THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

Anchorage of Corroded Reinforcement in Existing Concrete Structures

Experimental study

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Cover:
The cover picture shows an example of a Medium damaged specimen after testing. Photographed by Mohammad Tahershamsi on June 25, 2012

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ABSTRACT

Reinforcement corrosion is one of the most common causes of deterioration in reinforced concrete which limits the durability and performance of existing concrete structures. The corrosion mechanism involved and consequent structural behaviour of deteriorated reinforced concrete members have been studied by several researchers. Nevertheless, the knowledge obtained is primarily based on experimental investigations of artificially corroded specimens. Earlier studies have shown that artificial corrosion may affect the structural behaviour differently than natural corrosion. Therefore, it is important to gain a better understanding of these differences by conducting experiments on naturally corroded reinforced concrete members. The aim of the research presented is to investigate the remaining bond capacity of naturally corroded ribbed bars. Two test series on the bond behaviour of naturally corroded reinforcement in the anchorage region were carried out in this study.

The test specimens were taken from concrete edge beams of a 30-year old girder bridge, the Stallbacka Bridge in Sweden. These specimens were grouped into three classes differentiated by the levels of observed corrosion damage: *Reference* specimens with no sign of damage, *Medium damaged* specimens with splitting cracks and *Highly damaged* specimens with spalling of the concrete cover. The tests were carried out using an indirectly supported four-point bending test set-up. The overall structural behaviour of the specimens was examined through measurements of loads, vertical deflections and end-slips of the tensile reinforcement bars. The failure mode consisted of a splitting-induced pull-out failure in all tests. It was observed that the specimens with cracking or cover spalling had 5 to 10 % lower load-carrying capacity compared with the Reference specimens. The calculated bond stresses in the anchorage zones showed a reduction of 9 to 17 % in the bond strength of damaged specimens in comparison to that of Reference specimens. Furthermore, it was noted that the specimens with relatively lower stiffness showed a more ductile bond failure.

The decrease in bond capacity and its relationship to the crack widths and patterns documented were studied for both the naturally corroded specimens tested in this study and artificial corrosion tests from the literature. A reduction of bond strength with increasingly maximal crack widths was observed in both types of tests. However, the bond strength in the naturally corroded specimens was considerably higher than that of the artificially corroded specimens. Furthermore, the provisions given in Model Code 2010 in terms of the reduction in bond strength compared with crack width remained on the safe side. The knowledge gained in this research contributes to a better understanding of the mechanical effects of reinforcement corrosion in a naturally corrosive environment and can be used as reference data for further calibration and validation of existing models.

Keywords: Bond properties, anchorage, structural behaviour, natural corrosion, reinforced concrete structures, experiments, load-carrying capacity.

Contents

Preface

This presented licentiate thesis explores the anchorage and bond behaviour of naturally corroded reinforced concrete structures. The project was carried out at the Department of Civil and Environmental Engineering, Division of Structural Engineering, Concrete Structures, Chalmers University of Technology from October 2011 until December 2013. The author wishes to express his gratitude to the Swedish Transport Administration, *Trafikverket*, for financing this project.

I want to express my sincere gratitude to my supervisor, Professor Karin Lundgren, and co-supervisors Kamyab Zandi Hanjari, Ph. D., and Associate Professor Mario Plos for their support, encouragement, valuable discussions and advice throughout the study. I also wish to thank Jonas Magnusson, Ph. D., for taking the time out of his busy schedule to participate in both the reference group and several project meetings to share his expertise. I would also like to thank other members of the Reference group, including Robert Ronnebrant, Björn Engström, Kent Gylltoft, Peter Utgenannt and Poul Linneberg, for their interest in the project and for their excellent discussions and comments. My grateful thanks are also extended to Master's students Fredrik Berg, David Johansson, Eyrun Gestsdottir and Tomas Gudmundsson for their diligent participation within this project. Special thanks go to Natalie Williams Portal, my very good friend and office mate, and Gunilla Ramell for their language editing works of this thesis.

This study has included a large amount of experimental work. Thus, I would like to thank the laboratory engineer, Lars Wahlström, for his excellent work during the execution of tests.

I would like to thank my friends and colleagues for their help, support and all the constructive discussions.

My sincerest gratitude goes out to my family, specially my parents, for their heartfelt devotion, support and encouragement during all years of my study. Last but not least, I send my love and gratitude to my girlfriend, Johanna, for her endless love, support and understanding throughout the whole study.

Gothenburg, 2013

Mohammad Tahershamsi

LIST OF PUBLICATIONS

This thesis is based on the work presented in the following papers:

Paper I

Lundgren K., Tahershamsi M., Zandi Hanjari K. and Plos M. (2013): Tests on Anchorage of Naturally Corroded Reinforcement in Concrete. Accepted for publication in *Materials and Structures*.

Paper II

Tahershamsi M., Zandi Hanjari K., Lundgren K. and Plos M. (2013): Anchorage of Naturally Corroded Bars in RC Structures. Submitted for publication to *Magazine of Concrete Research.*

AUTHOR'S CONTRIBUTIONS TO JOINTLY PUBLISHED PAPERS

The contributions of the author of this licentiate thesis to the appended papers are described here:

I. Shared responsibility for the planning of the experiments. Responsible for the execution of a major part of the experiments. Contributed to writing the paper.

II. Responsible for the writing and for the major part of the planning of the paper. Responsible for planning and execution of the experiments.

ADDITIONAL PUBLICATIONS BY THE AUTHOR

Conference Papers

Tahershamsi M., Zandi Hanjari K., Lundgren K. and Plos M. (2012): Anchorage capacity of naturally corroded reinforced concrete beams. Proceeding of the *fib* Symposium, Concrete Structures for Sustainable Community, 11-14 June 2012, KTH Royal Institute of Technology, Stockholm, Sweden, p. 323-326.

Tahershamsi M., Zandi Hanjari K., Lundgren K. and Plos M. (2012): Anchorage in naturally corroded specimens taken from existing structures. Proceeding of the Fourth International Symposium on Bond in Concrete 2012: Bond, Anchorage, Detailing, Brescia, Italy, 17-20 June 2012, Editors: John w. Cairns, Giovanni Metelli, Giovanni A. Plizzari Vol. 1, General Aspects of Bond (2012), p. 345-349.

Lundgren K., Plos M., Zandi Hanjari K. and Tahershamsi M. (2012): Är förankringskapaciteten tillräcklig i broar med rostande armering? Bygg & Teknik (0281-658X). Vol. 104 (2012), 7, p. 17-19.

