due to the presence of an electrical field [2].

In uncracked concrete, the concrete cover acts as a physical barrier against the ingress of corrosion-inducing agents. Therefore, the cover depth and quality of concrete are crucial factors influencing the corrosion process of reinforcement. In practice, however, cracks originating from shrinkage, thermal gradients and/or mechanical loading can be found in the vast majority of reinforced concrete structures. These cracks often become preferential paths for the ingress of external agents. As a result, the transport properties of concrete are significantly altered and the durability of concrete structures is negatively affected.

The effect of cracking on the corrosion of reinforcement has been dealt with by several authors in the past, see e.g. [33–48]. Whereas it is generally accepted that the initiation period for cracked concrete is reduced compared to uncracked concrete, the influence of the crack width on corrosion is still a subject of contemporary studies. Most observations indicate that wider cracks tend to hasten the corrosion initiation [18,36,39], yet researchers are still divided into those who argue that the crack width influences the corrosion rate during the propagation period [38,42,45] and those who claim that a relation between crack width and corrosion rate might be only observed in the short-term [36,49,50].

In some of the investigations it is suggested that other crack parameters might be also relevant to understand the influence of cracks on the corrosion process. Schiessl and Raupach [36] observed that in cracked concrete the preferred corrosion mechanism is macro-cell corrosion, where the anodic site is located at the intersection between the crack and the rebar and the cathodic areas are located along the rebar embedded in uncracked concrete. Under macro-cell corrosion, it is argued that the crack spacing or crack frequency might have a significant influence on the corrosion rate due to variations in the anode-to-cathode ratio [43]. The orientation of the crack with respect to the reinforcement [51], the self-healing properties of the crack [52] or the stress level at the reinforcement [48,53,54] have been also identified as potentially influencing parameters.

More recently, Pease [55] proposed in his thesis the hypothesis that debonding along the concrete-reinforcement interface might be more important for the corrosion of reinforcement than surface crack width. Michel [56] found that it is the interfacial separation, i.e. the perpendicular displacement between the concrete and the rebar, which better correlates with the areas of reinforcement where corrosion is thermodynamically favoured according to potential measurements. In another thesis, Silva [57] concluded that the steel surface and presence of air-voids at the concrete-steel interface were major factors influencing the development of potential gradients along the rebar surface, thus influencing the corrosion process negatively, which is in line with the findings of Buendfeld et al. [58].

The only consensus amongst researchers today is that, if the cracks are above a certain limit, i.e. are too large, they will have a negative impact on the durability of RC structures. As a result, current structural codes specify permissible crack widths at the surface based on exposure conditions and expected service life, as a way to try to obtain durable structures.

2.3 Fibre reinforced concrete

2.3.1 Mechanical behaviour

Fibre reinforced concrete (FRC) is a cement-based composite material reinforced with short, discontinuous fibres which are usually added to the concrete during the mixing process. Fibres are dispersed throughout the concrete matrix but their distribution and orientation are influenced by the boundary conditions, the concrete rheological properties and casting procedure [59,60]. The main purpose behind adding fibres to concrete is to better control the fracture process by bridging discrete cracks. As a result, the presence of fibres increases the fracture energy of concrete, enhancing its toughness and leading to a more ductile behaviour. However, the post-cracking behaviour of FRC largely depends on various parameters, including the physical properties of the fibres, the fibre-matrix bond and the amount, orientation and distribution of the fibres throughout the concrete matrix [9,61].

Although fibres improve the toughness of the concrete in compression, the greatest beneficial effect of fibres is observed on the tensile properties of the concrete. Accordingly, fibre reinforced cementitious materials may be classified based on their tensile behaviour, as either strain softening (a quasi-brittle material) or pseudo-strain hardening [62,63]. Plain concrete is a strain softening material characterized by a sudden loss of stress once the tensile strength of the material has been reached. Conversely, cementitious materials presenting pseudo-strain hardening behaviour exhibit multiple-cracking up to the post-cracking strength, which is higher than the cracking strength. In practice, it is generally accepted that low fibre contents, below 1% vol., will lead to strain softening behaviour while pseudo-strain hardening is associated with higher fibre fractions, usually above 2% vol.

Typical curves for various cementitious materials presenting different tensile behaviour are presented in Fig. 2.4.

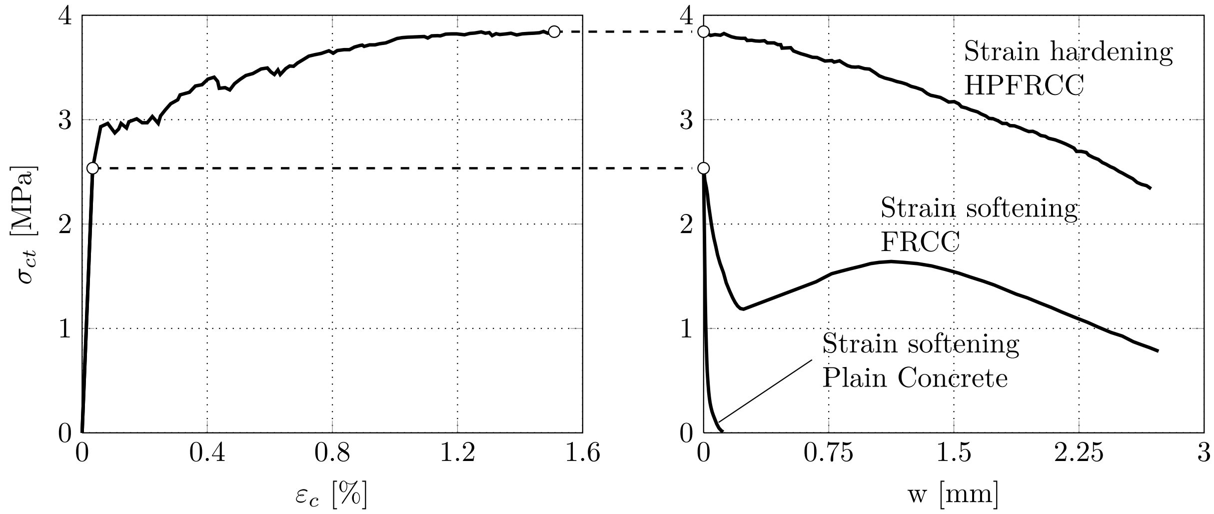


Figure 2.4. Tensile strength classification of cementitious materials, from [64]

Several research studies have shown that fibre reinforcement is particularly suitable for various structural applications, e.g. as shear reinforcement [65–72] or in seismic applications [73–75], where fibres have been regarded as having a similar or even better performance than conventional rebar. However, according to Bentur and Mindess [76], it is unlikely that fibres will completely replace the conventional reinforcement in large structural members. This can be attributed to the need for high fibre volume fractions and relatively high performance concretes in order to obtain a pseudo-strain hardening behaviour, added to the low efficiency of fibres caused by their random position and orientation throughout the concrete matrix.

Nevertheless, the combination of fibre reinforcement and steel bars, sometimes referred to as hybrid reinforcement, could be used to improve the mechanical response of RC elements [77]. Fibres can influence the behaviour of conventionally RC elements by carrying a fraction of the tensile load through cracks and by controlling the development of bond-splitting cracks. These two mechanisms lead to a series of enhancements, such as greater load-carrying capacity [69,78–80], increased tension-stiffening [81–84] and improved bond between the matrix and the bars due to the passive confinement provided by the fibres [85–88].

Furthermore, one of the primary benefits of using FRC in conventionally reinforced concrete elements is a better control of the cracking process, which results in a reduction of the crack widths and crack spacing [81,89–96]. Moreover, fibre reinforcement has been also found to reduce the interfacial damage occurring during mechanical loading between ribbed bars and the concrete matrix [97,98]. Consequently, fibre reinforcement could be used together with conventional steel bars for crack control purposes in order to mitigate the ingress of deleterious substances into the concrete and thus improve the overall durability of RC structures [78].

2.3.2 Influence of fibre reinforcement on corrosion of conventional rebar

Despite the great potential of FRC, a generalized use of fibre reinforcement in large civil engineering structures is, today, still limited to a few applications. One of the reasons for this might be a relatively small amount of research and experience regarding the long-term performance and durability of RC elements made of FRC compared to the amount of existing literature related to its mechanical behaviour. However, great efforts have been directed during the last decades towards gaining a better understanding of the durability of concrete elements with hybrid reinforcement. In this section, a summary of the research investigations studying the influence of fibre reinforcement on the corrosion process of steel bars is provided.

Regarding the influence of fibre reinforcement on the transport properties of the concrete, it has been shown that fibres do not significantly affect the permeation [99,100] and the chloride ingress [101–107] of uncracked specimens. On the other hand, a beneficial effect of the fibres on the permeation of cracked elements has been reported, particularly for crack widths exceeding 0.1 mm [108–114].

A summary of experimental studies investigating the influence of FRC on the corrosion of conventional reinforcement is presented in Table 2.1, where the most relevant parameters of the test setups, the corrosion phase investigated and the effect of FRC, are included.

Comparing the results of the different studies investigating the time to corrosion initiation in uncracked concrete, most of the studies found that the results were either inconclusive or that no apparent effect could be observed. These results support the fact that fibre reinforcement does not have a significant influence on the ingress of chloride into uncracked concrete elements. On the other hand, some researchers have shown that, when RC specimens made of plain concrete and FRC are subjected to the same load level, the crack control mechanisms of FRC can be advantageous to delay the initiation of reinforcement corrosion [4,115]. In **Paper II**, it was shown that that fibres could likewise contribute to a delayed corrosion initiation even for RC elements featuring the same surface crack width.

Regarding the effect of fibres on the corrosion rate, the results are mostly divided into those which exhibited a positive effect of the fibres and those for which no significant effect could be appreciated. However, when discerning the cause that led to a lower corrosion rate in studies showing a beneficial effect of fibres, most researchers reported similar explanations. The improved corrosion behaviour was most likely attributable to the arrested growth of existing cracks and the delayed appearance of subsequent corrosion-induced cracks, which hindered the additional ingress of aggressive agents. From these results, it might be inferred that steel fibres themselves do not significantly affect the corrosion process of steel reinforcing bars embedded in concrete. On the other hand, they might potentially delay and reduce the degradation of reinforcement by means of crack-control mechanisms. The formation of a galvanic cell between steel fibres and conventional steel bars has also been mentioned in some investigations [116,117] as a possible cause for the improved corrosion resistance of SFRC. According to the researchers, steel fibres in direct contact with a rebar might act as sacrificial anodes, thereby protecting the rebar, although this particular mechanism has not yet been specifically investigated.

Nevertheless, the number of available experimental studies on the corrosion process of steel bars embedded in FRC is still limited and difficult to compare due to variations in the materials, experimental setups and exposure conditions used. Moreover, most studies used either uncracked concrete specimens, artificially accelerated corrosion through impressed current, high fibre contents (>1.5% vol.) leading to pseudo-strain hardening behaviour or reduced exposure times (< 1 year). Therefore, further experiments are required to assess the potential effect of FRC, at low dosages, on the corrosion process of rebar in cracked concrete and on the mitigation of the structural effects caused by corrosion-induced damage.

Table 2.1. Review of experimental studies investigating corrosion of rebar in FRC

Author(s) [Ref.]	**Fibre reinforcement**		**Matrix**		**Rebar**	
	Material – length [mm] – aspect ratio	Content [% vol.]	*w/b*	Pre-cracks	Ø [mm]	Cover [mm]
Someh and Saeki [116]	Steel (zinc-coated) 30 - 60	1.5	Concrete 0.55 OPC	No	10	25
Grubb et al. [118]	Steel - ~ 4 - ~ 50	4.5	Mortar 0.45/0.55 OPC	No	9.52	32.7
Matsumoto et al. [119]	Steel – 43 - 57	1.0	Concrete 0.65 OPC	No	19	25
Kim et al. [99,105]	Steel – 30 – 55 Polypropylene – 39 – 90 PVA – 30 – 45	1.0 0.5 0.75	Concrete 0.44 OPC	No	n/p	n/p
Hou and Chung [120]	Carbon – 5 – 330	0.35	Concrete 0.5 Admixtures	No	9.52	34.2
Sanjuán et al. [121]	Polypropylene – 14 – n/p	0.5	Mortar 0.5 OPC	No	6	22
Al-Tayyib and Al-Zahrani [122]	Polypropylene – 19 – n/p	0.2	Concrete 0.45 to 0.65 OPC	No	12	25
Mihashi et al. [117,123]	Polyethylene – 6 – 500 Steel – 32 – 80	1.5 (P) 0.75+0.75	Mortar 0.45 OPC + SF	No	13	20
Maalej et al. [124]	Steel – 13 – 80 PVA – 12 – 300	1.0 + 1.5	Concrete 0.45 OPC + FA	No	16	52
Ahmed et al. [125]	Polyethylene – 6 – 500 Steel – 32 – 80	1.5 (P) 0.75+0.75	Mortar 0.45 OPC + SF	4PBT Fixed w Unloaded	13	20
Blunt et al. [4,126]	PVA – 8 – 200 + Steel – 30 – 55 + Steel – 60 – 80	0.2 + 0.5 + 0.8	SCC 0.54 OPC	Fixed load 5 load cycles	9.52	25.4
Niş et al. [127]	Steel – 35 – 65	0.5	Concrete 0.45 / 0.65 OPC	Fixed w Sustained/ Dynamic	14	25/45
Sappakittiparkorn et al. [115,128]	Polypropylene – 16 - 530	0.1 / 0.3	Concrete 0.55 OPC	4PBT Fixed load Sustained	10	25
Hiraishi et al. [129,130]	Polyethylene – 12 - 1000	1.5	Mortar 0.3 / 0.6 OPC	3PBT Fixed load Sustained	9	20

n/p: not provided

OPC: Ordinary Portland Cement, SF: Silica Fume, FA: Fly Ash, Admixtures: Latex and Methylcellulose

4PBT: 4-Point Bending Tests, 3PBT: 3-Point Bending Test

Unloaded: no load during exposure

Dynamic: cyclic loading during exposure

Sustained: applied load during exposure

Table 2.1. Review of experimental studies investigating corrosion of rebar in FRC (Cont.)

Author(s) [Ref.]	Exposure Method	Exposure Period	Phase investigated	Effect
Someh and Saeki [116]	3 kg/m^3 NaCl mixed-in + 12 h wet-dry cycles (5% NaCl solution at 35ºC and air circulation @ 35ºC)	6 months	Initiation	Positive
Grubb et al. [118]	Immersion in 3.5% NaCl sol.	7 months	Initiation Propagation	Unclear[(a)] Positive
Matsumoto et al. [119]	Cyclic immersion 3 days in 10% NaCl + 4 days air drying at ~55% RH	95 weeks	Initiation Propagation	None None
Kim et al. [99,105]	Cyclic ponding with 16.5% NaCl sol. 2 weeks wetting + 2 weeks air drying	660 days	Initiation Propagtion	Unclear[(b)] None
Hou and Chung [120]	Immersion in 0.5 N NaCl sol.	25 weeks	Initiation Propagation	Unclear[(c)] Negative
Sanjuaán et al. [121]	Ponding with 0.5 M NaCl sol. Stored in room @ 50ºC and 50% RH	135 days	Initiation Propagation	None Positive
Al-Tayyib and Al-Zahrani [122]	Ponding with seawater (Arabian Gulf)	240 days	Initiation	None
Mihashi et al. [117,123]	Cyclic wetting in 3% NaCl sol. + drying @ 20ºC and 60% RH + 3V DC Voltage	52 weeks	Propagation	Positive
Maalej et al. [124]	Cyclic wetting 3.5 days in 3% NaCl sol. + air drying + 8V DC Voltage	141 days	Propagation	Positive
Ahmed et al. [125]	Cyclic wetting in 3% NaCl sol. + drying @ 20ºC and 60% RH + 3V DC Voltage	60 weeks	Propagation	Positive
Blunt et al. [4,126]	Ponding with 3% NaCl sol.	9 months	Initiation Propagation	Positive[(d)] Positive
Niş et al. [127]	Cyclic ponding with 3.5% NaCl sol.	n/p	Initiation Propagation	Unclear[(e)] No/Positive[(f)]
Sappakittiparkorn et al. [115,128]	Cyclic immersion 3 day in 3.5% NaCl + 4 day air drying at ~55% RH, 22ºC	56 weeks	Initiation Propagation	Positive None
Hiraishi et al. [129,130]	Cyclic wetting 2 days in 3.1% NaCl sol. + 5 days drying @ 60% RH	n/p	Propagation	Positive

(a) The authors disregarded the initial 10 weeks of exposure.
(b) Positive effect for polypropylene and PVA fibres but negative effect for steel fibres.
(c) No conclusive results
(d) Macro-cracks were formed in plain concrete specimens during pre-cracking, but not in FRC.
(e) No conclusive results
(f) Positive effect only observed for dynamically loaded specimens.

2.3.3 Corrosion of steel fibres in concrete

Among the different materials used to manufacture fibres, steel is often preferred for crack control purposes due its high elastic modulus and good resistance to the highly alkaline conditions of concrete. However, there is a risk that steel fibres will corrode in the presence of chlorides as the corrosion of steel fibres and conventional rebar in concrete are governed by the same principles, described in Section 2.1. Nevertheless, it has been found that steel fibres possess an improved corrosion resistance compared to conventional rebar [131–133].

Available data indicates that, for uncracked concrete, the corrosion damage of steel fibres embedded in well-designed and executed concrete is limited to corrosion of the fibres located within approximately 5 mm from the exposed surface [11,19,105,134–140]. Moreover, according to Balouch et al. [134], the extension of the region where fibres are sensitive to suffer corrosion can be effectively decreased to only 0.2 mm by using *w/c* ratios below 0.5. However, it has been reported that corrosion of superficial fibres is commonly accompanied by extensive rust stains at the concrete surface [137,141] but unlike for conventional reinforcement, fibre corrosion does not cause concrete spalling [142].

On the other hand, fibres fully embedded in uncracked concrete will remain free of corrosion even if high chloride contents are present in the concrete. This can be explained by a significantly higher value of the critical chloride content for steel fibres compared to conventional rebar, as reported by several studies, e.g. 2.1–4.7% [143], 2.11% [144] and 2.4% [19] total chlorides by weight of cement.

The improved corrosion resistance of steel fibres has been mainly attributed to the combination of two factors. One of them is the short length and discontinuous nature of fibres, which impedes large potential differences along the fibre surface, thereby potentially limiting the formation of distinct anode and cathode regions [131]; The second factor relates to a well-defined interfacial layer of ~10 µm, rich in $Ca(OH)_2$, that forms in direct contact with the steel fibres, which is more uniform and presents less defects than that of conventional rebar [145,146], as a result of the casting conditions (floating in the matrix as opposed to rebar). That layer can act as a physical barrier against the penetration of chlorides and by buffering the pH of the pore solution at the steel surface [21,131].

Despite their apparently enhanced corrosion resistance, ordinary carbon steel fibres bridging cracks are susceptible to suffer corrosion. The available results in the literature regarding the influence of the crack width on corrosion of steel fibre are controversial. Some researchers have reported that crack widths of up to 0.5 mm will only cause limited corrosion of the fibres [135,144]. Others have reported that substantial fibre corrosion may occur for crack widths above 0.1-0.2 mm [10,138,147]. Whereas light fibre corrosion can lead to an increased peak load and post-crack carrying capacity due to an increased bond between the fibres and the concrete matrix [135,142], severe corrosion leads to a decreased strength of the material as well as a loss of toughness due to a change in the failure mode of the fibres, from pull-out to fibre breakage [10,141,142,148].

In a recently published report by Nordström [149], the residual capacity of sprayed concrete (shotcrete) SFRC beams exposed to three different field environments in Sweden, namely a motorway, a river side and a tunnel, was evaluated after a period of 17 years. The results revealed that for small deformations and a crack width of up to 0.1 mm, an increase of load-carrying capacity could be observed even after 17 years. However, for large deformations (2 mm deflection in 450 mm span length), a generalized loss of load-carrying capacity ranging between 20 and 60% was observed regardless of the crack width and exposure conditions. The conclusion of the study was that, with the type of steel fibres commonly used today, it is not reasonable to expect that cracked steel fibre reinforced sprayed concrete exposed to chlorides will retain its load-carrying capacity for a service life of 100 years. Consequently, when using steel fibres, limiting the crack width might be required in order to prevent early deterioration of crack bridging fibres, and the resulting loss of mechanical performance of the material, due to corrosion. Moreover, in such conditions, the contribution of the fibres near the surface, e.g. in the concrete cover, might need to be reduced or even neglected for design in ultimate limit state, whereas a positive contribution can still be expected for serviceability limit states [150].

3 Experimental programme

3.1 Overview of experiments

The experiments carried out in this project can be divided into two main categories according to Fig. 1.1:

(i) Long-term corrosion experiments.

(ii) Short-term specific experiments.

The long-term corrosion experiments, referred to as experimental study A, were specifically designed to investigate the influence of fibre reinforcement on chloride-induced corrosion of conventional reinforcement. The experimental study A was intended to encompass the different stages of the corrosion process while reproducing, as much as possible, realistic conditions. These conditions include the combination of naturally induced accelerated corrosion, flexural cracks formed under mechanical loading, varying crack widths and different loading conditions. The results of experimental study A, presented in **Papers II** and **VI**, aimed at providing experimental data to answer the questions of whether fibre reinforcement can influence corrosion of rebar, whether that effect is positive or negative and whether reinforcement corrosion is affected significantly or only slightly by the fibres.

The short-term experiments comprising experimental studies B to E, on the other hand, were designed to isolate the effect of fibres on specific parameters or mechanisms relevant to the corrosion process. These included:

- Diffusion of chloride ions into uncracked concrete.
- Internal morphology of bending cracks in conventionally reinforced beams.
- Electrical resistivity of concrete and its assessment.
- The formation of corrosion-induced splitting cracks in the concrete cover.
- Bond behaviour between concrete and corroding reinforcement.

The results of these experimental studies, presented in **Papers III-V**, provided additional data, complementary to the data from experimental study A, to help understanding the mechanism through which fibres can influence the corrosion process of reinforcement in concrete.

Table 3.1 summarizes the experimental programme indicating the different mechanisms investigated, their corresponding experimental study and in which paper the results are included. In Fig. 3.1 the different mechanisms are indicated in a schematic diagram of the deterioration process of reinforcement corrosion to illustrate their effect at different stages of the corrosion process.

Table 3.1 Overview of the experimental programme and relation to appended papers

	Mechanism / Parameter investigated	**Experimental study**	**Appended paper**
Initiation phase	Chloride ingress ①	B	(*)
	Internal cracking ②	C	III
	Time to corrosion initiation ③	A	II
Propagation phase	Resistivity of concrete ④	D	V
	Corrosion rate ⑤	A	VI
	Corrosion level to crack the cover ⑥	E	IV
Structural performance	Bond behaviour ⑦	E	IV
	Flexural capacity ⑧	A	VI

(*) Only reported in the introductory part of this thesis.

