Performance-based durability design of reinforced concrete structures with stainless steel bars

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Stainless steel reinforcement can be a suitable option for the achievement of the durability target for reinforced concrete structures exposed to aggressive chloride bearing environments. To quantitatively assess the benefits of using stainless steel bars, performance-based design models can be applied. However, although these models could, in principle, be used for the design with stainless steel bars, at the moment they do not provide any specific indication for the design with this type of bars particularly the critical chloride threshold values. This paper reports results of an experimental work aimed at evaluating the statistical distribution of the critical chloride threshold in concrete of low nickel duplex stainless steel (type 1.4362) reinforcement. Results of the potentiostatic polarisation tests showed that the statistical distribution of the chloride threshold may be fitted by a Beta probability distribution function that can be used as input parameter in performance-based models for structures exposed in atmospheric condition and to temperate marine environments.

Keywords: Stainless Steel - Corrosion - Modelling

INTRODUCTION

The use of stainless steel reinforcement may be an effective and economic strategy to guarantee the durability performance of reinforced concrete structures exposed to aggressive environments, especially in chloride bearing environments, or when a long service life is required [1]. Although stainless steel bars have a higher initial cost than ordinary black steel bars, they may allow considerable cost savings throughout the service life of the structure.

Although the initial costs due to the use of this type of reinforcement can be easily quantified, the economical advantages due to the future maintenance cost savings are hard to be determined. The first step to assess these economical benefits consists in the evaluation of its contribution in determining the actual service life of a structure. At this aim performance-based design approaches can be used.

Probabilistic performance-based approaches, by modelling the environmental actions, allow to define the design options (e.g. concrete composition, cover thickness, additional preventative techniques), in order to guarantee the durability requirement, i.e. the service life [2-4]. The most widely used procedure is the "Model code for service life design", proposed by the International Federation for Structural Concrete *(fib)* [5]. This model allows evaluating when a predefined limit state, associated to the end of the service life of the structure, is reached. For structures exposed in marine environments, the initiation time is calculated as the time at which the probability that chloride content at the depth of the bars reaches the critical threshold value, Cl_{th}, is equal to a target probability.

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Although this model may also be applied when stainless steel bars are used, it does not give any indication of Cl_{th} for stainless steels (only values for black steel bars are provided).

The experiences reported in the scientific literature show that the chloride threshold level can significantly vary for different types of stainless steel grades [6-11]. As a matter of fact, nowadays stainless steel bars with very different characteristics in terms of microstructure (e.g., austenitic or duplex), chemical composition and surface conditions may be used. If the different behaviour of the bars in terms of corrosion resistance is not adequately evaluated, there is the risk to make an inadequate choice.

Hence, there is the need to collect experimental data that can allow an evaluation of the statistical distribution of the critical chloride threshold. However, this parameter is not easy to be determined, since it is influenced by many factors [12]. Unfortunately, at this time, no standardised and commonly accepted method to assess the critical chloride threshold is available; therefore, the development of an experimental test that allows to evaluate this parameter is also necessary.

This paper describes a laboratory study aimed at evaluating of the critical chloride threshold for the corrosion initiation of stainless steel reinforcement of type 1.4362. Preliminary results are discussed and possible use of the results in performance-based models is shown, considering also limitations of this approach.