Tahershamsi M., Zandi Hanjari K., Lundgren K. and Plos M. (2013): Assessment of anchorage capacity of naturally corroded reinforcement. International Association for Bridge and Structural Engineering, IABSE Conference, Assessment, Upgrading and Refurbishment of Infrastructures, 06-08 May 2013, Rotterdam, The Netherlands, p. 556-557.

1 Introduction

1.1 Background

In recent years, demands on extending the service life and increased traffic loads have increased the interest in the durability and structural assessment of existing structures, in particular due to economic considerations. Meanwhile, ageing and deterioration due to aggressive environment have been occurring in many existing reinforced concrete (RC) structures, e.g. bridges, parking garages and off-shore structures. The deterioration may affect both the serviceability and ultimate load-carrying capacity. Consequently, understanding the actual behaviour of an impaired structure and a realistic estimation of its remaining service life are of great importance to responsible authorities, stakeholders, engineers and researchers.

The corrosion of embedded reinforcement in concrete is considered to be one of the main causes of the deterioration of many existing RC structures. Corrosion may affect the structural performance and integrity of reinforced concrete components in the long run to a considerable degree, see (CEB-fib, 2000). The corrosion of steel bars embedded in concrete may lead to several undesirable consequences, such as potentially severe damage resulting in the loss of a cross-sectional area of steel, which would reduce both the capacity and ductility of the reinforcement (Almusallam, 2001; Du et al., 2005a; Du et al., 2005b). Furthermore, by occupying a higher volume than the original steel, the corrosion products affect the surrounding concrete, thereby increasing the mechanical pressure around the reinforcement. Crack propagation and cover delamination are the two most common physical signs of this phenomenon according to Al-Sulaimani et al. (1990). The volume expansion of rust not only causes splitting stresses but also affects the steel-concrete bond properties, something that must be specifically taken into consideration in assessment when corrosion takes place in anchorage zones (Imbsen et al., 1987).

Over the past few decades, many experimental and numerical studies have been conducted focusing on the test results of damaged reinforced concrete specimens subjected to accelerated corrosion. The loss of ductility and stiffness during the service life (Cairns et al., 2005) and the decrease of load-carrying capacity in the ultimate limit state (Val et al., 2009; Zandi Hanjari et al., 2011) were the main findings of these studies. Saifullah et al. (1994) showed that the current density applied to accelerated corrosion tests may notably influence bond strength. The comparisons of test results with low and high corrosion rates showed deviant behaviour of the local bond (Sæther, 2010), differences were attributed to the chemistry of corrosion products, their ability to escape through cracks or penetrate the cement matrix, as well as concrete creep (CEB-fib, 2000). While much effort has been devoted to testing artificially corroded reinforced concrete, relatively little attention has been devoted to the problem of assessing the residual strength of corroded structures in natural environments. Accordingly, there is a strong need for experiments involving naturally corroded specimens in order to gain an understanding of the true behaviour of corroded structures as well as to value the validity of the results of accelerated-corrosion tests found in literature.

1.2 Aim and objectives

The aim of this study was to increase the knowledge of the bond and anchorage behaviour in naturally corroded reinforced concrete structures. More specifically, the aim was to study the bond behaviour of naturally corroded ribbed bars in anchorage regions to assess the anchorage capacity of corroded reinforcement in reinforced concrete members. Within this overall vision of the study, there are some specific objectives which relate to the different stages of the research project:

- To generate a database of naturally corroded reinforced concrete specimens.
- To examine the test set-up custom-designed to evaluate the anchorage capacity in existing concrete structures and to consider possible improvements.
- To study the average bond strength and to assess the anchorage capacity versus visible damage.
- To compare naturally corroded test results with available artificial corrosion tests.

1.3 Method and scientific approach

The scientific approach in this study has been primarily based on experiments and corresponding observations. Two series of experiments were carried out to study the effect of natural corrosion on the remaining load-carrying capacity of damaged concrete structures. The edge beams of a composite bridge deck were chosen as test specimens. The experiments were conducted by means of an indirectly supported four-point bending test set-up, specifically designed to enable the study of anchorage behaviour. The visible damage on specimens was thoroughly documented before tests and measured capacities were correlated accordingly. A literature study was conducted to identify the effects of reinforcement corrosion in reinforced concrete members and to make comparisons between natural and artificial corrosion.

1.4 Limitations

The limitations of the study are summarised as follows:

- As the test specimens were taken from a real-life structure, it became impossible to be in total control of the design and construction of the test specimens.
- Anchorage at the end regions alone was studied.
- Direct measurements of strains in the longitudinal and vertical reinforcements were infeasible in most specimens because the horizontal and vertical reinforcements were not exposed in all specimens. Therefore, it only became feasible to mount strain gauges on the horizontal reinforcements in two of the tests.
- Due to a lack of information where the splices in the specimens were located, their influence on the behaviour was left out of this study.
- To determine the corrosion level, the weight loss method was used to measure the remaining weight of the cleaned reinforcement bars from a few specimens.

Due to the limited number of samples and lack of information on the original reference steel bars, the corrosion levels measured are not considered reliable before a representative number of samples have been studied.

- It would be beneficial to compare the test results from this study to the results of other researchers; however, to the author's knowledge, no other anchorage tests on naturally corroded field specimens exist in the literature. Comparisons to artificially corroded specimens are also limited to a few relevant tests which will be expanded in future studies.

1.5 Original features

The new features of this study are summarised as follows:

- Experiments of naturally corroded specimens from the field were carried out; more specifically, bond and anchorage behaviour of naturally corroded ribbed bars were studied in two test series.
- A database on reinforced concrete beams exposed to a naturally corrosive environment was generated.
- The anchorage capacities of the tested specimens exposed to a naturally corrosive environment were compared with selected artificially corroded test specimens from literature.

1.6 Outline

The thesis consists of an introductory part and two appended papers. The introductory part provides a background on the subject treated in the papers. In *Chapter 1*, the aim, objectives and limitations of the study together with a general description of its scientific methods and original features are provided. *Chapter 2* presents a general background on the mechanisms of corrosion damage and on bond behaviour of corroded structures. In *Chapter 3*, the experimental work carried out in this project is briefly described; for more details, see *Papers I* and *II*. Conclusions and suggestions for future research are outlined in *Chapter 4*.