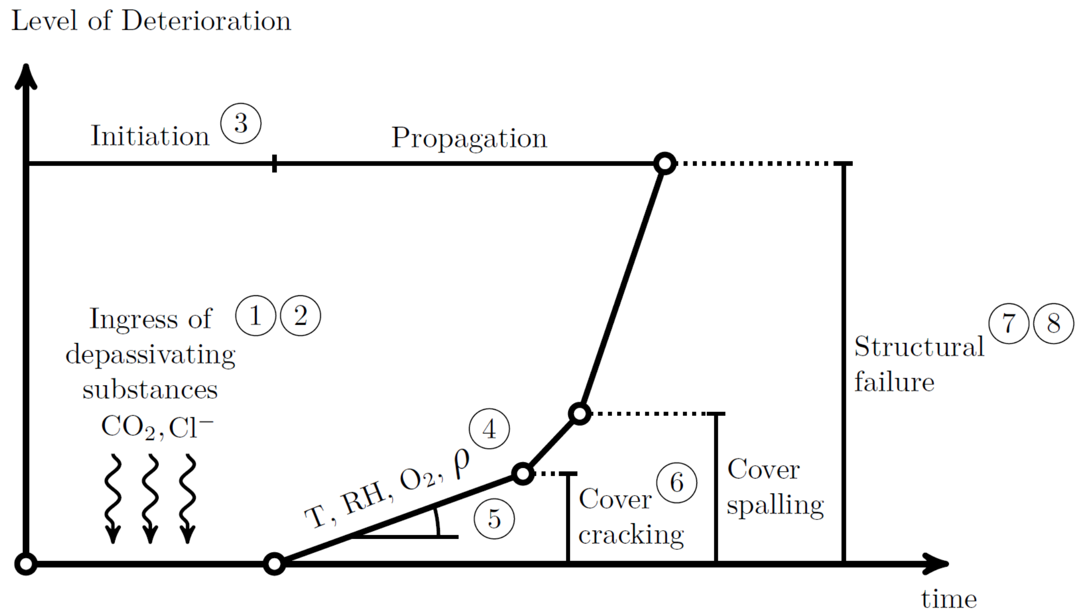


Figure 3.1. Deterioration process of reinforcement corrosion, adapted from [7] *indicating the different parameters investigated in the experimental studies in this work.*

3.2 Experimental study A – Long-term corrosion experiments

The experimental study A comprised the most important part of the entire experimental programme and was subdivided into two different phases. The first phase involved the conditioning of RC beams to promote chloride-induced corrosion on the reinforcement and the corresponding monitoring of parameters associated to corrosion. These were half-cell potential, surface resistivity, and corrosion penetration rate which were used to determine the end of the corrosion initiation period and estimate the corrosion rate during the propagation period. The second phase involved the assessment of the structural performance of the corroded RC beams and its correlation to the actual corrosion levels assessed through different methods.

3.2.1 Description of experiments

A total of 54 beam specimens were cast. Six of these were kept uncracked and stored in potable water to be used as reference samples, while the remaining were subjected to different loading conditions and subsequently exposed to chlorides. The four conditions considered were:

(a) *Uncracked* specimens, which were never loaded.
(b) *Unloaded* specimens, which were loaded only once to induce cracking.
(c) *Cyclic* specimens, which were subjected to five load cycles to promote greater damage at the rebar-concrete interface.
(d) *Loaded* specimens, which were initially pre-cracked and subsequently reloaded with a sustained load to keep cracks open.

For all the beams subjected to loading, crack widths ranging from 0.1 to 0.4 mm were investigated. Moreover, four different series of specimens were cast:

(a) *Plain* series: without fibre reinforcement.
(b) *Steel* series: containing 0.5 % vol. of 35 mm end-hooked low-carbon steel fibres.
(c) *Hybrid* series: combining 0.35% vol. steel fibres and 0.15% 18 mm straight PVA fibres.
(d) *Synthetic* series: with 0.75% vol. 30 mm straight PVA fibres.

The specimens used in the experimental study were 1100 mm long beams with cross-sectional dimensions of 180×100 mm and reinforced with three Ø10 mm ribbed bars positioned with a clear concrete cover of 30 mm from the bottom and lateral sides. A self-compacting concrete mix with a water cement ratio (*w/c)* of 0.47 was used for all the series in the experimental study. The reinforcement bars were of B500B steel grade and were used "as received" without applying any surface treatment prior to casting. Fig. 3.2 shows the geometry of the beam specimens, including the reinforcement layout, and the different types of fibres used to cast the different series.

<u>Phase 1: Pre-cracking, chloride exposure and corrosion monitoring</u>

Transverse cracks were induced in the *unloaded*, *cyclic* and *loaded* beams using a three-point bending pre-loading procedure. The procedure was performed at a constant displacement rate of 0.1 mm/min for the *unloaded* and *loaded* beams and 1 mm/min for the *cyclic* beams. Loading continued until the widest crack formed, measured using a crack detection microscope with a 20× magnification and 0.02 mm resolution, reached the target crack width. The surface crack width of most beams after unloading ranged between 0.02 mm and 0.06 mm.

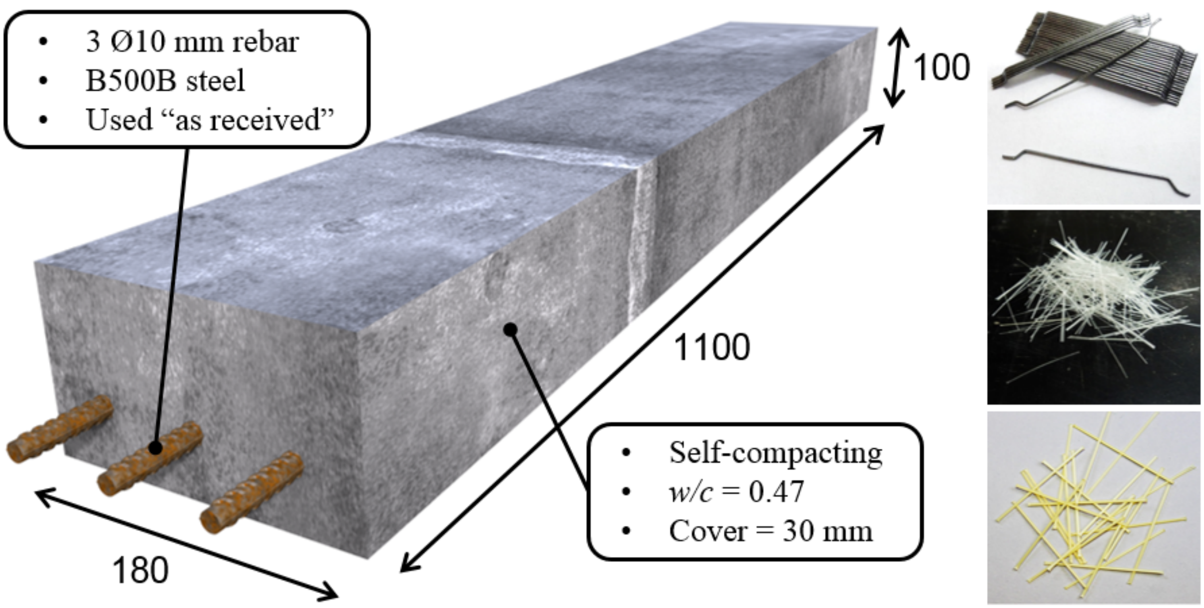


Figure 3.2. Specimen geometry, reinforcement layout and fibre types. Measurements in mm.

The *loaded* beams were in addition reloaded with a sustained load during the chloride exposure. The beams of the *plain* series were coupled to beams of the *steel* series according to the target crack width aimed during the pre-loading procedure. The coupled beams were clamped together using a setup consisting on two hollow rollers, fastened by means of threaded rods and nuts, placed on either end of the beams and a solid steel cylinder placed at mid-span between the two beams working as a hinge. Subsequently, the load was introduced by tightening the nuts on the threaded rods and measured by previously installed and calibrated strain gauges on the threaded rods.

The exposure of the beams to chlorides was performed by partial immersion in a highly concentrated chloride solution (16.5% wt. NaCl). The beams were placed standing vertically in plastic tanks and the immersion was performed cyclically. Two week wetting cycles during which the beams were submerged to approximately 75% of their length were alternated with two week drying cycles at laboratory conditions (20.5±3.6ºC and 45±15% RH). The chloride exposure period lasted for a total of three years.

During the chloride exposure period, two reinforcement bars from each beam, the central bar and one of the edge bars, were monitored. The corrosion monitoring was divided into two phases according to Tuutti's model of reinforcement corrosion [18]:

(i) Half-cell potential were monitored using a MnO_2 embedded reference electrode from Force Technology (ERE20) to determine the duration of the corrosion initiation phase. Potential measurements were recorded hourly using a data logger system.
(ii) Corrosion rates were estimated using a handheld device named RapiCor, based on the galvanostatic pulse technique [151], during the propagation phase. Corrosion rate measurements were performed manually with a frequency of one reading every 2 weeks, in the beginning, and every 6 weeks during the last 18 months.

Figure 3.3 illustrates the pre-loading procedure to induce cracking in the beams, the system used to introduce a sustained load and the equipment used for corrosion monitoring.

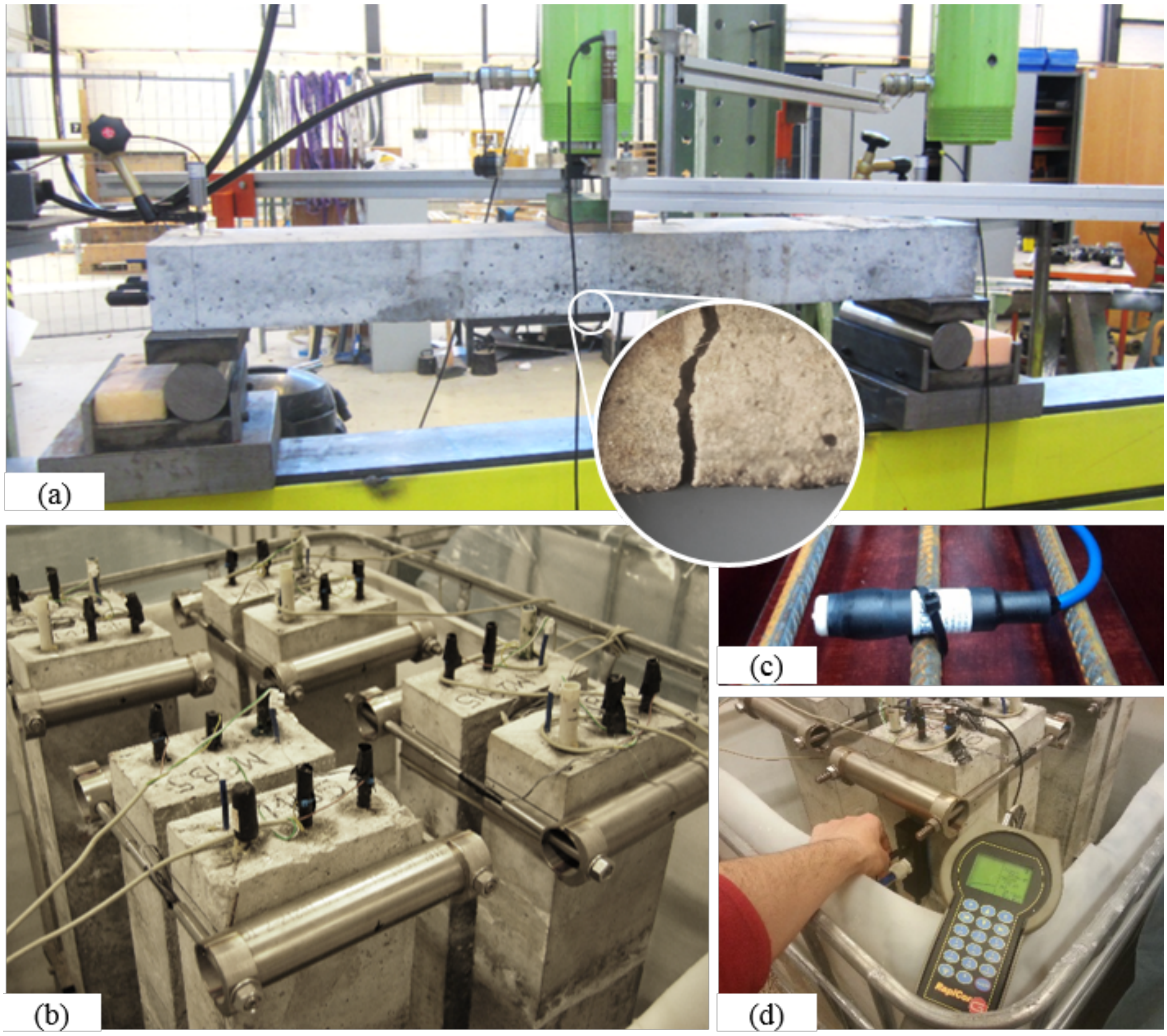


Figure 3.3.(a) Three-point bending procedure for pre-cracking of beams; (b) beams subjected to sustained load during exposure to chloride through partial immersion in a chloride solution; (c) embedded electrode ERE20 from Force Technology used for half-cell potential monitoring; and (d) monitoring of corrosion rates using the RapiCor device.

<u>Phase 2: Assessment of structural capacity and evaluation of reinforcement corrosion</u>

The flexural capacity of the beams was tested under three-point loading configuration. Loading was performed under displacement control at a displacement rate of 1 mm/min up to a mid-span displacement of 10 mm and thereafter at 3 mm/min until beam failure. Five linear variable displacement transducers (LVDTs) were placed on the top surface of the concrete beam to monitor displacements, one at the mid-span section next to the loading plate, two more at span quarters and the remaining two, one over each support. Additionally, a 65 mm strain gauge was also glued on the top surface of the concrete to monitor the compressive strain at the mid-span section. Digital Image Correlation (DIC) measurements were performed at the central 300 mm of the beams to track the crack development and strain/displacement fields.

After the flexural capacity tests, the reinforcement bars were extracted from the beams and were cleaned according to ASTM recommendations [152] by sand-blasting. Once cleaned, the final weight of all the bars was recorded and, subsequently, specific regions of the bars were 3D scanned to obtain more detailed information about the individual corrosion pits.

More details about the specimen geometry, materials and mix composition, casting and curing conditions of the specimens, as well as additional information on the loading setup, corrosion monitoring and evaluation of reinforcement corrosion can be found in **Papers II** and **VI**.

3.2.2 Summary of results

The results of experimental study A are presented in **Papers II** and **VI** and additional results from corrosion monitoring tests are included in **Appendix A**. Note that assessment of corrosion levels and flexural capacity tests were only carried out for part of the beams. The main results can be summarised as follows:

Cracking was the main factor controlling the duration of the corrosion initiation phase: the initiation period of the earliest *uncracked* specimen was more than twice the initiation period of the latest cracked specimen, as seen in Fig. 3.4. On the other hand, the difference in corrosion level between uncracked and cracked beams, considered as either the total weight loss (Fig. 3.5(a)) or the maximum cross-sectional loss (Fig. 3.5(b)), was less apparent.

Corrosion of reinforcement was observed to initiate almost immediately in all the *loaded* beams, indicating that cracks exceeding a certain threshold will have a major impact on corrosion initiation. Conversely, the surface crack width did not seem to have a significant influence on the corrosion rate as revealed by the corrosion levels.

Larger crack widths induced during the pre-loading procedure as well as cyclic loading generally led to shorter corrosion initiation times. Corrosion levels also displayed a tendency to increase for larger induced cracks but no clear correlation could be observed regarding the loading conditions.

Fibre reinforced mixes generally showed a slight improvement in terms of both corrosion initiation and corrosion level compared to plain concrete. The *steel* series exhibited the most limited effect, followed by the *hybrid* series and the *synthetic* series, which displayed more consistent results. Additionally, fibres were found to promote a more distributed corrosion pattern in the reinforcement with numerous light corrosion spots compared to corrosion in plain concrete which was characterized by fewer but more heavily corroded spots.

Fibre reinforcement proved to be effective in preventing brittle failure of the beams during the flexural capacity tests while providing a more stable post peak behaviour. On the other hand, a change in failure from concrete crushing to steel rupture was observed in uncorroded specimens with steel fibres.

Regarding the residual capacity of corroded beams, it was observed that fibre reinforced series consistently showed a greater load capacity than *plain* series. However, in relative terms, fibre reinforced series displayed the same loss of load capacity with increasing local corrosion levels as *plain* series. The rotation capacity was found to decrease much more rapidly than load capacity given a certain cross-sectional loss due to corrosion, see Fig. 3.6. Steel fibres did not significantly affect the rotation capacity of the beams although a small improvement was observed for the hybrid and synthetic series compared to plain concrete.

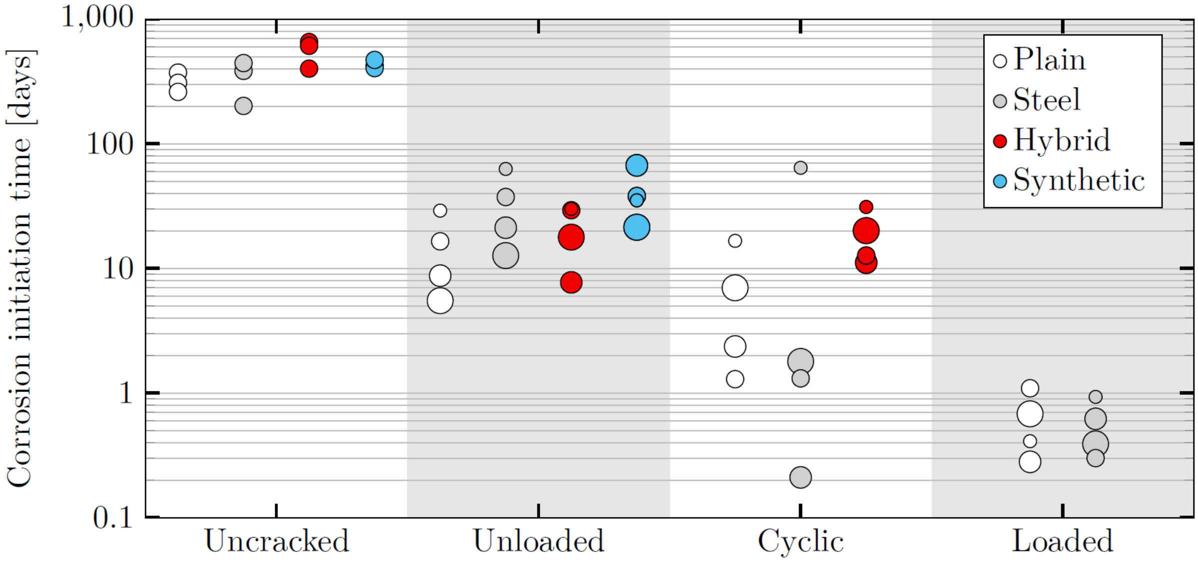


Figure 3.4. Corrosion initiation times: influence of fibre type and loading conditions. Each marker corresponds to the average of the two monitored rebar in each beam. The size of the markers indicates the relative target crack width aimed during the pre-loading procedure.

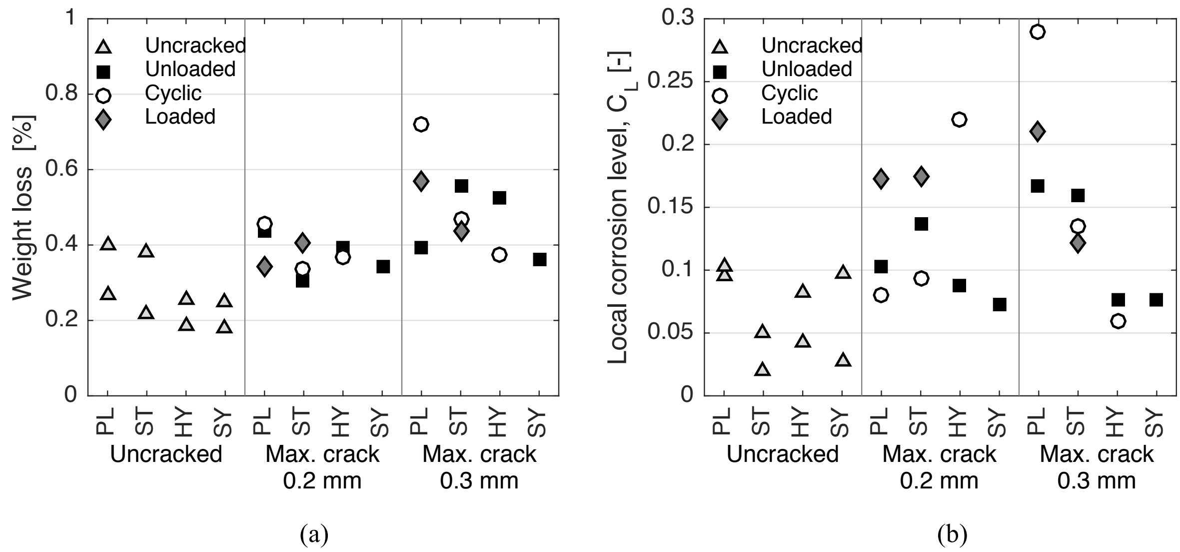


Figure 3.5. Corrosion levels: (a) average weight loss of three reinforcement bars relative to the initial weight before casting; and (b) maximum cross-sectional loss in any of the three reinforcement bars relative to the uncorroded section.

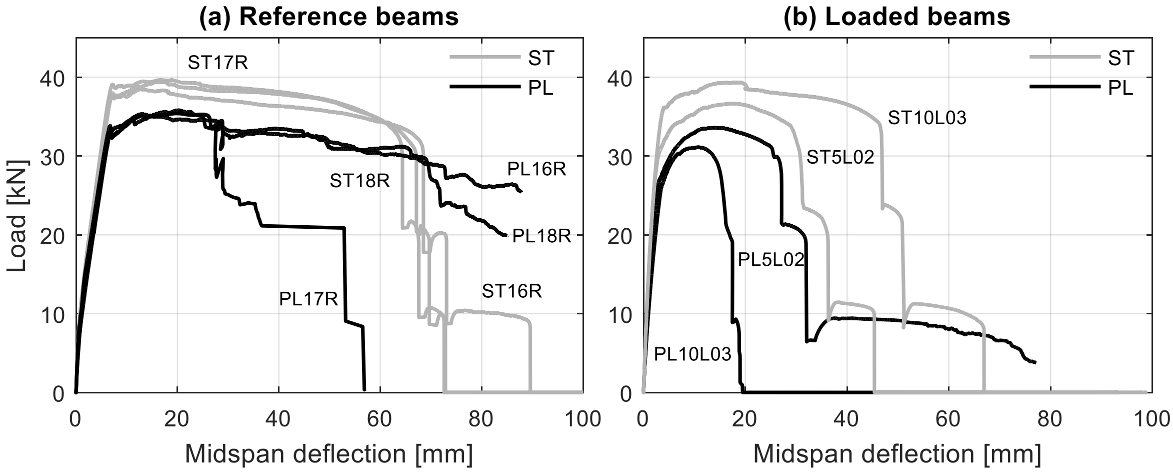


Figure 3.6. Load-deflection curves from flexural capacity tests for (a) reference beams (uncorroded) and (b) loaded beams.

3.3 Experimental study B – Diffusion of chloride ions

The ingress of chloride ions into concrete is one of the main causes leading to the depassivation of steel rebar in concrete. Therefore, limiting the ingress of chloride ions is essential to delay the initiation of reinforcement corrosion. Among the different transport mechanism that may take place in the concrete bulk material, i.e. in an uncracked matrix, diffusion is the predominant mechanism of chloride transport when the moisture condition of the concrete pore network is stable. Since chloride diffusion has been found to be influenced by the interfacial transition zone (ITZ) formed around the aggregates in the cement matrix [153–156], the addition of fibres raises questions regarding the potential effect of the fibre-matrix interface. However, a literature study, presented in **Paper I**, revealed that fibre reinforcement may not have any significant influence on chloride ingress based on results from diffusion and migration tests, cf. Chapter 2.

The aim of this experimental study was to corroborate the results from previous experimental investigations which reported that fibre addition does not alter the ingress of chloride ions into uncracked concrete and characterize the different concrete mixes used in experimental study A. Furthermore, the present study also evaluated the effect of fibre reinforcement on chloride ingress at different concrete ages.

3.3.1 Description of experiments

The resistance of concrete to chloride ingress was assessed according to two different standard tests for the four concrete mixes described in Section 3.2.1. On the one hand, the chloride migration coefficient from non-steady state migration experiments was determined according to the NT Build 492 [157]. Cylindrical specimens with Ø100 mm × 200 mm dimensions were water cured for seven weeks and subsequently three 50 mm thick discs were sawn from the central part. After pre-conditioning, the discs were subjected to a constant DC potential difference for 24 h using the setup schematically shown in Fig. 3.7, where the anolyte and catholyte were 0.3 N NaOH and 10% by mass (~2 N) NaCl, respectively. Subsequently, the disks were split axially into two pieces and sprayed with a solution of 0.1 M $AgNO_3$ and the chloride penetration front (see Fig. 3.7) was measured. Based on the applied voltage and the penetration front, the non-steady state migration coefficient was calculated.

