COIN

www.coinweb.no

SINTEF Building and Infrastructure Gro Markeset

Stainless steel reinforcement in concrete structures - State of the art

COIN Project report 4 - 2008

SINTEF

SINTEF Building and Infrastructure

Gro Markeset

Stainless steel reinforcement in concrete structures - State of the art

COIN P4 Operational service life design

SP 4.5 F Preventive measures

COIN Project report 4 – 2008

COIN Project report no 4
Gro Markeset
Stainless steel reinforcement in concrete structures - State of the art
COIN P4 Operational service life design
SP 4.5 F Preventive measures

Keywords:
Materials technology, Concrete, Stainless steel, Reinforcement, Durability

ISSN 1891-1978 (online)
ISBN 978-82-536-1074-0 (printed)
ISBN 978-82-536-1079-5 (pdf)

20 copies printed by AIT AS e-dit

Content: 100 g Scandia
Cover: 240 g Trucard

Address: Forskningsveien 3 B
POBox 124 Blindern
N-0314 OSLO
Tel: +47 22 96 55 55
Fax: +47 22 69 94 38 and 22 96 55 08

www.sintef.no/byggforsk
www.coinweb.no

Cooperation partners / Consortium Concrete Innovation Centre (COIN)

Aker Solutions
Contact: Jan-Diederik Advocaat
Email: jan-diederik.advocaat@akersolutions.com
Tel: +47 67595050

Borregaard Ligno Tech
Contact: Kåre Reknes
Email: kare.reknes@borregaard.com
Tel: +47 69118000

maxit Group AB
Contact: Geir Norden
Email: geir.norden@maxit.no
Tel: +47 22887700

Norcem AS
Contact: Terje Rønning
Email: terje.ronning@norcem.no
Tel: +47 35572000

NTNU
Contact: Terje Kanstad
Email: terje.kanstad@ntnu.no
Tel: +47 73594700

Rescon Mapei AS
Contact: Trond Hagerud
Email: trond.hagerud@resconmapei.no
Tel: +47 69972000

SINTEF Building and Infrastructure
Contact: Tor Arne Hammer
Email: tor.hammer@sintef.no
Tel: +47 73596856

Skanska Norge AS
Contact: Sverre Smeplass
Email: sverre.smeplass@skanska.no
Tel: +47 40013660

Spenncon AS
Contact: Ingrid Dahl Hovland
Email: ingrid.dahl.hovland@spenncon.no
Tel: +47 67573900

Norwegian Public Roads Administration
Contact: Kjersti K. Dunham
Email: kjersti.kvalheim.dunham@vegvesen.no
Tel: +47 22073940

Unicon AS
Contact: Stein Tosterud
Email: stto@unicon.no
Tel: +47 22309035

Veidekke Entreprenør ASA
Contact: Christine Hauck
Email: christine.hauck@veidekke.no
Tel: +47 21055000

Summary

Premature deterioration of concrete buildings and infrastructure due to corrosion of reinforcement is a severe challenge, both technically and economically. In recent years there has been an increasing interest in applying stainless steel reinforcement in concrete structures to combat the durability problems associated with chloride ingress.

This state-of-the-art report gives a brief overview of mechanical as well as corrosion properties of different types of stainless steel reinforcement. The review includes also a discussion of practical and economical application of stainless steel reinforcement in concrete structures. It may be concluded that designing structures with stainless steel reinforcement may in principle be performed by a simple replacement of ordinary carbon steel reinforcement with stainless steel reinforcement in the ratio 1:1 as the structural properties are about the same regarding strength and ductility. Stainless steel reinforcement can be combined with carbon steel cast into concrete with minimal risks of galvanic corrosion due to bi-metal - or galvanic - action. In fact, this is the precondition for general economical application of stainless steel reinforcement used only in the parts of the structure where this protection is needed, - so-called selective use.

Oslo, 2008

Tor Arne Hammer
Centre Manager

Gro Markeset

Foreword

COIN - Concrete Innovation Centre - is one of presently 14 Centres for Research based Innovation (CRI), which is an initiative by the Research Council of Norway. The main objective for the CRIs is to enhance the capability of the business sector to innovate by focusing on long-term research based on forging close alliances between research-intensive enterprises and prominent research groups.

The vision of COIN is creation of more attractive concrete buildings and constructions. Attractiveness implies aesthetics, functionality, sustainability, energy efficiency, indoor climate, industrialized construction, improved work environment, and cost efficiency during the whole service life. The primary goal is to fulfill this vision by bringing the development a major leap forward by more fundamental understanding of the mechanisms in order to develop advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.

The corporate partners are leading multinational companies in the cement and building industry and the aim of COIN is to increase their value creation and strengthen their research activities in Norway. Our over-all ambition is to establish COIN as the display window for concrete innovation in Europe.

About 25 researchers from SINTEF (host), the Norwegian University of Science and Technology - NTNU (research partner) and industry partners, 15 - 20 PhD-students, 5 - 10 MSc-students every year and a number of international guest researchers, work on presently 5 projects:

- Advanced cementing materials and admixtures
- Improved construction techniques
- Innovative construction concepts
- Operational service life design
- Energy efficiency and comfort of concrete structures

COIN has presently a budget of NOK 200 mill over 8 years (from 2007), and is financed by the Research Council of Norway (approx. 40 %), industrial partners (approx 45 %) and by SINTEF Building and Infrastructure and NTNU (in all approx 15 %). The present industrial partners are:

Aker Kværner Engineering and Technology, Borregaard LignoTech, maxitGroup, Norcem A.S, Norwegian Public Roads Administration, Rescon Mapei AS, Spenncon AS, Unicon AS and Veidekke ASA.

For more information, see www.coinweb.no

TABLE OF CONTENTS

1 Introduction

1.1 Background

Premature deterioration of concrete buildings and infrastructure due to corrosion of reinforcement is a severe challenge, both technically and economically. Repair-work on the public transportation infrastructure are causing significant inconveniences and delays for both the industry and the general public, and are now recognized as a substantial cost for the society.

The main sources of chloride ingress stems from seawater splash (on marine based structures) as well as from de-icing salts (on roads, bridges, parking decks and on external staircases and access balconies in large condominiums).

Carbon steel reinforcement embedded in concrete will not normally corrode due to the formation of a protective ion-oxide film, which passivates the steel in the strong alkaline conditions of the concrete pore water. However, this passivity may be destroyed by chlorides penetrating through the concrete, or due to carbonation, reaching the surface of the reinforcement. Corrosion, which is an electrochemical process involving establishment of corroding and passive sites on the steel surface, may then be initiated.

As a result of corrosion reaction, rust forms and occupies a volume several times that of the original metal, hence generating bursting forces. These forces might exceed the tensile strength of concrete, causing cracking and spalling of the concrete leading to further corrosion and loss of bond between the concrete and the steel. Hazardous situations might occur when pieces of spalled concrete fall and threaten the user or passer-by, or when the structural member looses cross-sectional area and thereby experiences increased stress on the remaining section, which potentially could lead to structural failure.

In recent years there has been an increasing interest in applying stainless steel reinforcement in concrete structures to combat the durability problems associated with chloride ingress. However, the use of stainless steel reinforcement (SSR) has so far been limited mainly due to high costs and lack of design guides and standards.

1.2 Classification and chemical composition of stainless steel

Stainless steels are a numerous family of material with wide variety of characteristics with regards to physical and mechanical properties, cost and resistance to corrosive environment. As a class, they are steels that contain a minimum of about 12.0 % chromium /1/. Chromium is the main alloy which provides the steel with improved corrosion resistance. This improved corrosion resistance can be seen in *Figure 1-1 /2/*.

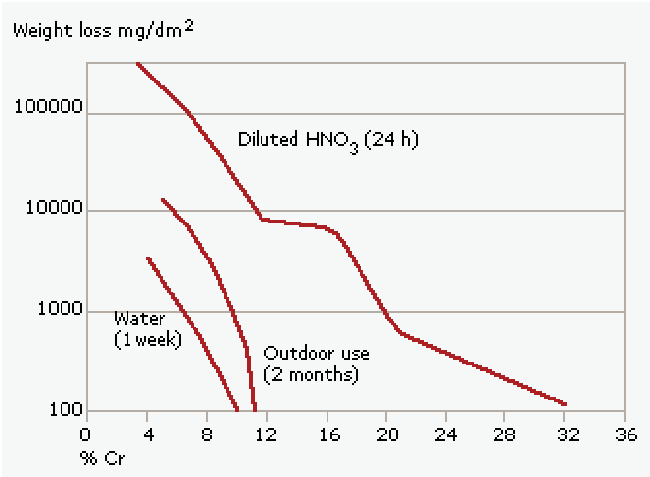

Figure 1-1: Influence of chromium on the corrosion resistance of stainless steel /2/

The improved corrosion resistance is due to a thin chromium oxide film that is formed on the steel surface and creates a so-called passive condition. It is important to realise that oxygen is required for the oxide film to form. The passivity is a dynamic process which is influenced by the surrounding environment, and especially temperature and humidity. The extremely thin chromium oxide film is also self-repairing under the right conditions, which includes presence of oxygen /3/, /4/.

