

A review on corrosion behaviour of stainless steel reinforcement in concrete

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A tribute to Professor Bertolini for its outstanding work in the field of stainless steel rebars

Abstract

In Europe, stainless steel rebars have been used since the mid-80s, while in North America their use has been progressively growing only since the mid-90s. Due to their higher resistance to corrosion in comparison to ordinary black steel bars, they have been employed in a wide number of applications worldwide to achieve the durability performance of reinforced concrete structures, especially in extremely corrosive marine environments or when long service lives are required. In this paper, a state of the art on the corrosion resistance of stainless steel bars is reported. In particular, the contribution of Professor Luca Bertolini in this research field is considered. Initially the different testing methods are presented to point out their advantages and limitations and then the results on corrosion behaviour of different grades of stainless steel bars (i.e. austenitic, ferritic and duplex), obtained especially with tests in concrete, are analysed. Afterwards some of the recent applications of stainless steel bars are illustrated.

Keywords

Stainless steel; critical chloride threshold; tests in concrete; seawater

1. Introduction

Stainless steel (SS) rebars can be a suitable design option to fulfil durability requirements in chloride bearing environments or when long service lives are required. The most suitable SS grade has to be selected considering the characteristic of the structure, the concrete and the exposure conditions (Lollini, Carsana, Gastaldi, Redaelli & Bertolini, 2015).

According to Tuutti's model (Tuutti, 1982), the service life (SL) of a reinforced concrete (RC) structure exposed to marine environment or de-icing salts, is divided into an initiation period, during which chloride ions penetrate the concrete cover and initiate pitting corrosion, and a subsequent propagation period, during which corrosion leads to a limit state affecting the serviceability or safety of the structure (Bertolini, Elsener, Pedferri, Redaelli & Polder, 2013).

During the initiation period, chloride ions penetrate the concrete cover until they reach a specific concentration, i.e. the chloride threshold (C_{th}), at the surface of the embedded steel, leading to a local breakdown of the protective oxide film present on the reinforcement surface (passive film). A subsequent localised corrosion attack (pitting) takes place. Areas in the pit act as anodes (active zones) with respect to the surrounding still passive areas where the cathodic reaction of oxygen reduction takes place. Once corrosion has initiated, a very aggressive environment is produced inside localised attacks, due to the autocatalytic mechanism of pitting corrosion. Consequently, corrosion can reach very high rates of penetration (up to 1 mm/year) that can quickly lead to a remarkable reduction of the cross section of the rebars. For this reason, the propagation stage of pitting corrosion is neglected in the design of concrete structures exposed to environments with chlorides and the service life of the structure is defined only on the basis of the initiation period.

In order to calculate the initiation period, the chloride threshold, i.e. the minimum amount of chloride ions that is required to breakdown the passive film and initiate pitting corrosion (i.e. to cause depassivation), should be defined. Although this is an apparently simple approach, the complex nature of pitting corrosion initiation

should not be neglected. Thus, the assessment of C_{th} under real exposure conditions is indeed rather difficult because it is affected by numerous interrelated parameters, such as: the pore solution chemistry, the electrochemical potential of the steel, the steel/concrete interface, the environmental temperature, the type of steel and the surface condition of the reinforcement (Bertolini, Elsener, Pedefferri, Redaelli & Polder, 2013; Page, 2009).

It is well known that SS rebars have higher corrosion resistance compared to traditionally used black steel bars and they have been used in a large number of structures worldwide to achieve the durability performance of reinforced concrete structures. Figure 1 depicts, for comparison, the typical evolution of the service life of a reinforced concrete structure subject to chloride contamination for carbon steel (1) and stainless steel rebars (2).

Several grades of SS have been proposed as reinforcement, which are characterized by notably different chemical composition, cost and corrosion resistance performances.

This paper reports a state of the art on the corrosion resistance of stainless steel bars. Initially, the different testing methods used to characterize the corrosion behaviour are presented and their advantages as well as limitations are discussed; afterwards, the results on corrosion behaviour of different grades of stainless steel bars (i.e. austenitic, ferritic and duplex), obtained especially with tests in concrete, are analysed attempting to rank them in relation with corrosion resistance. Finally, examples of use of SS rebars in real structures are described and a promising and innovative use in combination with chloride-contaminated raw materials to increase the sustainability of construction industries is illustrated.

2. Testing methods

Although the main factors affecting C_{th} have been widely investigated and some of them are well known, a quantification of C_{th} values for steel in concrete is still rather difficult. First of all, pitting corrosion initiation is a stochastic phenomenon that is influenced by a great number of parameters (Alonso & Sanches, 2009). C_{th} should be properly defined only through probability distributions that take into account the effects of those parameters. However, such an approach requires a huge amount of experimental data which is not available in the scientific literature. A second reason is the absence of a standardised or a generally accepted method, even for black steel bars, for the evaluation of C_{th} both on real structures and in laboratory specimens (Bertolini & Redaelli, 2009; Page, 2009; Alonso & Sanchez, 2009; Glass, 1997; Frederiksen, 2009; Lollini, Redaelli & Bertolini, 2016). Few data are available on real structures (since the detection of C_{th} implies the difficult task of measuring the chloride content at the depth of the steel bars at the time of corrosion initiation) and these deal only with conventional black steel bars. For other steels that are not commonly used, such as stainless steels, only results of laboratory tests are generally available.

Since there are no standardised methods for the evaluation of C_{th} , as well as for the detection of depassivation, a large variety of techniques has been used by different researchers.

Often electrochemical tests in solutions simulating the concrete pore solution, such as potentiodynamic tests at different Cl⁻ content in solution or potentiostatic polarisation tests made after progressive chloride additions, are used to compare the corrosion resistance of steel bars of different composition. The current exchanged at the steel surface is monitored and, when it increases sharply, steel depassivation is detected, allowing the determination either of a pitting potential value or of a chloride threshold concentration. Tests in solutions permit a rapid evaluation of the resistance to pitting corrosion, allowing a preliminary evaluation of the role of the type of steel and of environmental parameters. However, they do not allow an evaluation of the chloride threshold in concrete, since chlorides concentration in solution cannot be directly converted in chloride contents in concrete, and they may not be representative of the real conditions of a reinforcing bar in concrete. Furthermore, these tests may also be misleading even for the simple ranking of the corrosion resistance of different types of stainless steels (Bertolini & Gastaldi, 2011).

Tests in concrete or mortar have also been proposed; they vary for the way chlorides are introduced in the concrete (e.g. added to the mixing water or penetrated by diffusion or migration), the means of measuring the chloride content (e.g. total acid soluble chlorides or free chlorides) or the surface preparation of the rebar sample (e.g. pickled, sandblasted, ..). These variations of the experimental procedures may have a large influence on the resulting value of the chloride threshold (Nurnberger, Beul & Onuseit, 1993). In tests in

concrete, steel depassivation is usually detected with electrochemical (non destructive) methods, such as monitoring corrosion potential and corrosion rate. The determination of the chloride threshold is carried out either by measuring the chloride content when steel depassivation is detected by corrosion rate and/or potential monitoring in initially chloride free specimens subjected to chloride penetration, or by comparing corrosion behaviour in terms of corrosion rates and corrosion potential of specimens with different amounts of mixed-in chlorides. However even the definition of the initiation of pitting corrosion, and thus of the chloride threshold, is not simple. In fact, an initial phase where breakdown of the passive film alternates to repassivation at incipient anodic sites is followed by a permanent active corrosion stage, where sustained pit propagation takes place. Potentiostatic polarisation tests, both in concrete with mixed-in chlorides and with chlorides which penetrate from an external source, have also been suggested to measure the chloride threshold as a function of steel potential, and thus to correlate C_{th} to changes in the moisture content of concrete (Lollini, Gastaldi & Bertolini, submitted). In tests in concrete with mixed-in chlorides, rebars are directly placed in contact with chloride contaminated concrete and could not benefit of the initial passivation which occurs in free-chloride concrete and this might affect the test results. Conversely, tests with chlorides that penetrate from an external source have been usually carried out only in samples of porous mortar with low concrete cover thickness, since otherwise they would require a very long time. Compared to tests in solution, tests in concrete are more time consuming, since they require casting and curing of specimens and, if chlorides penetrate from an external source, the involved phenomena require longer durations to take place (penetration of chlorides in concrete and changes at the steel/concrete interface) also considering the high corrosion resistance of SS. However, tests in concrete are indeed more representative of real conditions, in particular in considering the role of the steel-concrete interface (Page, 2009).

3. Corrosion behaviour of stainless steel bars

Stainless steels are alloyed steel with chromium content of at least 10.5% (EN 10088-1, 2005), which allows the formation of a chromium-rich passive film at the steel surface in many environmental conditions. Usually Cr content higher than 13% is used and other alloying elements are added (typically Ni, Mo, N) in order to improve strength, corrosion resistance or other properties. Thermo-mechanical treatments are also applied to SS rebars in order to fulfill mechanical requirements for reinforcing bars.

Stainless steels are generally divided in four types (based on the steel microstructure): martensitic, ferritic, austenitic and duplex (austenitic-ferritic). For use as reinforcement, however, only specific grades of austenitic and duplex SS are typically used in concrete (Table 1). Traditionally, austenitic type 304L (i.e. with about 18%Cr-10%Ni) and 316L (i.e. with about 17%Cr-11%Ni-2%Mo) and duplex type 22-05 (i.e. with about 22%Cr-5%Ni-3%Mo) are generally used. Due to the fluctuations of the cost of some alloy element, above all nickel, in the last years the use of rebars of duplex and austenitic SS with low nickel and molybdenum content (in which manganese is often added in place of nickel to obtain the austenitic structure), e.g. XM-28 (i.e. with about 17%Cr-1/2%Ni-12%Mn), 23-04 (i.e. with 23%Cr-4%Ni) and 21-01 (with a composition of approximately 21%Cr, 1% Ni associated with the presence of Mn), has been proposed (Table 1) (Bertolini & Gastaldi, 2011; Hansson, 2016).