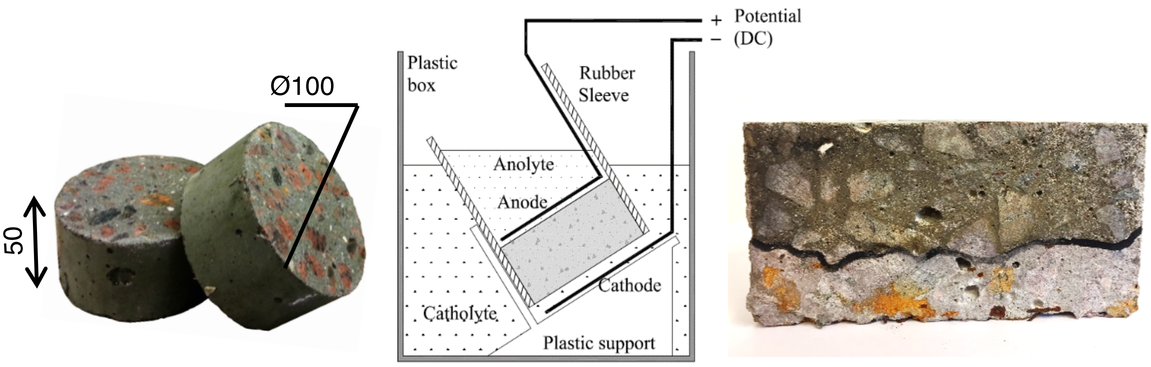


Figure 3.7. Specimen geometry, setup and chloride penetration front from non-steady state migration tests.

The resistance of concrete to chloride ingress was also investigated through determination of the chloride diffusion coefficient from long-term accelerated penetration tests (bulk diffusion) according to NT Build 443 [158]. Cubic specimens with 150 × 150 × 150 mm dimensions were introduced in a plastic tank after a curing period of 30 weeks wrapped in plastic sheets. The lateral sides of the cubes were not coated as it was considered that the specimens were sufficiently large to avoid three dimensional chloride ingress at the location where powder samples were going to be ground. Prior to the exposure to chlorides, the specimens were immersed for a week in tap water to stabilize their moisture conditions and minimise chloride ingress due to adsorption. Thereafter, 10% chloride solution by mass (165 g of NaCl by 1000 g of solution) was poured into the tank until the volume of chloride solution to specimen exposed surface area ratio was approximately 7.5 mL/cm^2. Cubes were removed from the tanks for determination of chloride content at two different exposure times, t_{exp}=210 days and t_{exp}=371. Cores, Ø75 mm were drilled from the centre of the cubes, as illustrated in Fig. 3.8 and subsequently powder samples were obtained at different depths through surface grinding. After oven-drying the samples at 105ºC, they were sent to Cementa Research to analyse the chloride content according to [159]. Afterwards, the chloride diffusion coefficient was calculated by fitting the Error Function (ERF) to the experimental chloride ingress profile through non-linear regression analysis according to [158].

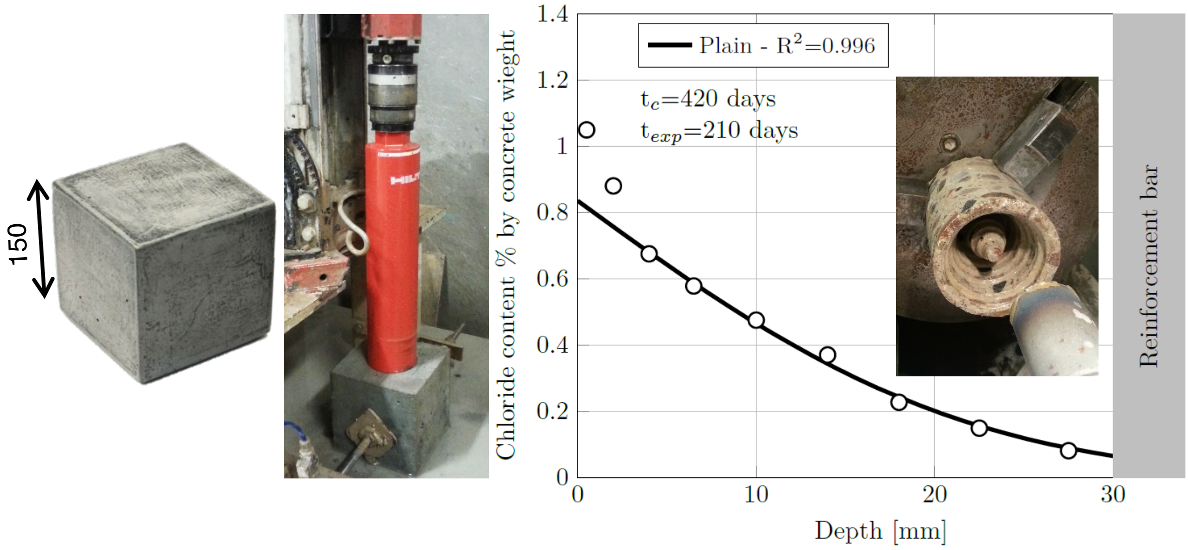


Figure 3.8. Specimen geometry, drilling procedure and chloride ingress profile (white markers are experimentally determined values and solid lines is the fitted curve).

3.3.2 Summary of results

The results of experimental study B, including all the individually determined chloride ingress profiles for the different mixes are presented in **Appendix A**.

A summary of the results is presented in Fig. 3.9, which shows a comparison of the calculated migration coefficient from non-steady state migration tests and the diffusion coefficient from accelerated penetration tests at two different ages. The age of the concrete at the end of each tests, t_c, and the exposure time, t_{exp}, for the natural diffusion tests, are indicated.

As observed in Fig. 3.9, the results show that the presence of fibres did not significantly alter the resistance to chloride ingress of uncracked concrete, regardless of the method used or concrete age. Minor differences were observed, which fell within or close to the average repeatability coefficient of variation of the test methods (typically 15% for NT Build 492 and 20% for NT Build 443, according to [160].

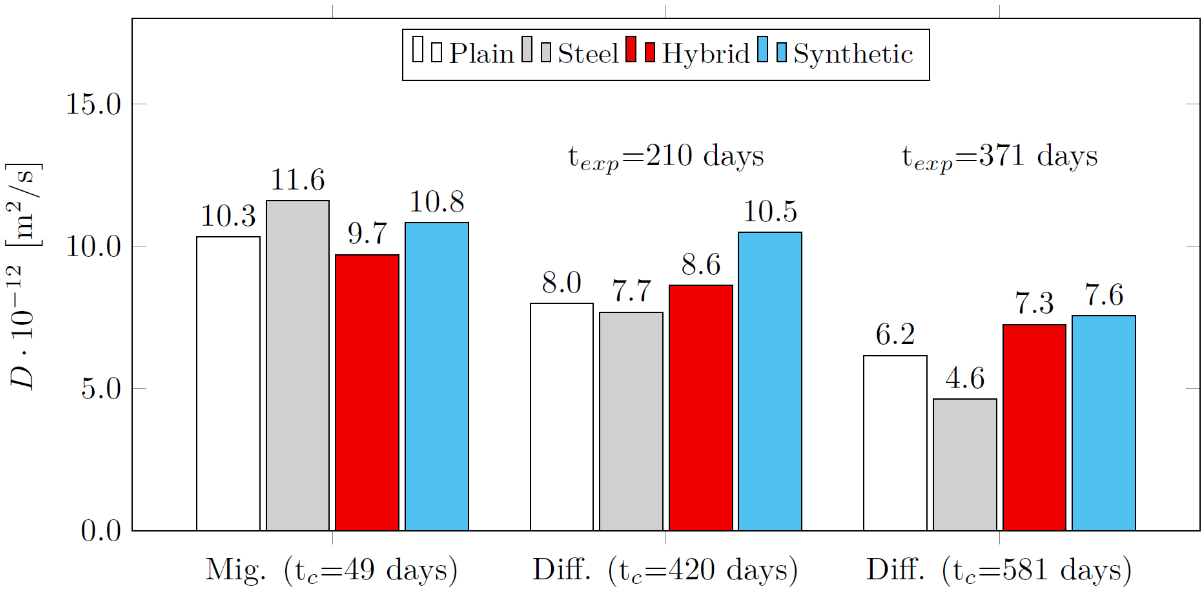


Figure 3.9. Chloride migration coefficient (Mig.) from non-steady state migration tests and chloride diffusion coefficient (Diff.) from long-term accelerated penetration tests. t_c denotes the age of the concrete at the end of the tests and t_{exp} indicates the length of the exposure period.

3.4 Experimental study C – Internal crack morphology

As discussed in Chapter 2, despite the considerable amount of research, the influence of the crack width on the corrosion rate of corroding reinforcement is still today a subject of debate. Researchers are divided among those who claim that the role of the crack width is not relevant in the long-term and those who maintain that corrosion rates are higher in concrete with wider cracks.

Nevertheless, one feature that most studies investigating the relation between crack width and corrosion rate of reinforcement have in common is that their conclusions are based on cracks measured at the surface of the concrete. However, another hypothesis that has been suggested by several researchers [48,54,161,162], is that the crack width at the reinforcement level together with the associated neighbouring areas of the steel-concrete interface affected by bond stresses, might govern the extension of the anodes formed on the rebar and might consequently be a better indicator of the risk of reinforcement corrosion.

The aim of this experimental study was to investigate the effect of adding low dosages of fibre reinforcement (<1% vol.) on the internal crack morphology of conventionally reinforced concrete beams subjected to bending loads.

3.4.1 Description of experiments

Three different concrete mixes were used to cast a total of twelve beams: (a) plain concrete (PC) beams, without fibre reinforcement; (b) steel fibre reinforced concrete (SFRC) beams, containing 35 mm long low-carbon steel fibres at 0.5% vol.; and (c) hybrid fibre reinforced concrete (HyFRC) beams, featuring a combination of the mentioned steel fibres and micro PolyVinyl-Alcohol fibres at 0.5 and 0.15% vol., respectively.

The beam specimens had cross-section dimensions of 150×150 mm and a total length of 550 mm. A notch, 10 mm deep, was sawn at the centre of the bottom side of each beam to act as a stress raiser and ensure cracks initiated at that location. Every beam was reinforced with two ∅10 mm ribbed bars with a clear concrete cover of 50 mm from the notch tip.

Two target crack widths, 0.5 and 1.0 mm, were investigated in the present study. The cracking procedure was carried out under displacement control at a constant loading rate of approximately 1.5 mm/min with the notched side of the beams facing upwards.

Once the target crack width at the notch tip was reached, the loading (displacement) was halted to apply a sustained load that would keep the crack open at the aimed width. Subsequently, a low viscosity (0.1 Pa·s) epoxy resin was combined with fluorescent dye and injected into the crack using a syringe. After the injected resin had hardened, the beams were sawn to obtain two crack specimens out of each beam at the reinforcement sections which were later subjected to a vacuum impregnation followed by surface grinding to obtain samples suitable for microscopy. The preparation process is schematically illustrated in Fig. 3.10.

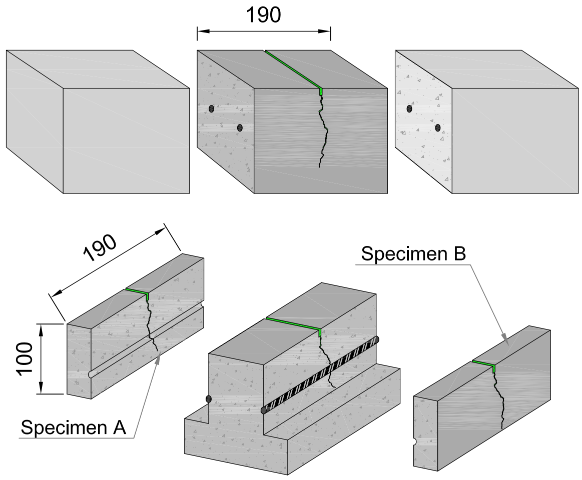
Later, image analysis was performed on images acquired with a microscope to characterise the internal crack morphology of the different samples. Three different equivalent crack widths were defined according to Eq. (3.1-3.3) to quantify the effect of fibre reinforcement on the internal crack pattern:

$$w_t = \sum_{i=1}^{n_c} w_i \qquad \text{total (accumulated) crack width} \qquad (3.1)$$

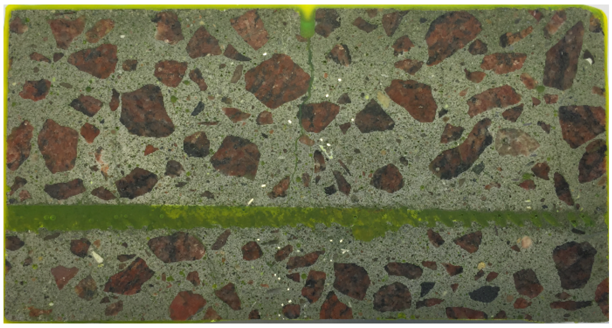
$$w_{ef} = \sqrt[3]{\sum_{i=1}^{n_c} w_i^3} \qquad \text{effective crack width} \qquad (3.2)$$

$$w_{max} = max\{w_1, \dots, w_{n_c}\} \qquad \text{maximum crack width} \qquad (3.3)$$

where w_i represents the individual crack widths and n_c the total number of cracks at a certain distance from the concrete surface.



(a)



(b)

Figure 3.10.(a) Schematic representation of the sawing process to obtain the resin-injected crack samples and (b) final result of the samples after vacuum impregnation and surface grinding.

More details about the geometry, materials and curing conditions of the specimens, as well as additional information on the setup and image analysis can be found in **Paper III**.

3.4.2 Summary of results

The results of experimental study C are presented in **Paper III**, including all the individual internal crack patterns with their corresponding crack measurements (see Fig. 3.11). The main results can be summarised as follows:

In order to achieve the same surface crack width, fibre reinforced beams needed a load almost 40% greater than their plain concrete counterparts.

The internal crack pattern of fibre reinforced beams revealed a distinctive change compared to the internal crack pattern of plain concrete beams. This change included a tendency of the main bending crack to branch out into two or more cracks, especially as it approached the reinforcement bar, as well as an increase of crack tortuosity. The observed behaviour was accentuated in the mix featuring a hybrid fibre reinforcement, but only branching seemed to be sensitive to the maximum crack tip width reached.

A comparison of the different equivalent crack widths investigated revealed that the total crack width was not affected by the addition of fibre reinforcement. However, as a consequence of the multiple crack branching, both the effective crack width (see Fig. 3.11) and the maximum crack width (see Fig. 3.12) in fibre reinforced concrete specimens were effectively decreased.

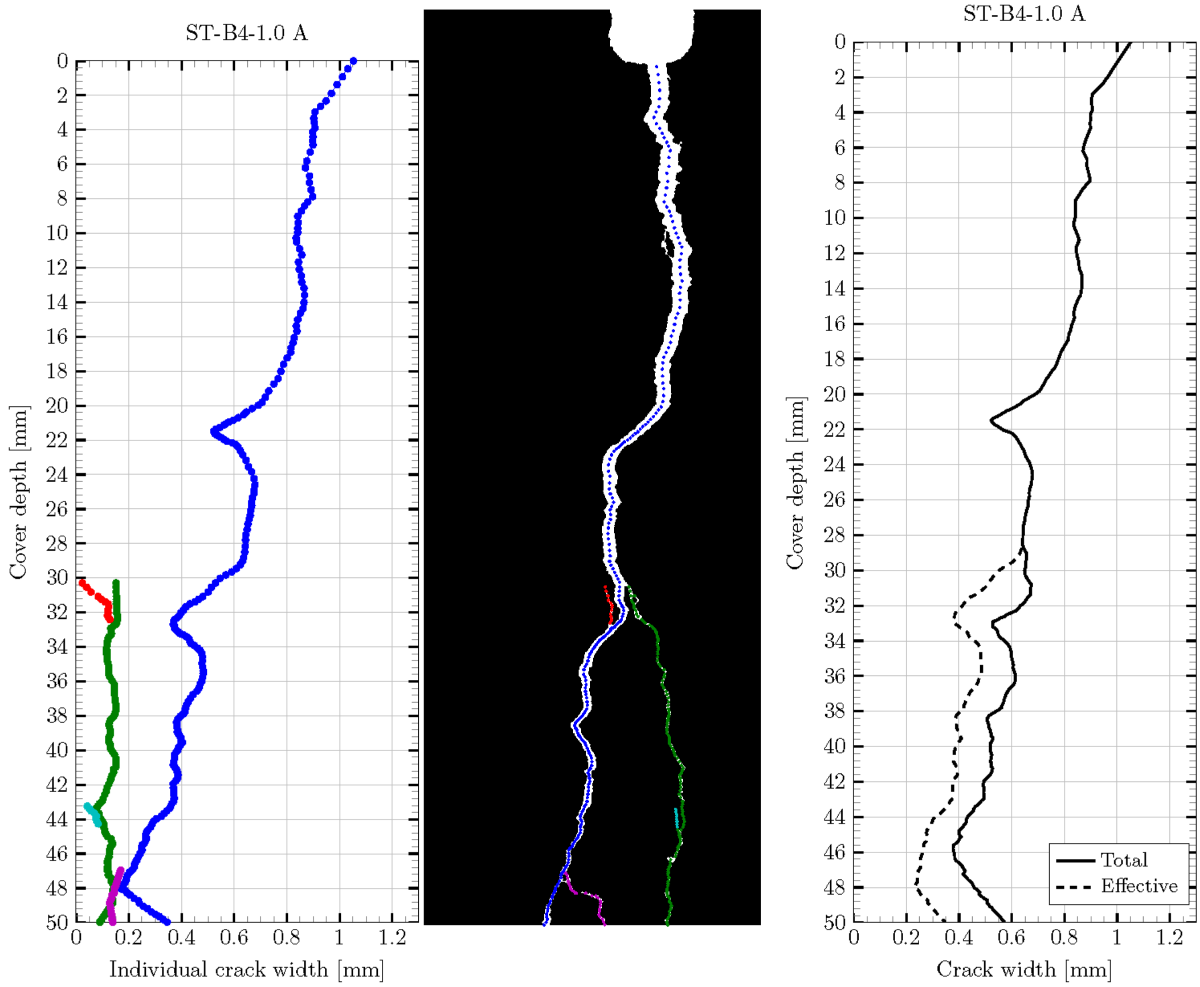
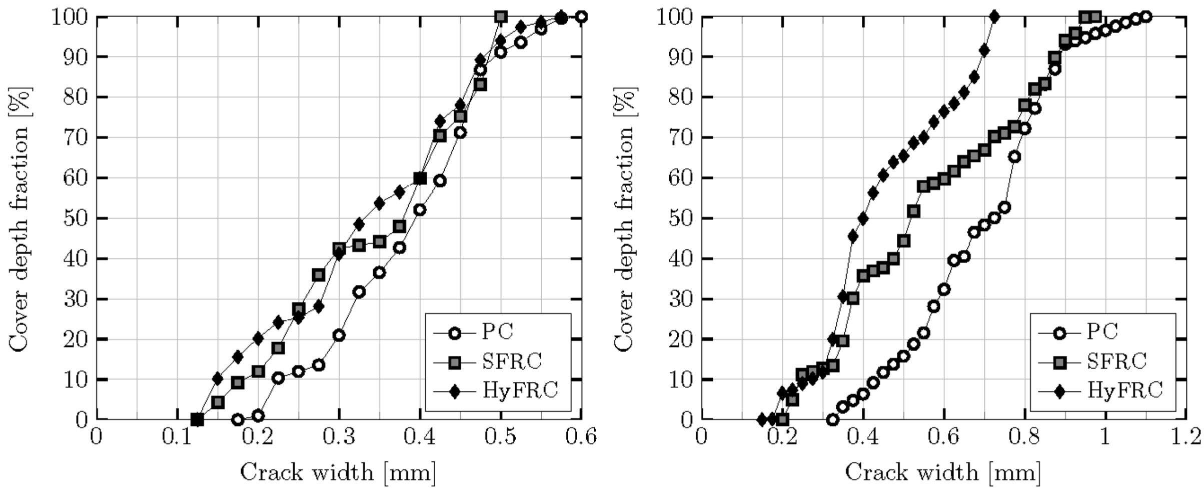


Figure 3.11. Example of crack pattern and crack measurement for a SFRC sample loaded to crack tip width of 1.0 mm.



(a) Crack tip width = 0.5 mm

(b) Crack tip width = 1.0 mm

Figure 3.12. Cumulative distribution curves showing the fraction of cover with an average maximum crack width smaller than the x coordinate value, presented as % of the cover depth.

3.5 Experimental study D – Resistivity measurements in SFRC

The resistivity of a material describes its ability to withstand the flow of electric current. In cementitious materials, electric current stems from the transfer of electrically charged ions dissolved in the pore solution. As a result, the resistivity of concrete can be used as an indicator of the resistance to chloride ingress [163,164] and ionic transfer between the anode and the cathode in reinforcement macro-cell corrosion [25,29]. Consequently, the resistivity of concrete is inherently linked to the corrosion process of reinforcement in concrete, where low resistivity values are often associated to a more rapid chloride ingress and higher corrosion rates. However, experimental studies investigating the relation between corrosion rate and resistivity in SFRC [99,107,118,128,165–169] have revealed some findings that contradict the general trend observed for plain concrete. Although steel fibres have been reported to significantly decrease the resistivity of concrete, similar or even lower corrosion rates have been consistently measured for SFRC compared to plain concrete. The origin of the discrepancy between the behaviour of plain concrete and SFRC may arise from the generalised use of alternate current (AC) at certain fixed frequencies as the preferred technique to measure the resistivity of concrete. Indeed, some studies [170–172] have shown that steel fibres, and any conductive fibre in general, can significantly alter the impedance response of cement-based materials, as illustrated in the Nyquist plots presented in Fig. 3.13(a). This change has been attributed to the frequency-dependent behaviour of steel fibres, which conduct current at medium to high frequencies but remain insulated by the passive layer at low frequencies. Furthermore, it has been shown that the DC resistivity of concrete, the actual parameter relevant for the ionic transfer involved in the corrosion process, is not affected by the addition of conductive fibres [173], provided the intensity of the electric field does not exceed a certain threshold [174,175].

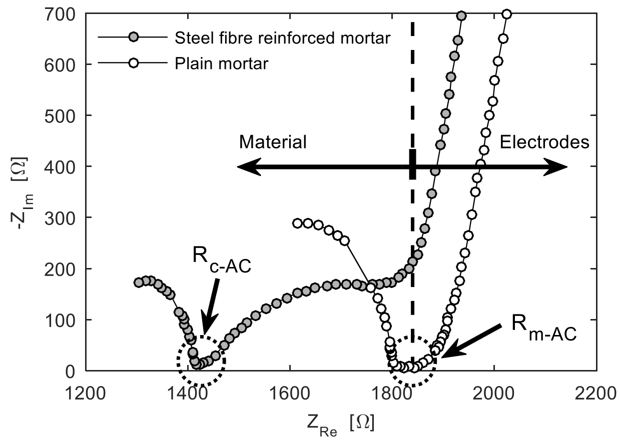
The aim of this experimental study was to investigate the impedance response and DC resistivity of cement-based materials with steel fibre reinforcement in order to evaluate the frequency range needed to correctly assess the matrix resistivity, $\rho_{m\text{-}AC}$.

3.5.1 Description of experiments

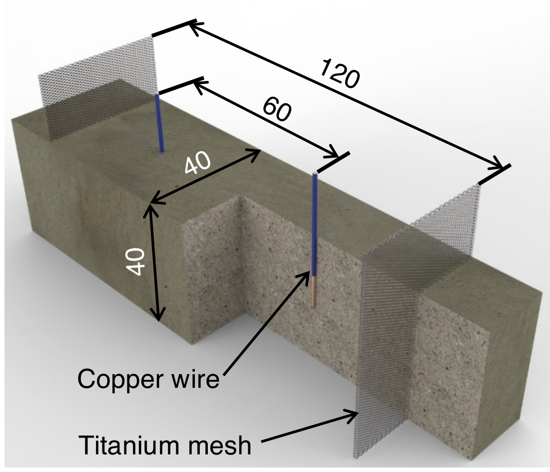
The experiments carried out within this study were aimed at investigating how the geometrical features and dosage of short steel fibres influenced the impedance response of steel fibre reinforced mortar (SFRM). To that end, standard size prisms of dimensions 40×40×160 mm (see Fig. 3.13(b)) were cast using a mortar mix with a *w*/c ratio of 0.55 and with different types of fibre reinforcement. The main parameters investigated included: (i) the fibre dosage; (ii) the fibre length; and (iii) the fibre diameter. In addition, a series of specimens were cast with polymeric fibres to assess the potential impact of having an increased ITZ.