Besides chromium, typical alloying elements are molybdenum, nickel and nitrogen. Nickel is mostly alloyed to improve the formability and ductility of stainless steel. Alloying these elements brings out different crystal structures to enable different properties of the steel for machining, forming, welding etc. /5/, /6/.

Stainless steels can be divided into four categories, based on their microstructure:

- Martensitic
- Ferritic
- Austenitic
- Austenitic-Ferritic (duplex)

Only austenitic and duplex stainless steels are normally used as reinforcement in concrete structures.

Austenitic stainless steel is the most widely used type of stainless steel /7/. It has a nickel content of at least 7%, which makes the steel structure fully austenitic and gives it ductility, a large scale of service temperature, non-magnetic properties and good weldability. The range of applications of austenitic stainless steel includes house wares, containers, industrial piping and vessels, architectural facades and constructional structures. Currently such steels are rated in the higher range of corrosion resistance for reinforcement.

Austenitic-Ferritic (Duplex) stainless steel has a combined ferritic and austenitic lattice structure - hence the common name: duplex stainless steel. This steel has some nickel content for a partially austenitic lattice structure. The duplex structure delivers both strength and ductility. Duplex steels are mostly used in petrochemical-, paper-, pulp- and shipbuilding industries. Changing price levels of some of the key alloying elements may at times result in duplex steels being cost effective compared to austenitic steels. Currently such steels are rated in the very high range of corrosion resistance.

The high costs of the traditional stainless steels - originally developed to solve corrosion problem in other areas that in reinforced concrete structures - have during the past few years made the stainless steel producers to search for methods of producing a robust stainless steel which does not suffer so much from price volatility of the key alloying components. This has in particular led to new products with much reduced nickel content and possibly also low molybdenum content, so-called low-nickel duplex types (**Lean Duplex)**, but with sufficient nickel content to maintain the highly corrosion resistant austenitic-ferritic crystal structure. Though none of these products are in large scale running production yet (2006) they seem to have very interesting both corrosion resistance and mechanical properties /8/.

Traditionally stainless steels have been classified according to one of the following systems, /5/ /6/:

- The American Iron and Steel Institute (AISI) in which ferritic and martensitic steels are classified, as 400 series alloys i.e. 403 would represent ferritic steel. The austenitic steels are classified as 300 series alloy i.e. 304 or 316. Other than identifying the generic group type these steel grades provided no other information regarding chemical composition or physical and mechanical properties. Traditionally UK standards, such as BS 9705 /9/ and BS 6744 /10/ etc. have followed the AISI classification with the addition of "S" sub-grades such as Grade 316S33. However, UK standards are being replaced with European standards and those relevant to stainless steel will adopt the current European classification for steels discussed below.
- The German or DIN classification based on the concept of a material number such as 1.44xx.
- The French classification based on a unique material number for a given steel i.e. X18Cr8Ni3Mo would be an austenitic stainless steel with a nominal alloy composition of 18% chromium, 8% nickel and 3% molybdenum. Although a somewhat cumbersome designation this classification has the advantage of providing nominal compositions for each type of steel.

In 1995 a new European standard EN 10088-1 /11/ was issued that provided a uniform method of classification for stainless steels. In effect the standard adopted both the German and French systems. Thus every stainless steel now has a generic number that identifies its grouping and an individual material number referred to as its name giving the nominal alloy composition.

The designation system can be understood for the following example of a stainless steel classified as:

- Material number: 1.4436
- Material name: X3CrNiMo 17-13-3

The material number has the following components:

- 1 Denotes a steel
- 44 Denotes one group of stainless steels
- 36 The individual material identification

The material name has the following components:

- x Denotes a high alloy steel

- 3 Represents 100 times the carbon content (in this case 0.03%), CrNiMo chemical symbols of the main alloying elements 17-13-3 represents the nominal percentage of the main alloying elements.

Additional chemical symbols, for example N for Nitrogen, represent minor but significant alloying elements. The influence of Nitrogen on the corrosion resistance has not been included in the material name. This designation system appears to be more cumbersome than the AISI one it is intended to replace. However, it is more logical and provides an understanding of the alloy composition and therefore material type within the classification.

The new European standards are currently being implemented and the use of this new classification will take over from the more traditional method. *Table 1-1* provides a comparison of the old and new methods of classification for common stainless steel grades and the corresponding pitting resistant equivalent number.

Increasing the level of alloying elements, especially chromium, nickel, nitrogen and molybdenum, will increase the corrosion resistance. However changing the balance of the alloying elements will influence the structure as well as the other properties. Therefore members of the stainless steel family are usually combined in groups having the same metallographic structure. The chemical compositions of the stainless steel grades given in *Table 1-1* are listed in *Table 1-2*.

Table 1-1: Classification of stainless steel according to international standards, and corresponding PREN values.

Steel Type	Steel grade		USA	Great Britain	Sweden	PREN-value
	EN 10088-1	Designation	AISI	BS	SS	
Austenitic	1.4301	X5CrNi 18-10	304	314S11/314S15	2332	19
Austenitic	1.4401	X5CrNiMo 17-12-2	316	316S33	2347	25
	1.4429	X2CrNiMoN 17-13-3	316LN	316S63	2375	26
	1.4436	X5CrNiMo 17-12-2	316		2343	26
	1.4571	X6CrNiMoTi 17-12-2	316Ti		2350	25
Ferritic-austenitic (lean duplex types)	1.4362	X2CrNiMo 23-4	-	-	-	24
Ferritic-austenitic (Duplex)	1.4462	X2CrNiMoN 22-5-3	-	318	2377	36

EN grades are given steel numbers in groups:
1.40xx for grades with < 2,5% Ni, without Mo, without special additions;
1.41xx for grades with < 2,5% Ni, with Mo, without special additions;
1.43xx for grades with • 2,5% Ni, without Mo, without special additions;
1.44xx for grades with • 2,5% Ni, with Mo, without special additions;
1.45xx and 1.46xx for grades with special additions, such as Ti, Nb or Cu

In order to compare stainless steel grades with different alloying, correlation of the influence of the different elements has been made resulting in the expression of pitting resistance equivalent number (**PREN**). This expression can be considered as a relative measure of the total resistance resources for the steel grade and thus as a comparable value for ranking the corrosion resistance against chloride pitting corrosion. The expression is calculated from the content of the alloying elements in the steel grade.

For austenitic steels the expression is:

PREN = %Chromium + 3.3 * %Molybdenum + 16 *%Nitrogen

For duplex steels the effect of nitrogen is considered higher resulting in the expression

PREN = %Chromium + 3.3 *%Molybdenum + 30 *%Nitrogen

The susceptibility to pitting corrosion increases with the decrease in PREN value. As the PREN values have been developed to represent the level of corrosion resistance of different grades of stainless steel directly exposed to a corrosive environment the values cannot be directly transferred to represent the absolute pitting corrosion resistance of stainless steel reinforcement cast into alkaline concrete. As reported by Bertolini and Pedeferri /12/ the effect of molybdenum on the resistance to pitting may be less important than in neutral environments and therefore the difference in behaviour between steels like 304 and 316 can be reduced. Further, under conditions of temperature common to hot climate, the nickel content may have a certain influence on the resistance to pitting corrosion /12/.

Summarizing, *Table 1-1* and *Table 1-2* show the composition of a range of stainless steels, which are available in a product form for use as reinforcement. The materials are arranged with increasing corrosion resistance represented by the PREN values in the tables.