Several studies have been carried out in the last 40 years, in order to evaluate the corrosion resistance of different types of stainless steels used as reinforcing bars and the main findings will be reported in the next sections. Tables 2 and 3 summarise all the publications considered in the present evaluation, whilst Figure 2 shows the critical chloride threshold obtained in the different publications for austenitic and duplex SS.

3.1 Austenitic and ferritic stainless steels

Earlier studies were carried out on austenitic and ferritic grades of SS. From the late 1970s, the results of an extensive study on the behaviour of SS reinforcement in chloride contaminated concrete were published (Brown, Harrop & Treadaway, 1978; Flint & Cox, 1988; Treadaway, Cox & Brown, 1989; Cox & Oldfield, 1996). Tests in the above mentioned papers were performed on plain bars embedded in concrete prisms and beams made with 3.2% of mixed-in chlorides by mass of cement. Concrete beams, with a chloride content added in the mix up to 0.96% by mass of cement, were cracked before exposure to the aggressive environment.

Concrete specimens were exposed to an industrial environment (Beckton, UK); furthermore some cracked concrete beams, initially free of chlorides, were exposed to the splash zone of a marine environment (Langstone Harbour, UK). After 10 years of exposure, no corrosion was observed on austenitic stainless steels 302 (comparable to 304, but with an higher carbon content) and 316. Conversely, ferritic stainless steels 405 and 430 showed to suffer pitting corrosion in high permeability concrete (w/c = 0.75) with up to 1% chloride by mass of cement. Austenitic stainless steels did not show any sign of serious corrosion even after 22 years of exposure. Indeed, only slight pitting attacks occurred on 302 stainless steel in concrete with 3.2% of chloride by mass of cement (exposed to industrial atmosphere) (Cox & Oldfield, 1996).

Afterwards, several studies were carried out on 304 and 316 grades. The good corrosion resistance of austenitic SS was confirmed by a study on commercial ribbed bars of 304 and 316 austenitic SS bars in mortar (a sulphate resistant portland cement was used) with up to 8% of mixed-in chlorides (Sorensen, Jensen & Maahn, 1990); no corrosion was observed in these specimens exposed outdoor for 5 months (Denmark). Further potentiostatic polarisation tests on the same SS at +200 mV/SCE (that can be considered representative of the maximum potential values reached in atmospheric exposure conditions) showed that corrosion could initiate at chloride contents of 3.5-5% by mass of cement and that the corrosion resistance of 316 was only marginally higher than that of 304.

A further study showed that fully passive conditions were maintained by plain bars of 304 and 316 austenitic SS embedded in concrete with mixed-in chlorides up to 3% by mass of portland cement and exposed in urban atmosphere (Milan, Italy) for 18 months (Pastore & Pedferri, 1991).

Corrosion resistance of austenitic 316 Ti and ferritic 410 ribbed bars was also studied in alkaline and carbonated portland cement concrete contaminated with up to 2.5% of chlorides by mass of cement (Nurnberger, Beul & Onuseit, 1993). Tests in cracked concrete, reinforced with austenitic and ferritic SS, initially free of chlorides and sprayed with chloride solution for 2.5 years were also carried out (Nurnberger & Beul, 1999). Austenitic stainless steel did not suffer pitting corrosion whether in alkaline or carbonated concrete with up to 2.5% Cl⁻ and in cracked concrete specimens when a chlorides content of about 4.5% by mass of cement was reached at the steel surface. Conversely, the ferritic stainless steels did not show pitting corrosion in alkaline concrete containing up to 2.5% Cl⁻ but were susceptible to pitting attack in carbonated concrete with 1% Cl⁻.

Tests in limestone-portland cement concrete contaminated with chlorides showed that bars of austenitic SS 304L and 316L did not undergo corrosion in alkaline and carbonated concrete with a chloride content up to 6% by cement mass, even after 8 months of exposure in very aggressive conditions simulating tropical climates (at 40°C and 95-98% R.H.) (Bertolini, Gastaldi, Pastore & Pedferri, 2000). Also ferritic 430 steels were tested showing a lower corrosion resistance at 40°C compared to austenitic steels.

A further study showed that no corrosion occurred even at potential values up to +400 mV/SCE (potential values that can be reached only in the presence of external polarisation, as in the case of stray currents) on 304L and 316L in concrete with 5% of mixed-in chlorides. In carbonated concrete with 5% of chlorides, a rather small increase in potential of 50 mV versus the free corrosion potential was enough to initiate pitting corrosion on 304L, showing that under this very aggressive condition (5% Cl⁻ + carbonation) 304L may be susceptible to pitting corrosion; for 316L a higher anodic polarisation of 150 mV was required to initiate corrosion (Bertolini, Gastaldi, Pedferri & Redaelli, 2002) (Figure 3).

In concrete with 2 and 4% mixed-in chlorides, 304 and 316, kept constantly wet using pads soaked in water, did not show initiation of pitting corrosion after approximately two years of exposure (García-Alonso et al., 2007a). Even in mortar with 2 and 5% mixed-in chlorides, the same rebars did not experience the initiation of pitting corrosion after the exposure to humidity cycles for about three years (García-Alonso et al., 2007b). No corrosion initiation was observed on 304L and 316L stainless steels during ponding tests, even with a chloride content at the steel surface higher than 6% (Hartt, Powers & Kessler, 2009).

Another study (Bertolini & Gastaldi, 2009) showed that corrosion initiation did not take place on ribbed bars of austenitic SS 304L and 316L, embedded in alkaline concrete with a content of chloride by mass of cement up to 8% and exposed at 20°C and 90% R.H. The passive condition was preserved also at temperatures higher than 40°C (Gastaldi & Bertolini, 2014).

In recent years, the austenitic stainless steel XM-28, with manganese added in place of nickel, has been proposed. Few works investigated its corrosion resistance and it has been observed that it can be significantly affected by the differences in chemical composition (different producers vary the C, Ni and Mo content) and/or processing details (Hansson, 2016). According to (Gastaldi, Lollini & Bertolini, 2013), with potentiostatic polarisation tests at +200 mV/SCE for 24 hours carried out on a set of 10 bars embedded in concrete with mixed-in chlorides in contents varying from 2 to 5%, C_{th} of XM-28 ranged between 2.3% and 5.5% by cement mass. According to (Van Niejenhuis, Bandura & Hansson, 2016), with potentiostatic polarisation tests at +200 mV/SCE for 4 days, corrosion occurred on 3 out of 3 bars embedded in concrete with 5% mixed-in chlorides and in 2 out of 3 bars embedded in concrete with 3% mixed-in chlorides. With potentiostatic polarisation tests at +100 mV/SCE for 4 days, corrosion did not occur on the three rebars in concrete with 3% mixed-in chlorides. In another study (Van Niejenhuis, Walbridge & Hansson, 2016) the XM-28 in sound concrete exhibited passive behaviour throughout more than 850 days' exposure to salt brine containing 21% Cl⁻, however no indication of the chloride content at the bar depth at the end of exposure is reported, and hence a minimum value for the critical chloride content cannot be discerned. Conversely, in concrete with cracks longitudinal to the bar, corrosion initiated after about 50 days.

The above mentioned studies show that traditional austenitic SS, i.e. of 316 and 304 grades, with and without molybdenum, have a high corrosion resistance in concrete. No corrosion was observed in alkaline concrete with chloride contents higher than 6% by mass of cement and even in carbonated concrete containing more than 4% of chlorides by mass of cement. Even under aggressive exposure conditions simulating tropical climates, i.e. at 40°C and 95-98% R.H., they remained passive. 316 grade showed a better corrosion resistance than 304 only if an anodic polarisation was applied. The more recent austenitic SS of grade XM-28 seems characterised by a lower corrosion resistance in comparison to 304 and 316. Conversely, ferritic stainless steels showed a poor corrosion resistance; pitting corrosion initiation was observed even with 1% of chloride by cement mass.

3.2 Duplex stainless steel

Austenitic-ferritic duplex SS have also been proposed for the use in concrete structures. The first study on this steel was performed in 1993 (Nurnberger, Beul & Onuseit, 1993): corrosion occurred neither in carbonated concrete with up to 2.5% Cl⁻ by cement mass nor in cracked alkaline concrete with a chloride content higher than 4.5% Cl⁻ by mass of cement.

The corrosion resistance of commercial ribbed bars of 22-05 stainless steel embedded in concrete with 5% of chlorides by mass of cement added in the mix was also analysed and compared to austenitic SS (Bertolini, Gastaldi, Pedferri & Redaelli, 2002). Results showed that the corrosion rate of duplex SS was negligible in alkaline concrete in which either limestone-portland cement (CEM II/A-L) or ground granulated blastfurnace slag cement (CEM III/B) were used, even during the exposure at 40°C and 90-95% R.H. Furthermore, corrosion initiated neither on bars in specimens in carbonated concrete with 5% of chlorides by cement mass nor in alkaline concrete subjected to ponding with sodium chloride solution, although a chloride content higher than 6% by mass of cement was reached at the steel surface (Bertolini, Gastaldi & Pedferri, 2001).

Potentiostatic polarisation tests performed on these concrete specimens confirmed the outstanding corrosion resistance of 22-05 steel showing that passivity was maintained even at potential values up to +400 mV/SCE both in alkaline and in carbonated concrete (Figure 3) (Bertolini, Gastaldi, Pedferri & Redaelli, 2002).

Conversely, as previously observed, austenitic stainless steels showed a decrease in the corrosion resistance in carbonated concrete with 5% of chloride when they were anodically polarised. The higher corrosion resistance of this SS, compared to 304L and 316L, in carbonated concrete and also in presence of cracks was also observed by (Bautista, Alvarez, Paredes, Velasco & Guzman, 2015; Islam, Bergsma & Hansson, 2013; Van Niejenhuis, Walbridge & Hansson, 2016). This behaviour can be correlated to the high PREN of this SS grade.