2 Load-carrying capacity of corroded RC structures

2.1 Mechanism of corrosion damage

Many environmental factors can influence the durability of reinforced concrete. Corrosive agents, e.g. de-icing or seawater salts, are the most common causes of deterioration in RC structures. The embedded reinforcement is initially in a passive state and the intact concrete surrounding is its best protective medium. The steel passivity can, however, be broken down by a loss of alkalinity due to chloride attack or carbonation of concrete; this phenomenon leads to an increased vulnerability of steel reinforcement to corrosion (Domone et al., 2010).

Corrosion causes damage both to steel reinforcement and surrounding concrete. When corrosion takes place, corroded bars lose their regular round shape (Du et al., 2005a; Du et al., 2005b) and ribs of deformed bars will eventually diminish (CEB-fib, 2000). The physicochemical reaction of corrosion leads to major changes in RC members. For instance, corrosion of steel bars produces rust materials which occupy a larger volume in comparison to the original steel. The volume expansion thereby creates splitting stresses acting on the concrete which leads to cracking. Consequently, the cracks result in spalling of the concrete cover. Ultimately, such damage may intensify the corrosion rate. Meanwhile, the cross sectional area of the reinforcement bars reduce. Cover cracking and spalling affect the bond mechanism, i.e. the interaction between the steel reinforcement and the surrounding concrete, see (Lundgren, 2005). Corrosion mechanism and its consequences have been demonstrated by Cairns et al. (1999) as seen in Figure 1. Due to effects on the bond mechanism, the load-carrying capacity and the ductility in the ultimate state (Zandi Hanjari et al., 2011; Coronelli et al., 2004), as well as the stiffness distribution and deflection in the service state (Val et al., 2009), may be influenced. The mechanical properties of corroded bars and the influence on the bond mechanism are discussed in the following sections.

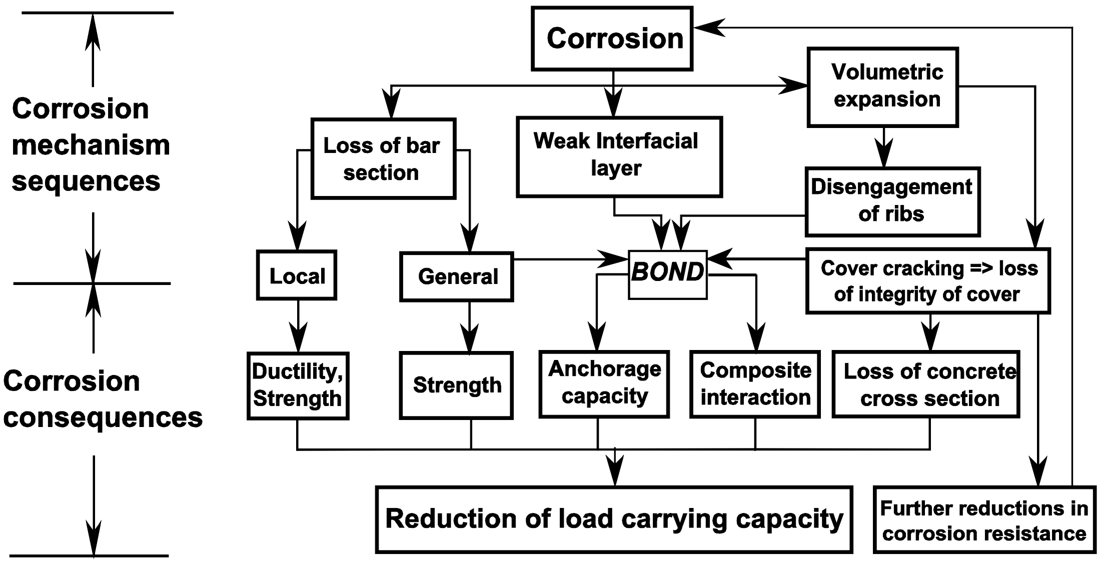

Figure 1. Mechanism sequences and consequences of corrosion on reinforcements, reproduced from (Cairns et al., 1999).

2.2 Mechanical properties of corroded steel bars

The effects of corrosion on the mechanical properties of reinforcement have been studied by many researchers. According to CEB-fib (2000), corrosion may be classified into two categories: general and local. General corrosion occurs when the corrosion is uniformly distributed along the reinforcement, whereas localized corrosion forms local pits.

Pitting corrosion is invariably associated with chloride contamination, while carbonation is commonly claimed to cause general corrosion (CEB-fib, 2000). In the case of pitting, the ultimate strain and ductility are severely reduced by corrosion. It is sufficient with only 10 % of non-uniform corrosion to reduce the ductility of bars embedded in the concrete to below the minimum requirement specified in design codes for use in high ductility situations (Du et al., 2005a). However, steel parameters, such as the strength ratio and elastic modulus, are not significantly altered by the corrosion (Du et al., 2005b; Du et al., 2005a). Furthermore, Almusallam (2001) concluded that the stress-strain characteristics of corroded reinforcements indicate a decrease in the ductility with an increase in the corrosion level.

The overall effect of pitting corrosion on a reinforcement bar subjected to tension is the formation of large and localized strain. Since the length of pitting corrosion is short, about twice the bar diameter, the average strain on the entire bar becomes less than the strain on a local pit (Stewart et al., 2008), causing the corroded bars to fail at strains much lower than the ultimate strain of the original bar; thus, corrosion causes the reinforcement to behave in a brittle manner (Coronelli et al., 2004; Du et al., 2005a).

2.3 Bond between corroded reinforcement and concrete

Bond between reinforcement and concrete is the most important parameter providing the composite action in RC members. The load transfer is always achieved by means of transferring bond stresses in the interaction zone. Studies of the bonding forces for reinforcing bars indicated that bond is made up of three components: (1) chemical adhesion, (2) friction and (3) the mechanical interaction between concrete and steel (Lutz et al., 1967; Tepfers, 1979). Thus, bond strength initially originates from weak chemical bonds between steel and hardened cement; this resistance is, however, usually broken at low stress levels. The loss of chemical bond leads to the occurrence of radial micro cracks in the concrete, see Figure 2.