Two sets of electrodes were embedded in the specimens during the casting process. The first set were rectangular pieces of titanium mesh separated 120 mm. The second set consisted of two copper wires, placed at 30 mm from the former and separated 60 mm between them. Fig. 3.13(b) illustrates the position of the electrodes. After casting, the specimens were sealed in a container partially filled with water for 7 days and thereafter they were immersed in a highly alkaline solution.

All the electrical measurements were performed 28 days after casting. Electrochemical Impedance Spectroscopy (EIS) measurements were carried out with a two-electrode configuration and a frequency scan from 1 MHz down to 100 mHz, using a logarithmic point spacing at 30 points per decade and an AC amplitude of 500 mV rms. DC galvanodynamic measurements were carried out using a four-electrode configuration, generating a current at the outer electrodes, the magnitude of which was monotonically increased at a constant rate of 50 µA/s, while the potential difference between the inner electrodes was continuously recorded in order to obtain the voltage-current curve of the specimen.



(a)



(b)

Figure 3.13. (a) Example of a Nyquist plot for plain and 0.5% vol. steel fibre reinforced mortar samples, showing the AC matrix resistance, $R_{m\text{-}AC}$, and AC composite resistance, $R_{c\text{-}AC}$, respectively. (b) 3D representation of the specimens used in the experimental study D showing a cross-sectional cut to illustrate the embedded electrodes position. Measurements are in mm.

More details about the studied parameters, mix composition, materials and curing conditions of the specimens, as well as additional information on the setup and electrical measurements can be found in **Paper V**.

3.5.2 Summary of results

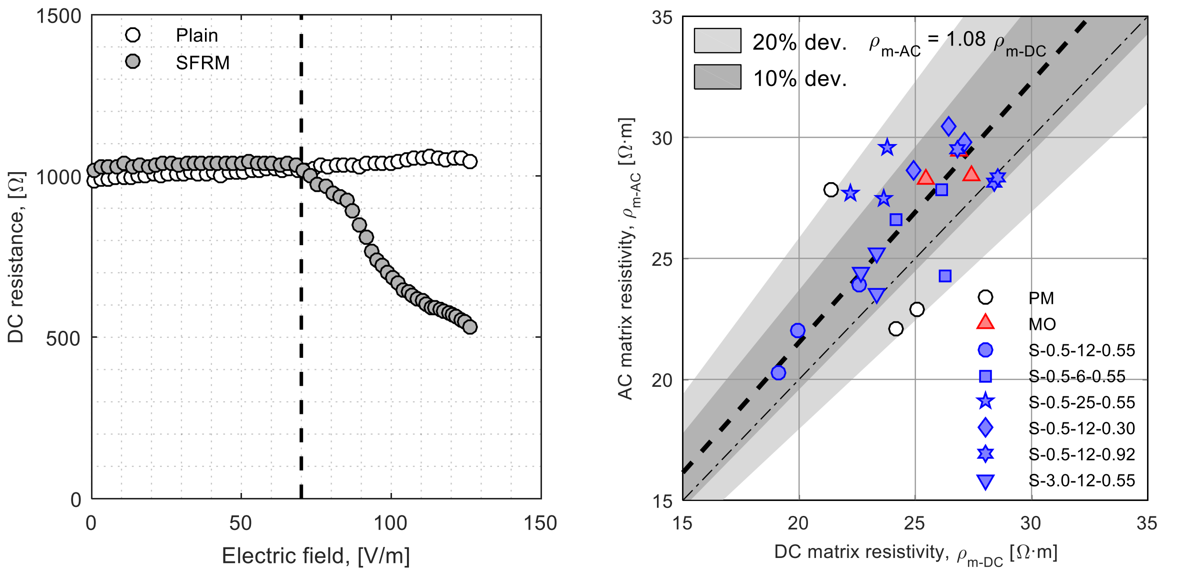
The results of experimental study D are presented in **Paper V**, including the complete set of individual Nyquist and Bode plots. The main results can be summarised as follows:

Steel fibres modified the impedance response of mortar specimens, changing from single-arc to dual-arc behaviour, see Fig. 3.13(a), whereas polymeric fibres did not show any apparent effect. The impedance response of SFRM specimens was clearly influenced by the geometric fibre features and fibre dosage, being the fibre length the parameter with the greatest impact.

The DC resistance of plain mortar specimens, calculated as the slope of the voltage-current curves obtained from the DC galvanodynamic measurements, remained nearly constant for an electric field of increasing strength. In the case of SFRM specimens, an electric field threshold dependent on the fibre length, above which the DC resistance readily decreases, was observed. This is presented in Fig. 3.14(a), where the results show that the threshold value found in this study was ca. 70 V/m for 25 mm long fibres.

As shown in Fig. 3.14(b), polymeric fibres and steel fibres, irrespective of the length, diameter and dosage, did not significantly influence the AC matrix resistivity, $\rho_{m\text{-}AC}$, obtained from the EIS measurements nor the DC matrix resistivity, $\rho_{m\text{-}DC}$, from the DC galvanodynamic measurements.

Although no significant differences were observed between the matrix resistivity of plain mortar and SFRM specimens, a major impact was detected on the associated AC matrix frequency, $f_{Rm\text{-}AC}$, which decreased from ~1000 Hz for plain mortar to ~1 Hz for SFRM, see Fig. 3.15.



(b) (b)

Figure 3.14. (a) Variation of DC resistance with increasing electric field intensity for a plain mortar specimen and a SFRM specimen with 25 mm long fibres. (b) Comparison of the AC matrix resistivity, $\rho_{m\text{-}AC}$, obtained from the EIS measurements and the DC matrix resistivity, $\rho_{m\text{-}DC}$, from the DC galvanodynamic measurements, for the mortar specimens used in this study.

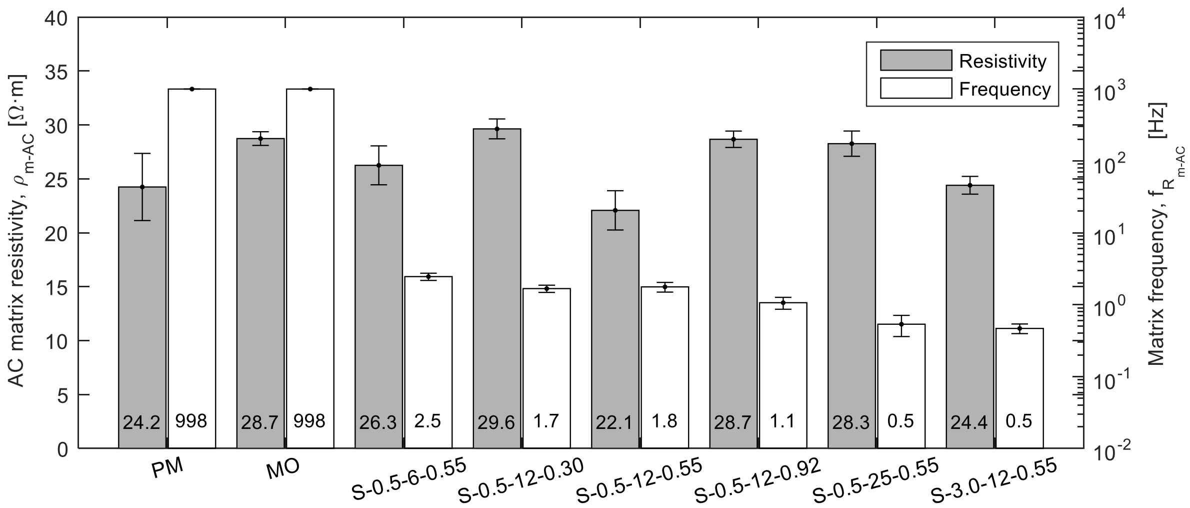


Figure 3.15. AC matrix resistivity, $\rho_{m\text{-}AC}$, and the associated AC matrix frequency, $f_{Rm\text{-}AC}$, for the mortar specimens used in this study.

3.6 Experimental study E – Corrosion-induced cracking & bond behaviour

The corrosion of reinforcement embedded in concrete entails a series of degradation mechanisms that impair the structural integrity of RC elements [176]. One of these mechanisms is the accumulation of expansive corrosion products at the steel-concrete interface which exert an internal pressure that may lead to the formation of longitudinal splitting cracks in the concrete cover. These cracks greatly reduce the confinement action of the concrete which results in a rapid loss of bond capacity between steel and concrete, thus increasing the risk of anchorage failure. Several investigations have shown that using relatively high dosages of fibre reinforcement (≥1.5% vol.), the formation of corrosion-induced cracks can be significantly delayed [117,124,126]. However, experimental results regarding the potential effect of fibre reinforcement at low dosages (< 1% vol.) on delaying the formation of corrosion-induced cracks are lacking. Furthermore, although the bond behaviour of conventional rebar in FRC has been widely investigated, see e.g. [85,86,177–181], little information is available regarding the effect of fibres on the bond behaviour of corroding reinforcement.

The aim of this experimental study was to investigate the influence of low dosages of fibre reinforcements on the formation of splitting cracks induced by corrosion of rebar and to quantify the contribution of fibres to the bond behaviour of corroding reinforcement bars.

3.6.1 Description of experiments

In this experimental study, 42 pull-out tests were performed at three different stages of corrosion on specimens subjected to accelerated corrosion tests. The specimens were divided into three groups: group I, uncorroded specimens used as reference samples; group II, specimens corroded up to the onset of corrosion-induced cracking; and group III, specimens corroded beyond the onset of splitting cracks. Furthermore, two different cover to bar diameter ratios, *c/Ø*, were investigated for the bond-behaviour and a third one was included for the crack initiation stage.

The test specimens consisted in 100 mm high concrete cylinders with different diameters and a single Ø16 mm ribbed bar embedded along the cylinder axis with a bonded length of 70 mm. A self-compacting concrete mix with a water to cement ratio (*w*/*c*) of 0.47 was used to prepare both the plain and the steel fibre reinforced concrete, including minor variations in the aggregate content to incorporate the fibres. End-hooked Dramix steel fibres, 35 mm long with diameter 0.55 mm, were used as fibre reinforcement at 0.5% by volume. Sodium chloride was incorporated into the mix at 4% by weight of cement to prevent the formation of the passive layer on the steel bar.

The experimental procedure involved two different phases, namely accelerated corrosion tests and pull-out tests. The experimental setup is schematically represented in Fig. 3.16. For the accelerated corrosion tests, an impressed current was applied to the specimens, connected in series, to achieve a constant current density of 100 $\mu A/cm^2$ within the bonded length of the rebar. During the accelerated corrosion tests, the potential difference between the steel rebar and the external copper mesh used as the cathode was continuously monitored. The electrical resistance was derived from Ohm's Law and then used to identify the onset of cracking as the point in time when the electrical resistance started decreasing. The pull-out tests were carried out after the accelerated corrosion tests and were performed at a constant displacement rate of 0.2 mm/s. During the pull-out tests, the parameters measured were the tensile load applied at the active end of the bar and the slip at the passive end. After the pull-out tests, the reinforcing bars were extracted from the cylinders and cleaned for gravimetric steel loss measurements to determine a uniform corrosion level.

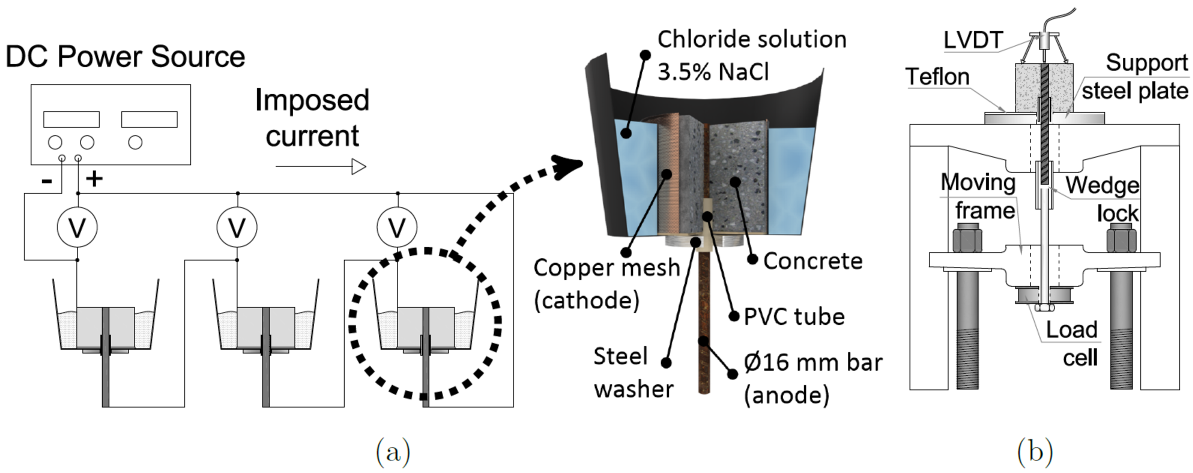


Figure 3.16. (a) Setup of accelerated corrosion tests and (b) setup of pull-out tests.

More details about the mix composition, materials, curing conditions of the specimens, as well as additional information on the setup and determination of crack initiation and corrosion levels can be found in **Paper IV**.

3.6.2 Summary of results

The results of the experimental study E are presented in **Paper IV**, including all the individual local bond-slip curves. The main results can be summarised as follows:

As observed in Fig. 3.17, the addition of steel fibres at 0.5% by volume resulted in a delay of corrosion-induced cracking, where the effect became more noticeable as the *c/Ø* ratio was decreased.

For the specimens in Group III, the maximum crack width, measured at the end of the accelerated corrosion tests, was reduced by a factor of 2 in SFRC compared to plain concrete.

For uncorroded specimens, the fibres did not have any significant effect on the bond strength, τ_{sp}. However, as shown in Fig. 3.18(b)., for plain concrete specimens τ_{sp} rapidly decreased with increasing corrosion levels whereas SFRC specimens retained their initial strength up to a corrosion level of 8%.

The addition of fibres had a major impact on the post-peak bond stress, which changed from a sudden loss of bond stress in plain concrete to a considerable amount of remaining capacity in SFRC even at large slips, as illustrated in Fig. 3.18(a). This effect was observed in all fibre reinforced specimens, regardless of the *c/Ø* ratio or corrosion level investigated.

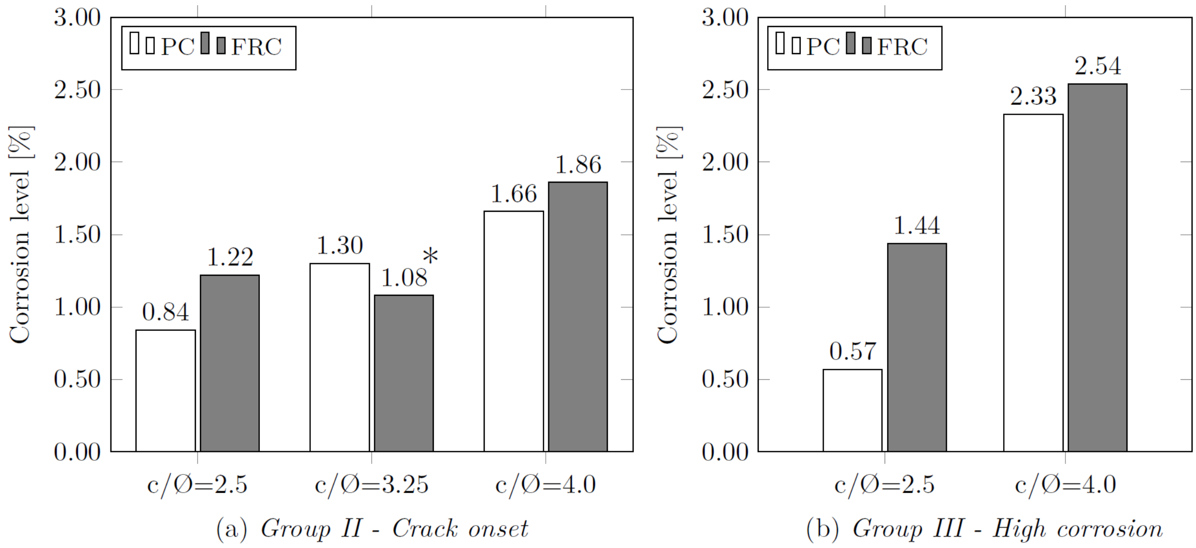


*Figure 3.17. Average corrosion levels at crack initiation. *FRC specimens with c/Ø=3.25 in Group II deviated from the general trend followed by the rest of specimens and were considered outliers.*

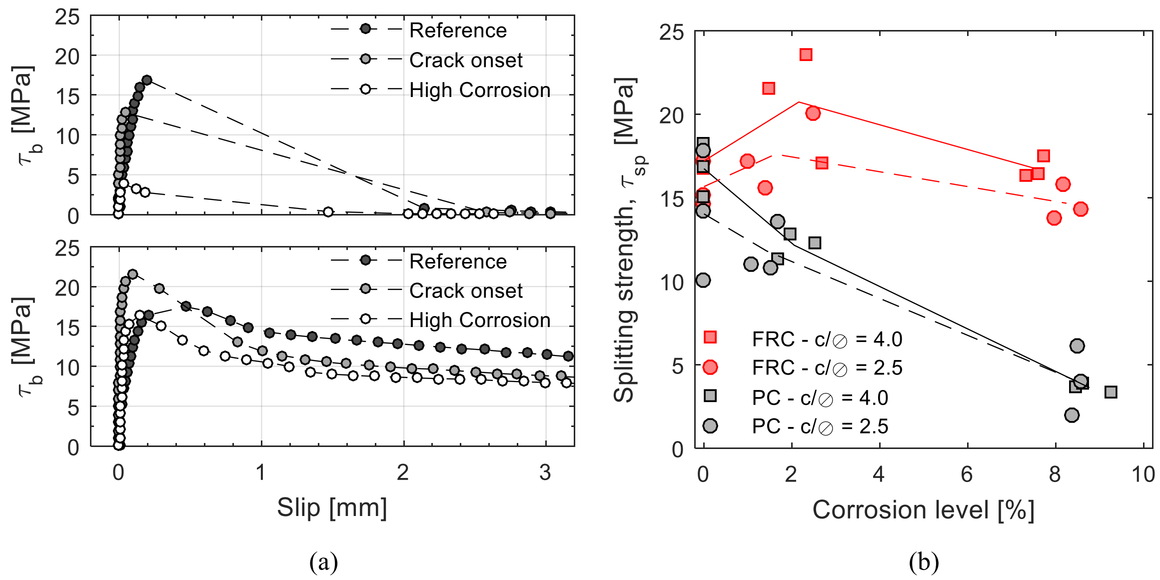


Figure 3.18.(a) Bond stress versus passive slip for selected specimens with c/Ø= 4 and varying corrosion levels (PC top; SFRC bottom) and (b) Bond strength determined experimentally as a function of the corrosion level (lines indicate mean behaviour).

4 Main findings and discussion

In this chapter, the most important findings from the literature review and the experimental studies undertaken within this project are discussed.

4.1 Corrosion initiation phase

4.1.1 Effect of fibres on uncracked concrete

In addition to the recognised beneficial crack control mechanisms provided by fibre reinforcement, it is also important, and necessary, to ensure that uncracked concrete regions will not be adversely affected by the addition of fibres in terms of early corrosion initiation or accelerated corrosion rate.

Most research publications report that steel fibres do not significantly affect the diffusion of chlorides ions into concrete. The migration and diffusion coefficient experimentally determined in the present investigation support the available results, not only concerning steel fibres but also for mixes containing PVA fibres. Moreover, from the diffusion tests, the time-dependency of the diffusion coefficient does not appear to be influenced by the fibres. Consequently, the results from both the literature and the present study indicate that the interfacial transition zone (ITZ) formed at the interface between the fibres and the cement paste, which features a higher porosity compared to the bulk matrix, does not represent a preferential path for the ingress of chloride ions into FRC with no preferential fibre orientation.

From the long-term corrosion tests, the corrosion initiation period of rebar in uncracked FRC was found to be similar or even slightly longer compared to plain concrete, thus providing further indication that fibres do not negatively affect the ingress of chloride ions. In particular, the most significant delay of corrosion was observed for the *hybrid* series combining the steel and PVA micro-fibres, followed by *synthetic* series with only PVA fibres. This could be explained by the shorter length of micro-fibres and the stronger bond of PVA fibres with the cement paste which could be more effective than steel fibres alone in controlling shrinkage-induced micro-cracks caused by internal restraint of conventional reinforcement.

It is interesting to note that the suitability of methods based on ion migration for SFRC, i.e. where an external DC electric field is applied to the concrete, has been questioned [107], despite that results of migration and diffusion tests being very similar. Frazao et al. argued that since steel fibres are prone to become heavily corroded during the test, chlorides could settle on the fibres. Despite the corrosion of the fibres might not necessarily be caused by chlorides but rather be a consequence of the high voltage applied, there are still some aspects, discussed in Section 4.2.1, that need to be taken into consideration before using migration tests for determination of chloride diffusion in SFRC.

4.1.2 Effect of cracking, crack width and loading conditions

Cracking was, by far, the most important factor influencing the duration of the corrosion initiation period. Irrespective of the presence of fibres, the loading conditions applied or the maximum crack width achieved during the pre-loading procedure, the corrosion initiation time of cracked beams was reduced by one order of magnitude compared to uncracked beams.

A critical crack width above which reinforcement corrosion can initiate almost immediately was found to be the main factor influencing the duration of the initiation phase among the cracked beams, and in the present study this surface crack width was somewhere below 0.1 mm. The concept of a critical crack width for initiation of reinforcement corrosion has been previously discussed in the literature, yet different values have been proposed by different authors. Otieno et al. [39] concluded that the definition of a universal critical crack width might not be possible, as it may depend on parameters such as the *w/c* ratio, the binder type, the cover depth or the exposure conditions. Thus, values found in individual research studies cannot be directly extrapolated to real structures.

For the unloaded series, corrosion was generally observed to initiate earlier for beams that had been subjected to wider cracks, i.e. to higher loads, during the pre-cracking procedure. Corrosion initiated earlier even though a minimal variation in the surface crack width was measured among the different beams after unloading. For cyclically loaded beams, the effect of the target crack width was less apparent but the results showed that cyclic loading also tended to promote early corrosion. These findings point in the direction that interfacial damage caused by mechanical loading, which is greater for higher loads and repeated load cycles, might be a better indicator of an increased risk of corrosion initiation than surface crack width, as previously hypothesised by Pease [161].

The existence of a critical crack width threshold highlights the importance of controlling crack widths to delay corrosion initiation. On the other hand, the surface crack width is related to the crack width at the reinforcement level, which in turn is governed by the bond behaviour between steel and concrete. Hence, it follows that a relationship between interfacial damage caused by mechanical loading, i.e. debonding, and surface crack width should exist and, consequently, controlling the crack width could be considered as an indirect way of limiting debonding of the rebar. However, according to a study by Michel et al. [162], the extent of the reinforcement steel surface where corrosion is thermodynamically favoured is associated to the interfacial separation between the steel and concrete and not the longitudinal slip. A better understanding of the interaction between loading, interfacial damage and corrosion initiation is required, which could potentially lead to more effective methods to extend the service life of RC structures than controlling crack width.

4.1.3 Effect of fibres on cracked concrete

The results from experimental study C revealed that even though the cracks forming on the surface of plain and fibre reinforced concrete might look similar, the addition of fibres can produce significant changes to the internal crack morphology. Specifically, the most noticeable effect was a change from a main single crack in plain concrete to multiple crack branching in FRC, particularly in the vicinity of the main reinforcement. Moreover, in plain concrete the cracks propagated almost perpendicularly from the surface to the rebar, whereas in FRC a more tortuous crack path was formed.