The higher corrosion resistance of duplex stainless steel 22-05 with respect to austenitic stainless steels was also confirmed by tests in alkaline (pH 12.6) and neutral (pH 7.5) solutions (Bertolini, Gastaldi, Pedferri & Redaelli, 2002). Nevertheless, it was shown that the presence of welding oxide has a negative effect also on 22-05 stainless steel, since it decreases the passivity range (Figure 4).

In recent years the increase in the cost of the nickel has led manufacturers of SS reinforcing bars to develop low-nickel duplex stainless steel rebars. Attention was initially focused on duplex SS of the type 23-04 and, later on, on SS of the type 21-01. Only few data are available in the literature regarding the corrosion resistance of these steels in concrete. Most of the published studies have been merely aimed at the evaluation of the pitting potential in alkaline solutions.

At the beginning of the 1990s, a study was carried out on 23-04 plain bars embedded in concrete with mixed chlorides up to 3% vs mass of cement and no corrosion was experienced during the 18 months of exposure in urban atmosphere (Pastore, Pedferri, Bertolini, Bolzoni & Cigada, 1991). Later on tests were performed on the cross section of bars of duplex austenitic-ferritic 23-04 and, for comparison, on austenitic 304, 304L, 316 and 316L in solution simulating the concrete pore solution and in solution with a pH of 12.6 at 20°C (Bertolini, Bolzoni, Pastore & Pedferri, 1996; Bertolini, Pedferri & Pastore, 1998). Figure 5 shows the trend of pitting potential as a function of chloride content in solution at pH of 12.6. In the potentiostatic polarisation tests, at +200 mV/SCE, a critical chloride content of 3.5% by mass in solution was found during tests at 40°C for 23-04 duplex SS, whilst for austenitic SS corrosion took place at 4.5% by mass in solution.

Other Authors (Bourgin, Chauveau & Demelin, 2005) showed that in tests in alkaline solutions at pH 12 with 21 g/l of NaCl (about 1.3% Cl⁻ by mass of solution), and at a temperature of 50°C, neither duplex 23-04 nor 22-05 nor austenitic 304L and 316L SS bars suffered pitting corrosion during potentiodynamic polarisation tests.

In potentiostatic polarisation tests at +100 mV/SCE in alkaline solution (pH 13-13.5) at room temperature, 23-04 stainless steel (in pickled condition) showed an average content of chlorides for corrosion initiation of 7.5% by mass of solution (Lysogorski & Hartt, 2006).

With potentiodynamic and potentiostatic polarisation tests at +200 mV/SCE in an alkaline solution (pH = 12.6), at 20°C, the ribbed 23-04 rebars showed a pitting potential of +500/+600 mV/SCE with 5% of chlorides vs mass of solution (in potentiodynamic tests) and the initiation of corrosion with a chlorides content of 7.5-8% vs mass of solutions (in potentiostatic tests) (Bertolini & Gastaldi, 2009; Bertolini & Gastaldi, 2011).

In more recent years, few studies were carried out in concrete contaminated by chlorides, which, however, gave a different indication about the corrosion resistance of the 23-04 duplex stainless steel in comparison to tests in solution (Bertolini & Gastaldi, 2011). As a matter of fact, duplex 23-04 stainless steels showed pitting corrosion initiation even in concrete with 3% of chlorides by cement mass (Bertolini & Gastaldi, 2009).

Therefore, even though tests in solution suggested a corrosion resistance of 23-04 stainless steel similar to that of 304L stainless steel, tests in concrete showed a lower corrosion threshold for the former. This suggests that the behaviour of 23-04 stainless steel in concrete needs to be further investigated.

According to (Van Niejenhuis, Walbridge & Hansson, 2016), in sound concrete, the 23-04 SS exhibited passive behaviour throughout the more than 850 days' exposure to salt brine containing 21% Cl⁻ (no indication of the chloride content at the bar depth at the end of exposure is reported in the paper).

Even a cheaper duplex stainless steel, i.e the 21-01, has been very recently proposed for reinforcing bars.

Although the number of studies dealing with the corrosion resistance of these types of steel is rather modest, the available literature clearly shows that they have a chloride threshold even lower than 23-04 duplex stainless steel. In potentiostatic polarisation tests at +200 mV/SCE in an alkaline solution (pH 12.6), the chloride content for corrosion initiation for the 21-01 was lower than Cl⁻/OH⁻ ratio of 8 (corresponding to about 1% Cl⁻ vs mass of solution), while in the austenitic 316L the Cl⁻/OH⁻ ratio was always higher than 20 (about 3% Cl⁻ vs mass of solution) (Hurley & Scully, 2005; Hurley & Scully, 2006). Another study with potentiostatic polarisation tests in saturated calcium solutions showed that corrosion initiation on the duplex 21-01 steel occurred with 3.5-6% of chloride by mass of solution (Bertolini & Gastaldi, 2009) and showed that the corrosion resistance of this steel is lower than 23-04, 304LN and 316LN steels (Figure 6a).

Others authors (Hartt, Powers & Kessler, 2009) showed that in tests on concrete specimens (exposed in laboratory at room temperature) subjected to ponding, 21-01 steel bars showed a corrosion resistance lower than ferritic 410. The chloride threshold was estimated as the chloride level that led to the initiation of corrosion in 2% of the tested bars; a value of 1.33% of chlorides by mass of cement was evaluated for 21-01 steel which was even lower than the level of 1.63% of chloride by cement mass that was obtained for the ferritic 410.

In another study in chloride bearing concrete, exposed at 20°C and 90% R.H., pitting corrosion took place on 21-01 in concrete specimens with 3% of chloride by cement mass (Bertolini & Gastaldi, 2009).

The previous results seem to be in contrast with the conclusions of some published works that claim that 21-01 stainless steel has a corrosion resistance similar to that of 304L, 316L and 23-04 SS (Bergquist, Iversen & Qvafort, 2005; Sederholm, Almqvist & Randstrom, 2009). The conclusion of these papers is unsubstantiated, since it is not based on the evaluation of the chloride threshold, but it is simply argued from the observation of a similar behaviour of the two grades of steel in mild exposure conditions ($T = 20^{\circ}\text{C}$).

In order to assess the effect of temperature on the corrosion resistance of 21-01 steel, potentiostatic polarisation tests at +200 mV/SCE were carried out in chloride contaminated alkaline solutions (pH 12.6) at 40°C. Figure 6b shows that the chloride content for corrosion initiation on 21-01 stainless steel decreases to about 2%, showing a reduction of about 60% compared to the values at 20°C (Figure 6a). Tests at higher temperature were also carried out on stainless steel bars embedded in concrete. The duplex 21-01 stainless steel suffered pitting corrosion in concrete with 2.5% of chloride by cement mass exposed to 40°C.

3.3 Final consideration

The previous analysis of the literature shows that the pitting resistance equivalent number ($\text{PREN} = \% \text{Cr} + 3.3\% \text{Mo} + 16-30\% \text{N}$), which is normally related to the ability of stainless steel to resist pitting attack in neutral environments, may not be reliable in alkaline environments such as concrete. In particular, the presence of molybdenum seems to have a lower effect on the corrosion resistance, as confirmed by the small differences observed between 304LN (without molybdenum) and 316LN; furthermore nickel has shown to give a positive effect on corrosion resistance especially in simulated tropical environment (Bertolini, Bolzoni, Pastore & Pedferri, 1996; Elsener, Addari, Coray & Rossi, 2011a; Elsener, Addari, Coray & Rossi, 2011b; Bertolini & Gastaldi, 2011). In carbonated concrete (or in the presence of cracks, since SS are directly exposed to the atmosphere, as discussed in Van Niejenhuis, Walbridge & Hansson, 2015), conversely, PREN index might still be a useful ranking index.

Furthermore these results suggest that, depending also on the experimental techniques adopted by different researchers, a wide range of values of chloride threshold is reported. Nevertheless, the studies are in agreement to show that different grades of stainless steel have different chloride threshold for corrosion initiation. In general a very good behaviour is reported for duplex 22-05 and austenitic 316L stainless steels, even in concrete with high chloride contamination (e.g. 5% of chlorides by mass at the steel surface) and exposed to hot environments (e.g. 40°C or higher). These types of SS therefore may be appropriate for the use in harsh environments where high chloride contamination is associated to wet and hot exposure conditions. The austenitic 304L showed, in concrete, a slightly lower corrosion resistance than 316L and 22-05. All other types of stainless steel bars considered in this review showed to have a lower corrosion resistance and therefore are likely to be appropriate only in milder environments. Anyway, the dissimilar testing procedures used in the different works make the definition of design values of the chloride threshold for the different grades of stainless steel exposed to different environmental conditions difficult. In fact, only general information about the corrosion resistance of the austenitic and duplex stainless steel are reported on technical reports available to the designer (The Concrete Society, 1998 & 2008). In Figure 7 an attempt has been made to depict approximate values of the range of the C_{th} for the different grades of SS rebars, based on previously reported data. Values reported in this figure should be assumed only as indicative values. In the figure it can be observed that, although indicative, the range of C_{th} for the 21-01 SS is between 1.33 and 3% by mass of cement and for the XM-28 SS is between 2.3 and 5% by mass of cement. For the other SS only the minimum value can be detected, considering that, in real cases, chloride contents higher than 5% by mass of cement are unlikely reached at the concrete cover depth of the steel surface and, hence, Figure 7 has been limited to this value (values suggested in literature exceeding 5% have been identified by a rightward arrow). The minimum values of C_{th} for the austenitic 304 and 316 SS were around 3.5% by mass vs cement, detected under anodic polarisation (Sorensen, Jensen & Maahn, 1990); whilst the C_{th} minimum value for the duplex 23-04 SS was 2.7% by mass of cement. For the duplex 22-05 SS values higher than 5% by mass of cement were detected in all the studies and, hence, it can be considered that the C_{th} for this SS is higher than 5% by mass of cement.