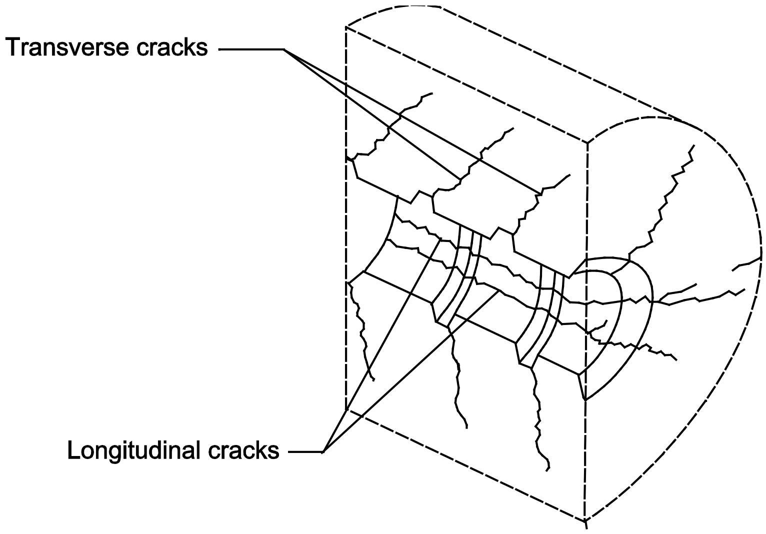

Figure 2. Longitudinal and transverse cracks caused by bond, as modified by Magnusson (2000) from Vanderwalle (1992)**.**

In the case of slipping, bond resistance acts in the form of friction, especially in plain bars. For ribbed bars, bond strength mainly comes initially from friction and thereafter from the mechanical interlock between ribs and the surrounding concrete. The bonding stress in ribbed bars can be divided into two directions, axial and normal bond stress along the reinforcement, see Figure 3. In general, bond characteristics are dependent on many parameters, including concrete strength, position and type of the main reinforcements, confinement by concrete cover and transverse reinforcement (CEB-fib, 2000).

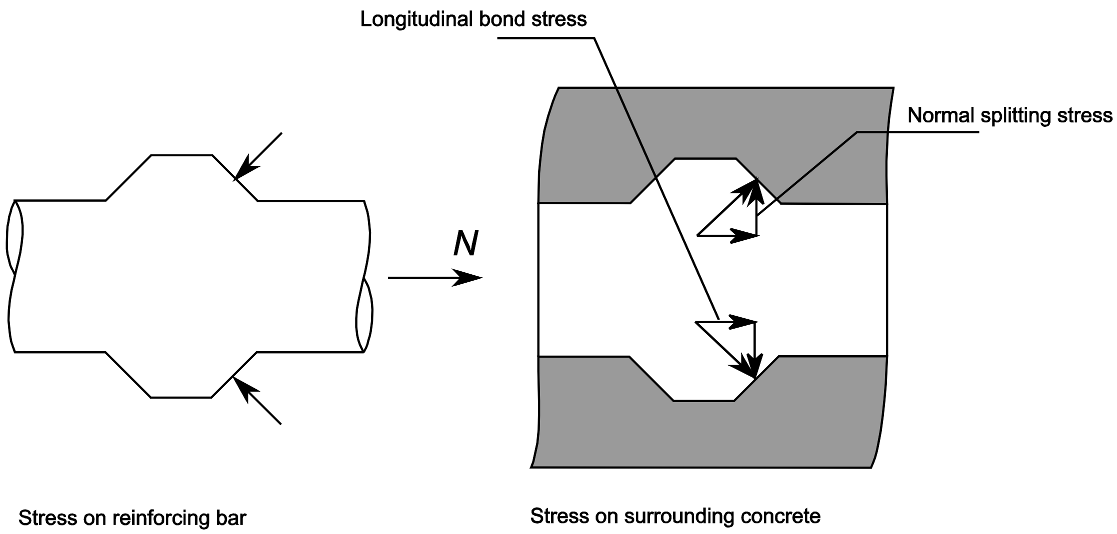

Figure 3. Bond between a ribbed bar and the surrounding concrete by mechanical interlocking, as modified from Magnusson (2000).

3 Experiments on load-carrying capacity of naturally corroded RC specimens

In this study, experiments were conducted to investigate the load-carrying capacity of existing naturally corroded specimens. The aim was to better understand the effects of natural corrosion on cracking and bond strength in the anchorage regions. The structural behaviour of corrosion-induced damage in the form of corrosion-induced cracking and cover spalling were studied. The experiments were carried out in two test series:

- First test series comprised eight specimens from the southern edge beams of the Stallbacka Bridge. The results from the structural tests, corrosion level measurements and concrete and steel material tests were evaluated and presented in detail in *Paper I*.
- Second test series consisted of thirteen tests of naturally corroded reinforcements from the northern edge beams of the same bridge. The test results were evaluated and compared with some artificially corroded specimens from the literature (*Paper II*).

3.1 Test specimens and test set-up design

A total of 21 naturally corroded test specimens were taken from the edge beams of the Stallbacka Bridge. The specimens revealed different extent of corrosion-induced damage; as such, a simple classification system was introduced based on the visible surface damage, see Figure 4. The classification consisted of three classes of damage: Reference, with no visible surface cracking; Medium damaged with splitting cracks but no spalling; and Highly damaged with both cracking and spalling of the concrete cover. All damage was thoroughly documented in the laboratory for all specimens and as for the second test series, documentation was additionally executed at the bridge site.

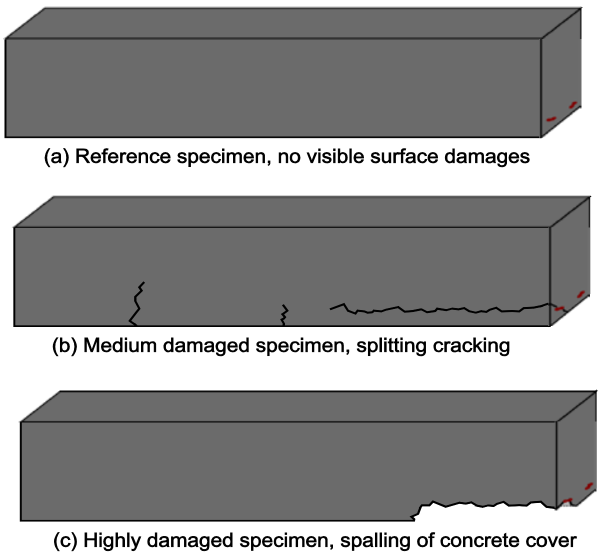

Figure 4. Categorization of the specimens based on different extents of corrosion induced

damage.

The test configuration was designed to ensure anchorage failure for beams with various corrosion damage levels; details are given in *Paper I* and in Berg et al. (2011). After a consideration of various potential test set-ups, a four-point bending test with indirect suspension hanger supports was selected similar to the test used by Magnusson (2000), as illustrated in Figure 5. The test set-up was considered to be the best choice having the least interference with the natural damage of the specimens and without any lateral pressure from the supports in the anchorage zones. The test set-up designed was used in both test series. However, in the second test series, some minor modifications were made to the support and end-slip measurement systems. More details of specimen specifications, test-set-up design and improvements are provided in *Papers I* and *II*.