Table 1-2: Chemical composition of stainless steel of relevance as reinforcement

Type	Steel grade		Chemical composition									
	EN 10088-1	Designation	C max	Si max	Mn max	P max	S max	Cr min/ max	Ni min/ max	Mo min/ max	N min/ max	Ti min/ max
Austenitic	1.4301	X5CrNi 18-10	0.07	1.0	2.0	0.045	0.03	17.5/ 19.5	8.0/ 10.50	-	max 0.11	-
Austenitic	1.4401	X5CrNiMo 17-12-2	0.07	1.0	2.0	0.045	0.03	16.5/ 18.5	10.0/ 13.0	2.00/ 2.50	max 0.11	-
	1.4429	X2CrNiMoN 17-13-3	0.03	1.0	2.0	0.045	0.015	16,5/ 18,5	11.0/ 14.0	2.5/ 3.0	0.12/ 0.22	-
	1.4436	X5CrNiMo 17-12-2	0.05	1.0	2.0	0.045	0.03	16.5/ 18.5	10.5/ 13.0	2.5/ 3.0	max 0.11	-
	1.4571	X6CrNiMoTi 17-12-2	0.08	1.0	2.0	0.045	0.03	16,5/ 18,5	10.5/ 13.5	2.0/ 2.5	-	5xC/ 0.7
Ferritic-Austenitic												
	1.4362	X2CrNiMo 23-4	0.03	1.0	2.0	0.035	0.015	22,0/ 24,0	3.5/ 5.5	0.1/ 0.6	0.05/ 0.20	-
Ferritic-austenitic (Duplex)	1.4462	X2CrNiMoN 22-5-3	0.03	1.0	2.0	0.035	0.015	21,0/ 23,0	4.5/ 6.5	2.5/ 3.5	0.10/ 0.22	-

2 Mechanical and physical properties

2.1 Strength and ductility

The stress-strain relationship for different types of stainless steels is illustrated in *Figure 2-1 /2/*. Note that only the austenitic and the ferritic-austenitic (duplex) steel are relevant as reinforcement. Austenitic and duplex (and ferritic) grades of steels show early plastic deformation in test, and continue to sustain increasing load with increasing strain.

Cold working will increases the strength of the steels and is therefore used to meet the requirements for use as reinforcement in concrete. Cold working usual results in martensite formation in 1.4301 types, whereas in 1.4401/1.4436 and duplex materials, this is not the case. For the austenitic types cold working results in a reduction of the elongation from 40% to 20-25%.

For small dimensions (<16 mm) also warm working (at temperature somewhat lower than normal for such process) may be used for increasing the strength, resulting in mechanical properties similar to those obtained by cold working.

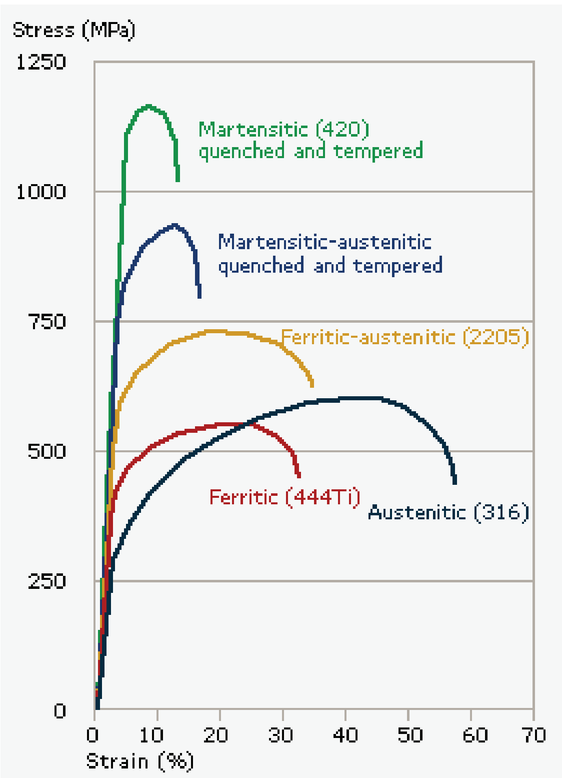

Figure 2-1: Stress-strain curves for different stainless steels at room temperature /2/

Another way of increasing strength is addition of nitrogen (0.15-0.2%). This is however not sufficient to reach the required strength and must therefore be combined with either cold or warm working.

European Standards that deals with reinforcement for concrete structures generally prescribe requirements of strength based on the characteristic values of the tensile strength and for yield strength (or the 0.2 % proof stress). Ductility of the steel is evaluated by means of characteristic values of the ratio between the tensile strength and the yield strength and the characteristic value of the strain at maximum force. For instance, Eurocode 2 /13/prescribes $\varepsilon_{uk}>5\%$ and $(f_t/f_y)_k)1.08$ for high ductility steel. (class B).

As listed in *Table 2-1*, stainless steels can be produced as ribbed bars within the normal range of strength and deformability required for application in concrete.

The modulus of elasticity (E-modulus) for the relevant SSR is about 200 kN/mm^2, in the same range as for carbon steel reinforcement (210 kN/mm^2).

Owing to their excellent mechanical properties in the as-rolled conditions, duplex steels are of particular interest as material for reinforcement. For example, the duplex steel of grade 1.4462 (X2CrNiMoN 22-5) as cold rolled, has proof strength of 950 MPa, tensile strength of 1059 MPa and elongation of 14 % for 10 mm bars.

Some concern has been arisen about the performance of stainless steel reinforcement under seismic action. However, producers of stainless steel reinforcement can adapt strength and ductility to requirements and are normally able to satisfy ductility requirements for /12/.

Table 2-1: Mechanical properties of different types of stainless steel reinforcement

	Steel grade	Dimension [mm]	Proof stress $f_{0,2k}$ [N/mm^2]	Tensile strength f_{tk} [N/mm^2]	Elongation ε_{uk} [%]	$(f_t/f_{0,2})_k$	E-modulus at 20°C [kN/mm^2]
Cold worked	1.4301	3-16	≥550	≥600	≥5	≥1.10	200
	1.4436	3-16	≥550	≥600	≥5	≥1.10	200
	1.4571	3-16	≥550	≥600	≥5	≥1.10	200
Hot rolled	1.4301	20-40	≥500	≥700	≥5	≥1.10	200
	1.4571	20-32	≥500	≥700	≥5	≥1.10	200
	1.4462	20-50	≥550	≥700	≥5	≥1.10	200

2.2 Physical properties

The density of stainless steel reinforcement varies only marginally from normal carbon steel reinforcement, as seen in *Table 2-2*, and in all practical applications the small variations cannot be of concern.

Stainless steel reinforcement has a thermal expansion which for the austenitic steels is approximately 16 x10^{-6}, and the austenitic-ferritic duplex steels have a thermal expansion of approximately 13 x10^{-6}, compared to the carbon steel with a thermal expansion of 12 x10^{-6}, see *Table 2-2*.

Table 2-2: Physical properties of stainless steel /6/

Steel grade	Density kg/m^3	Thermal expansion [10^{-6}/°C]
Carbon steel	8000	12
1.4301	7900	16
1.4436	8000	16
1.4462	7800	13

In general austenitic type stainless steels are considered to be practically non-magnetic. However, cold drawn bars gain some magnetic permeability. The magnetic permeability decreases in the designation order 1.4301>1.4436>1.4429>1.4529. Therefore stainless steel reinforcement required to have a low magnetic permeability (not magnetic) must be hot-rolled and be of a specific compositions or alternatively tested.

Duplex stainless steels are magnetic, as are carbon steels.

2.3 Application at elevated temperatures

The difference between the thermal expansion of austenitic and carbon steel is not negligible (16 x 10^{-6}/°C vs. 12 x 10^{-6}/°C, see *Table 2-2.*), and might theoretical cause minor defects and cracks in concrete sections subjected to high temperatures. However, there are no practical evidence or laboratory results supporting this assumption /1/.

In design the issue is to compare the thermal coefficient between the reinforcement and the concrete. Depending on the concrete mix and type of aggregate used, it is found that the concrete itself can have a thermal expansion coefficient which may vary say 20%, and the elastic modulus of the concrete may also vary 20-30% or more, depending on the mix. These variations in strain properties have never been reported giving structural or performance related difficulties in concrete structures either.

Carbon steel experience a considerable drop in proof stress at elevated temperatures, particularly at temperatures above say 500 °C. Similarly, they experience a considerable loss in ductility and increased brittleness at temperatures below zero. Below -20 °C most carbon steels behave very brittle and would not be adequate as reinforcement in structures exposed to sudden impact loading or seismic actions.

This situation is very different for stainless steel reinforcement The austenitic stainless steels maintain their strengths at considerable higher temperatures than carbon steel. Therefore such steels are more resistant and robust under fire loading than carbon steel. Similarly, austenitic steels maintain their strength and ductility at very low temperatures, so-called cryogenic temperatures, which may reach as low as -196 °C. In addition their strengths increase slightly under decreasing temperatures.

Although stainless steels are most commonly used for their corrosion resistance stainless steels are often used for their high temperature properties. Stainless steels can be found in applications where high temperature oxidation resistance is necessary and in other applications where high temperature strength is required. The high chromium content which is so beneficial to the wet corrosion resistance of stainless steels is also highly beneficial to their high temperature strength and resistance to scaling at elevated temperatures.

The particular crystalline structure of the austenitic steels allows them to maintain a high degree of toughness (Charpy impact test) with a large temperature range, from elevated temperature to far below the freezing point. Due to the difference in crystalline structure between austenitic steel and duplex steel, (where duplex is in part ferritic) duplex steel undergoes a marked decrease in toughness at low temperature, an effect which starts at about -50°C.