3.4 Practical aspects

As far as practice at the construction site is concerned, it should be observed that compared with other types of corrosion resistant rebars (such as epoxy coated or galvanised steel), corrosion resistance is a bulk property of stainless steel. Therefore, the integrity of stainless steel is unaffected if its surface is cut or damaged during handling. Obviously, this does not apply to clad bars (i.e. usual carbon steel bars clad with a thin layer of stainless steel) that in some cases have been proposed as a cheaper alternative to solid stainless steel bars (which have not been considered in this paper).

The chemical composition of the stainless steel reinforcement guarantees the weldability (mainly obtained by decreasing the carbon content). Nevertheless, welding is not recommended under site conditions unless adequate control is maintained; in fact, welding may have some negative consequences with regard to mechanical properties and corrosion resistance. Welding oxides and the mill scale, which negatively affect the corrosion resistance, should be removed. As a matter of fact, the good corrosion resistance of austenitic grades may be affected by the presence of oxide produced at high temperature (i.e. mill scale or welding oxides). The influence of welding oxide scale on the surface of the austenitic SS was analysed by several authors. All of the published studies show that high temperature oxides have a deleterious effect on the corrosion behaviour of the stainless steel bars. For instance, it was shown that, in the presence of a welding oxide scale on the surface of austenitic 304 and 316 SS embedded in mortar, the chloride threshold decreased from up to 8% by cement mass to 5-8% in the specimens in free corrosion condition (exposed outdoor) and from 3.5-5% to 1-2% in potentiostatic tests at +200 mV/SCE (Sorensen, Jensen & Maahn, 1990). In reference (Nurnberger, Beul & Onuseit, 1993) it was demonstrated that ferritic stainless steel, that did not show pitting corrosion in alkaline concrete containing up to 2.5% Cl⁻, was susceptible to pitting attack in the presence of welding oxide in specimen with 1% Cl⁻. Pits were also observed on the welded bars of 316Ti stainless steel bars embedded in cracked concrete specimens where a chloride content of about 4.5% by mass of cement was reached at the steel surface. These results show that the corrosion resistance of the stainless steel bars is remarkably affected by the presence of high temperature oxide scale. Therefore it is good practice to fully remove both the mill scale and welding oxides from the surface of the steel.

The coefficient of thermal expansion of austenitic steels is higher (about $1.8 \cdot 10^{-5} \text{ }^\circ\text{C}^{-1}$) than that of concrete and of the traditional carbon steel bars (about $10^{-5} \text{ }^\circ\text{C}^{-1}$); austenitic-ferritic steels are in an intermediate position. Although this may raise concern about differential expansion especially during fire, no cases of damage have been reported. Furthermore, the thermal conductivity of austenitic stainless steel is much lower than that of carbon steel and thus the increase in temperature throughout the steel is delayed. Finally stainless steels generally retain more of their room temperature strength than carbon steel above temperatures of about 550 °C, and more of their stiffness than carbon steel across the whole temperature range (Gardner & Ng, 2006). Austenitic stainless steels are generally considered non-magnetic (although cold drawing can increase the magnetic permeability) (Bertolini, Elsener, Pedferri, Redaelli & Polder, 2013).

In the past, concern has been expressed about the risk of galvanic corrosion of black steel induced by coupling with SS bars, in order to use the more expensive SS bars only where it is necessary to fulfil the durability requirements. In principle interaction of metals with different electrochemical behaviour could both promote corrosion initiation (e.g. due to anodic polarisation) or increase the corrosion rate (due to macrocell effects) in one of the coupled metals. Experimental tests (Bertolini, Pedferri & Pastore, 1998; Bertolini, Gastaldi, Pastore, Pedferri & Pedferri, 1998a, Bertolini, Gastaldi, Pastore, Pedferri & Pedferri, 1998b) showed that when both carbon steel and stainless steel rebars are passive and embedded in aerated concrete, the macrocell does not produce appreciable effects, since both steels have almost the same free corrosion potential. Only when the black steel undergoes corrosion (i.e. due to bad design or execution that does not prevent chloride penetration for the expected service life), the macrocell current becomes significant. However, as shown in Figure 8, the increase in corrosion rate on carbon steel embedded in chloride-contaminated concrete due to galvanic coupling with austenitic SS (316L) is significantly lower than the increase brought about by coupling with passive black steel (Concrete Society, 1998; Bertolini, Pedferri & Pastore, 1998; Bertolini, Gastaldi, Pastore, Pedferri & Pedferri, 1998a). Since corroding black steel is always coupled with passive areas of black steel, the further coupling with stainless steel minimises the

increase of the corrosion rate. By means of cathodic polarisation curves it was shown that this behaviour is explained by higher overvoltage for the cathodic reaction of oxygen reduction on austenitic stainless steel with respect to carbon steel (Figure 9).

As a consequence of these findings, even in technical reports it is stated that stainless steel bars will minimise problems which could occur in neighbouring corroding and passive areas (The concrete society, 1998).

Furthermore, increased galvanic current can occur in the presence of welding scale on stainless steel. Oxide scale produced at high temperatures increases the macrocell current density generated by stainless steels, to the same order of magnitude or even greater than that produced by coupling with carbon steel (Figure 8) (Bertolini, Gastaldi, Pastore, Pedferri & Pedferri, 1998a). This risk can be avoided by removing the welding scale, either mechanically or by pickling.

Further studies have confirmed that macrocell formed when duplex 22-05 stainless steel was electrically connected with corroding carbon steel is lower with respect to those due to the coupling with the passive carbon steel. Nevertheless a higher macrocell current density was generated with respect to those produced with an austenitic stainless steel cathode. This behaviour can be explained with the different kinetics of oxygen reduction on duplex stainless steel; in fact duplex stainless steel has shown a lower overvoltage for the cathodic reaction with respect of those of austenitic stainless steel (Gojkovic, Zecevic, Obradovic & Drazic, 1998; Sagües, Virtanen & Schmuki, 2005). This suggests that the cathodic reaction is less inhibited in steels with the presence of the ferritic phase together with the austenitic one. No data are available for duplex stainless steel with lower nickel content (i.e. 23-04 and 21-01).

4. Applications

SS rebars have 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 long service lives. In several structures the required amount of SS rebars and, hence, the entire cost of a structure, were limited through the use of SS in the outermost horizontal and vertical reinforcing layer of the most exposed parts of the structures, while the remaining reinforcement was ordinary carbon steel reinforcement.

The first reported application of stainless steel bars dates back to 1941 for the construction of the Progreso de Castro Pier in Yucatán (Mexico), in which plain bars of 304 were used (Castro-Borges et al., 2002). Later in Europe stainless steel rebars have been widely used since the mid-80s, while in North America their use has been progressively growing only since the mid-90s. Table 4 shows some examples of structures, built or restored in recent years, where SS rebars of different grades were employed

(https://www.nickelinstitute.org/~media/Files/TechnicalLiterature/Ni_StainlessSteel-Rebar-LD.ashx. June 2016; <http://www.stainlesssteelrebar.org/applications/>. June 2016; <http://www.reval-stainless-steel.com/applications.html>. June 2016; Gupta, 2016). For instance, the grade 304 was employed for the construction of Schaffhausen Bridge on the Rhine River in Switzerland, for which a service life of 80 years was required, whilst the steel grade 22-05 was used for the tower of the Stonecutters Bridge which connects Nam Wan Kok, Tsing Yi Island and Stonecutters Island to provide the required combination of strength and corrosion resistance through the entire service life of 120 years (Hui & Wong, 2009).

From Table 4 it can be observed that stainless steel rebars are usually utilised in extremely corrosive marine environments, for instance in the Coastal Protection at Cromer, UK, or in the presence of massive chloride contamination from deicing salts, for instance in the Värtan Junction, in Sweden. However SS rebars are also employed to prevent carbonation-induced corrosion, as in the GuildHall Yard East in London, which is a building hosting a Roman amphitheatre, built in 2000 with a design service life of 750 years, where SS rebars were used for the new reinforced concrete walls. SS rebars are both employed for the construction of new structures or for the repair and renovation of existing structures where very long design lives are required. As a matter of fact, SS rebars can be beneficial in those repair cases where carbon steel bars are corroded to such an extent that local replacement or additional reinforcement is needed as part of a repair or to control cracking where concrete cover is low in the repaired zones. In the latter case fine welded mesh reinforcement is often used. At this regard, some examples are the rehabilitation of walls of the Thorold Tunnel, Canada in 2004 or the maintenance of the Gladstone Bridge, Australia, which, although built in 1960, showed in recent years

corrosion of the reinforcing carbon steel on the deck. In the repair work of this bridge stainless steel ribbed bars type 316L joined with the original carbon steel were used.

Finally, in Table 4 it can be observed that stainless steel rebars are commonly used to guarantee long service lives, also higher than 100 years; often the indications on the required service life are lacking or service lives also of the order of 300 years, in marine environments, are prescribed. In the latter case, some doubts could arise that the stainless steel grade employed for those structures could really guarantee such a long design life.

In the framework of the durability, but also of sustainability of reinforced concrete structures, a promising and innovative application of SS rebars can be considered when chloride-contaminated raw materials are used for concrete. As a matter of fact, the construction industry could greatly benefit from the use of chloride-contaminated raw materials for the production of concrete, since great amounts of natural resources such as fresh water or mined rocks for aggregates could be saved. Within the framework of ERA-NET Plus Infravation 2014, the SEACON project "Sustainable concrete using seawater, salt-contaminated aggregates, and non-corrosive reinforcement" was started, with the aim of demonstrating the safe utilisation of seawater and salt-contaminated aggregates for a sustainable concrete production when combined with non-corrosive reinforcement (GFRP and stainless steel bars) (Lollini et al., 2016; Lollini et al. 2017; Redaelli et al. 2017).