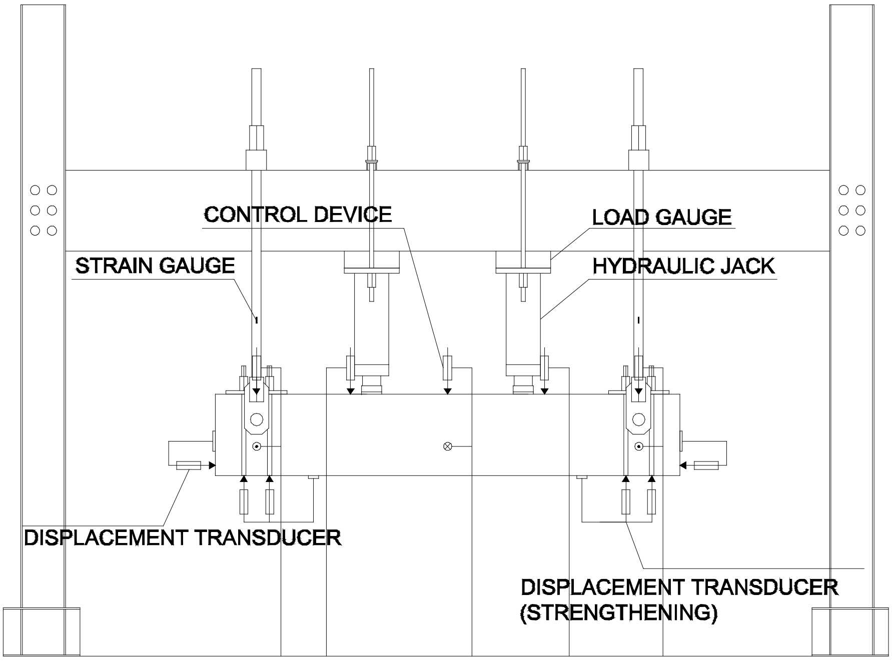

Figure 5. Four-point bending test with indirect supports.

3.2 Results

In this section, an overview of the study and a summary of experimental results are provided. The experiments were successfully executed in both test series such that comparable results were obtained. All 21 specimens showed similar behaviour in terms of crack development and failure mode. A splitting-induced pull-out became the failure mode in all tests. In both test series, the damaged specimens showed around 5 to 10 % lower load-carrying capacity compared with the undamaged ones; this value was 10 % for the first and 5 % for the second test series. The concrete compressive strength, f_c, in damaged specimens was slightly lower compared with that in the Reference specimens; the samples from damaged specimens showed a 10 to 15 % reduction in strength (refer to *Paper II*). An example of the results for one of the

Highly damaged tests, specimen H7, is depicted in Figure 6. In this case, the first shear cracks appeared at the 125 kN load level. By further increasing the load, the bond between the reinforcement and the concrete was activated in the anchorage zones and the end slips gradually increased from a load level of 150 kN. When the failure load was approaching, splitting cracks occurred around the main bars on the side of the beam which later failed. It can be noted that the bars in one bundle generally slipped together and in some tests, there were some differences between the two bundles; see Figure 6(b). The main bundled bars on the side featuring cover spalling in specimen H7 (bars 15 and 16) showed a more brittle failure, while the post-peak slips of bars 13 and 14 on the side with only splitting cracks were quite large, see Figure 7.

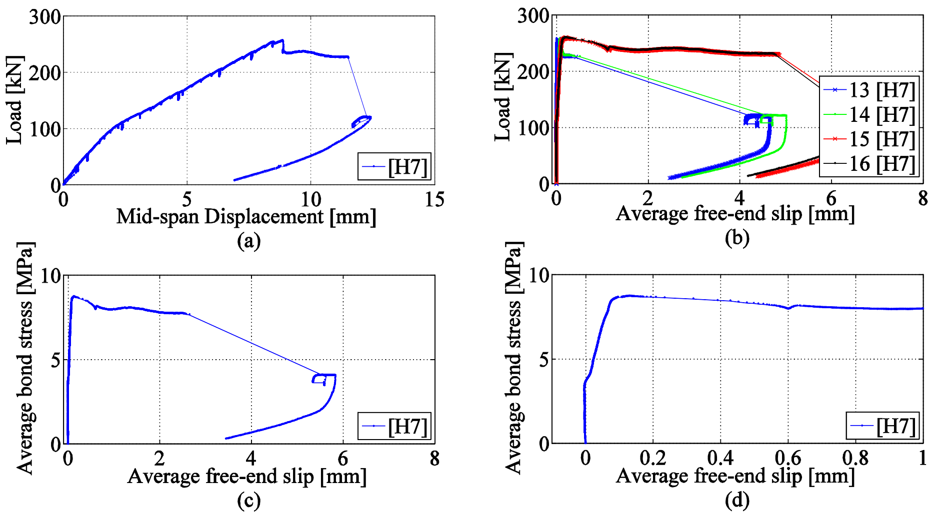

Figure 6. Overview of results from test H7: (a) Average load in the hydraulic jacks versus deflection at mid-span; (b) Average load from the hydraulic jacks versus the end slips in each of the bundled bars; (c) Average bond stress versus average free-end slip; (d) Enlarged figure of (c).

The average bond stress along the bundled bars was calculated based on the applied load, the measured available anchorage length and the circumference of the bundled bars. It should be mentioned that the available anchorage length was considered to be the average of the available anchorage length measured for the back and front sides of the failed region of the beams. The available anchorage length was almost constant with an average value of 300 mm in the first test series whereas it varied between 250 to 500 mm in the second test series. The free-end slips of the two bundled bars were quite similar up to the maximum failure load. Therefore, the calculated average bond stress versus the measured average free-end slip was found to be a representative comparison; see Figure 6(c and d).

(a) (b)

Figure 7. (a) Spalling along the main bundled bars 15 and 16 in beam H7. (b) Splitting-induced crack failure on the front-side in beam H7.