Internal crack branching was observed to increase with increasing surface crack width, which can be explained by the formation and propagation of new secondary cracks originated by bridging fibres. On the other hand, the tortuosity of cracks did not significantly change with the load level, as once the cracks have propagated through the entire cover, a load increase does not modify the crack shape. Among the types of fibre reinforcement used, the combination of steel fibres with PVA micro-fibres had the largest impact on the two effects described, which might be attributed to a multi-scale crack-bridging effect of the fibres.

The comparison of the accumulated crack width of all individual cracks located at a certain distance from the rebar revealed that for a given surface crack width, the variation of the accumulated crack width was independent of the addition of fibre reinforcement. Consequently, if the number of cracks is greater in FRC and as long as the accumulated crack width remains unchanged, the individual cracks must be narrower.

An effective crack width (Eq. 3.2) was defined as the crack width yielding a flow equivalent to the accumulated flow through individual cracks based on Poiseuille's law [182]. Using the effective crack width, combined with the observed change in tortuosity, it was determined that low fibre dosages could potentially reduce the permeation of concrete elements subjected to bending cracks. Moreover, by reducing the maximum crack width, specially near the reinforcement, self-healing of cracks by hydration of unreacted cement or filling with other substances, could be also favoured, thus providing an additional mechanism to slow down the ingress of deleterious agents towards the reinforcement.

In experimental study A, a positive effect of the fibres was also generally observed for the corrosion initiation time of cracked beams, though not for the *loaded* beams, which, as previously discussed, started to corrode almost immediately regardless of fibre addition. More specifically, for *unloaded* beams all the fibre reinforced series provided a slightly delayed corrosion initiation compared to the *plain* series, where the *synthetic* series were found to be the most effective. For *cyclic* beams, two of specimens of the *steel* series started corroding earlier than their plain concrete counterparts whereas the *hybrid* series showed initiation times comparable to those of *unloaded* beams, indicating cyclic loading did not affect beams with a combination of steel and PVA micro-fibres. The explanation for the shorter initiation period of the two beams of the *steel* series subjected to *cyclic* loading is not clear. One possibility could be the formation of micro-cracks at the cement paste surrounding the fibres due to the bond stresses [183]. However, they could have been also affected by local defects along the reinforcement interface and differences in its surface characteristics, which are factors inherent to the corrosion process of steel in concrete [184].

Nevertheless, it should be noted that in the present investigation the beams from the different series are compared in terms of the maximum crack width reached at the surface. This condition entails that the loads applied during the pre-cracking procedure were between 10% and 20% higher in fibre reinforced series compared to *plain* series. In the case of the beams tested in the experimental study C, the load necessary to achieve the same crack width was increased up to 40% in fibre reinforced mixes. Although the load increase observed in this investigation is attributable to the particular geometry of the specimens used, with a large ratio between cover and internal lever arm, it might still have had an influence.

4.2 Corrosion propagation phase

4.2.1 Effect of steel fibres on the electrical resistivity

Corrosion is an electrochemical process and, as such, the ohmic resistance between the anode and the cathode of a corrosion macro-cell is described by the electrical resistance measured under a DC field. Nevertheless, to assess the resistivity of concrete the use of AC fields is usually preferred to DC fields in order to avoid certain problems associated to polarization of the electrodes and migration of ionic species within the concrete. Several studies have shown that when the moisture content of the concrete is high, frequencies in the range of approximately 10^2 Hz to 10^4 Hz are suitable to accurately assess the DC electrical resistivity.

The inverse relation observed between the resistivity of concrete and the corrosion rate of embedded reinforcement together with the relatively easy and quick execution of non-destructive resistivity measurements has spurred the use of resistivity as an indicator to estimate the corrosion durability of RC structures. This practice has caused many researchers to adopt methods intended to measure the resistivity in plain concrete, i.e. based on AC measurements, to evaluate the corrosion resistance of SFRC. As discussed in **Paper I**, resistivity measurements carried out in SFRC using AC and a frequency in the range deemed adequate for plain concrete results in a significantly lower measured resistivity. This situation has led some researchers to question the suitability of using SFRC in combination with conventional reinforcement in corrosive environments.

Contrary to what would be anticipated from the results of "standard" resistivity measurements, experimental results from the literature as well as from the present work, indicate that the use of steel fibres in cementitious materials does not pose a risk of increased corrosion rates for reinforcing steel compared to plain concrete. In fact, the general trend shows that corrosion rates in SFRC are usually lower than in plain concrete.

The reason of the apparent lack of correlation between resistivity and corrosion rate of rebar in SFRC can be attributed to the modification of the impedance response caused by the frequency-dependent behaviour of steel fibres in concrete. The prevailing hypothesis suggests that the high impedance of the passive layer formed in the alkaline environment of the concrete matrix insulates the fibres at low frequencies but this is short-circuited at medium-to-high frequencies rendering the fibres conductive. However, specific data about the impedance spectra of SFRC mixes in the frequency domain is very scarce. As a result, no recommendations or guidelines on how to perform resistivity measurements in SFRC are available today while many researchers continue to use unsuitable methods to evaluate the corrosion resistance of SFRC.

A direct implication of the modified impedance response of SFRC is that the oscillation frequency of resistivity methods based on the application of AC fields has to be adjusted to adequately assess the true resistivity of the SFRC. In the present investigation, an adequate frequency was found to be around 1 Hz for low-carbon steel fibres, regardless of the fibre geometry and fibre dosage. Further results are needed to confirm this finding, including the effect of *w/c*, binder type, degree of saturation and presence of chlorides / concrete carbonation (potentially corroding fibres), among others.

Moreover, when using four-point measurements and DC fields, it has been shown that while steel fibres modify the impedance response of concrete, they do not alter its DC resistivity, as long as the field intensity does not exceed a certain value. The critical value of the electric field altering the DC resistivity of SFRC has been, so far, hardly investigated and its implications have not yet been addressed.

In the present investigation, the critical electric field above which embedded fibres became conductive was found to be around 70 V/m for 25 mm long fibres, although this value is strongly dependent on the fibre length and possibly on the orientation of the fibres with respect to the applied field. For instance, for specimens with 12 mm long fibres used in experimental study D, electric fields of up to 130 V/m did not cause a change in the material resistivity. In another investigation [175], however, a threshold of 15 V/m was observed for 35 mm long fibres aligned with the electric field.

Given the limited potential gradients generated in a corrosion macro-cell, it seems very unlikely that steel fibres would become conductive as a result of an electric field produced by reinforcement corrosion. On the other hand, certain test methods based on the application of a constant DC voltage in relatively small concrete samples create very high electric fields, e.g. 1200 V/m for ASTM C1202 [185], 600 V/m for NT Build 492 [157]. Methods such as the ASTM C1202, which is used to assess the resistance to chloride ingress based on the total amount of current transferred, should be not be used for SFRC since transfer of both ionic and electronic current will occur, hence the principle of the method is no longer valid. For methods such as the NT Build 492, where the penetration of the actual chloride front is measured, the consequences of using steel fibres might be only limited to modify the parameters of the test setup to adjust the applied potential based on the initial current measurements. The applicability of other techniques based on the application of a DC field, such as cathodic protection [3] or electrochemical chloride extraction [186], should be also investigated for SFRC.

4.2.2 Effect of cracking, crack width and loading conditions

In the previous section it was discussed that cracking and crack width had a strong influence on the corrosion initiation period of the specimens from experimental study A. However, this was not the case during the propagation phase. First of all, the corrosion levels determined for uncracked beams, either global corrosion levels from gravimetric measurements or critical cross-sectional loss from 3D scanner measurements, were only slightly lower than those determined for cracked beams. Considering that corrosion initiation occurred significantly later in the uncracked beams, differences in the average corrosion rate during the propagation phase would be insignificant.

For the *loaded* beams with open cracks, no apparent difference in the corrosion level could be observed with respect to the *unloaded* and *cyclic* beams, indicating that the crack width during the exposure period did not play a significant role for the corrosion rate. Nevertheless, open cracks did have an influence on the corrosion pattern. Unlike for beams with re-closed cracks, a corrosion pit was found in all of the three bars in each *loaded* beam at the location where the widest crack had formed. Additionally, the extension of the corrosion spots formed in the *loaded* beams, was significantly smaller than for the other loading conditions. These findings indicate that open cracks contribute to sustain corrosion in the pits initially formed and at the same time they may confine corrosion within a limited region thereby preventing or limiting the corrosion of neighbouring areas.

The global corrosion level displayed a tendency to increase with the target crack width aimed during the pre-loading procedure. On the other hand, the corrosion level of cracked beams did not seem to be influenced by the different loading conditions. Particularly, the negative impact of cyclic loading identified for the corrosion initiation, was not observed for the propagation phase. Previously, it was concluded that a better indicator than the surface crack width for the risk of corrosion initiation could be the damage at the steel-concrete interface caused during mechanical loading, which can be promoted by wider induced cracks or repeated loading. Assuming that interfacial damage may be indeed a relevant parameter during the corrosion propagation phase, the comparison of the corrosion initiation times and the global corrosion levels, suggests that wider induced cracks might damage the interface in a different way than cyclic loading.

It could be argued that as the maximum load applied during the pre-loading procedure increases to reach a wider crack, a larger number of secondary cracks would form along the rebar-concrete interface [187]. These secondary cracks could become new preferential sites for corrosion onset along the reinforcement, thus leading to an increased global corrosion level. However, based on that premise, fibre reinforcement should have increased that effect due to an enhanced crack branching, which was not the case. Besides, the analysis of the corrosion pattern revealed that the number of corrosion spots along the reinforcement remained unaltered when increasing the target crack width from 0.2 mm to 0.3 mm. Moreover, the comparison of the corrosion and crack patterns also showed that only some of the corrosion spots were directly located at the position where the bars intersected a flexural crack. Consequently, although the maximum crack width reached during the pre-loading procedure seemed to have a stronger influence on the global corrosion level than the crack width during the exposure period or repeated cyclic loading, the mechanisms behind this observation remain unclear.

Regarding the maximum cross-sectional loss at individual pits, no clear trend could be identified for the different loading conditions, whereas only the *plain* series showed a seeming relation between cross-section loss and target crack width. Consequently, it was concluded that the local conditions at each individual pit are likely the main determinant with respect to local corrosion rates.

4.2.3 Effect of fibre reinforcement

From the results of experimental study A, fibre reinforcement had an overall positive effect on the corrosion propagation phase. The gravimetric steel loss measurements revealed that fibre reinforced mixes consistently exhibited a slight improvement in terms of reduced global corrosion level compared to the *plain* series. Moreover, the analysis of the corrosion pattern showed that this reduction of the corrosion level was accompanied by an increase of the number of corrosion spots in the reinforcement bars. These results seem to indicate that fibre reinforcement contributes to a more distributed corrosion on rebars, consisting of numerous corrosion spots with lighter corrosion as opposed to rebars in plain concrete featuring less but more heavily corroded corrosion spots. However, the reason for the increased number of corrosion spots cannot be only attributed to multiple cracking, as this was also observed in uncracked beams. Possibly, entrapped air generated during the mixing of the fibres, due to mechanical action, could also lead to the formation of small defects at the steel-concrete interface in the form of air voids, which may become preferential locations for corrosion initiation.

Examining the maximum cross-sectional loss of individual pits, no clear trend could be observed regarding the effect of fibres. For uncracked beams, fibre reinforced series yielded a slight reduction of the maximum cross-sectional loss compared to the *plain* series. For cracked beams with a target crack width of 0.2 mm, fibres had a rather limited impact, being slightly unfavourable in some cases. For cracked beams with a target crack width of 0.3 mm, on the other hand, a tendency towards reduced cross-sectional losses was evident. Although it might be possible that a potentially favourable effect of fibres is more pronounced when a certain crack width is exceeded, the fact that several beams with a target crack width of 0.2 mm featured greater cross-sectional losses than those with a target crack width of 0.3 mm, still points in the direction that local corrosion levels are controlled by the conditions at the steel-concrete interface of each individual pit.

As corrosion of reinforcement proceeds, one of the earliest observable effects is the appearance of corrosion-induced cracks at the concrete surface, which arise from the internal pressure originated by the accumulation of expansive corrosion products at the steel-concrete interface. Such cracks often propagate longitudinally, along the corroding reinforcement, thereby facilitating and accelerating the ingress of moisture, oxygen and depassivating substances along the rebar. As a result, corrosion-induced cracks can promote higher corrosion rates and are, therefore, considered especially harmful with regard to durability. Moreover, the development of additional corrosion-induced cracks may result in spalling of the concrete cover, thus leaving the reinforcement bars fully exposed and further increasing the corrosion rate. However, corrosion-induced cracks are also unequivocal signs of the underlying problem. Consequently, whereas controlling the development of such cracks is desirable, their complete suppression, or significant delay, may mask the real condition of a structure during a visual inspection.

The corrosion pattern of the beams in experimental study A, after three years of chloride exposure, revealed only a few cracks attributable to corrosion damage; namely three cracks for the *plain* series, one for the *steel* series and one for *hybrid* series. Unfortunately, their formation process during the exposure period could not be documented, hence no information is available regarding the time to cover cracking. Moreover, it is worth noting that the limited amount of corrosion-induced splitting cracks could perhaps be partly ascribed to the formation of black rust around the reinforcement bars. Black rust is formed in conditions where oxygen availability is limited and therefore it is less expansive than other types of rust, hence less harmful in terms of concrete cracking. As seen in Fig. 4.1, the black/greenish rust located mainly in the vicinity of the bars turned brown/reddish as it approached the concrete surface, indicating oxygen was readily available.

Figure 4.1. Image illustrating the formation of black rust around the reinforcement and the progressive change towards red rust as corrosion products propagated towards the concrete surface.

From experimental study E, it was found that the formation of splitting cracks, induced through accelerated corrosion, could be somewhat delayed by fibre reinforcement, particularly for small *c/Ø* ratios. The explanation of the delayed cracking, inferred from the results of non-linear finite element analyses, was attributed to the ability of the fibres to enable the simultaneous development of multiple cracks through their passive confinement effect. When the confinement of the cover was not sufficient, a single crack propagated rapidly through the entire cover of plain concrete specimens before secondary cracks initiated, whereas in fibre reinforced concrete specimens, various cracks propagated concurrently. For larger concrete covers providing well-confined conditions, this effect was less evident, as various cracks were able to develop simultaneously for both plain and FRC specimens, resulting in only a minor crack delay for the latter.

The effectiveness of fibre reinforcement to prevent spalling of the cover could not be directly assessed, since a uniform corrosion level of 8% was not enough to produce the complete detachment of the concrete surrounding the rebar. However, based on the results of the pull-out tests and the unaffected integrity of the specimens after a complete pull-out of the rebar, and considering that fibres can keep transferring stresses through cracks a few millimetres wide, it is reasoned that fibres could effectively prevent cover spalling.

The positive effect of fibre reinforcement on reduced corrosion levels as well as on the delay of corrosion-induced cracks and the suppression of cover spalling, suggest that adding fibres to conventionally reinforced concrete structures could contribute to extend their service life by limiting the access of further detrimental agents during the propagation phase.

4.3 Structural performance

The effect of fibre reinforcement on the local bond behaviour and structural performance of RC elements was investigated through pull-out tests and three-point bending tests, respectively. Tests were performed for both uncorroded specimens and for specimens with corroding rebars.

From the pull-out tests carried out in experimental study E, the effect of fibres could be clearly divided into two parts: the effect on the bond strength and the effect on the post-peak bond stress. The effect of fibres on the bond strength was negligible for reference specimens but became very evident for corroded specimens. More specifically, the bond strength of plain concrete specimens exhibited a clear degradation with increasing corrosion levels. Conversely, for uniform corrosion levels of up to 8%, the SFRC specimens displayed the same bond strength as that of uncorroded specimens, and even showed a slight increase for intermediate corrosion levels. Furthermore, this behaviour was found to be independent on the *c/Ø* ratio.

Equally, or even more important, was the influence of fibre reinforcement on the post-peak bond stress. Whereas the post-peak bond stress of plain concrete specimens was generally reduced to zero due to a complete loss of confinement after the peak strength, all of the SFRC specimens tested, regardless of the *c/Ø* ratio or corrosion level, exhibited a residual bond stress of 5 MPa or higher for a passive slip of 5 mm. That stress level corresponded to about one third of the bond strength of SFRC. Based on the residual bond stress suggested by the Model Code 2010, i.e. 0.4 times the bond strength of elements with stirrups under splitting failure, the previous results show that fibres possess a confining effect comparable to that of stirrups for a transverse reinforcement ratio, K_{tr}, of 2%, as defined in Model Code 2010 [7].

The most important consequence of the improved bond behaviour provided by fibre reinforcement is a substantial reduction of the length needed to anchor the yield force of the embedded rebars. To quantify this effect, a one-dimensional bond-slip model, developed by Lundgren et al. [188], was used in combination with the experimental local bond-slip curves to calculate the required anchorage length of a Ø16 mm bar under the different scenarios investigated. The results of the model revealed that for SFRC specimens the anchorage length was practically unchanged, increasing from 128 mm for an uncorroded specimens with a *c/Ø* = 4.0 to merely 157 mm for a corroded specimen with *c/Ø* = 2.5. Consequently, the main finding was that the risk of anchorage failure, even for high corrosion levels, can be greatly reduced by using fibre reinforcement.

The general behaviour of the beams during the three-point bending tests carried out in experimental study A, as observed in the load-displacement diagrams shown in Fig. 3.5(a). This consisted of an initial linear branch up to cracking, followed by a second, less stiff linear branch up to yielding of the reinforcement and a subsequent marginal load increase up to the maximum load determined by crushing at the compressive zone. This was followed by a post-peak descending branch under which the beams were able to carry a significant proportion of the maximum load until ultimate failure.

The examination of the load-deflection diagrams provided a significant amount of information, regarding both the effect of fibres and corrosion of reinforcement. The comparison of the diagrams of the reference beams of the *plain* and *steel* series revealed three clear effects attributable to fibre reinforcement.

The first one was an increase of the load capacity, both maximum load and load at yielding of reinforcement, of about 15%. The influence of fibre reinforcement on the bending capacity of conventionally reinforced concrete members is, however, largely influenced by factors such as the reinforcement ratio, the geometry of cross-section as well as type and amount of fibres added. Therefore, the increase of load capacity observed in the present study, as previously mentioned, is likely not representative for more realistic sectional designs.

The second effect identified was a smoother post-peak branch without sudden load drops attributed to a more controlled stress redistribution during the progressive concrete crushing due to the increased toughness of FRC.

Finally, the third effect observed was an earlier rupture (at a smaller mid-span deflection) of the rebars, which was attributed to a reduction of the yielding penetration, leading to less total deformation in the bars. This effect is due to the improved steel-concrete bond-slip behaviour of rebar embedded in FRC.

The combination of all these effects indicates that, in RC members with high reinforcement ratios prone to suffer concrete crushing, fibres may contribute to increase the deformation capacity but a limited increase of load capacity might be expected. On the other hand, in elements with low reinforcement ratios, a greater gain of load capacity can be achieved at the expense of a lower deformation capacity.

The examination of the load-deflection diagrams of reference and *loaded* beams, which were the group of beams with the greatest loss of steel cross-section at the rupture point, also revealed an obvious impact of pitting corrosion on the structural behaviour of the beams. The most striking effect of corrosion was a marked loss of deformation capacity, which was, proportionally, much more pronounced than the loss of load capacity. In addition to that, the overall shape of the load-deflection diagram was also affected by corrosion. In particular, with increasing cross-sectional loss, the yielding point became less defined, a behaviour that has been also observed at the material level for the stress-strain relationship of corroded steel bars.

A detailed comparison of the relative load loss at yielding associated to the loss of cross-sectional area at the steel rupture point, displayed an approximately linear relationship where the load decreased slightly more rapidly than the cross-sectional area. This could be explained by an uneven stress distribution caused by the abrupt geometry change in the pit, which leads to stress concentrations, known as the notch effect [189]. Regarding the effect of fibre reinforcement, a consistent increased load capacity was observed for the fibre reinforced series compared to the plain series. However, relative to the reference beams of each series, fibre reinforced beams exhibited the same relative load loss as the plain concrete ones.

Similar results were obtained when comparing the relative loss of deformation capacity, expressed as the relation between the total rotation capacity of the beams and the loss of cross-sectional area at the steel rupture point. In this case, though, the relative loss of rotation capacity decreased nearly four times faster than the loss of cross-sectional area, most likely due to localisation of plastic strain in the pit. The effect of fibre reinforcement on the rotation capacity of beams with corroding bars was rather limited. The *steel* series exhibited a similar rotation capacity as the *plain* series, whereas a slight improvement was observed for the *hybrid* and *synthetic* series.

4.4 Further observations

During the course of this work, the author has detected a series of observations regarding the behaviour of FRC and also some common practice among researchers that, although not directly related to the main research question formulated in the project, are worth mentioning.

The first observation concerns the corrosion of steel fibres embedded in concrete. As discussed in Section 2.3.3, fibres have been found to possess an increased corrosion resistance compared to conventional steel bar. Nevertheless, it has been reported that fibres laying near the concrete surface or bridging cracks, can be readily corroded.

Regarding the corrosion of near surface fibres, it has been shown that it mostly affects those fibres that are located within just a few millimetres of the most external layer of the concrete cover. Although the number of surface fibres might be proportionally small to the total amount of fibres in the concrete bulk, the corrosion of surface fibres leads to the appearance of conspicuous rust stains on the concrete surface (see Fig. 4.1). Even though these rust stains may not necessarily imply that the structural contribution of the fibres is impaired, they might hinder the early detection of corrosion of conventional reinforcement during a visual inspection. Moreover, rust stains pose a particular problem for the aesthetical appearance of the concrete. Nevertheless, it is interesting to note that, in Fig. 4.1, the appearance of rust stains is limited to the zones where the beams were immersed in the chloride solution. Thus, steel fibres located in the side of the beam that was kept above the water level at all times (right side in Fig. 4.2) did not corrode despite the expectedly high concentration of airborne chlorides. On the other hand, surface fibres that were partially exposed, i.e. they were not fully embedded in the concrete, readily corroded in the presence of moisture, even if chlorides were absent.

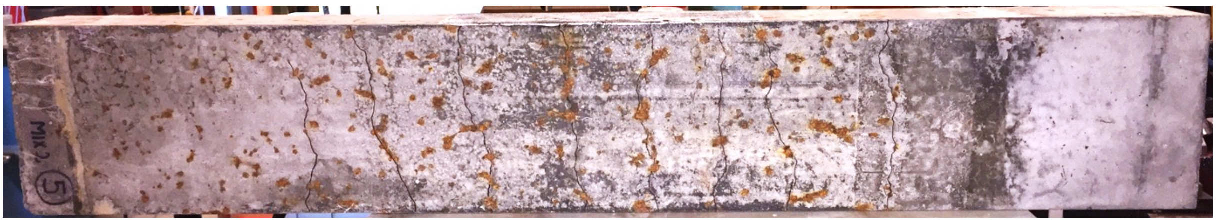


Figure 4.2. Aspect of the tension face of a steel fibre reinforced loaded beam with a target crack width of 0.2 mm after three years of cyclic exposure to chloride solution.

When it comes to crack bridging fibres, it has been reported that steel fibres will readily corrode when the crack width exceeds a certain threshold. As for conventional rebar, the influence of crack width on the corrosion of steel fibres is also a subject of controversy among researchers.

Nevertheless, unlike the corrosion of surface fibres, the formation of corrosion pits on crack-bridging fibres may compromise the structural performance of fibre reinforced concrete. Consequently, although corrosion of steel fibres was not the main focus of this work, fibre corrosion is equally important since most of the findings previously discussed are based on the assumption that fibres can effectively arrest cracking. Therefore, the state of crack-bridging fibres exposed to chlorides was visually inspected after mechanical testing of the specimens.