5. Concluding remarks

Stainless steel rebars have been widely used worldwide both for the construction of new structures and infrastructures and the repair of existing structures. Laboratory and field experience has shown that stainless steel bars can prevent corrosion even in reinforced concrete structures exposed to the most severe environments and that they are able to significantly increase the chloride threshold, by a factor of even 4-10, compared to conventional carbon steel bars.

Furthermore they can be coupled with ordinary black steel bars, since the effect of the galvanic coupling is negligible. Hence, they can be used only in selected parts of the structures, exposed to the most aggressive exposure conditions, employing the ordinary black steel bars in the other parts.

Today a range of stainless steel grades is commercially available which provide different corrosion resistances and costs. Nevertheless, in order to evaluate the grade of stainless steel to be used to guarantee the target durability requirements for the construction of reinforced concrete structures, the designers need to know their corrosion resistance and, in particular, the critical chloride threshold for corrosion initiation.

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Table 1 – Grades of stainless steel most commonly used as reinforcement: main alloy elements (% by mass), designation and microstructures.

<i>Steel name</i>	<i>Designation</i>			<i>Microstructure</i>	<i>Main alloy elements (% by mass)</i>			
	<i>EN 10088-1</i>	<i>AISI</i>	<i>UNS</i>		<i>Cr</i>	<i>Ni</i>	<i>Mo</i>	<i>Other elements</i>
304L	1.4307	304L	S30403	Austenitic	17.5-19.5	8-10	-	-
316L	1.4404	316L	S31603	Austenitic	16.5-18.5	10-13	2-2.5	-
22-05	1.4462	318L	S31803	Duplex	21-23	4.5-6.5	2.5-3.5	0.1-0.22 N
23-04	1.4362	-	S32304	Duplex	22-24	3.5-5.5	0.1-0.6	0.05-0.2 N
21-01	1.4162	-	S32101	Duplex	21-22	1.4-1.7	0.1-0.8	4-6 Mn, 0.2-0.25 N
XM-28	-	-	S24100	Austenitic	16.5-19	0.5-2.5	-	11-14 Mn, 0.2-0.45 N

Table 2 – Published C_{th} values obtained on austenitic stainless steel bars (Test in: C = concrete; M = mortar; S = solution; Method: F = free corrosion conditions; PS = potentiostatic polarisation tests; PD = potentiodynamic polarisation tests).

Type of SS	Type of bar	Test in	Cl ⁻ (%)	Method	Exposure		Duration (years)	C_{th}	note	References
					Location	T/R.H.				
302	plain	C	up to 3.2	F	Industrial environment (Beckton, UK)		22	>3	small pitting attacks after 22 years	Brown, Harrop & Treadaway, 1978; Flint & Cox, 1988; Treadaway, Cox & Brown, 1989; Cox & Oldfield, 1996
302	plain	C	-	F	marine environment (Langstone Harbour, UK)		22	>3	no corrosion even after 22 years in cracked specimens	Brown, Harrop & Treadaway, 1978; Flint & Cox, 1988; Treadaway, Cox & Brown, 1989; Cox & Oldfield, 1996
304	ribbed	M	8	F	outside environment (Denmark)		0.4	>8	in presence of welding oxide scale C_{th} decrease to 5-8%	Sorensen, Jensen & Maahn, 1990
304	ribbed	M	3.5-5	PS				3.5+5	test at +200 mV/SCE. In presence of welding oxide scale C_{th} decrease to 1-2%	Sorensen, Jensen & Maahn, 1990
304	plain	C	up to 3	F	outside environment (Milan)		1.5	>3		Pastore & Pedferri, 1991
304L	plain	C	up to 6	F	exposure cycles	40°C/95-98%	0.67	>6	in carbonated concrete up to 4%	Bertolini, Gastaldi, Pastore & Pedferri, 2000
304L	plain	C	up to 4	F	exposure cycles	40°C/95-98%	0.67	>4	in presence of simulated welding oxide scale	Bertolini, Gastaldi, Pastore & Pedferri, 2000
304L	ribbed	C	-	F	ponding with NaCl			>6		Bertolini, Gastaldi & Pedferri, 2001
304L	ribbed	C	5	PS					Test up to +600 mV/SCE. In alkaline concrete no corrosion up to a potential of +400 mV/SCE; in carbonated concrete corrosion occurred at +50 mV/SCE	Bertolini, Gastaldi, Pedferri & Redaelli, 2002
304L	ribbed	S	up to 10	PD		20°C		9-10	pH = 12.6 and pH = 7.5	Bertolini, Gastaldi, Pedferri & Redaelli, 2002
304	ribbed	C	up to 4	F	constantly wetted		2	>4		García-Alonso et al., 2007a
304		S	1.3	PD		50°C		>1.3	pH = 12	Bourgin, Chauveau & Demelin, 2005
304	ribbed	M	up to 5	F	exposure cycles	40+95%	3	>5		García-Alonso et al., 2007a
304	ribbed	C	-	F	ponding			>6		Hartt, Powers & Kessler, 2009
304L	ribbed	C	up to 8	F	climatic chamber	20°C/90%		>8		Bertolini & Gastaldi, 2009
304L	ribbed	C	up to 8	F	exposure cycles	20°C/40%		>8		Gastaldi & Bertolini, 2014
316	plain	C	up to 3.2	F	Industrial environment (Beckton, UK)		22	>3	no corrosion even after 22 years in cracked specimens	Brown, Harrop & Treadaway, 1978; Flint & Cox, 1988; Treadaway, Cox & Brown, 1989; Cox & Oldfield, 1996
316	plain	C	-	F	marine environment (Langstone Harbour, UK)		22	>3	no corrosion even after 22 years in cracked specimens	Brown, Harrop & Treadaway, 1978; Flint & Cox, 1988; Treadaway, Cox & Brown, 1989; Cox & Oldfield, 1996
316	ribbed	M	8	F	outside environment (Denmark)		0.4	>8	in presence of welding oxide scale C_{th} decrease to 5-8%	Sorensen, Jensen & Maahn, 1990
316	ribbed	M	3.5-5	PS				3.5+5	Test at +200 mV/SCE. In presence of welding oxide scale C_{th} decrease to 1-2%	Sorensen, Jensen & Maahn, 1990
316	plain	C	up to 3	F	outside environment (Milan)		1.5	>3		Pastore & Pedferri, 1991

316Ti	ribbed	C	up to 2.5	F				>2.5	in alkaline and carbonated concrete	Nurnberger, Beul & Onuseit, 1993; Nurnberger & Beul, 1999
316Ti	ribbed	C	-	F	spraying with Cl ⁻ solution		2.5	>4.5	also in cracked concrete	Nurnberger, Beul & Onuseit, 1993; Nurnberger & Beul, 1999
316Ti	ribbed	C	-	F	spraying with Cl ⁻ solution		2.5	<4.5	in presence of welding oxide scale	Nurnberger, Beul & Onuseit, 1993; Nurnberger & Beul, 1999
316L	ribbed	C	-	F	ponding with NaCl			>6		Bertolini, Gastaldi & Pedferri, 2001
316L	plain	C	up to 6	F	exposure cycles	40°C/95-98%	0.67	>6	in carbonated concrete up to 4%	Bertolini, Gastaldi, Pastore & Pedferri, 2000
316L	plain	C	up to 4	F	exposure cycles	40°C/95-98%	0.67	4	in presence of simulated welding oxide scale	Bertolini, Gastaldi, Pastore & Pedferri, 2000
316L		S	1.3	PD		50°C		>1.3	pH = 12	Bourgoin, Chauveau & Demelin, 2005
316L	ribbed	C	5	PS					test at +600 mV/SCE. In alkaline concrete no corrosion up to a potential of +400 mV/SCE; in carbonated concrete corrosion occurred at +150 mV/SCE	Bertolini, Gastaldi, Pedferri & Redaelli, 2002
316L	ribbed	S	up to 10	PD		20°C		9-10	pH = 12.6 and pH = 7.5	Bertolini, Gastaldi, Pedferri & Redaelli, 2002
316LN		S	up to 7	PD		20°C		>7		Hurley & Scully, 2005
316LN		S		PS		20°C		3	test at +200 mV/SCE	Hurley & Scully, 2005
316	ribbed	C	up to 4	F	constantly wetted		2	>4		M.C. Garcia-Alonso et al., 2007a
316	ribbed	M	up to 5	F	exposure cycles	40+95%	3	>5		M.C. Garcia-Alonso et al., 2007a
316L	ribbed	C	-	F	ponding			>6		Hartt, Powers & Kessler, 2009
316L	ribbed	C	up to 8	F	climatic chamber	20°C/90%		>8		Bertolini, Gastaldi, 2009
316L	ribbed	C	up to 8	F	exposure cycles	20°C-40°C		>8		Gastaldi, Bertolini, 2014
XM-28	ribbed	C	up to 5	PS				2.3+5.5	test at +200 mV/SCE for 24h	Gastaldi, Lollini, Bertolini, 2013
XM-28	ribbed	C	5	PS				<5	test at +200 mV/SCE for 4 days	C.B. Van Niejenhuis, T.W. Bandura, C.M. Hansson, 2016
XM-28	ribbed	C	3	PS				>3	test at +100 mV/SCE for 4 days	C.B. Van Niejenhuis, T.W. Bandura, C.M. Hansson, 2016
XM-28	ribbed	C	-	F	exposure to salt brine with 21% Cl ⁻		2.3			C. B. Van Niejenhuis, S. Walbridge, C. M. Hansson, 2016

Table 3 – Published C_{th} values obtained on duplex stainless steel bars (Test in: C = concrete; M = mortar; S = solution; Method: F = free corrosion conditions; PS = potentiostatic polarisation tests; PD = potentiodynamic polarisation tests).