In two of the Highly damaged tests, namely H6 and H7, it was possible to make direct measurements of the strains in the longitudinal reinforcement bars due to spalling of the concrete cover; thus, the main bars were exposed prior to structural testing. Figure 8 and Figure 9 show the steel stress evaluated based on the measured strains along one of the bundled bars (bar 16 in test H7) in the anchorage zone, assuming a Young's modulus of 200 GPa. As seen from the figures, the stresses increased to maximum values of 500 and 434 MPa along the bundled bars at the maximum applied loads for specimens H6 and H7, respectively. It may be noted that the bond stress was considered to be constant in *Papers I* and *II* evaluations; however, as seen in Figure 8 and 9, the steel stresses did not increase linearly.

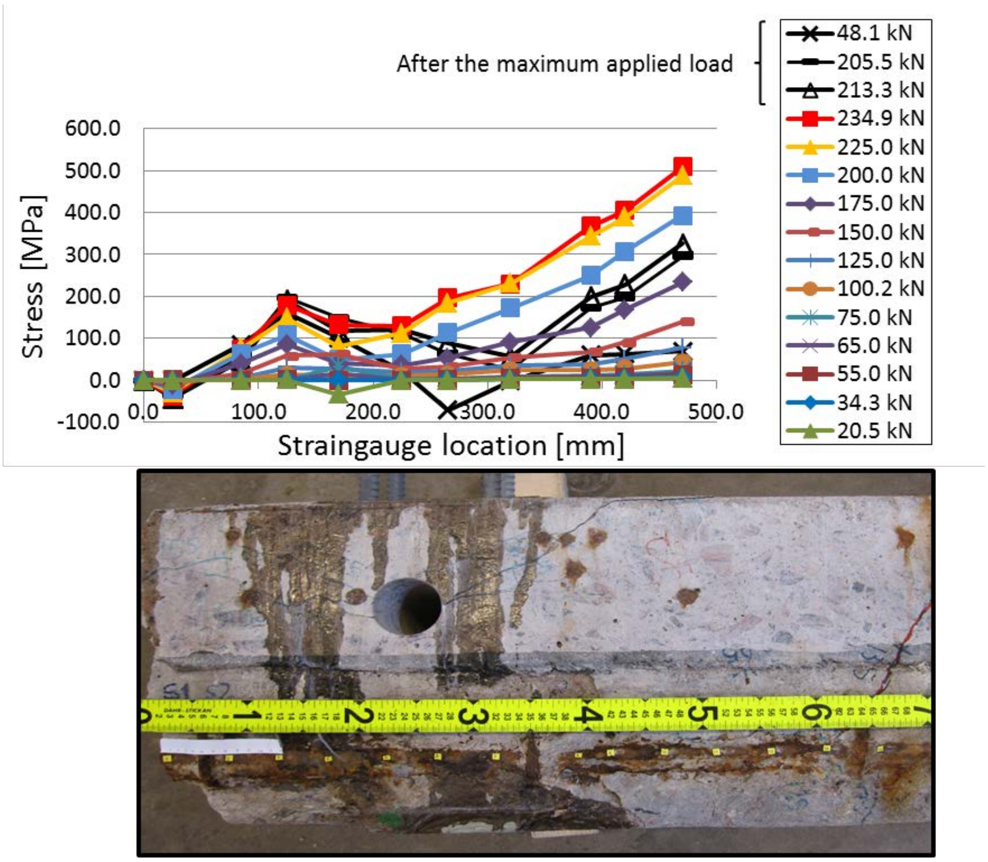

Figure 8. Measured strains on a longitudinal bar in specimen (H6) and the distribution of stresses in different load increments in the anchorage zone.

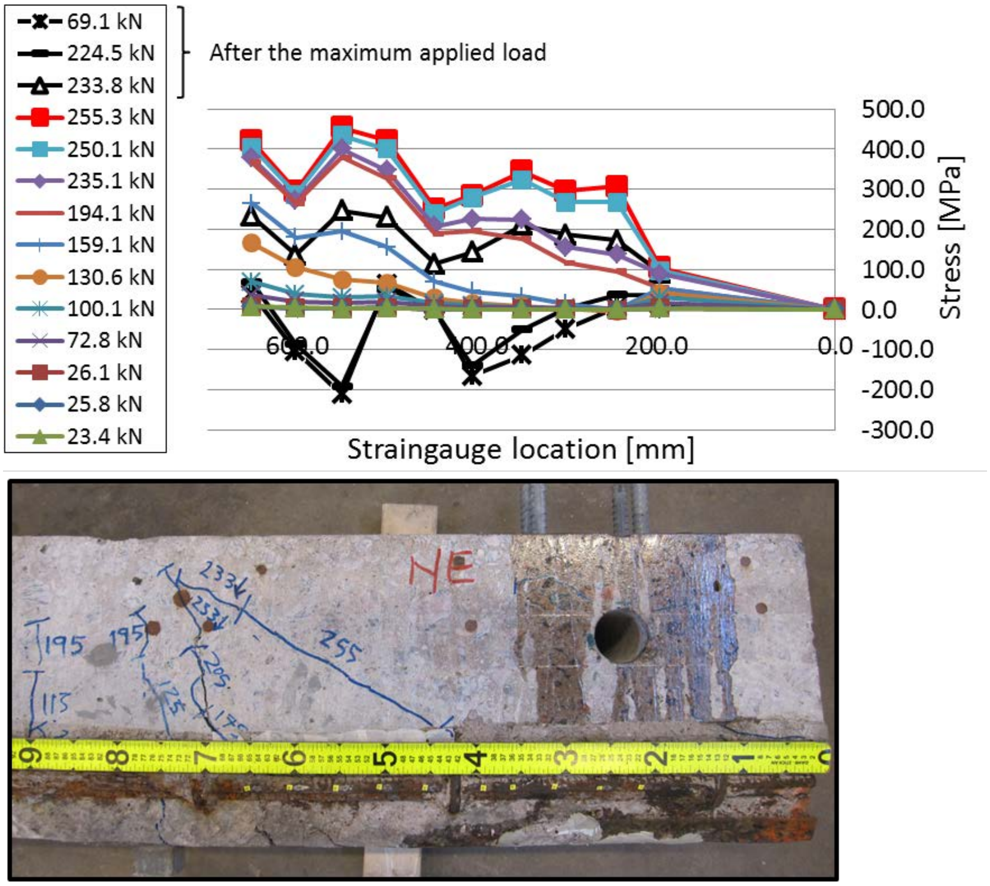

Figure 9. Measured strains on a longitudinal bar in specimen (H7) and the distribution of stresses in different load increments in the anchorage zone.