2.4 Fatigue

Stainless steel reinforcement has fatigue properties similar to that of carbon steel reinforcement when tested in the atmosphere. However, the critical issue of fatigue for reinforcement is the special situation of a fatigue loading in a corrosive environment. In this case the much increased corrosion resistance of stainless steel compared to carbon steel reinforcement results in a marked increased corrosion fatigue resistance of stainless steel reinforcement compared to carbon steel reinforcement.

The fatigue limit (upper limit of fatigue stress to be supported indefinitely) for stainless steel reinforcement is related to the tensile strength of the steel. In this case, the increased strength of several of the types of stainless steel compared to carbon steel reinforcement leads to a corresponding increased fatigue limit.

3 Corrosion resistance

3.1 General

Stainless steels are a family of alloys that derive their corrosion protection from the formation of a stable, passive oxide film on their surface. This film is formed very rapidly by reaction of the alloying elements in the steel, especially chromium, with water and oxygen-bearing atmospheres.

Theoretically, different forms of corrosion of stainless steel reinforcement in concrete structures may occur: pitting corrosion, crevice corrosion, stress corrosion cracking, and intergranular corrosion.

In practice, pitting is the only form of corrosion expected on stainless steel in concrete. Crevice corrosion is a form of localized corrosion and occurs under the same conditions as pitting, i.e. in neutral or acidic chloride solutions. However, attack starts more easily in a narrow crevice than on an unshielded surface. Because of the pore solution and the porosity of cement paste, crevice corrosion is also unlikely on stainless steel in contact with concrete /14/. A higher chromium, molybdenum and nitrogen content in the steel increases the resistance to pitting and crevice corrosion/14/. A material failure may be accelerated by the combined effect of a corrosion process and a mechanical stress. Such stress corrosion cracking does not take place in normal service conditions but only in combination of high concentrated chloride-containing environments, high temperature and carbonated concrete /6/, /12/. However, other contaminants, such as H2S, may increase the risk of SCC in chloride containing environments. Intergranular corrosion induced by welding is avoided by using specially alloyed steels or steels with a controlled carbon content.

3.2 Resistance to pitting corrosion

In chloride contaminated concrete, stainless steels can undergo pitting corrosion similarly to carbon steel. However, because of the higher stability of the passive film of stainless steel, the chloride content required for the higher stability of the passive film of stainless steel, the chloride content required for the initiation of corrosion is higher.

As far as resistance to pitting attack is of concern it is well known that for austenitic and duplex steels, an increase in the content of chromium, molybdenum, nickel and nitrogen improves the corrosion resistance. The onset of corrosion is dependent on the critical chloride concentration at the level of the reinforcement triggering corrosion by eliminating the passive layer locally. This so-called threshold value for chloride corrosion initiation depends on the degree of alloying of the steel, the level of alkalinity of the surrounding concrete and the level of the ambient temperature /16/. However, the corrosion resistance of stainless steel reinforcement depends also on the microstructure and surface condition of the steel, on the alkalinity of the concrete and the electrochemical potential of the steel.

Since the late seventies, several experimental studies have been carried out in order to investigate the corrosion properties of stainless steels in chloride contaminated structures. The first extensive study of the behaviour of stainless steel reinforcement in chloride contaminated concrete started in the late seventies at the UK Building Research Establishment tests (BRE) /17/, /14/, /18/. A range of the most typical types of SSR were examined by casting them into concrete prisms with varying levels of cast-in chloride concentrations and immersed in seawater. The conclusion of these tests was that austenitic SSR were virtually immune to corrosion attack. A further interesting observation from the seawater immersion was the limited level of pitting attack observed on the 316-type stainless steel reinforcement (1.4436 and 1.4429) in the unfavourable condition of having bare steel projecting from the concrete. In these tests, the corrosive attack of the exposed areas was non-existing or superficial, even after 22 years in marine conditions. All the austenitic steels tested showed very high corrosion resistance with no serious corrosion of any bars, but recommendations were made that the molybdenum bearing alloys (1.4436 (316) and higher 1.4462 (duplex)) should be used in chloride-contaminated conditions to minimise the risk of corrosion, especially where high chloride contents and/or carbonation to the full depth of cover were anticipated.

Similar studies were carried out at the Politecnico di Milano /19/, /20/, /21/ and /22/ on several types of stainless steel reinforcement in concrete and in solutions simulating the concrete pore liquid. These tests evaluated the corrosion conditions in concrete exposed to various environments, i.e. different temperatures, chloride levels and alkalinity. Testing temperatures of 20°C and 40°C were used to simulate temperate and hot climates. These test programmes led to conclusions regarding the chloride corrosion resistance of the different grades of stainless steel: (see figure 3-1)

- As the alkalinity increased, chloride induced corrosion decreased
- The critical chloride threshold levels exceeded 10% Cl^- by weight of cement in the highly alkaline solution (pH 13.9), at both 20°C and 40°C
- Tests in nearly neutral pore water solutions (pH 7.5) showed a lower resistance to chloride induced corrosion, especially when the chromium content was low
- In the case of carbonated concrete (pH has fallen to a value in the order of approximately 9) the stainless steel will unlike carbon steel, remain passive. Stainless steel will also be of benefit where the concrete is both carbonated and chloride contaminated to the level of the reinforcement.
- By increasing the temperature to 40°C, a general reduction of corrosion resistance was observed, except with the super austenitic steel 1.4529. (The duplex type 1.4462 is expected to have similar good corrosion resistance under these circumstances).

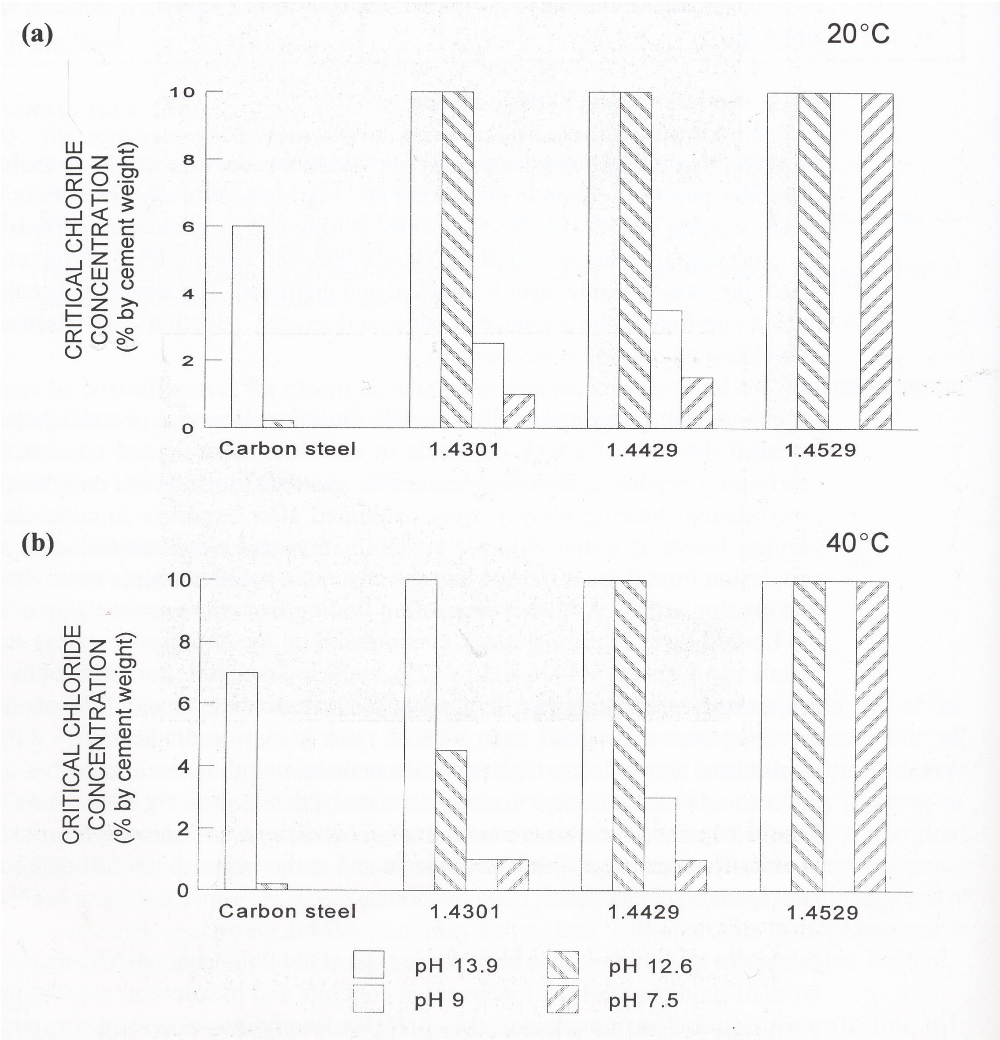

Figure 3-1: Critical chloride concentration (% by cement weight) for different steel types in solutions simulating the pore liquid /23/

Regarding stainless steel results from the literature provide critical chloride threshold values basically from tests where the steels are exposed to simulated concrete pore solutions or from concrete tests where the results only indicates that these stainless steel have not activates after some extended time period. The passive condition has been reported to vary from 3.2 % to 5-6 % by cement weight of chlorides /17/, /24/, /16/, /20/.