The examination of steel fibres on the crack surface of specimens, from both experimental studies A and E, revealed that most of the fibres did not exhibit any apparent sign of corrosion. Some of the fibres, however, did present signs of corrosion, generally either where the fibres met the crack surface or at the fibre hook (see Fig. 4.3). The extent of corrosion was most likely limited to only light surface corrosion since a change of the failure mode of fibres from pull-out to fibre rupture was not observed. This observation supports the enhanced corrosion resistance compared to conventional rebar, which in the same conditions as the fibres suffered considerable pitting damage. Nevertheless, the conditions under which corrosion of steel fibres can be effectively prevented are still being investigated.

Figure 4.3. Example of the aspect of several embedded steel fibres in a loaded beam with a target crack width of 0.2 mm after three years of cyclic exposure to chloride solution.

As already mentioned earlier, an important issue regarding the use of fibres in combination with conventional rebar is to ensure that techniques and methods developed to assess the condition of reinforcement in plain concrete are also applicable to fibre reinforced concrete. Previously, the limitations on the applicability of techniques in which an external electric field is applied have been discussed. Another unusual behaviour was also observed for the half-cell potential measurements.

In every beam, except for the *loaded* ones, the initial half-cell potential measurements of fibre reinforced beams were approximately 100 mV higher than for plain concrete beams. In the present investigation, this shift towards more positive potentials was not an issue, since corrosion initiation was determined based on a certain potential drop. However, in existing recommendations, cf. [190,191], a fixed range of potentials is suggested to estimate the probability of having active corrosion in the reinforcement. In such cases, an effect of fibres on the measured half-cell potential could be problematic. Nevertheless, results supporting this observation [127,162] and the opposite [122,126], i.e. that fibres do not have any effect on half-cell potential of reinforcement, are reported in the literature, which indicates that further research is needed to elucidate the cause of this behaviour.

The last reflection relates to the definition of the term ‘ductility’ and its suitability to describe the behaviour of corroded RC structures. First of all, ductility can be defined as the ability of a structural element to develop plastic deformation prior to collapse without a significant loss of bearing capacity. The key term in the previous definition is *plastic deformation*, meaning that ductility concerns the deformation occurring after the end of the elastic range. Consequently, ductility is commonly measured using a ductility factor defined as the ratio between the ultimate deformation and the deformation at yielding, where the parameter used to describe the deformation can be either strains, displacements or rotations, etc. However, the use of the term ‘ductility’ has become so widespread that it is often misused to refer to the deformation capacity.

In the study of the structural behaviour of corroded RC structures, it is common practice to evaluate the structural effects of corrosion by comparing the mechanical properties of corroded specimens to those of identical uncorroded ones. However, to the author’s knowledge, a discussion about how to evaluate the ductility of corroded elements with respect to uncorroded ones, has not been carried out. Since the load capacity, ultimate deformation and deformation at yielding are all susceptible to decrease due to reinforcement corrosion, comparing the ductility of corroded and uncorroded elements might become ambiguous and potentially misleading. For instance, it may occur that the ductility factor of a corroded elements remains similar or even increases compared to that of an uncorroded element despite a substantial loss of deformation capacity. Consequently, it is argued that the ductility factor is not an adequate parameter to describe the behaviour of corroded RC elements. Instead, the deformation capacity, which can be easily compared and has a straightforward interpretation, is more suitable.

5 Conclusions and future research

5.1 General conclusions

The main conclusion that can be drawn from the findings of this PhD thesis is that FRC may well be used in civil engineering structures exposed to chloride environments to effectively delay and reduce reinforcement corrosion as well as to mitigate the structural effects of corrosion-induced damage, leading to an extended service life of those structures. Based on the results from the different experimental studies carried out, the extension of the service life provided by the fibre reinforcement can be attributed to several mechanisms, as illustrated in Fig. 5.1. These mechanisms can be summarized as follows:

- Delayed time to corrosion initiation: a slower ingress of depassivating substances stemming from arrested crack development in FRC, in conjunction with a potential reduction of damage at the steel-concrete interface, can lead to longer initiation periods.
- Lower corrosion rate: multiple internal cracking and narrower individual cracks can promote a more distributed corrosion pattern and increase the capacity for autogenous crack healing, resulting in an overall reduction of steel loss.
- Delayed corrosion-induced cracking: due to the increased passive confinement provided by FRC, the appearance of corrosion-induced longitudinal cracks and their harmful impact on the corrosion of rebar can be delayed.
- Suppression of cover spalling: the crack bridging effect of fibres can effectively maintain the integrity of the concrete cover even at high corrosion levels, which can prevent the accelerated deterioration of reinforcement bars directly exposed to aggressive environments.
- Improved structural performance: fibre reinforcement can increase the load-carrying capacity and rotation capacity of concrete elements with corroding reinforcement while reducing the risk of brittle collapse, e.g. anchorage failure and shear failure, thereby mitigating the structural effects of corrosion damage.

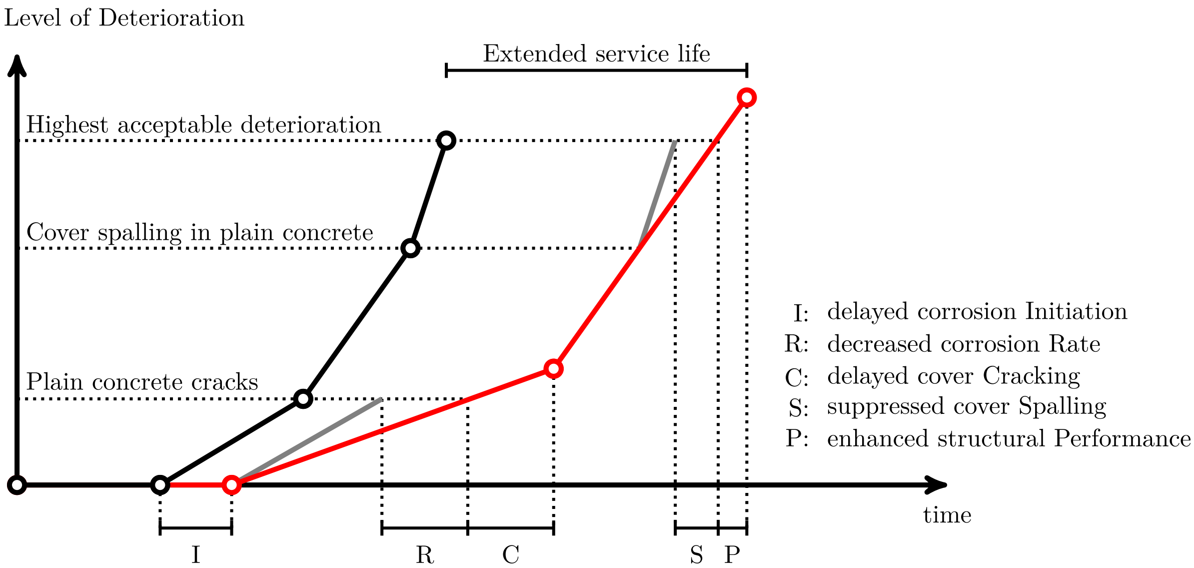


Figure 5.1. Mechanisms of fibre reinforcement to extend the service life of corroding RC structures. Note that the presented model assumes initially cracked concrete.

Some additional conclusions that can be drawn from the results presented herein are the following:

- Using relatively low fibre dosages (<1% vol.), which can be more cost-efficient and easier to incorporate into the concrete mix design than the fibre contents required to achieve a pseudo-strain hardening material, may be sufficient to obtain an improved corrosion durability.
- The choice of fibres should be specifically tailored to arrest both micro- and macro-cracking. In particular, the use of hybrid reinforcement combining different fibre sizes and materials proved to be a good compromise between enhanced mechanical performance and reduced rebar corrosion.

Based on the findings from the literature review, presented in **Chapter 2** as well as in **Paper I**, it should be noted that:

- Commonly used low-carbon steel fibres can readily corrode when bridging cracks above a certain width, which can lead to a considerable loss of its mechanical performance. Therefore, the crack width should be limited when using SFRC to minimize the corrosion of the fibres whereas some reduction of capacity for cracked SFRC is to be expected when exposed for long periods of time to an aggressive chloride environment. The reduction of capacity can be accounted for by, e.g. neglecting the structural effect of the fibres in the concrete cover.
- Available experimental data on the corrosion process of steel bars embedded in FRC is sparse, sometimes inconsistent and often difficult to contrast due to differences in the materials, experimental setups and exposure conditions used. This fact indicates a need for further research studies to clarify certain aspects for which currently available results are still inconclusive.

5.2 Specific conclusions

In the following, the conclusions drawn regarding the specific objectives presented in Section 1.2 are summarised. For a more detailed description of the concluding remarks related to these objectives, refer to **Papers I-VI**.

The influence of fibres on the resistance of uncracked concrete to chloride ingress was investigated by examining experimental results reported in the literature and the experimental results obtained from non-steady state migration tests and bulk diffusion tests carried out in this project. The following conclusions can be drawn:

- The effect of steel fibres on chloride ingress based on the results reported in the literature generally ranged from none to slightly improved resistance, for varying *w/c* ratios and different assessment methods.
- The results found in the present investigation were in line with previous findings reported in the literature, also for mixes with polyvinyl-alcohol (PVA) fibres.
- Based on the average repeatability coefficient of variation of the methods used to determine the resistance to chloride ingress, the differences found both in the literature and in the experimental results were not significant.

- All of the abovementioned observations point to the fact that the interfacial transition zone formed between the surface of the fibres and the bulk matrix does not act as a preferential zone for the transport of chloride ions.

The internal crack pattern of RC beams subjected to bending was investigated by injecting cracks with a low viscosity dyed epoxy resin and subsequently processing microscopy images taken from cut and polished samples in order to find differences in the variation of the crack profile and crack morphology induced by fibres. Through this evaluation, it was found that:

- Despite presenting a single surface crack of identical width, the internal crack pattern of the beams was systematically changed by the presence of fibres.
- Changes in the crack morphology included a tendency towards multiple crack branching, particularly near the rebar, and an increased crack tortuosity in FRC compared to relatively straight single cracks in plain concrete.
- The influence of fibres on crack branching was found to be dependent on the maximum load or surface crack width achieved, whereas tortuosity did not vary significantly with increasing surface crack width.
- Crack morphology changes were more apparent in beams featuring a hybrid fibre reinforcement, combining end-hooked steel fibres and PVA micro-fibres, compared to steel fibres alone.
- The crack width profile, i.e. the variation of the crack width along the cover depth, was evaluated according to three different equivalent crack widths. The results revealed that whereas the accumulated crack width was not influenced by the fibres, the effective and maximum crack widths were successfully reduced.
- The reduction of the effective crack width entails a lower permeation of the material in cracked state whereas the limitation of the maximum crack width, especially near the reinforcement, favours the possibility of autogenous crack healing.

The influence of steel fibres on the electrical resistivity of cementitious materials was explored through a review of available results from previous investigations. Additional experiments were carried out to evaluate how fibres may affect the existing methods used to measure resistivity and to better understand whether fibres might pose a risk for increased corrosion rates of conventional reinforcement. The conclusions obtained after the completion of this task are:

- The literature review revealed that steel fibres do not affect the DC resistivity, provided a certain electric field intensity is not exceeded.
- The critical electric field found in the present investigation was approximately 70 V/m for 25 mm fibres, which is in line with the findings of previous studies.
- Considering the limited potentials generated in corrosion macro-cells, the likelihood of exceeding the critical electric field in natural conditions seem very minor. Therefore, passivate steel fibres are not expected to contribute to increased corrosion rates. However, measurement techniques based on resistivity measurements in which high DC voltages are applied, might be greatly affected, to the point that they might be unsuitable for SFRC.
- Results in the literature as well as results from the present investigation showed that steel fibres have a clear influence on the impedance response of cementitious materials.

The most apparent effect was a change of the Nyquist plot from single to dual-arc, indicating a clear frequency-dependent behaviour of the steel fibres, which was strongly dependent on the fibre length.

- A shift of the AC frequency needed to determine the matrix resistivity of mortar samples was discovered, shifting from ~1 kHz for plain mortar samples down to 1 Hz for steel fibre reinforced mortar.
- As evidenced by the literature review, the lack of specific guidelines for resistivity measurements of steel fibre reinforced cementitious materials has led many researchers to adopt unsuitable methods, originally intended for plain concrete, which may lead to wrong conclusions.

The combined effect of fibre reinforcement and cracking on corrosion of conventional rebar was investigated through long-term experiments combining various fibre types and different loading conditions. The following conclusions can be drawn from the realization of these experiments:

- Cracking, i.e. the presence of flexural macro-cracks in this investigation, was by far the most important factor controlling the time to corrosion initiation.
- Beams subjected to sustained loading conditions, i.e. with open cracks, during the exposure to chlorides, pointed towards the existence of a critical crack width above which the corrosion initiation phase can in practice be disregarded, regardless of the presence of fibres.
- Larger crack widths induced during the pre-loading procedure and repeated load cycles generally led to earlier corrosion initiation, indicating that interfacial damage may be a better indicator than surface crack width for the risk of corrosion initiation.
- The effect of fibre reinforcement on the initiation of rebar corrosion was rather small but generally positive. The most noticeable improvements were observed for hybrid series in uncracked specimens and synthetic series in unloaded specimens. Steel series had a more limited impact.
- Based on the corrosion levels obtained from gravimetric steel loss measurements and analysis of local pits from 3D laser scanning, neither cracking, the surface crack width nor the loading conditions during the exposure period had a predominant influence on the corrosion rate during the propagation phase.
- Fibre reinforcement generally yielded a slight improvement compared to plain concrete for both the global and local corrosion levels, particularly for larger induced cracks. Moreover, fibres promoted a more distributed corrosion pattern with more spots featuring lighter corrosion compared to few more heavily corroded spots in plain concrete.

Through a combination of accelerated corrosion tests and finite element numerical analyses, the ability of steel fibres to delay corrosion-induced cracking and arrest subsequent crack propagation that may lead to cover spalling was investigated. The main findings can be summarized as follows:

- The addition of 0.5% vol. steel fibres can lead to a delay of longitudinal cracks caused by reinforcement corrosion.

- The delayed crack initiation was attributed to the additional source of passive confinement provided by the fibres that enable multiple cracking to develop simultaneously, thereby slowing down the propagation of cracks towards the surface.
- The beneficial effect of fibres was more noticeable for smaller c/Ø ratios and decreased as the c/Ø ratio increased, suggesting that for well-confined rebars, the effect of 0.5% vol. steel fibres would be negligible.
- After the appearance of cracks, the crack width was effectively controlled by steel fibres, resulting in a reduction of approximately 50% compared to the crack width of plain concrete specimens, for similar uniform corrosion levels (ca. 8% corrosion).
- Although cover spalling of SFRC was not observed in the experiments, the remaining integrity and crack-bridging capacity of the tested specimens after the complete pull-out of the rebar indicate that spalling of the cover could be effectively prevented in SFRC.

The contribution of fibres to the local bond behaviour and structural performance of RC elements, both uncorroded and with corroding reinforcement, was evaluated through pull-out and flexural tests. This evaluation yielded the following conclusions:

- Steel fibres did not have any significant impact on the bond strength of uncorroded specimens compared to plain concrete. On the other hand, uniform corrosion levels of up to 8% did not affect the bond strength of SFRC whereas they dramatically decreased the bond strength of plain concrete.
- Unlike for plain concrete specimens, SFRC specimens are able to retain a considerable amount of bond capacity after bond-splitting occurs, even at large slips, regardless of the *c/Ø* ratio and corrosion level.
- A considerable contribution of the fibres to the load capacity of beam elements was observed in the present investigation. This effect was augmented due to the high cover depth to internal lever arm ratio.
- The load capacity of corroded beams was found to decrease slightly faster than the average bar cross-sectional area at the steel rupture point. This could be attributed to peak stresses developing in critical pits due to a non-uniform distribution of stresses near the pit.
- The flexural tests revealed that the increased toughness of FRC can positively affect the rotation capacity of RC elements by better controlling the stress redistribution occurring during concrete crushing or avoiding sudden brittle failures. However, for RC elements with high rotation capacity, fibres can produce the opposite effect as a result of a decreased yield penetration in the rebar due to an improved bond behaviour of FRC.
- The rotation capacity of corroded beams was found to decrease almost four times faster than the load capacity in relation to the loss of cross-sectional area of the rebars.
- Beams with steel fibres exhibited the greatest increase of load capacity compared to plain concrete beams, although no improvement of the rotation capacity was observed. Conversely, PVA macro-fibres showed the highest contribution to the rotation capacity but a limited addition of load capacity. Hybrid fibres displayed an intermediate behaviour between steel fibres and PVA macro-fibres.

5.3 Suggestions for future research

The investigation of key aspects in the present study has provided valuable information regarding the influence of fibre reinforcement on the corrosion of conventional rebar in concrete. Although the available results are promising, further research is required to address additional aspects that could not be included in this thesis. A suggestion for future research is presented in the following:

Fibres, cracking and corrosion of rebar

The conclusions drawn in the present study are mostly based on the experimental results obtained from a limited number of specimens with a specific geometry. Consequently, there is a need for further experimental data regarding the effect of fibres on corrosion of reinforcement embedded in cracked concrete, particularly with respect to the propagation phase, in order to quantify the effect of fibres and obtain statistically significant conclusions. Different types and dosages of fibre reinforcement should be investigated, especially hybrid FRC combining different materials and fibre sizes, which was found to be a promising candidate. Moreover, the effect of fibres on cracking and corrosion for larger elements with more realistic concrete covers should be also investigated as fibres could give a more beneficial contribution. Ideally, laboratory tests should be complemented with long-term field exposure tests (e.g. marine and road environments).

Galvanic corrosion

It has been mentioned in the literature that metallic fibres could form a galvanic couple with conventional reinforcement, becoming sacrificial anodes that might protect the main reinforcement. However, given the greater corrosion resistance of steel fibres, a galvanic cell could in practice proceed in the opposite direction, i.e. the steel fibres could increase the corrosion rate of steel bars. Nevertheless, studies specifically aimed at investigating the feasibility of this mechanism, its extent and the conditions under which this type of corrosion might occur have not been found in the literature. Hence, specific experiments to assess this aspect should be conducted.

Steel-concrete interface

In the past years, the number of studies, including the present one, that indicate that the condition of the steel-concrete interface has a major role on the corrosion of rebar, has increased. More investigations are needed directed at better understanding the effect of different loading conditions on the damage caused at the steel-concrete interface, particularly with regards to the separation (normal displacement). Moreover, since it has been shown that fibres can, to some extent, control the level of interfacial degradation due to mechanical loading, it would be beneficial to deepen the understanding on the relation between fibre reinforcement and interfacial damage. Learning more about both of these aspects might result in more effective methods to delay the initiation of reinforcement corrosion through interfacial damage control.

Cracking

Cracking in the present investigation was limited to mechanical induced bending cracks. However, other type of cracks are often present in RC structures, e.g. shrinkage and/or thermal cracks. These type of cracks, arising due to restraint forces, are inherently different from mechanical cracks and might have a different influence on the corrosion process. Studying the effect of fibres on the corrosion of RC members with other types of fibres would provide a more sound understanding of the potential benefits of using fibre reinforcement in different types of structure and applications.

Electrical behaviour of SFRC

The resistivity of concrete is a fundamental parameter for several techniques, e.g. characterisation tests for different concrete properties, systems for cathodic protection of steel reinforcement and electrochemical chloride extraction. Understanding the influence of conductive fibres is essential to transfer the existing knowledge of such techniques, intended for plain concrete, to SFRC, Consequently, the effect of e.g. the *w/c* ratio, chloride content, moisture content and temperature, on the frequency for AC resistivity measurements should be investigated to enable quick and easy resistivity measurements on SFRC under a wide range of conditions. More information is also needed regarding the non-linear voltage-current diagram observed for SFRC, particularly with regards to the relationship between the fibre length and the electric field threshold.

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Appendices

Appendix A:

Supplementary experimental data

This appendix includes experimental data that has not been included in the main body of thesis nor in the appended papers. The data in this appendix comprises the corrosion potentials and corrosion rates measured in the beam specimens from experimental study A and the chloride ingress profiles obtained from the long-term diffusion tests carried out in experimental study B.

Experimental study A

The position of the embedded reference electrode (ERE20) used to measure the corrosion potentials and the position of the electrodes of the RapiCor device used to measure corrosion rates are illustrated in Fig. A.0.

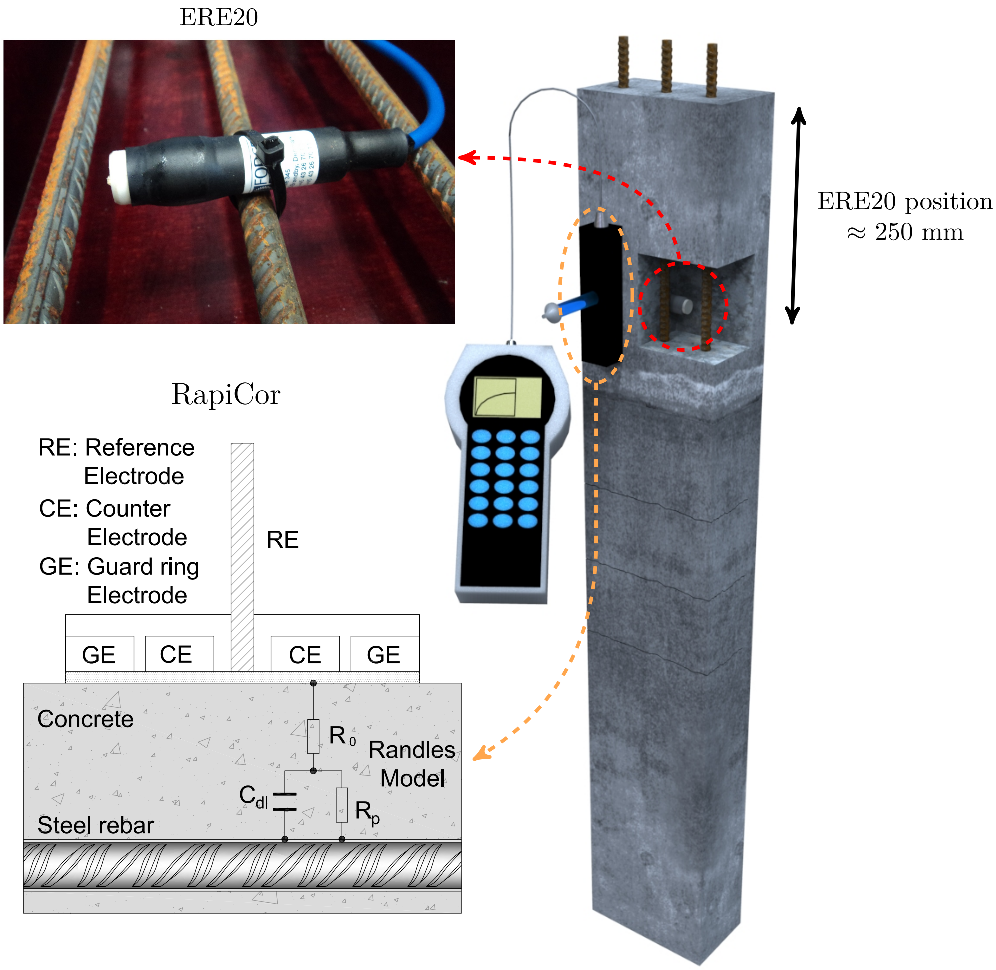

Figure A.0. 3D representation of the corrosion monitoring setup illustrating the position of the ERE 20 and the RapiCor device on the beam specimens. Note that the cut-out in the beam is only included to better illustrate the position of the ERE 20 in the beam.