The calculated average bond stress in the anchorage zone was about 16 to 17 % lower in the beams with corrosion cracks compared with the Reference specimens, whereas it was 9 to 13 % lower in the beams with cover spalling; more information is provided in *Papers I and II*.

A comparison of beams within each category revealed that the specimens with relatively lower stiffness in the load versus deformation graphs had a more stable increase of slip just before the maximum load, as well as slightly larger slips at post-peak behaviour. For instance, Figure 10 shows that in specimens H6 and H7, the post-peak behaviour was more stable with slip values increasing up to 2.5 mm. For Specimen H5, in which failure took place on the side without cover-spalling, the anchorage of the main bars failed in a more brittle way.

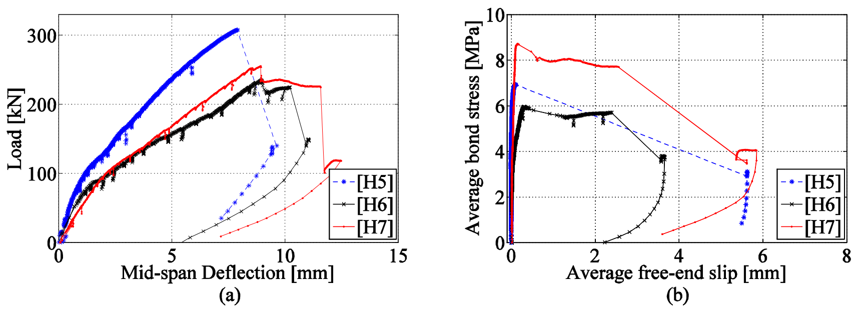

Figure 10. (a) Average load in the hydraulic jacks versus deflection at mid-span. (b) Average bond stress versus the average free-end slip for the Highly damaged specimens.

3.3 Comparison to other experimental work

In this study, the damage observed was correlated to the bond strength of the test specimens. The crack widths were measured in each specimen before the structural testing. For the Medium damaged specimens, the anchorage failure occurred on the side where the widest splitting crack was located. These values were plotted against the maximum average bond stress normalized according to the average value of the Reference specimens, see Figure 11. The results indicated a decreasing bond capacity with increasing crack width. The results of this study were compared with tests of artificially corroded specimens carried out by Zandi Hanjari et al. (2010); Coronelli et al. (2011). The comparison indicates that naturally corroded specimens from this study are different than the artificially corroded specimens. Accordingly, the bond strength of the naturally corroded bars was considerably higher than that of the artificially corroded specimens. It was also observed that the residual bond capacities of the naturally corroded specimens were higher than the limits given in the Fib Model Code (2010). Lastly, the scatter in measured crack widths of the naturally corroded specimens was larger in comparison with that of the artificially corroded specimens.

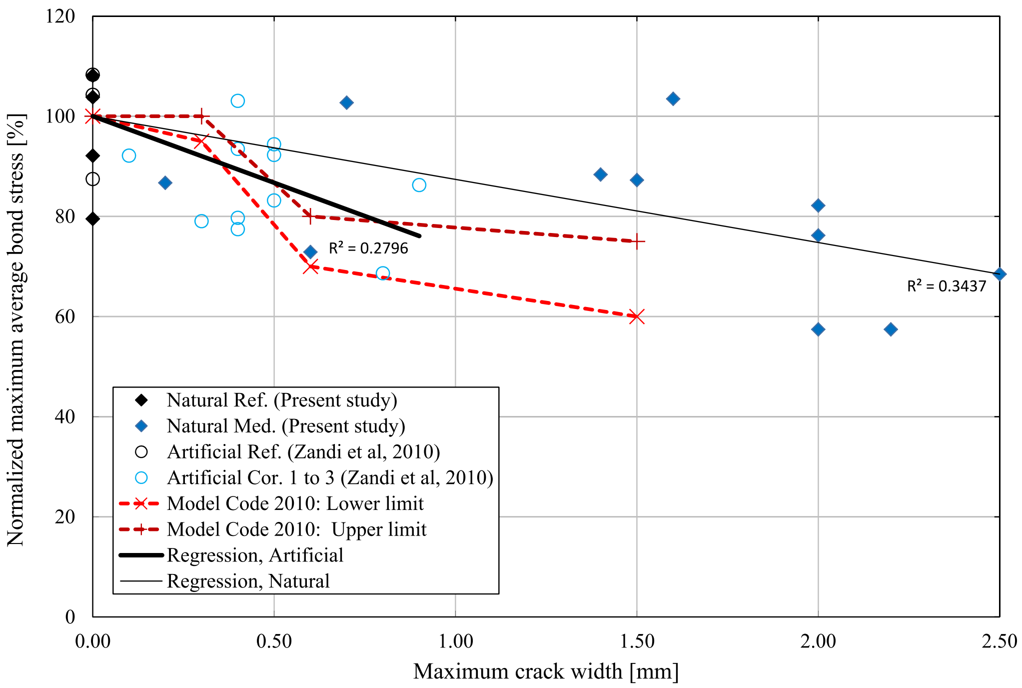

Figure 11. Comparison of test results from the naturally corroded specimens with artificially corroded tests and with Model Code 2010 in terms of bond strength, normalized with respect to the average maximum bond strength obtained from reference samples, versus maximum crack width of splitting cracks.

The experimental studies selected for comparison slightly differed in terms of corrosion environment. For instance, the corrosion rate for the specimens taken from field was much lower than that of the artificially corroded specimens. The rate was estimated to be an average value of approximately 4.0 $\mu A/cm^2$ for the naturally corroded specimens. This value was estimated based on an average 3% weight loss of the reinforcements during 30 years of exposure to a corrosive environment (*Paper I*), whereby the steel corrosion-rate conversion factor given in Roberge (2008) was included. This estimated value is reasonable as it can be compared with natural corrosion rates of 10-25 µA/cm^2 in chloride contaminated concrete structures from field measurements, see CEB-fib (2000). Conversely, the corrosion rate was much higher in the artificially corroded tests, around 100 µA/cm^2, see Table 1.

The geometrical parameters of the specimens in the two tests also differed as well as the test methods, e.g. the cover thickness was constant in the artificially corroded specimens whereas it varied in the naturally corroded specimens. In the artificial corrosion tests, either the middle bar or the two corner bars of the specimens were pulled out in an eccentric pull-out test set-up whereas for the naturally corroded specimens; two bundles were pulled out simultaneously in a bending test configuration.