Figure 3-2 outlines fields of application of stainless steels in chloride contaminated concrete exposed to 20°C and 40°C, respectively /22/. Fields have been plotted by analysing the critical chloride values obtained by different authors from exposure test in concrete or from electrochemical test in solution and mortar. In the figure the corrosion threshold level is defined as the level at which corrosion of the different types of reinforcement starts; below this level the reinforcement is in a passive condition. It is essential to note that carbon steel reinforcement is susceptible to localized corrosion at low chloride contents even in alkaline concrete. Further, the effect of temperature on the threshold values is illustrated based on comparative test results performed at 20°C and 40°C, respectively. The effect of the alkalinity, pH value, is pronounced in both situations, i.e. when chloride penetration occurs in conjunction with carbonation of concrete (e.g. highway tunnels), corrosiveness is increased. Special attention shall be drawn to the considerable effects observed within the range of pH=12.5-13. This relatively small difference in alkalinity of the pore water would represent the normal difference in pH of noncarbonated concrete made with either a highly blended cement (lower pH value) or with an OPC cement (higher pH value).

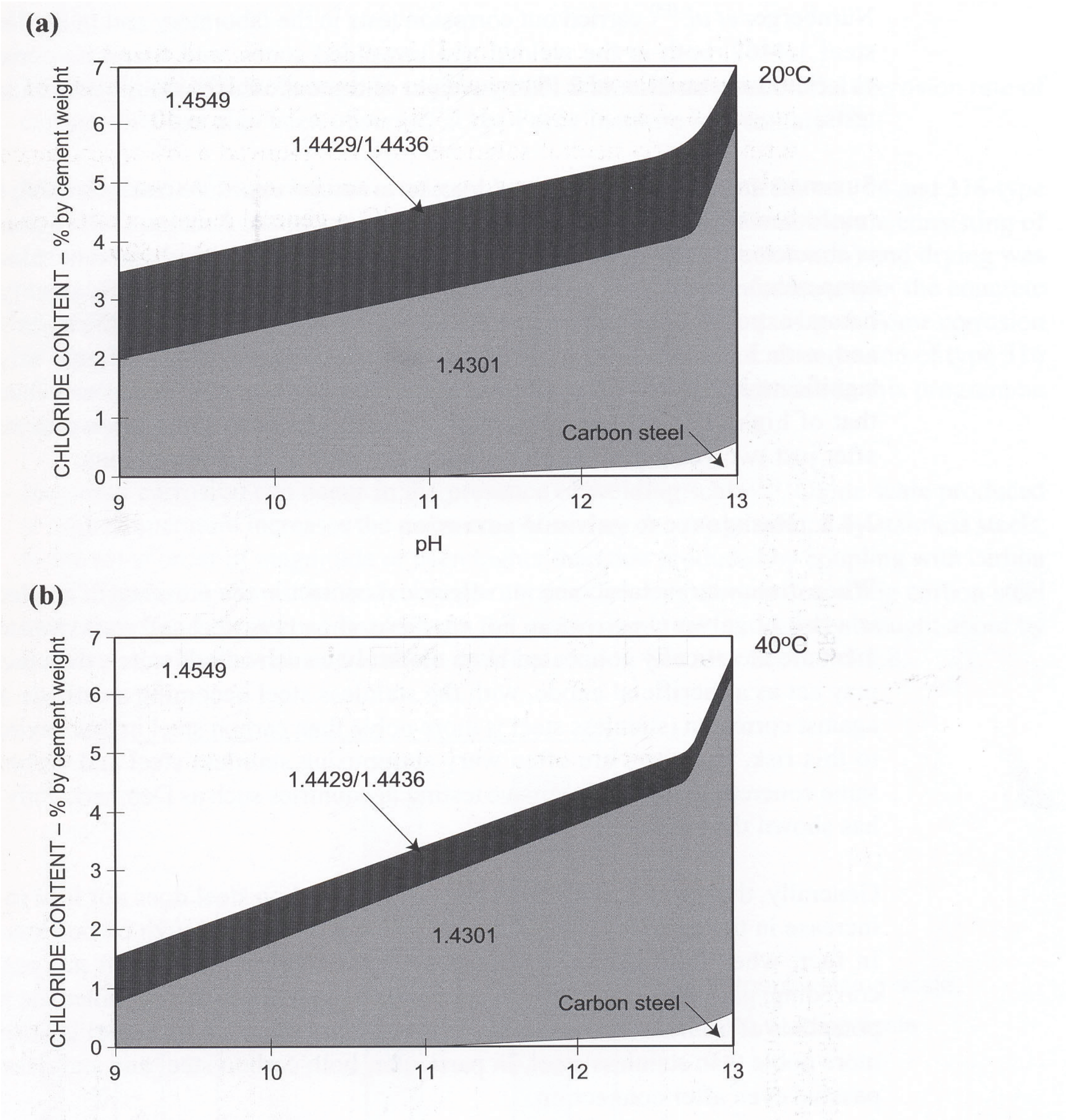

Figure 3-2: Schematically representation of fields of application of different steels in chloride containing environments. The threshold levels are indicative only, as local conditions may increase as well as reduce the indicated values /22/

Recently, the critical chloride level of steels SS304 and SS316LN was evaluated and compared with carbons steels ASTM A615 and A706 using accelerated chloride threshold testing by /25/. They found mean critical chloride threshold values of 5.0 and 10.8 kg/m^3 for SS304 and SS316LN respectively and values of 0.5 and 0.2 kg/m^3 for ASTM A615 and ASTM A706, respectively. This indicates that steel AISI 304 (1.4301) has a threshold level 10 times higher than ordinary carbon steel and 316LN (1.4429/1.4436) even higher.

3.3 Resistance to galvanic corrosion

Consequences of galvanic coupling with carbon steel have to be considered in concrete structures where both carbon steel and stainless steel reinforcement are used. When two dissimilar metals are connected electrically and immersed in a conductive liquid, an electrolyte, their corrosion performance might differ significantly when compared with the metals, uncoupled. As a rule, the less noble material, the anode, is attacked, whilst the more noble metal, the cathode, is essentially protected from corrosion. This phenomenon is called galvanic corrosion.

Possible consequences of galvanic coupling of stainless steel and the ordinary reinforcement have been subject to extensive research. This research has shown that the risk of increased corrosion du to galvanic effects is generally small, and that intense galvanic coupling is likely to be limited to certain special cases /19/, /20/, /22/, /26/, /27/, /28/, /29/. It was found that when carbon steel and stainless steel reinforcement are in a passive condition (not corroding), coupling does not produce any appreciable galvanic effects, and both steels remain passive. Further, if the carbon steel becomes active, the use of stainless steel does not lead to an increase in corrosion rate of the carbon steel compared with the situation when the stainless steel is not present. Indeed, coupling with stainless steel seems less dangerous than coupling with passive areas on carbon steel that always surround the area where localized corrosion take place, as stainless steel reinforcement are a less efficient cathode /12/, /16/, /19/, /27/. However, in areas where the stainless steel has been welded the current is in the same range for both carbon reinforcement and reinforcement made of stainless steel, see Figure 3-3.