Type of SS	Type of bar	Test in	Cl ⁻ (%)	Method	Exposure		Duration (years)	C_{th}	note	References
					Location	T/R.H.				
22-05	ribbed	C	up to 2.5	F				>2.5	in alkaline and carbonated concrete	Nurnberger, Beul & Onuseit, 1993; Nurnberger & Beul, 1999
22-05	ribbed	C	-	F	spaying with Cl ⁻ solution		2.5	>4.5	also in cracked concrete	Nurnberger, Beul & Onuseit, 1993; Nurnberger & Beul, 1999
22-05	ribbed	C	5	PS				>5	test up to +600 mV/SCE. In alkaline and carbonated concrete no corrosion up to a potential of +600 mV/SCE	Bertolini, Gastaldi, Pedferri & Redaelli, 2002
22-05	ribbed	C	-	F	ponding with NaCl			>6		Bertolini, Gastaldi & Pedferri, 2001
22-05	ribbed	S	up to 10	PD		20°C		>10	pH = 12.6 and pH = 7.5	Bertolini, Gastaldi, Pedferri & Redaelli, 2002
22-05		S	1.3	PD		50°C		>1.3	pH = 12	Bourgini, Chauveau & Demelin, 2005
22-05	ribbed	C	-	F	ponding with NaCl		2.3		no corrosion even in cracked specimens	Van Niejenhuis, Walbridge & Hansson, 2016
23-04	plain	C	up to 3	F	outside environment (Milan)		1.5	>3		Pastore, Pedferri, Bertolini, Bolzoni & Cigada, 1991
23-04	ribbed	S	up to 10	PS		20°C		7.5-8	pH = 12.6	Bertolini, Gastaldi, 2009
23-04		S	1.3	PD		50°C		>1.3	pH = 12	Bourgini, Chauveau & Demelin, 2005
23-04		S		PS		20°C		7.5	test at +100 mV/SCE. pH = 13-13.5	Lysogorski & Hartt, 2006
23-04	ribbed	C	up to 8	F	inside exposure	20°C/90%		3		Bertolini, Gastaldi, 2009
23-04	ribbed	C		F	ponding with NaCl		2.3		no corrosion at the end of exposure	Van Niejenhuis, Walbridge & Hansson, 2016
21-01		S	up to 7	PD		20°C		>7		Hurley & Scully, 2005
21-01		S		PS		20°C		1	test at +200 mV/SCE	Hurley & Scully, 2005
21-01	ribbed	S	up to 10	PS		20°C		3.5-6	pH = 12.6	Bertolini, Gastaldi, 2009
21-01		C	up to 6	F	ponding			1.33		Hartt, Powers & Kessler, 2009
21-01	ribbed	C	Up to 3	F	inside exposure	20°C/90%		<3		Bertolini, Gastaldi, 2009

Table 4 – Examples of applications of different grades of SS rebars (un = unknown).

Type of SS	Structure	Location	Date	SL (years)	Ref.
304	Bridge on I-696	Detroit, Michigan, USA	1984	un	www.nickelinstitute.org
304L	Schaffhausen bridge	River Rhine, Switzerland	1995	80	www.stainlesssteelrebar.org
304LN	Guildhall	East London	2000	750	Bertolini et al. 2013
316	Underpass	Newcastle, Tyneside, UK	1995	un	www.nickelinstitute.org
316L	Broadmeadow Bridge	Dublin, Ireland	2003	un	www.stainlesssteelrebar.org
316LN	Gladstone Bridge	Queensland, Australia		un	www.reval-stainless-steel.com
	Bridge	Ajax, Ontario, Canada	1998	un	www.nickelinstitute.org
	Thorold Tunnel	Ontario, Canada	2004	un	www.nickelinstitute.org
21-01	Gateway Bridge	South-east Queensland, Australia	2011	300	[www.stainlesssteelrebar.org
	Buddhist Temple	Thailand	2013	300	www.stainlesssteelrebar.org
	Junction Värtan	Stockholm, Sweden	2015	un	www.stainlesssteelrebar.org
22-05	Ramp for Garden State Parkway	New Jersey, USA	1998	un	www.nickelinstitute.org
	Haynes Inlet Slough Bridge	Oregon, USA	2004	120	www.stainlesssteelrebar.org
	Belt Parkway Bridge	Brooklyn, USA	2004	100	www.nickelinstitute.org
	Driscoll Bridge	New Jersey, USA	2004	un	www.nickelinstitute.org
	Siena Footbridge	Siena, Italy	2006	120	www.nickelinstitute.org
	Stonecutters Bridge	Hong Kong, China	2009	120	[www.stainlesssteelrebar.org
	Sea wall construction	Arabian Gulf	2009	un	www.nickelinstitute.org
	Little Bay Bridge	Newington, New Hampshire, USA	2011	un	Gupta, 2016
	Sakonnet River Bridge	Rhode Island, USA	2012	un	www.nickelinstitute.org
	Hurdman Bridge	Ontario, Canada	2014	un	www.stainlesssteelrebar.org
	Bayonne Breakwater	Bayonne, France	2014	un	www.stainlesssteelrebar.org
	Burgoyne Bridge	St. Catharine's, Ontario, Canada	2016	un	Gupta, 2016
	23-04	Cameron Heights Dr. Bridge	Edmonton, Alberta, Canada	2010	un
S. Saskatchewan River Bridge, Medicine Hat		Alberta, Canada	2011	un	www.nickelinstitute.org
Caminada Bay Bridge		Louisiana, USA	2011	un	Gupta, 2016
Hastings Bridge		Minnesota, USA	2012	100+	www.stainlesssteelrebar.org
Riverwalk		Brisbane, Australia	2013	100	www.stainlesssteelrebar.org
Allt Chonoglias Bridge		Scotland, UK	2013	120	www.stainlesssteelrebar.org
Coastal Protection		Cromer, UK	2014	50	www.stainlesssteelrebar.org
Kenaston Overpas		Winnipeg, Manitoba, Canada	2014	un	www.nickelinstitute.org
Daniel Hoan Bridge		Milwaukee, Wisconsin, USA	2014	un	Gupta, 2016
Macau Bridge		Hong Kong - Zhuhai - China	2016	120	www.stainlesssteelrebar.org
New Champlain Bridge	Montreal, Canada	2016	un	www.stainlesssteelrebar.org	
XM-28	Light rail transit	Edmonton, Alberta, Canada	2012	un	Gupta, 2016
	Osborne Bridge	Winnipeg, Manitoba, Canada	2012	un	Gupta, 2016
	Pulasky skyway	Newark, Jersey City, USA	2014	un	Gupta, 2016
	Kosciuszko Bridge	New York City, USA	2019	un	Gupta, 2016

List of figures

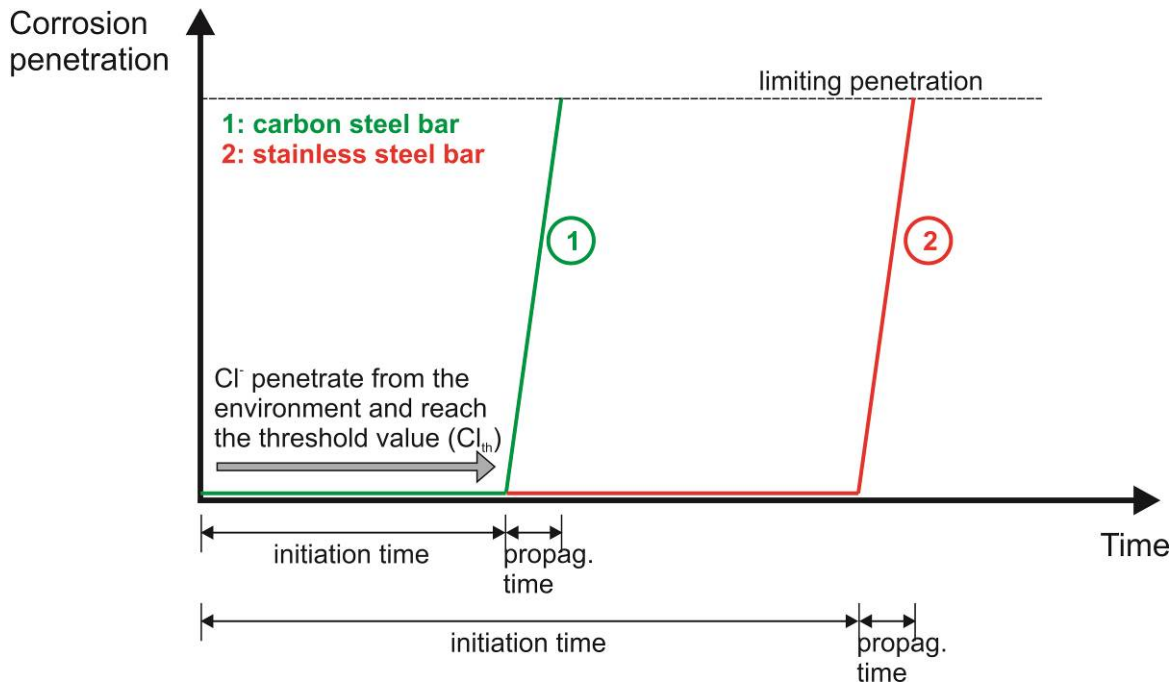


Figure 1 - Schematic time-evolution of steel corrosion in RC exposed to chlorides (Tuutti's diagram) for carbon steel and stainless steel bars.