The measured available anchorage length in naturally corroded specimens varied between 250 to 500 mm whereas in the accelerated-corrosion tests, this parameter was fixed to a value of 210 mm. Furthermore, the artificially corroded specimens had a higher amount of stirrups. In spite of these differences, higher bond stresses were obtained in the naturally corroded tests than in the artificially corroded specimens for the same crack width. Additional comparisons of the corrosion conditions, specimen dimensions and material properties of the naturally and artificially corroded tests are provided in Tables 1 to 3.

Table 1. Comparison of the test conditions and corrosion exposure in natural tests of the Stallbacka Bridge and artificially corroded tests from the literature.

Specimens	**Test type**	**Initiation of exposure to corrosive agents**	**Duration of corrosion**	**Corrosion rate**
Naturally Corroded (Stallbacka Bridge test samples)	Indirect four-point bending	Unknown	Maximum 30 years	~4.0 µA/cm^2 (appr. 3% weight loss in maximum 30 years)
Artificially Corroded (Zandi Hanjari et al., 2010)	Eccentric pull-out on beam-end specimens	After 28 days (3% of sodium chloride was mixed into concrete)	Up to 10 months	100 µA/cm^2

Table 2. Comparison of dimensions and material properties in naturally corroded specimens of the Stallbacka Bridge and artificially corroded specimens from literature (more details in *Papers I* and *II*).

Specimens	**Specimen dimensions**		**Anchorage length**	**Concrete cover**	**Concrete properties**		
	h (mm)	**b (mm)**	**l_a (mm)**	**c (mm)**	**f_c (MPa)**	**f_t (MPa)**	**E_c (GPa)**
Naturally Corroded (Stallbacka Bridge test samples)	400	350	250-500	30-70	32-62	3.04-4.09	17.3-27.7
Artificially Corroded (Zandi Hanjari et al., 2010)	400	400	210	30	34-38	Not evaluated	Not evaluated

Table 3. Comparison of the steel reinforcement dimensions and material properties in naturally corroded specimens of Stallbacka Bridge and artificially corroded specimens from literature.

Specimens	**Stirrups in the anchorage zone**	**Longitudinal bar diameter (mm)**	**Number of bars in each bundle**	**Steel class**
Naturally Corroded (Stallbacka Bridge test samples)	∅10 mm @ 300 mm	16	2	Main bars: KS 60 Stirrups: KS 40
Artificially Corroded (Zandi Hanjari et al., 2010)	4∅8 mm @ 48 mm	20	-	500 MPa

The bond strength at cracking ranges between 50 to 120 % for ‘high’ and ‘low’ artificial corrosion rates respectively based on the non-corroded specimen strength according to CEB-fib (2000). For the naturally corroded tests, the normalized residual bond strength ranges from 57 to 103 % for Medium damaged specimens based on the average bond strength for Reference specimens.

The crack width that may lead to cover spalling can be related to given structural parameters, e.g. the cover-to-bar diameter or the position of the bar. Some researchers report crack widths in excess of 0.6 mm without spalling, whereas Rodriguez et al. (1994) observed that the concrete cover did not spall even where the cracks reached 2 mm in width. In the naturally corroded specimens from Stallbacka Bridge, it was observed that splitting cracks widened up to a width of 2.5 mm with no signs of concrete cover spalling. Nevertheless, the structural integrity between reinforcement and concrete can be severely damaged even prior to spalling of the concrete cover (CEB-fib, 2000).

4 Conclusions

4.1 General conclusions

An experimental study of the mechanical behaviour of concrete structures with naturally corroded bars was carried out, investigating different levels of corrosion damage, e.g. cracking and cover spalling of concrete. The results were compared with artificially corroded tests from literature as well as the provisions in Model Code 2010. Based on the outcome of the study, the following conclusions were drawn:

- A database containing the results obtained from the naturally corroded specimens was created.
- The test set-up designed worked properly. Some minor modifications were made in the second test series based on the experience gained from the results of the first test series. Improvements were made to both documentation of the damage on the bridge and measurements of the support settlements and end-slips.
- In all experiments, the same failure mode, splitting induced pull-out failure, occurred after the occurrence of diagonal shear cracks.
- The test results showed 5 to 10 % reduction in load-carrying capacity for the damaged specimens in comparison with the Reference specimens.
- Material tests on concrete showed that the damaged specimens had a slightly lower compressive strength, approximately 15 %, compared with the Reference specimens.
- The calculated average bond stress in the anchorage zone indicated that the Medium damaged specimens with only spalling cracks had capacities of approximately the same magnitude as the Highly damaged samples with cover spalling, whereas, this value was about 9 to 17 % lower in comparison with the average of the Reference specimens.
- The specimens with relatively lower bending stiffness showed a more ductile bond failure of the main bars.
- The results indicated that the average bond strength of the naturally corroded bars was related to the maximum crack widths observed. A comparison of these results against the artificially corroded specimens and the limits given in the Fib Model Code, 2010 indicated that the naturally corroded tests had higher bond strength.

4.2 Suggestions for future research

The following steps are suggested for future research:

- Comparison of the results obtained from naturally corroded samples against more accelerated induced corrosion test results. Attempt to correlate the results with the current densities used in artificial corrosion tests.
- Measurement of the corrosion level in the samples tested; the reinforcement can be taken out and the weight loss method or volumetric 3D-scanning measurement method can be applied. Thereafter, other destructive tests, e.g. tensile strength testing can be carried out on the corroded bars.
- Evaluation of the experimental data obtained from tests of natural corrosion with advanced methods using non-linear finite element tools in order to increase the

knowledge about mechanical characteristics of naturally corroded concrete structures and understand the origin of the difference between artificial and natural corrosion.

- Further calibration of the bond models developed by Lundgren (2005) and Zandi Hanjari et al. (2013). In this way, the effects of relevant parameters such as cover, concrete strength, etc. on the mechanical behaviour of naturally corroded RC structures could be studied.
- Develop a simplified method to estimate the required anchorage length of naturally corroded reinforcement in order to estimate whether sufficient anchorage capacity exist in corroded structures. The method could be applied in assessments of the residual load-carrying capacity of corroded structures.
- Because of the lack of data on naturally corroded reinforcement in concrete structures, it would be wise to plan experiments on full-scale specimens exposed to natural corrosive environments in order to clarify the corrosion effects in natural conditions and to study the difference between natural corrosion and accelerated corrosion.
- Carry out additional experiments on naturally corroded reinforcement bars taken from real-life damaged structures to expand the database created in this work. This database would lead to a more accurate assessment of the load-carrying capacity of damaged structures and increase possibilities to estimating the remaining life of such structures.

5 References

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