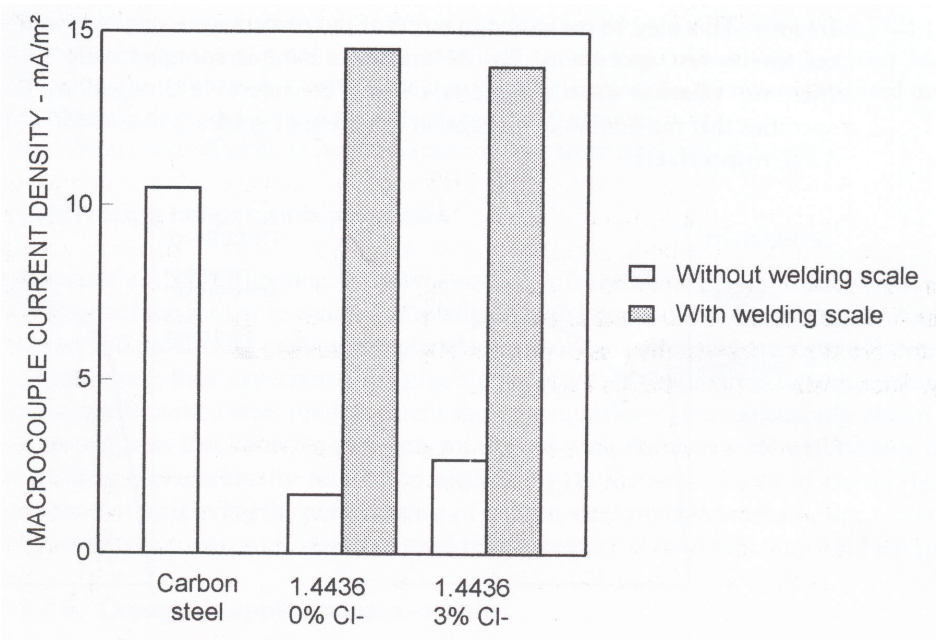

Figure 3-3: Macro-couple current for carbon steel starting to corrode coupled to either stainless steel or passive carbon /19/

The fact that stainless steel is a far less effective cathode in concrete than carbon steel, makes stainless steel a useful reinforcement material for application in repair projects. When part of the corroded reinforcement, e.g. close to the concrete cover, is to be replaced, it could be advantageous to use stainless steel instead of carbon steel. In being a poor cathode, the stainless steel would minimize any possible problems that may occur in neighbouring corroding and passive areas after repair /6/, /29/.

A significant macro-coupling can arise in some circumstances. For example, when the stainless steel is embedded in concrete that is heavily contaminated with chlorides and is non-aerated (i.e. water saturated), and the carbon steel is in aerated concrete, the risk of pitting initiation on the stainless steel increases up to the level typical of aerated conditions /12/, /19/, /22/.

3.4 Influence of welding on corrosion

In the presence of chlorides the corrosion resistance of stainless steel in concrete can be adversely influenced in the region of the weld and the heat affected zone /16/, /19/, /22/, /30/. This is because welding results in the formation of high temperature oxides on the surface of the steel, often referred to as heat tint, or welding scale, and these oxides do not remain as stable (passive) as the oxide layers on the bare stainless steel when exposed to chloride environments.

The corrosion resistance can be reinstated by the complete removal of all heat tint scale after welding. This is not easily done under conditions prevailing on construction sites. Primarily because the heat tint scales are very adherent and difficult to remove, in practice the only methods that can guarantee removal are either abrasive blast cleaning or the use of pickling pastes both of which are difficult to carry out on site. However, welding in factory conditions, where welding condition can be closely controlled, can be carried out successfully.

Where bars need to be joined alternative methods of connection, such as lapping or mechanical couplers, should be used. If welding is unavoidable then a post cleaning process should form part of the welding procedure qualification. The quality procedures should also include accelerated testing to demonstrate that the cleaning process reinstates the corrosion resistance of the stainless steel surface.

3.5 Surface finish

The presence of a scale or oxides on stainless steel reinforcement should be avoided because it can increase the risk of galvanic corrosion. In addition, the surface of stainless steel reinforcement may be polluted with carbon steel particles when being stored together with carbon steel or handled on equipment also handling carbon steel reinforcement. Such extensive superficial surface pollution should be avoided as there is a small risk that galvanic corrosion may develop. However, this is of very minor importance in practice, as the effect of the corrosion of the carbon steel particles is negligible from a structural point of view. This is due the fact that these particles cannot cause any cracking or damage to the concrete cover. They only result in unsightly discoloration of the stainless steel reinforcement surfaces when stored outdoors or when exposed through breakouts in the concrete polluted with chlorides.

One unresolved issue at present is the risk of having carbon steel particles pressed deeply into the crystal lattice of the stainless steel reinforcement through handling with carbon steel equipment, and then these particles corrodes when critical amounts of chlorides reach the steel surface/32/.

3.6 Stress corrosion

A material failure may be accelerated by the combined effect of a corrosion process and a mechanical stress. Two examples of such processes are stress-corrosion cracking and corrosion fatigue. The most common type is trans-granular stress-corrosion cracking that may develop in concentrated chloride-containing environments.

The most common austenitic type of steel with about 18 % of chromium and 8 to10 % of nickel is sensitive, because the nickel content is at a critical value. As the tendency to stress corrosion normally increases with increasing chloride content and temperature and decreasing pH, this form of attack is unlikely to be a problem in concrete elements /1/.

4 Application of stainless steel reinforcement

4.1 Practical experiences

The last 30 years stainless steel reinforcement has been used in a wide range of applications, such as bridges, tunnels and underpasses, retaining walls, foundations, marine structures, historic buildings and other structures with special long service lives /5/, /6/.

A documentation of the long-term performance of stainless steel reinforcement in highly chloride contaminated concrete is presented by the 70 year old concrete pier at Progresso in Mexico /31/. This pier was reinforced with stainless steel reinforcing bars (quality 1.4301) and no significant corrosion was found for the reinforcement with a cover larger than 20 mm, despite the extremely high chloride contents of up to 1.9 % Cl^- of dry concrete weight.

The most cost optimal solution is to use stainless steel reinforcement in the most exposed zones/parts of the structure. Recently a number of very large and prestigious bridges in corrosive marine environments have adopted stainless steel reinforcement in the outermost horizontal and vertical reinforcement layer of the most exposed parts of the structures. These are the Stonecutters Bridge, *Figure 4-1*, and the Shenzhen Corridor in Hong Kong or the Sheik Zayed Bridge in Abu Dhabi, *Figure 4-2* /32/.

Figure 4-1: Stonecutters Bridge, Hong Kong. Pylons reinforced with steel type 1.4462 in the outer layer of the multi-layer of reinforcement /32/

Figure 4-2: Sheik Zayed Bridge, Abu Dhabi. Lower part of supports are of reinforced concrete with steel type 1.4462 in the outer layer of reinforcement /32/

Stainless steel reinforcement is now being introduced into more repair projects. As stainless steel is a much poorer cathode than carbon steel, such reinforcment can be beneficial in those repair cases where ordinary carbon steel has corroded to such an extent that local replacement or added reinforcement is needed as part of a repair. Typical examples are replacement of parts of seawalls, e.g. in Sydney Harbour, and edge beams exposed to de-icing salt.

4.2 Life cycle costing

The often-stated barrier to use stainless steel reinforcement is the high initial cost. In comparison with the unit price of carbon steel, the stainless steel bar is about six to ten times higher, depending on bar size and steel type, based on the price level in 2006 /32/. However, the cost of cutting and bending, transportation and fixing stainless steel reinforcement remains the same as for carbon steel.

In /33/ the costs of replacing some of the carbon reinforcement with stainless steel reinforcement has been investigated for three marine constructions made during the years 1995-1996. Although the material cost of SSR in this case was stipulated to 5 times the cost of ordinary reinforcement the effect on the total construction costs of introducing stainless steel reinforcement in the most critical zones of the structures turned out to be marginal, e.g. by replacing 10 % of carbon steel with SSR the initial construction costs increased by 1- 2 %.

As service life design relates to the structure's performance over a long period of time it is relevant not only to consider the initial construction costs, but also the operation and maintenance costs over the expected design life of the structures. It is now recognized that for many structures the cost, difficulty and operational disruption resulting from both planned and unplanned maintenance and repair are significant burden to the owner of the structures as well as to the users. For example, the user costs due to traffic delays are now being rated so high, that this becomes the dominating basis for selecting the type and timing of maintenance and repairs.

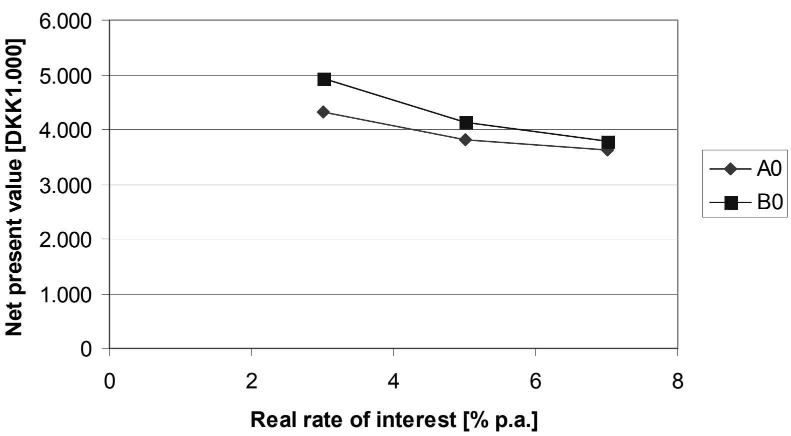

Figure 4-3: Net present value as function of real rate of interest /32/

In /32/a life cycle costs (LCC) analysis is performed to evaluate the costs for replacing approximately 100 meter edge beams using stainless steel and carbon steel, respectively. The calculation is based on an estimated service life of 50 years for both types of reinforcement. Maintenance costs for carbon steel are estimated at an extra 200.000 DKK every 5th year during the last 30 years of the service life. The indirect costs are secondary costs caused by the estimated traffic disturbances. *Figure 4-3* shows the net present value as function of various real rate of interest a result of the calculations (A0 : Stainless steel reinforcement and B0 : Carbon steel reinforcement). In *Table 4-1* the key figures are summarized for the total costs and the costs of a present value calculation using a real rate of 7 %. As seen the use of stainless steel is the most financially advantageous solution both with respect to total costs as well as present value calculation.