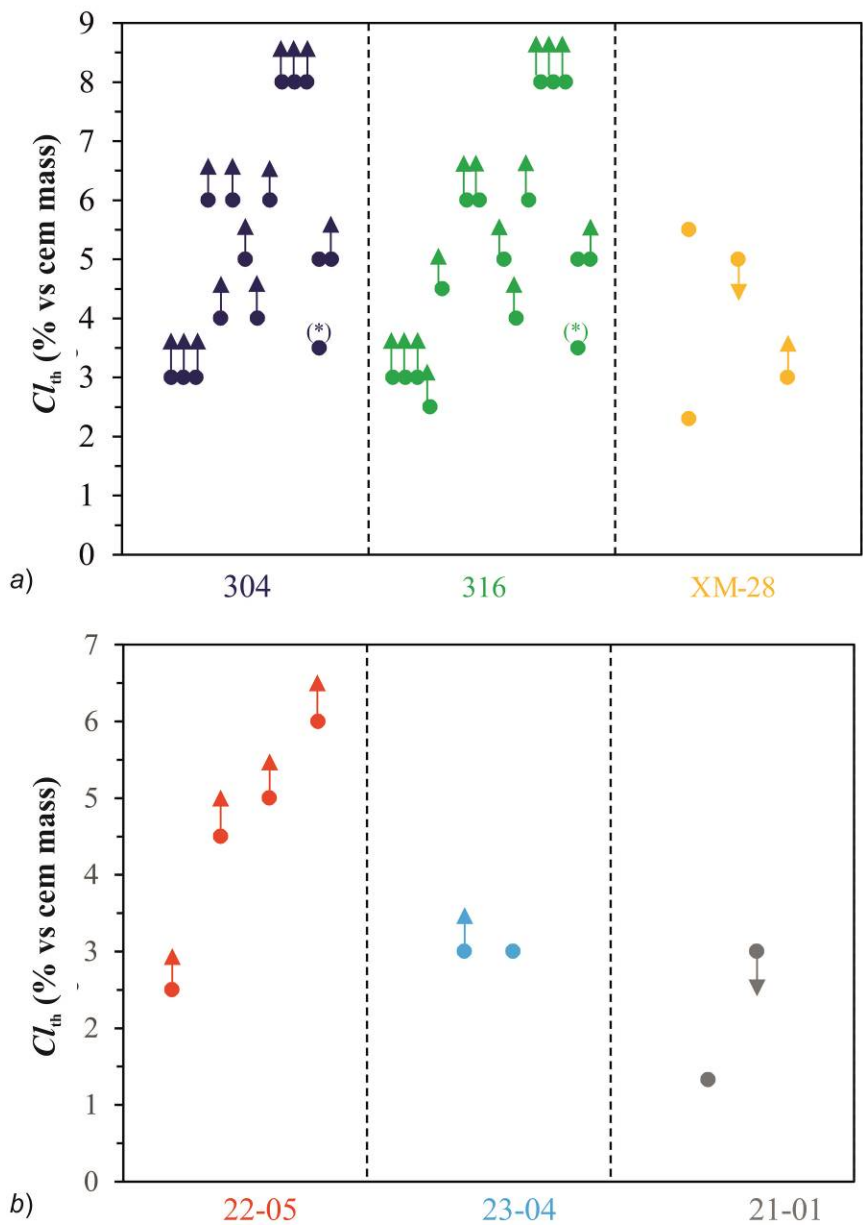


Figure 2 - Cl_{th} values obtained, in concrete and mortar tests, in the literature on austenitic (a) duplex (b) stainless steel bars (\uparrow = value higher than; \downarrow = value lower than; * = value detected under anodic polarisation by (Sorensen, Jensen & Maahn, 1990)).

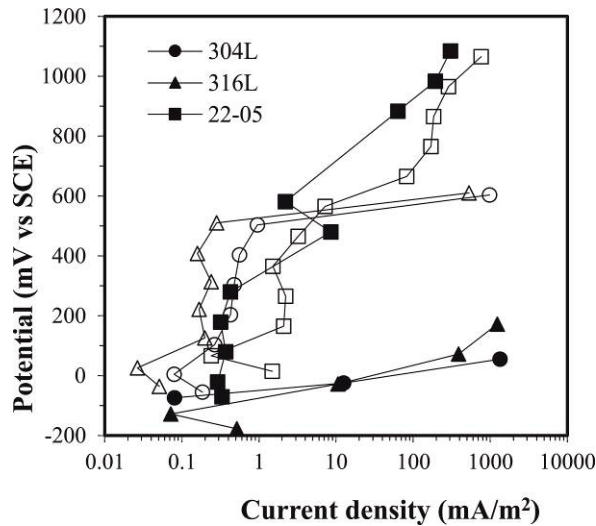


Figure 3 - Results of potentiostatic polarisation tests on steel bars (ϕ 8 mm) embedded in alkaline (empty symbols) and carbonated (black symbols) concrete with 5% chloride by mass of cement (L. Bertolini, M. Gastaldi, P. Pedferri, E. Redaelli, 2002).

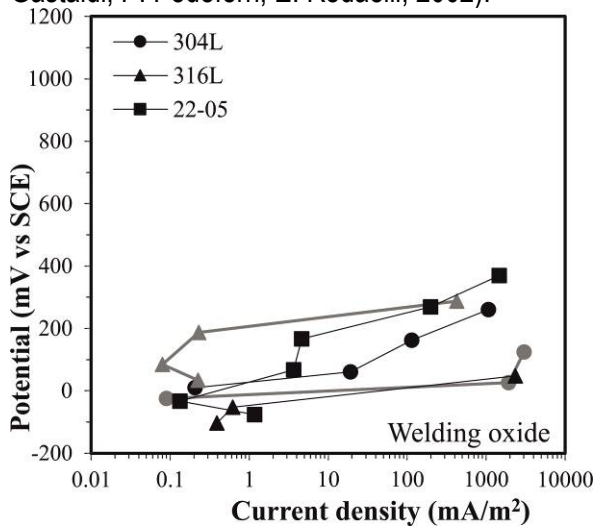


Figure 4 - Results of potentiostatic polarisation tests on stainless steel bars (ϕ 8 mm) with simulated welding oxide in concrete with 5% Cl⁻. Grey symbols show tests on annealed bars (Bertolini, Gastaldi, Pedferri & Redaelli, 2002).

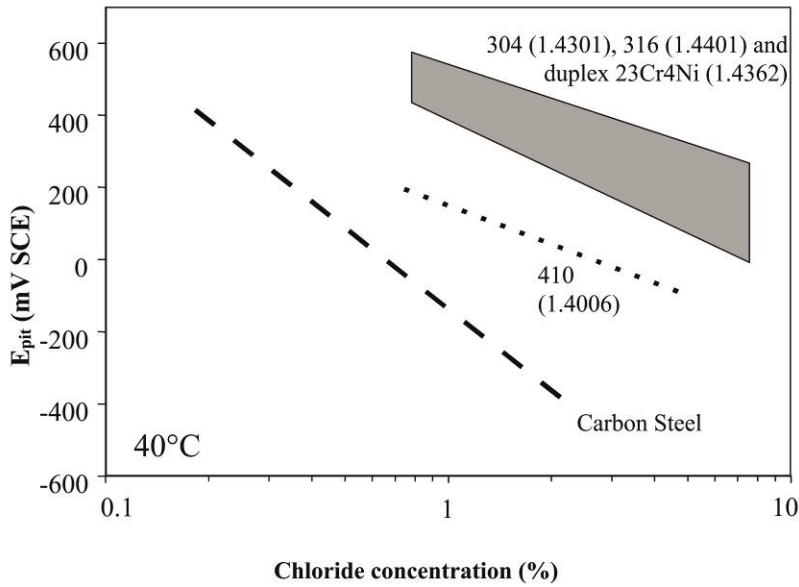
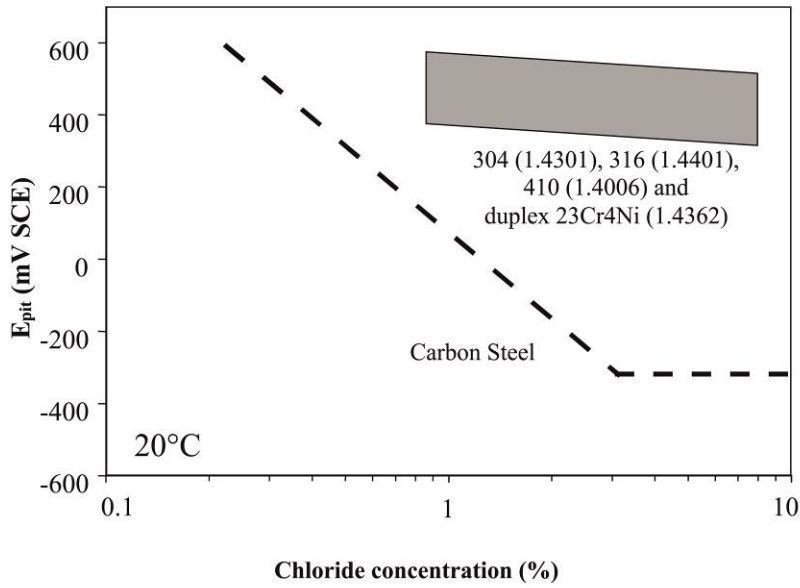
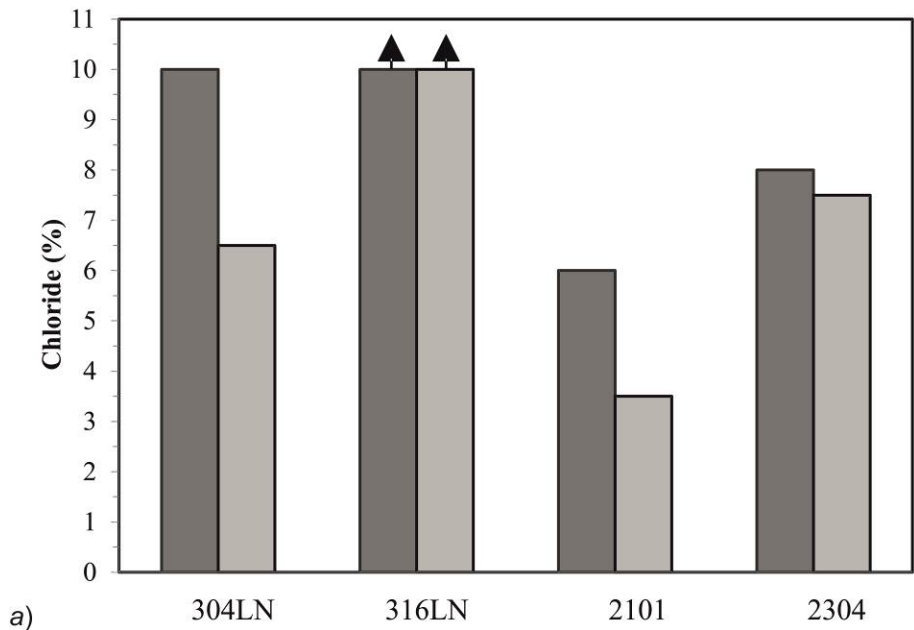
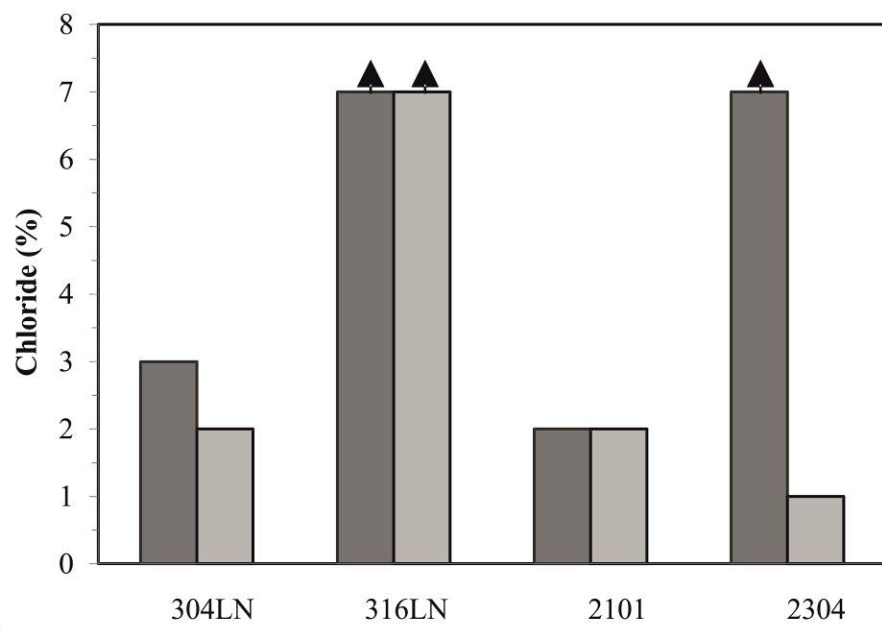