To ease the reference to the different specimens and facilitate the interpretation of results to the reader, the following nomenclature has been introduced:

ST·12·C·02 E ⟵ Position of the rebar in the beam – **C**: central, **E**: external

Target crack width (mm) – 0.2 mm or 0.3 mm

Loading conditions – **R**: reference, **N**: uncracked, **U**: unloaded, **C**: cyclic, **L**: loaded

Beam identification number

Series – **PL**: plain, **ST**: steel, **HY**: hybrid, **SY**: synthetic

Corrosion potentials

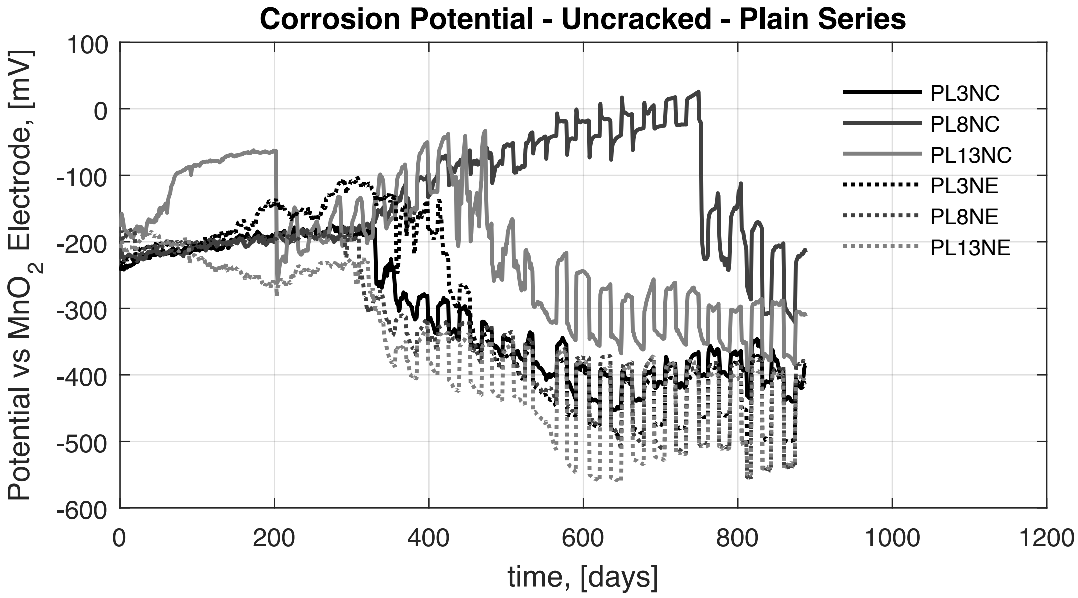

Figure A.1. Corrosion potentials for uncracked beams in the plain series

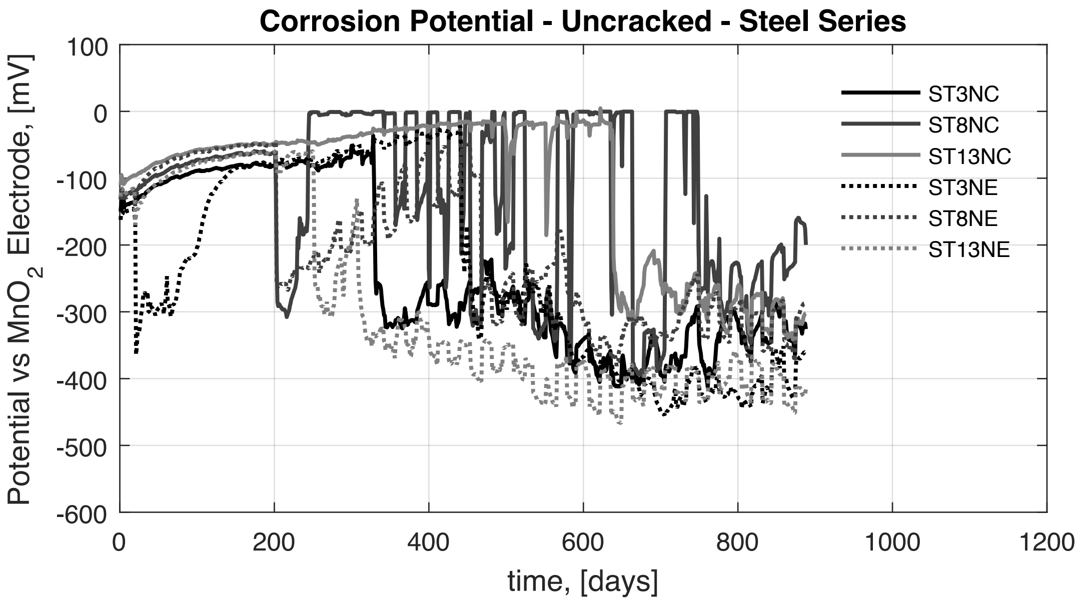

Figure A.2. Corrosion potentials for uncracked beams in the steel series

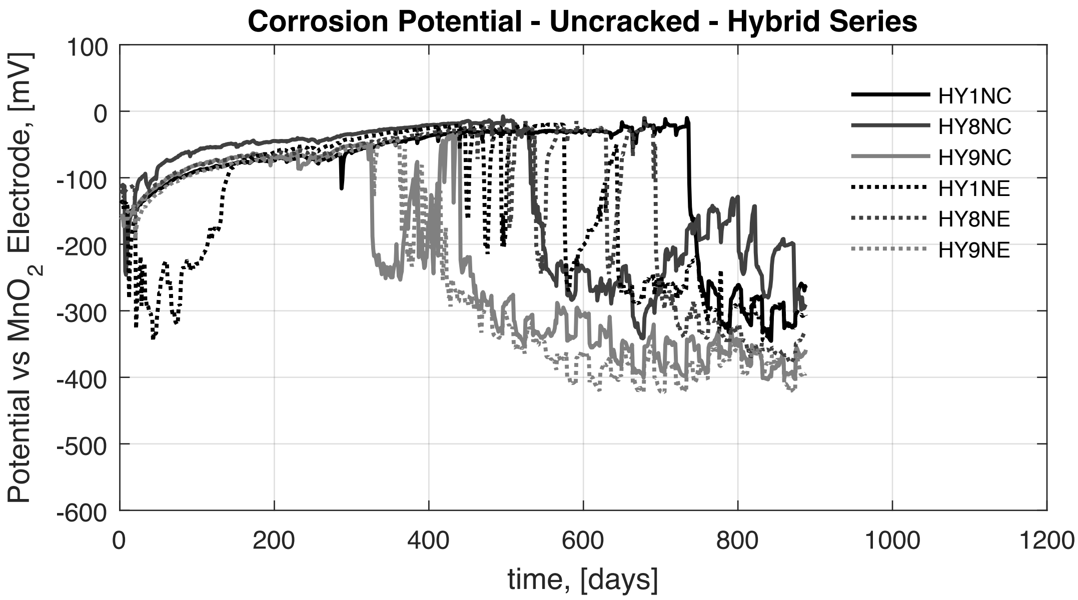

Figure A.3. Corrosion potentials for uncracked beams in the hybrid series

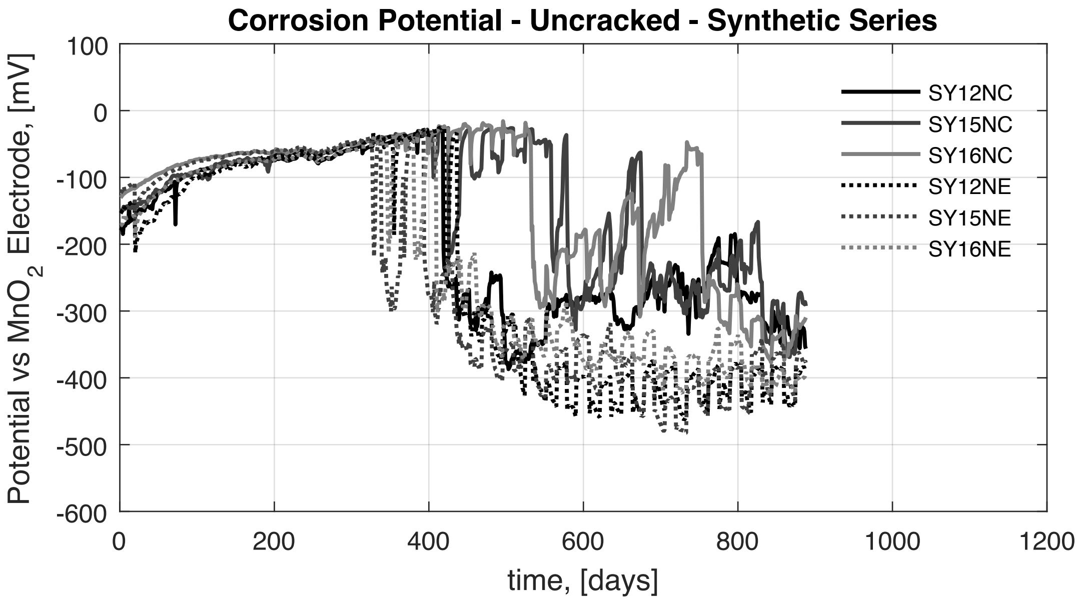

Figure A.4. Corrosion potentials for uncracked beams in the synthetic series

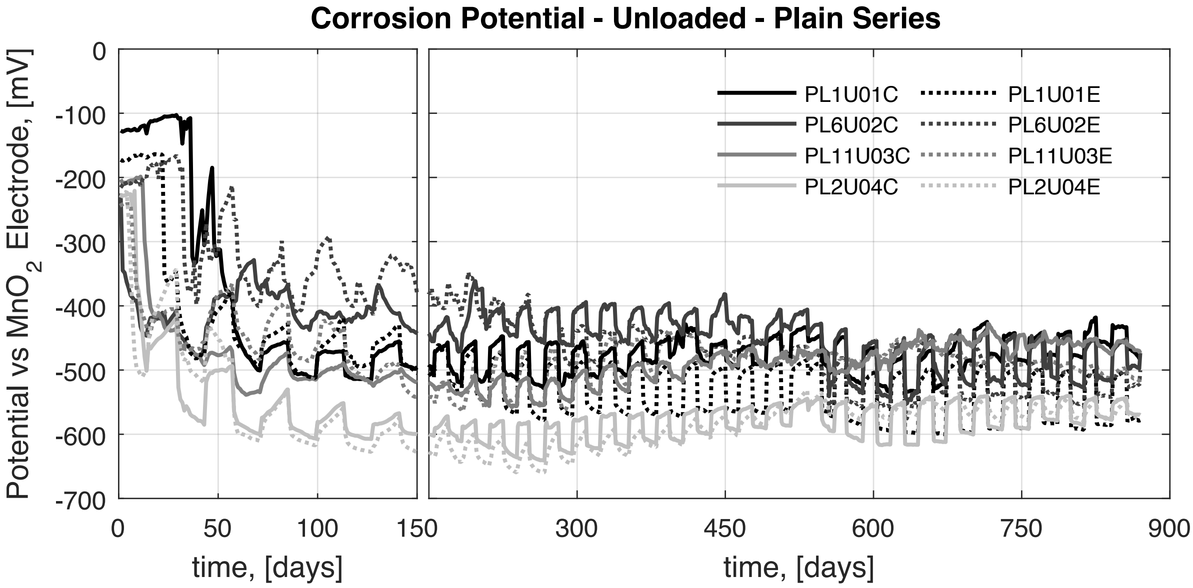

Figure A.5. Corrosion potentials for unloaded beams in the plain series

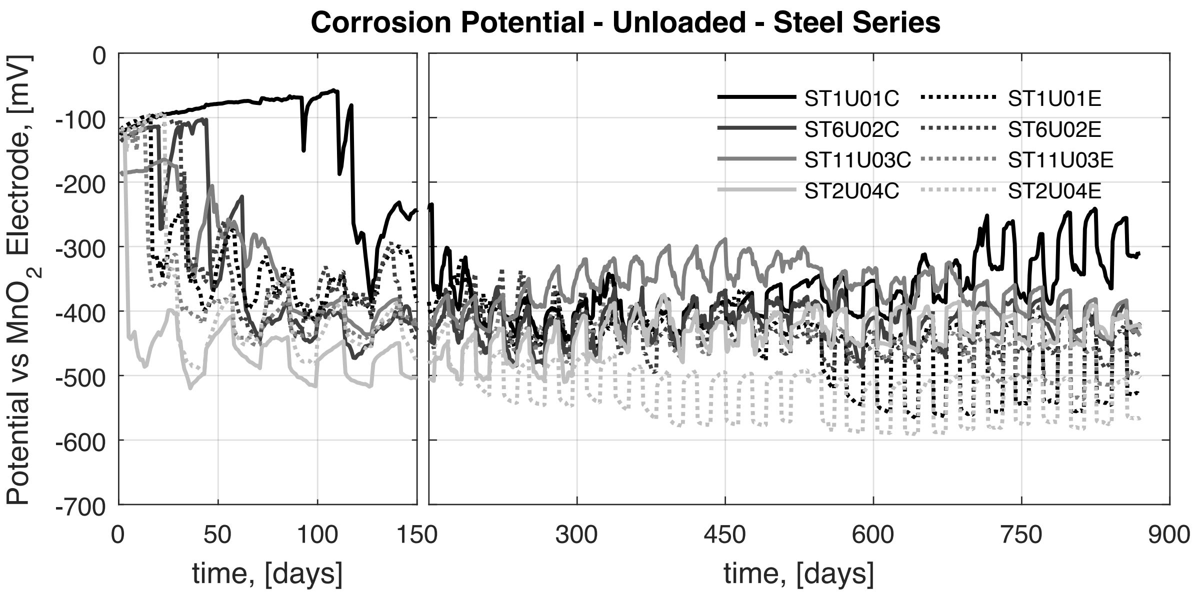

Figure A.6. Corrosion potentials for unloaded beams in the steel series

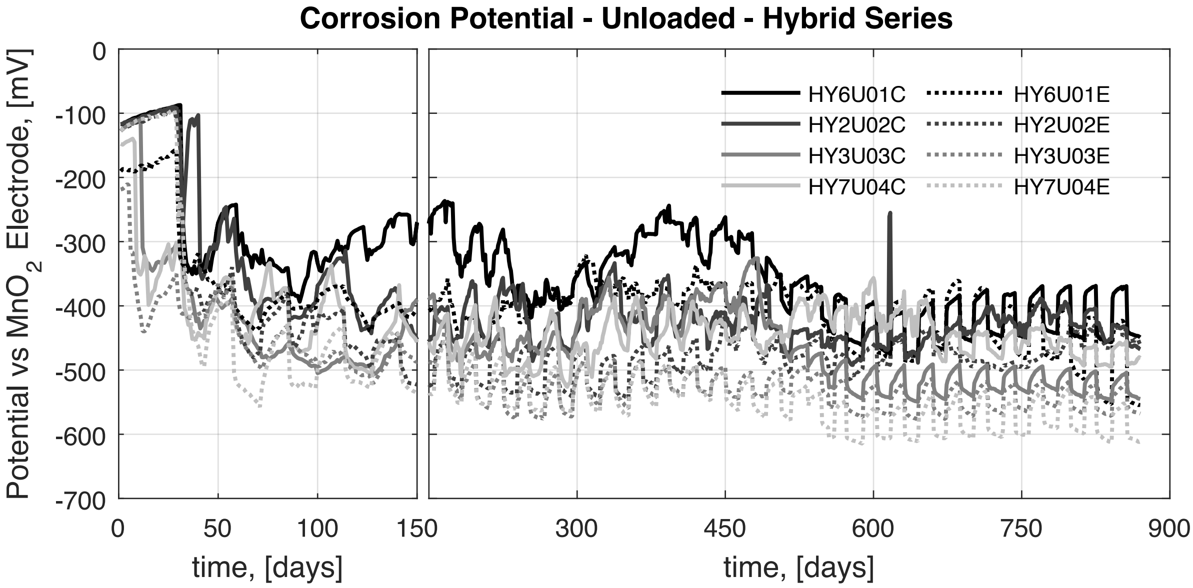

Figure A.7. Corrosion potentials for unloaded beams in the hybrid series

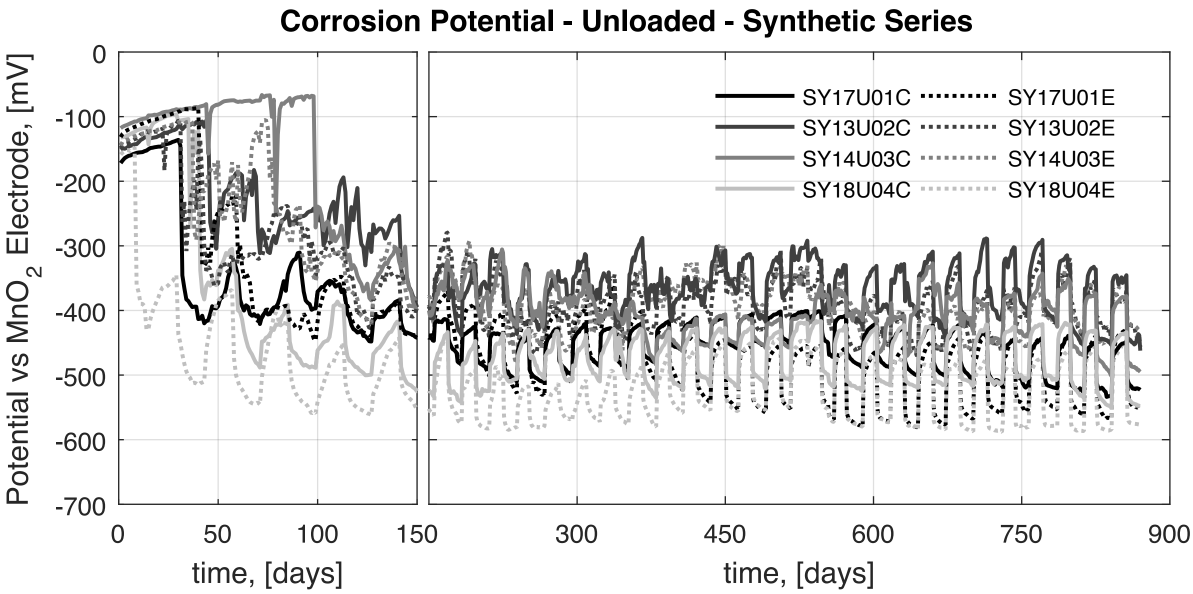

Figure A.8. Corrosion potentials for unloaded beams in the synthetic series

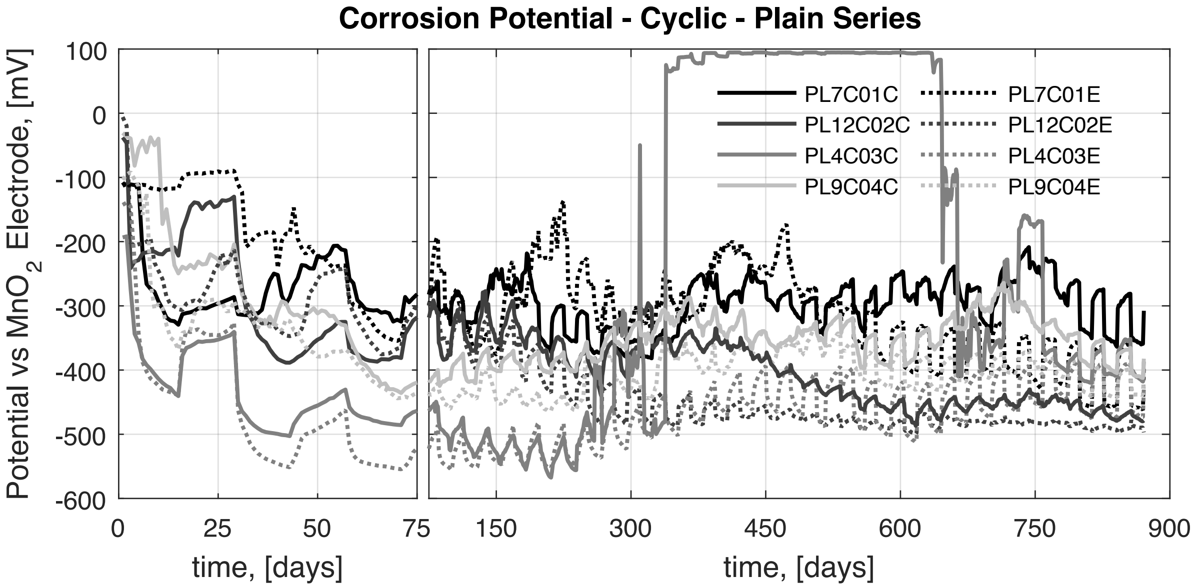

Figure A.9. Corrosion potentials for cyclic beams in the plain series