Table 4-1: Costs in mill. DKK /32/

	Strategy A Stainless steel	Strategy B Carbon steel
Total costs	7,0	8,6
Present value, real rate 7 %	3,6	3,8

4.3 Issues related to design and construction

4.3.1 General

When considering the adoption of stainless steel reinforcement to eliminate the corrosion risk problems within a stipulated long service life, the additional costs for the stainless steel obviously becomes a key issue and alternative corrosion preventive measures are frequently tabled. Due to the cost implications and the level of reliability of the alternative solutions, these issues should be addressed at a very early stage of the design process in order for the owner and client to select the final solution being the optimal for him.

An optimal design strategy should be an economic optimization of the costs throughout the whole life of the structure. In addition to actual financial costs (cost of the construction, repair and maintenance etc), user benefits, environmental effects and other external effects should be included in the economic analysis of the project. Such Life Cycle Cost (LCC) analysis evaluates whether the project is beneficial to society as a whole.

4.3.2 Selection of stainless steel reinforcement

In general most of the stainless steels used for reinforcement are within the austenitic stainless steel types 1.4301 and 1.4436. Only in extreme corrosive environments like de-icing salts or marine environments and high temperatures more resistant materials are considered like the ferritic-austenitic (duplex) type 1.4462.

The specifications listed in *Table 4-2* represent an overview of available European standards for the characterization of currently available equalities of stainless steel reinforcement.

These National Standards specifies requirements and describes methods of test. National certification bodies certify producers of stainless steel reinforcement according to the national product standards.

Table 4-2: Current Specifications relevant for the documentation of stainless steel reinforcement

Relevant European Standards	
ID. No.	***Title***
BS 6744	Stainless steels bars for reinforcement of and use in concrete – Requirements and test methods
BS 8666	Specification for Scheduling, dimensioning, bending and cutting of steel reinforcement for concrete
EN 10204	Metallic products - Types of inspection documents
EN 10088-1	Stainless steels - Part 1: List of stainless steels
EN 10088-3	Stainless steels - Part 3: Technical delivery conditions for semi-finished products, bars, rods and sections for general purposes

4.3.3 Concrete section design

The inherent corrosion resistance of stainless steel reinforcement allows room for changes in the design for durability compared to current designs based on carbon steel reinforcement. These changes reflect relaxations which also will result in overall cost savings on the individual items, an issue which will compensate for the prevailing high costs for the stainless steel reinforcement compared to the carbon steel reinforcement.

- The structural aspect of anchorage is the same for the two types of reinforcements. Hence minimum covers allowed for carbon steel reinforcement shall also govern for stainless steel reinforcement.
- No additional corrosion protection of the stainless steel reinforcement is required. Only in zones where the stainless and carbon steel reinforcement is coupled or lapped, or where only carbon steel reinforcement is used shall the traditional covers prevail
- The need for fire protection is similar for the two types of reinforcements. However, the stainless steel reinforcement is more tolerant to high fire-induced temperatures by loosing strength only at higher temperatures than carbon steel.
- Having solved the corrosion problem through the selection of an appropriate grade of stainless steel reinforcement then the selection of the concrete mix can be optimized by taking a number of other properties into account. With reference to the type of mix usually adopted to protect carbon steel reinforcement, these additional properties would typically lead to relaxations regarding the concrete denseness and permeability properties.
- The crack widths needed to be controlled according to prevailing codes and standards refer to the visible and measurable crack widths on the concrete surface. The control of cracking on a concrete structure is determined by the amount, size, strength and

distribution of steel reinforcement, the concrete cover and the concrete strength, together with the level of strain (stress) in the main reinforcement. Where stainless steel is used an unlimited value of maximum crack can theoretically be tolerated from a purely corrosion point of view. However, visually acceptable cracks widths and tightness - together with possible effects on deflections and vibrations - will govern the tolerable size of crack width.

- Where watertight structures are concerned special cases can apply.
- As for carbon steel care shall be taken to ensure sufficient reinforcement to ensure a good distribution of cracks and thus avoid large size single cracks.
- Adopting stainless steel reinforcement together with the corresponding slight relaxation in the concrete binder ratio may reduce the plastic shrinkage and the thermal cracking problem.

4.4 Site considerations

Stainless steel reinforcement should in general not be stored in contact with carbon steel because of the risk of rust staining. It shall be stressed that such rust staining it is only the small carbon steel particles on the surface of the stainless steel reinforcement that corrodes. This results often in the misconception that the Stainless steel is corroding, but this is not the case. Similarly, leftover microscopic remains of the mill scale from the production of the stainless steel might give cause to similar harmless discolouring prone to misunderstandings. The observation is only of visual - and psychological - importance.

The self-repairing characteristics of the oxide film on stainless steel mean that the integrity of the film is maintained, even if the stainless steel reinforcement suffers mechanical damage during handling.

Stainless steel reinforcement should only be cut with equipment designed solely for that purpose. If such reinforcement are cut with a disc cutter or angle grinder any “blueing” of the steel, i.e. thermal oxides caused by the cutting, must be removed with a proprietary pickle paste, otherwise the corrosion resistance of the steel may be impaired.

Austenitic and duplex stainless steels can be bent to shape using the methods commonly used for carbon steel, providing that allowance is made in the loading rating of the equipment used, as more force is required to bend stainless steel than carbon steel (because of strain hardening) /6/.

Welding of stainless steel is possible but not recommended in site conditions, because if the weld products is not completely removed, corrosion resistance is reduced. Pickling or shot-blasting the weld can often solve the problem, but is not practical on construction sites. In the factory or at precasting yards welding is no problem provided the general rules for welding stainless steel and stainless steel in contact with carbon steel is ensured.

Stainless steel couplers are available for connecting lengths of bar longitudinally, providing in most cases a direct alternative to welding. They can be used to connect two lengths of carbon steel, carbon and stainless, or of stainless steel. The risk of galvanic corrosion is virtually non-existing under most realistic conditions.

Stainless steel reinforcement should always be fixed with softened stainless steel tying wires of the same quality as the structural steel. Spacers made with concrete, or cement mortar should be used. It is recommended to use stainless steel chairs for support.

Traditional cover meters cannot detect austenitic stainless steel reinforcement, as they work using an induction method requiring magnetic reinforcement. Special cover meters have been developed claiming that measurements can be conducted on non-magnetic reinforcement. Duplex stainless steel is magnetic but has a poor conductivity. They are detectable by conventional cover meters but the signal received will be weak. Thus, the measured cover depth should be checked by visually control of the spacers (number, cover and distribution) and spot checks by drilling after the reinforcement has been tentatively located, and the readings calibrated with this measurement.

5 Conclusions and further research

In recent years there has been an increasing interest in applying stainless steel reinforcement in concrete structures to combat the durability problems associated with chloride ingress.

A convincing documentation of the performance of stainless steel reinforcement in highly chloride contaminated concrete is presented by the 70 year old concrete pier at Progresso in Mexico. This pier was reinforced with stainless steel reinforcing bars (quality 1.4301) and no corrosion has taken place within the structure yet despite the harsh environment. The chloride levels, at the surface of the reinforcement are more than 20 times the traditionally assumed corrosion threshold level for carbon steel.

It may be concluded that designing structures with stainless steel reinforcement may in principle be performed by a simple replacement of ordinary carbon steel reinforcement with stainless steel reinforcement in the ratio 1:1 as the structural properties are about the same regarding strength and ductility (or better for several of the available types of stainless steel). Further, using stainless steel reinforcement in design other advantages could also be utilized, such as: relaxation of concrete cover requirements, crack width requirement, and maybe concrete quality (permeability) requirements.

Stainless steel reinforcement can be combined with carbon steel cast into concrete with minimal risks of galvanic corrosion due to bi-metal - or galvanic - action. In fact, this is the precondition for general economical application of stainless steel reinforcement used only in the parts of the structure where this protection is needed, - so-called selective use.

Ribbed stainless steel reinforcement is available in a number of different material grades. Choice of material grade should depend on the design service life and the environmental aggressivity.