Figure 5 - Schematic variations of pitting potential for austenitic 304 and 316, duplex 23-04 and martensitic 410 stainless steels, as a function of the chloride content in saturated $\text{Ca}(\text{OH})_2$ solution, at 20°C (a) and 40°C (b) (Bertolini, Bolzoni, Pastore &.Pedefferri, 1996; Bertolini, Pedefferri & Pastore,1998).



a)



b)

Figure 6 - Chloride content for pitting corrosion initiation in potentiostatic polarisation tests at +200 mV/SCE in saturated Ca(OH)₂ solution at 20°C (a) 40°C (b) carried out on two replicate specimens for each grade of SS (Bertolini & Gastaldi, 2009).

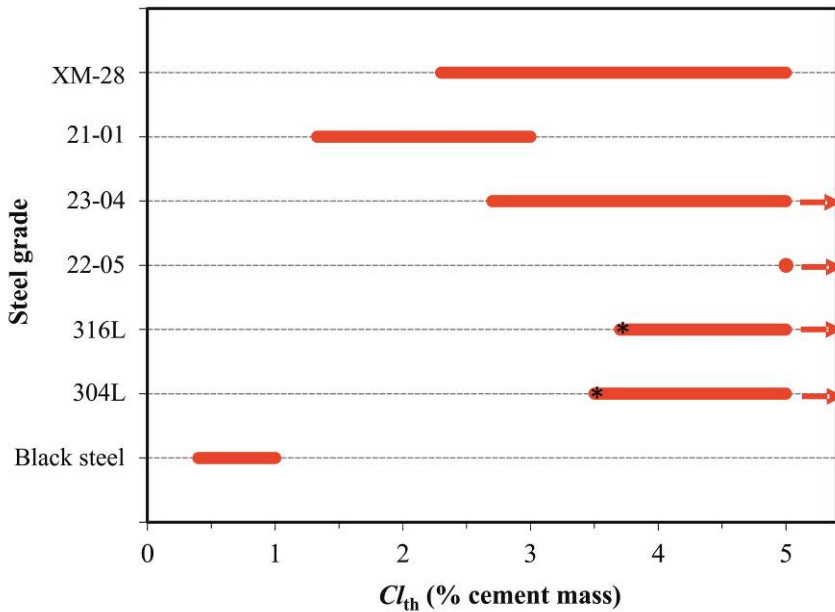


Figure 7 – Approximate values of C_{th} for different grades of stainless steel rebars obtained from the different studies (* = min. value detected under anodic polarisation by Sorensen, Jensen & Maahn, 1990).

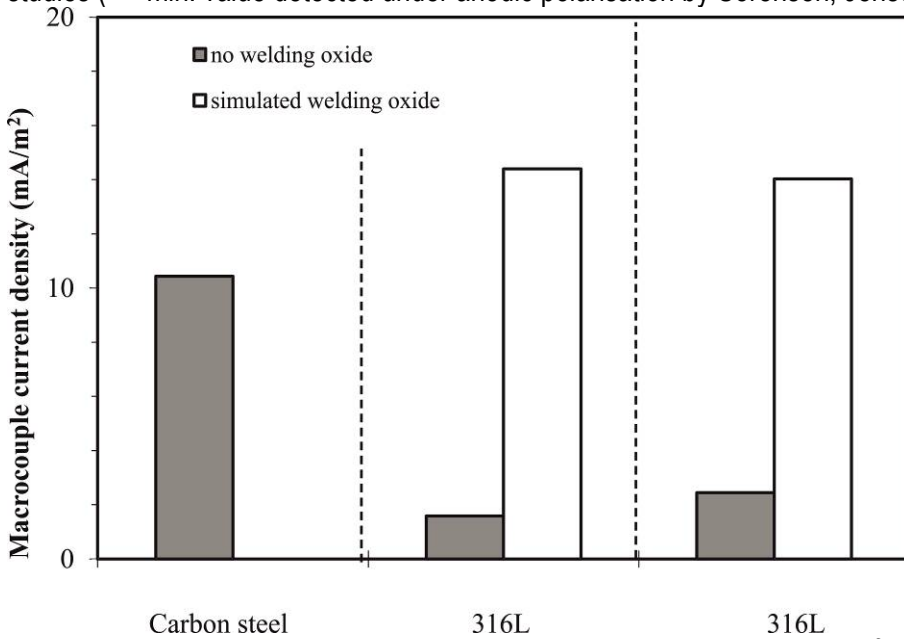


Figure 8 - Macrocell current density exchanged between a corroding bar of carbon steel in 3% chloride contaminated concrete connected with a (parallel) passive bar of: carbon steel in chloride free concrete, 316L stainless steel in chloride free concrete and in 3% chloride contaminated concrete (20°C, 95% R.H.). Results on stainless steel bars with simulated welding scale are also reported (Concrete Society, 1998).

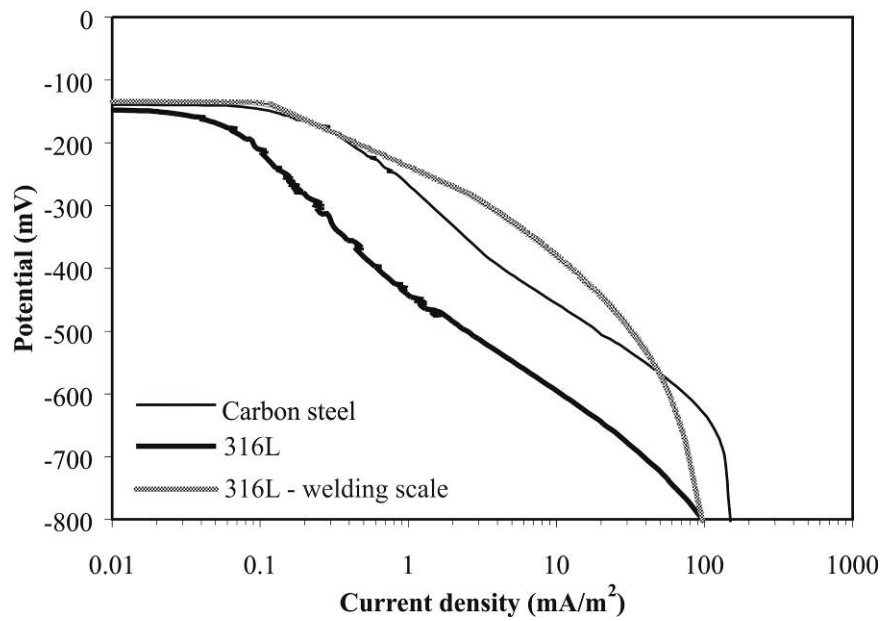


Figure 9 - Cathodic polarisation curves in saturated $\text{Ca}(\text{OH})_2$ solution (pH 12.6) of 316L stainless steel compared with the curve of carbon steel. Tests on stainless steels with simulated welding scale are also shown (Bertolini, Gastaldi, Pastore, Pedferri & Pedferri, 1998b).