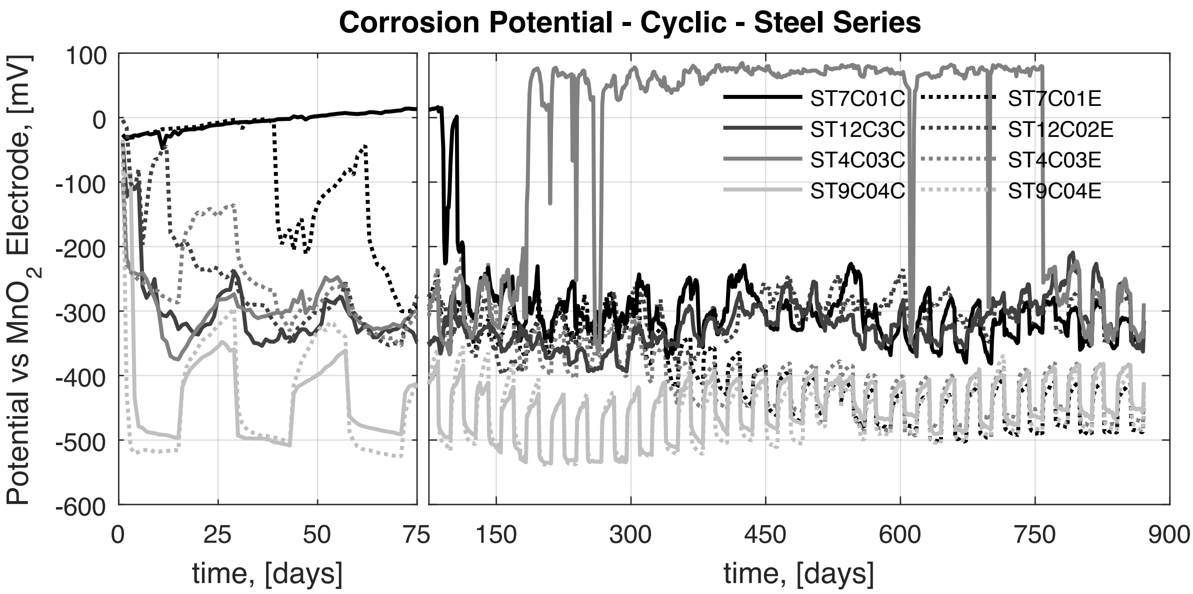

Figure A.10. Corrosion potentials for cyclic beams in the steel series

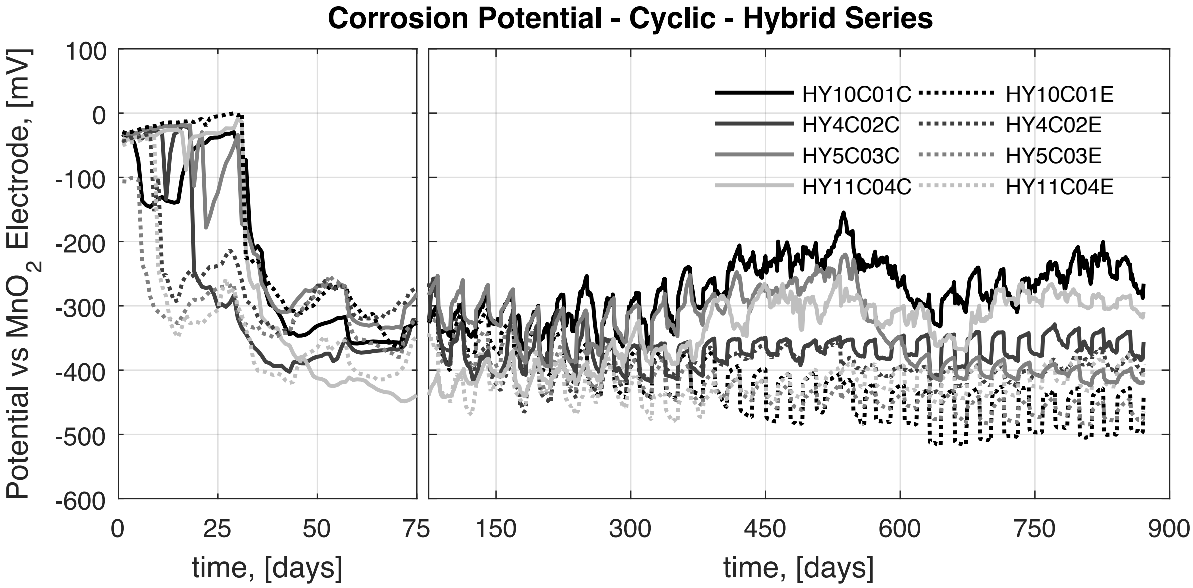

Figure A.11. Corrosion potentials for cyclic beams in the hybrid series

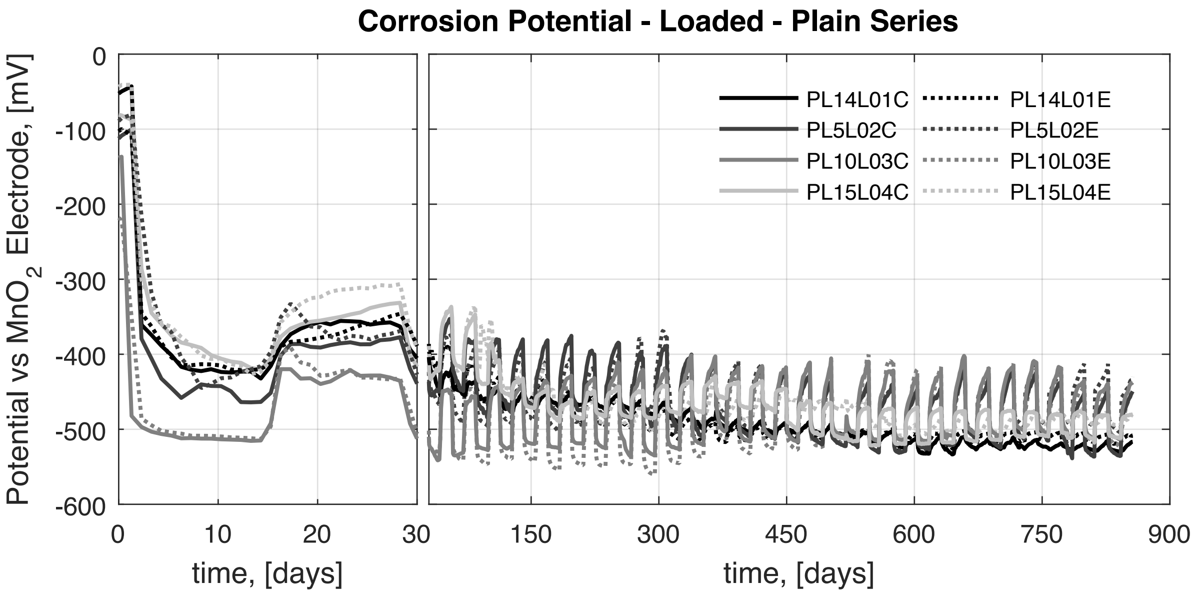

Figure A.12. Corrosion potentials for loaded beams in the plain series

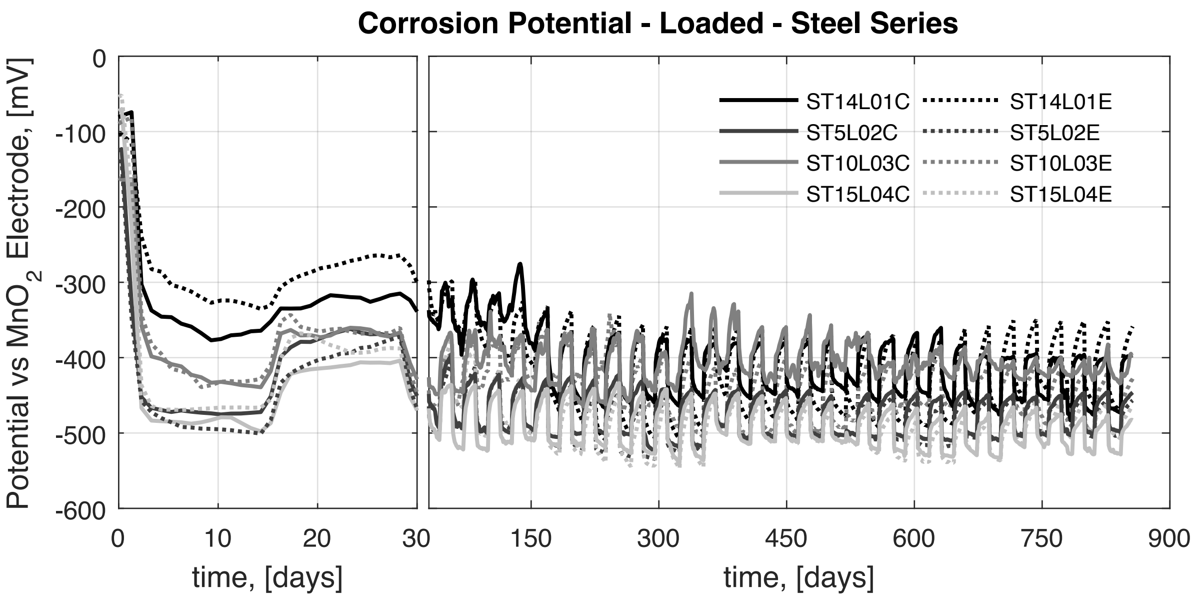

Figure A.13. Corrosion potentials for loaded beams in the steel series

Corrosion rates

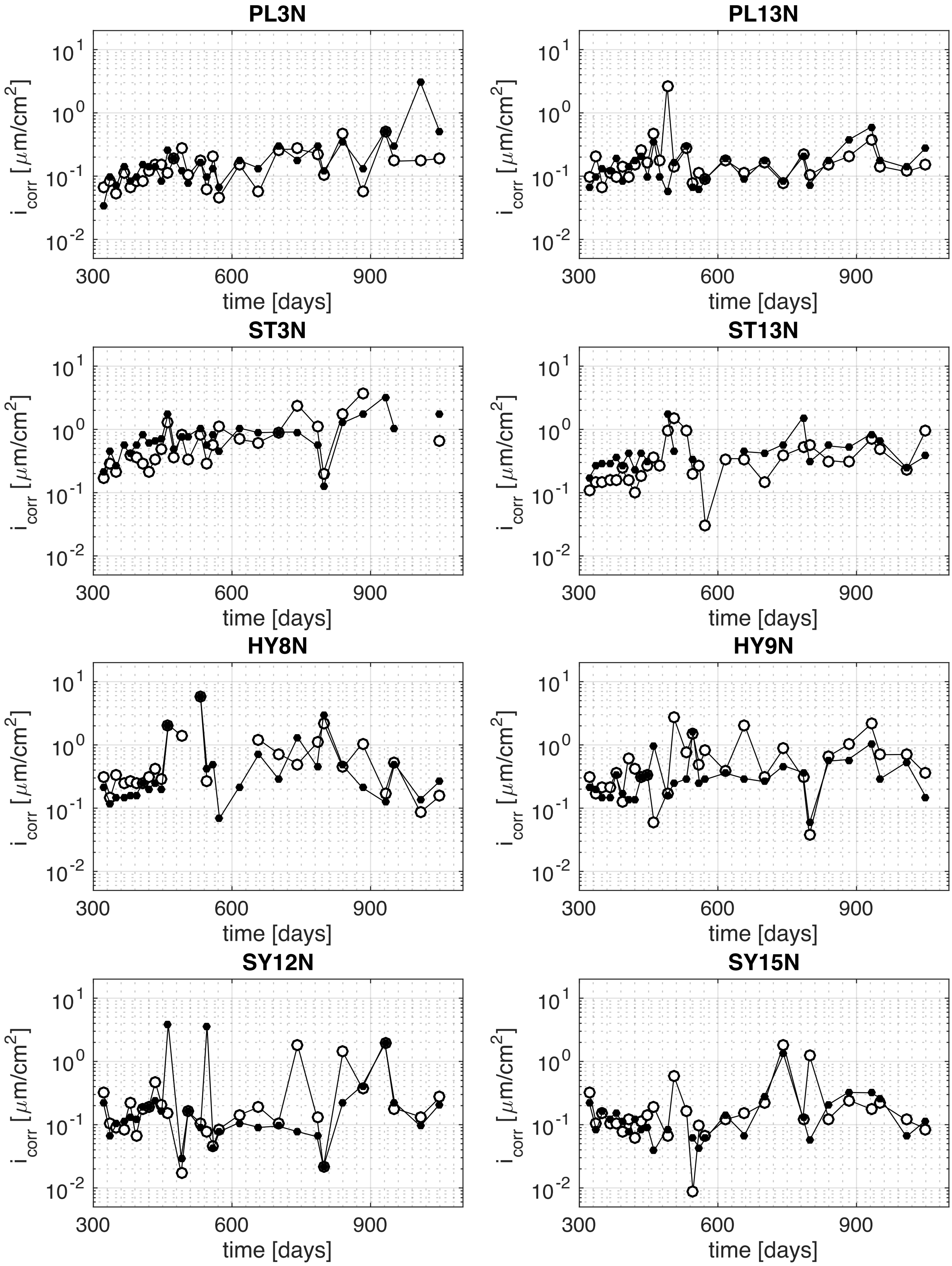

Figure A.14. Evolution of the corrosion rate during the exposure period for uncracked beams.

In the plots, (○) denotes a corner rebar and (●) denotes the central rebar.

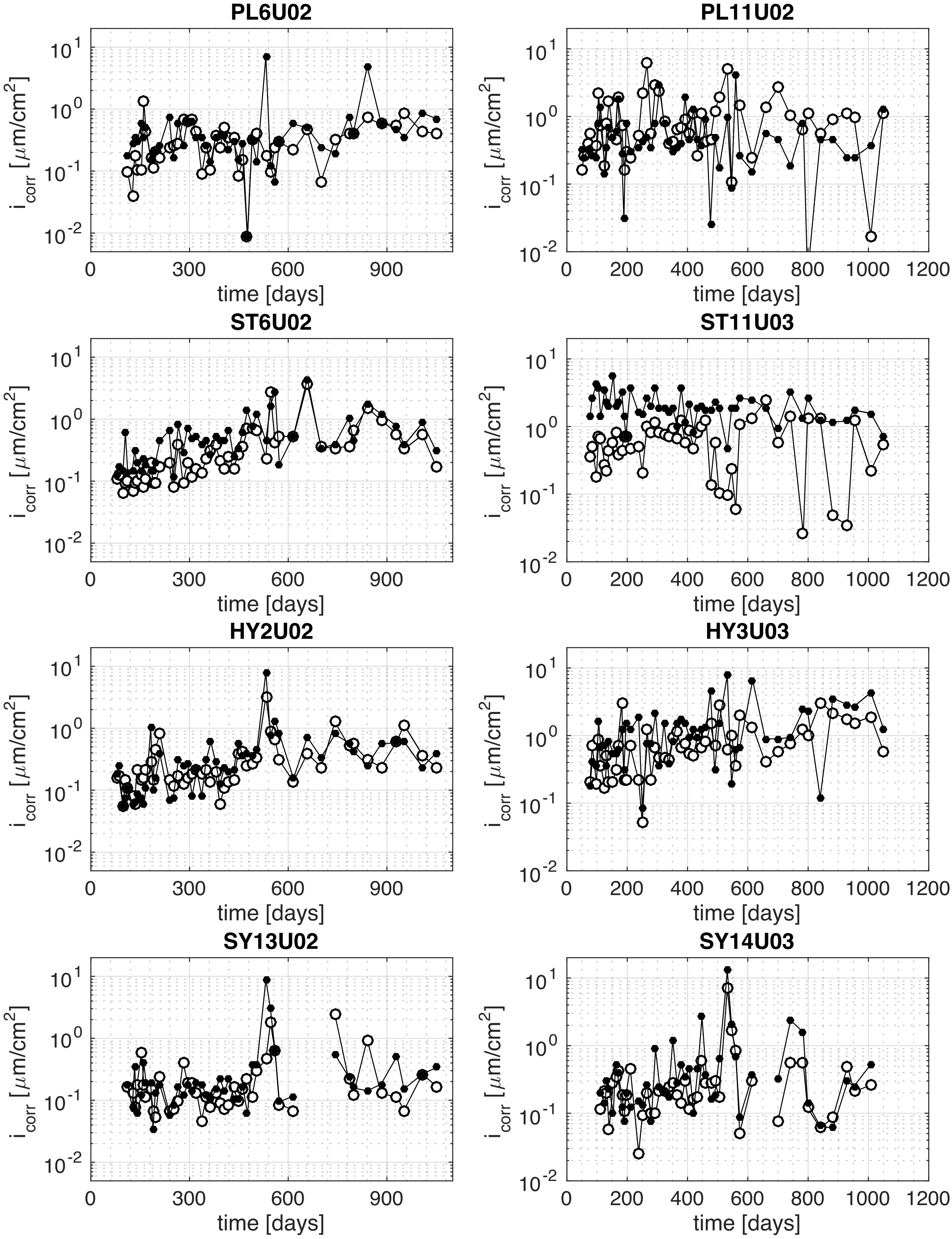

Figure A.15. Evolution of the corrosion rate during the exposure period for unloaded beams.

In the plots, (○) denotes a corner rebar and (●) denotes the central rebar.

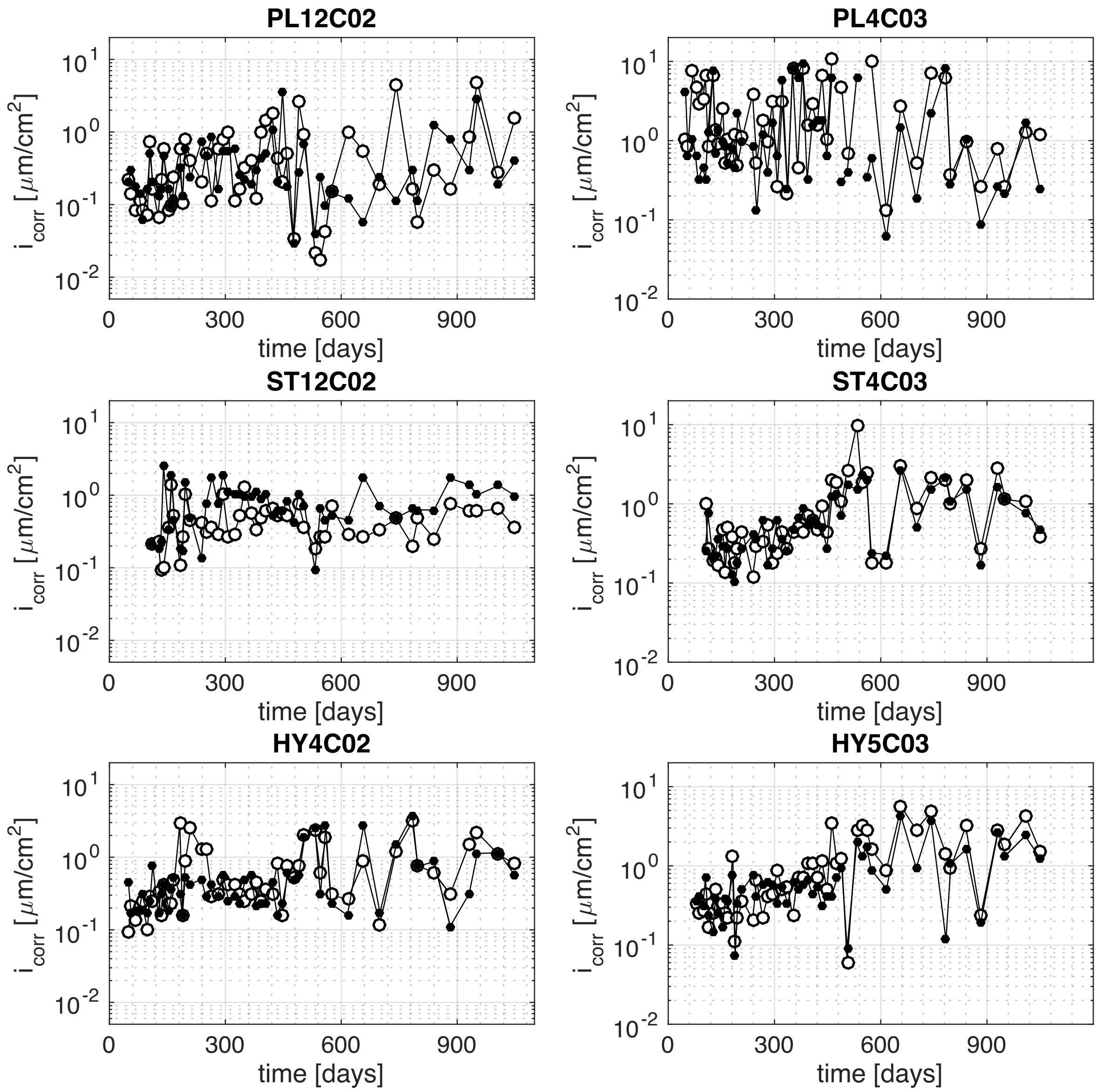

Figure A.16. Evolution of the corrosion rate during the exposure period for cyclic beams.

In the plots, (○) denotes a corner rebar and (●) denotes the central rebar.

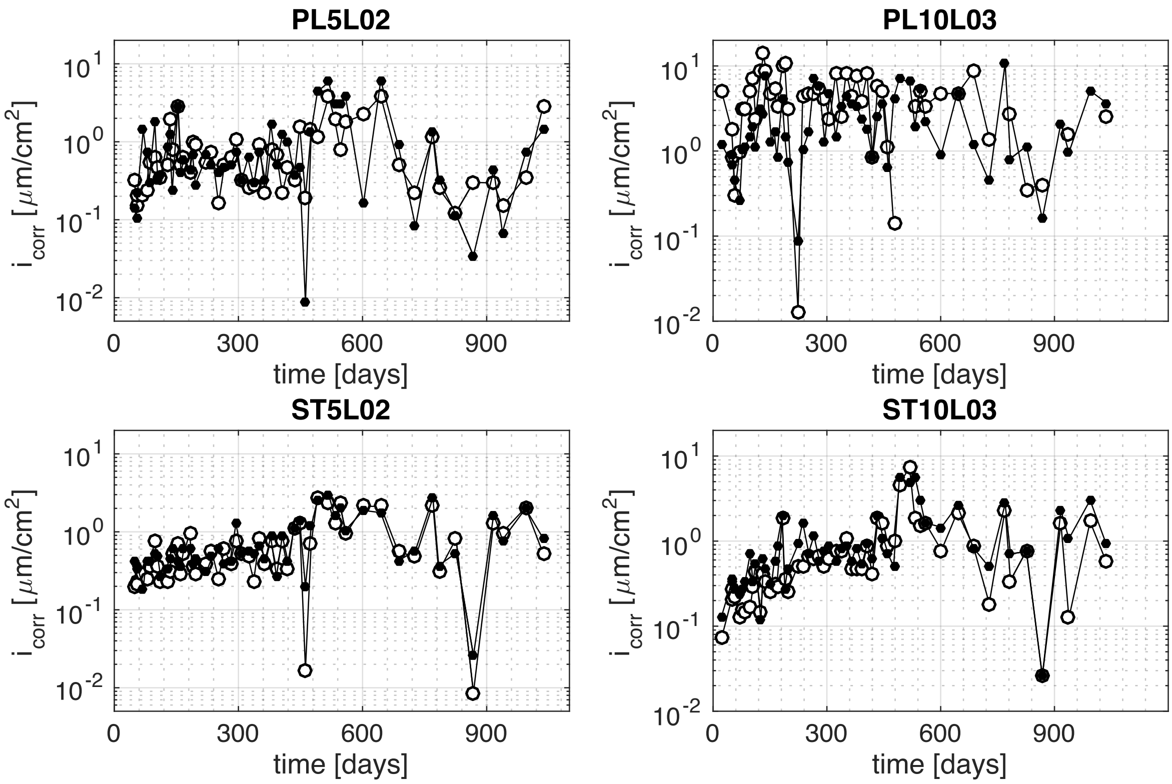

Figure A.17. Evolution of the corrosion rate during the exposure period for loaded beams.

In the plots, (○) denotes a corner rebar and (●) denotes the central rebar.

Experimental study B

Chloride ingress profile from long-term diffusion tests

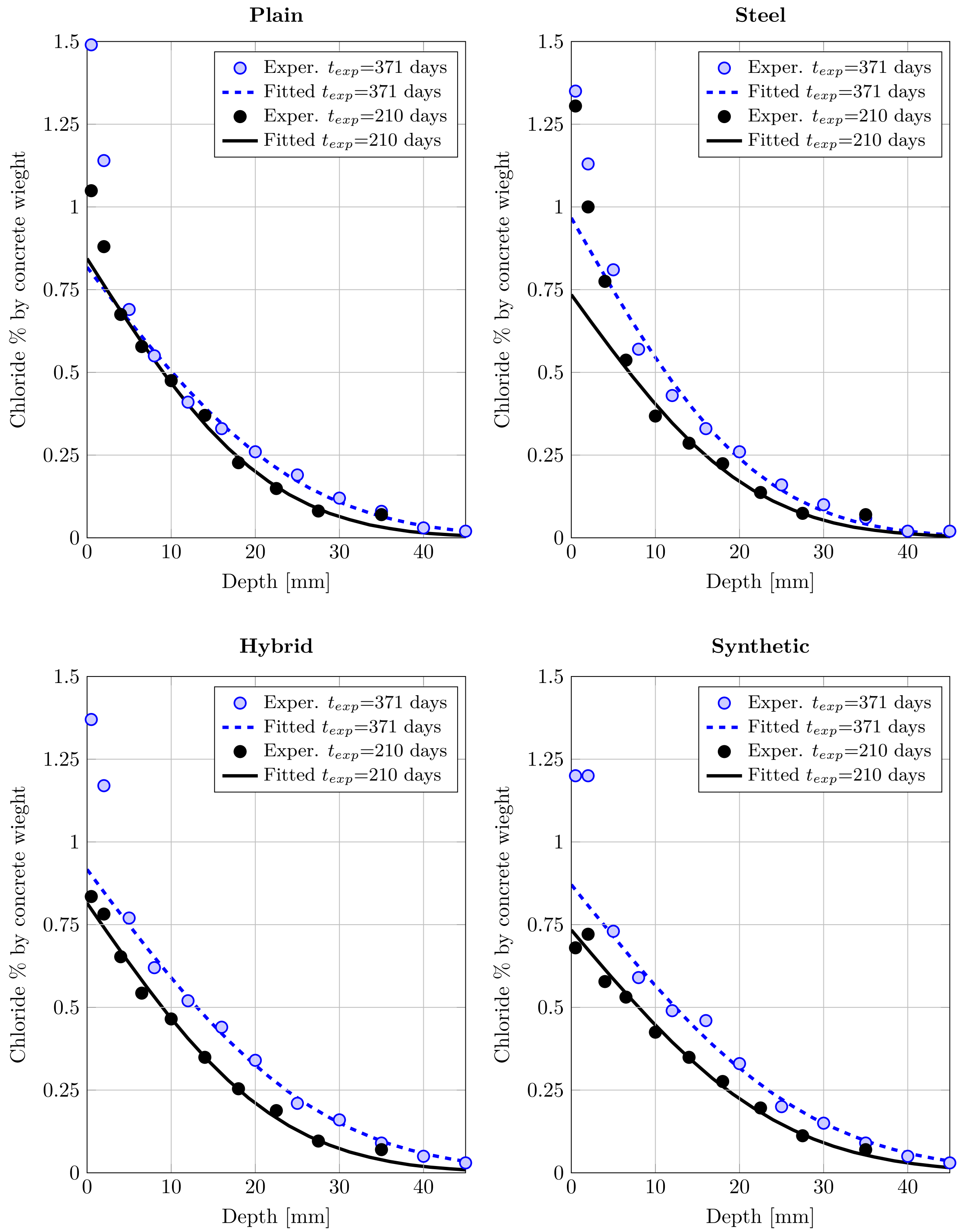

Figure A.18. Total chloride content profiles from long-term diffusion tests. Markers denote experimental measurements and lines show fitted profiles.