If stainless steel reinforcement is to be used cost effectively, it is essential that the design and specification of reinforcement minimizes the impact of the initial cost increase from the use of stainless steel. This can be achieved in a number of ways:

- by adapting life cycle costing (LCC) as an integral part of the service life design process
- by correct selection and specification of stainless steel material grade
- by changing the design approach for durability requirements developed for carbon steel by a new approach adapted that reinforcement corrosion is solved through the use of stainless steel reinforcement
- by using stainless steel selectively only on structure elements or at surfaces of structures that are at risk of degradation from chloride induced corrosion

There are still some investigations and tests that should be made when discussing the application of stainless steel reinforcement to solve the worldwide corrosion problems of concrete structures. Among such tests are:

- Objective determination of the critical chloride values for onset of corrosion for the different grades of stainless steel. It is a general impression that some "overshooting" governs the selection of grades, to be on the safe side. Of particular interest will be methods clarifying the uncertainties related to corrosion properties for the more cost effective “low grades stainless steel” and the new types steel like the Lean Duplex types.
- Testing to clarify reality of the theoretical concern of a possible corrosion risk from carbon particles pressed into the lattice of the different grades of stainless steel reinforcement.
- Testing influence of welding on the different grades of steels in general, and on the coupling between carbon and stainless steel particularly. It should be expected that welding will reduce the corrosion resistance by reducing the chloride threshold levels, which is due to the combined effect of oxide and insufficient compaction of concrete around the weld.
- Comparative study of corrosion properties of different types of stainless steel reinforcement and cladded steel by determination of chloride threshold values under accelerated exposure conditions. An important question is whether the properties also are valid for bended or welded steels.

6 References

/1/ COST 521: "Corrosion of Steel in Reinforced Concrete Structures", Final report, Luxembourg University of Applied Science, Ed, Romain Weydert, February 2002,

/2/ Outokumpu, webpage: http://www.outokumpu.com/ Products information

/3/ Haynes, J. M., "Stainless Steel Reinforcement", Civil Engineering, 1984

/4/ Kilworth, S. R., Fallon, J., "Stainless Steels for Reinforcement", development of the paper "Fusion Bonded Epoxy Coated Reinforcement in the Gulf", presented at the Corrosion and Protection of Reinforced Concrete Conference, Dubai, 1994

/5/ "Stainless steel reinforcement in concrete. The use of stainless steel reinforcement in bridges", British Steel Association, April 2002

/6/ "Guidance on the use of stainless steel reinforcement", Concrete Society Technical Report 51, Concrete Society, 1998

/7/ "Stainless Steel in Concrete", European Federation of Corrosion Publications, Number 18, The Institute of Materials, 1996

/8/ "Comparison of the corrosion resistance of some new metallic reinforcing bars in concrete blocks exposed to chloride ions", Virginia Transportation Research Council and Federal Highway Administration Report, October 2003

/9/ BS 9705 "General inspection and testing procedures and specific requirements"

/10/ BS 6744 "Stainless steel bars for the reinforcement of and us in concrete – requirements ad test methods"

/11/ EN 10088-1:2005 "Stainless steels. List of stainless steels"

/12/ Bertolini, L. and Pedeferri, P., "Laboratory and filed experience on the use of stainless steel to improve durability of reinforced concrete", Corrosion Reviews, Vol. 20, No 1-2, pp129-152, 2002

/13/ EN 1992-1-1, Eurocode 2, Part 1-1:"Design of structures. General rules and rules for buildings"

/14/ Flint, G.N. and Cox, R.N., "The Resistance of Stainless Steel Partly Embedded in Concrete to Corrosion by Seawater", Magazine of Concrete Research, Vol. 40, No.142, 1988

/15/ Hunkeler, F., "Einsatz von nichtrostenden Bewehrungsstählen im Betonbau" (Use of non-corroding Reinforcing Steels in Concrete Construction), Eidgenössisches Departement für Umwelt, Verkehr, Energie und Kommunikation / Bundesamt für Strassen, Switzerland, May 2000

/16/ Sørensen, B., Jensen, P.B. and Maahn, E., "The Corrosion Properties of Stainless Steel Reinforcement", Corrosion of reinforcement in concrete, (eds. Page, Treadaway, Bamforth), Elsevier Applied Science, 1990

/17/ Treadaway, K.W.J., Cox, R.N. and Brown, B.L., "Durability of Corrosion Resisting Steels in Concrete", Proc. Inst. Civ. Engineers, Part 1, pp 305-331,1989

/18/ Cox. R.N. and Oldfield, J.W., "The long term performance of austenitic stainless steel in chloride contained concrete". Corrosion of reinforcement in concrete construction, (eds: Page, Bamforth and Figg), Royal Society of Chemistry, Cambridge 1996

/19/ Pedeferri, P., “Stainless steel in concrete”, Corrosion of steel in reinforced concrete structures, Proceedings of COSTS21 workshop, Paris 20-21 April, 1998

/20/ Bertolini, L., Pedeferri, P. and Pastore, T., "Stainless Steel in Reinforced Concrete Structures", Proceedings of the Second International Conference on “Concrete under Severe Conditions”, Vol. 1, Tromsø, Norway, June 21-24, 1998 (published by E&FN Spon)

/21/ Pastore, T., Pedeferri, P., Bertolini, L. and Bolzoni, F., “Electrochemical Study on the Use of the Duplex Stainless Steel in Concrete”, Duplex Stainless Steels 91, 1991, Beaune Borgogne, France

/22/ Pedeferri, P, Bertolinim L., Bolzoni, F and Pastore, T., “Behaviour of stainless steel in simulated concrete”. Repair and rehabilitation of reinforced structures- state of the art report, American Society of Civil Engineering, pp 192-206, 1998

/23/ Bertolini, L., Bolzoni, F. Pastore, T. and Pedeferri, P. “Behaviour of Stainless Steel in Simulated Concrete Pore Solutions”, British Corrosion Journal, Vol. 31, 3No. , pp 218-222, 1996

/24/ Brown, B. L., Harrop, D. and Treadaway, K. W. J., “Corrosion testing of steels for reinforced concrete”, Building Research Establishment, Garston, 45/78, 1978

/25/ Trejo, D. and Radhakrishna G. P., Accelerated Chloride Threshold Testing –Part II: Corrosion-Resistant Reinforcement” ACI Materials Journal, Vol 101, No 1 pp. 57-64, 2004

/26/ “Materials for Corrosion Cell Cathodes”, Internal Report by The Danish Corrosion Centre as a part of report regarding BRITE Contract 102 D, 1990

/27/ Klinghoffer, O., Frølund, T., Kofoed, B., Knudsen, A., Jensen, F.M. and Skovsgaard T., “Practical Aspects of Application of Austenitic Stainless Steel, AISI 316, as Reinforcement in Concrete”, Publication No. 31 of European Federation of Corrosion, Corrosion of Reinforcement in Concrete, Corrosion Mechanisms and Corrosion Protection, Papers from EUROCORR ´99, 1999, pp. 121-134

/28/ Jäggi, S., Elsener, B. and Böhni, H., “Oxygen reduction on passive steel in alkaline solutions”, Book of Abstracts, EUROCORR ’99, 1999

/29/ Nürnberger, N., ”Corrosion of Reinforcement in Concrete Construction”, The Royal Society of Chemistry, pp 623 – 629, 1996

/30/ Nürnberger, U., Beul, W. and Onuseit, G., “Corrosion Behaviour of Welded Stainless Reinforced Steel in Concrete”, Otto-Graf-Journal, 1993

/31/ “Pier in Progreso, Mexico, Inspection report, Evaluation of the stainless steel reinforcement”, ARMINOX, 1999

/32/ Markeset, G, Rostam, S. and Klinghoffer, O., “Guide for the use of stainless steel reinforcement in concrete structure” Nordic Innovation Centre project-04118, Byggforsk report 405, ISBN 82-536-0926-4, 2006

/33/ Markeset, G., Rostam, S. and Skovsgaard, T.; “Stainless Steel Reinforcement - An Owners, a Designers and a Producers Viewpoint”, Proceedings, 6th International Conference on "Deterioration and Repair of Reinforced Concrete In the Arabian Gulf", Bahrain, November, 2000, 18 pp

SINTEF Building and Infrastructure is the third largest building research institute in Europe. Our objective is to promote environmentally friendly, cost-effective products and solutions within the built environment. SINTEF Building and Infrastructure is Norway's leading provider of research-based knowledge to the construction sector. Through our activity in research and development, we have established a unique platform for disseminating knowledge throughout a large part of the construction industry.

COIN – Concrete Innovation Center is a Center for Research based Innovation (CRI) initiated by the Research Council of Norway. The vision of COIN is creation of more attractive concrete buildings and constructions. The primary goal is to fulfill this vision by bringing the development a major leap forward by long-term research in close alliances with the industry regarding advanced materials, efficient construction techniques and new design concepts combined with more environmentally friendly material production.