EXPERIMENTAL PROCEDURE

Tests were carried out on ribbed reinforcing bars, with a diameter of 20 mm, of stainless steel types 1.4362 (UNS S32304) with a duplex (austenitic-ferritic) microstructure. Table 1 shows the mechanical properties and the chemical composition of the steel. The bars were subjected to commercial sand blasting and pickling, in order to remove the oxide scale produced during hot forming. Before testing they were degreased with acetone.
Bars were embedded in concrete and mortar specimens with different amounts of mixed-in chlorides. Concrete with water/cement ratio of 0.5, 400 kg/m^3 of ordinary portland cement (CEM I 52.5R, according to standard EN 197-1), 200 l/m^3 of deionised water and 1704 kg/m^3 of crushed limestone aggregate (with maximum size of 9 mm) was utilised. Chlorides were added as $CaCl_2$ to the mixing water, to reach chloride contents of 2.7%, 3%, 4% and 5% by mass of cement. Mortar specimens were cast with 1350 g of sand, 450 g of cement and 225 g of deionised water; chloride contents of 3%, 3.5%, 4% e 5% by mass of cement were added to the mixing water. An acrylic-based superplasticiser was added to the mixing water.
Specimens were cylinders with diameter of 75 mm and height of 100 mm, with a stainless steel reinforcing bar along the axis. The two ends of each bar, before casting, were masked with a styrene-butadiene-modified cement mortar and coated with a heat shrinkable sleeve; a length of the bar of 60 mm was exposed to the concrete.
Each test was carried out on ten replicate specimens. At the end of casting, specimens were cured in a climatic chamber at 23°C; 24 hours after casting, specimens were removed from the mould and individually immersed in a $Ca(OH)_2$ saturated solution for 6 days before the beginning of the test. A silver/silver chloride (Ag/AgCl) reference electrode, calibrated with respect to a saturated calomel reference electrode (SCE), and an activated titanium mesh for counter-electrode, were used. Tests were carried out at 23°C. At the end of the curing period of 7 days, a potential of +200 mV vs SCE was imposed to the bar for 24 hours and the circulating current was monitored. At the end of the polarisation tests, the potential was monitored for 4 hours (depolarisation phase). Finally the steel bar was removed from the specimen and its surface was observed with a stereomicroscope, in order to detect corrosion attacks.

Steel Type	D (mm)	Mechanical properties		Major alloy elements (%)					
		Rs0.35% (MPa)	Rm (MPa)	C	Cr	Mo	Ni	Mn	N
1.4362	20	496	819	0.03	23.58	0.45	4.61	1.41	0.13

Table 1 – Mechanical properties and main alloy elements of the 1.4362 stainless steel.

Tabella 1 - Proprietà meccaniche e principali elementi di lega dell'acciaio inossidabile 1.4362

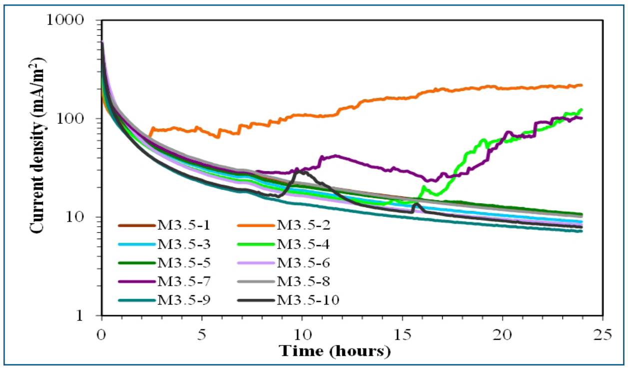

Fig. 1 – Current density of the bars of 1.4362 stainless steel in mortar specimens with 3.5% Cl$^-$ by cement mass, during the 24 hours of polarisation at +200 mV vs SCE.

Fig. 1 – Andamento della densità di corrente delle armature in acciaio inossidabile 1.4362, nei provini di malta con 3.5% di cloruri in massa rispetto al cemento, nelle 24 ore di polarizzazione a +200 mV vs SCE.

RESULTS AND DISCUSSION

Initiation of the corrosion during the potentiostatic test may be detected through the trend of the polarisation current and the visual observation of the surface of the bars at the end of the test. However conflicting results were obtained with the two approaches.
Figure 1 shows, as an example, the current density of the bars measured during the 24 hours of anodic polarisation at +200 mV vs SCE of mortar specimens with 3.5% of chlorides by cement mass. Initial values were around 600 mA/m^2, and they decreased to 100 mA/m^2 after 1 hour. On six of the ten replicate specimens the current density continued to decrease in time, reaching values of 7-11 mA/m^2 after 24 hours. After switching off the polarisation (depolarisation phase), the potential of these steel bars decreased reaching, after 4 hours, values around 0 mV vs SCE. After the demolition of the specimens, no pits were observed with the naked eye; however with careful observation with a stereomicroscope some small pits, with maximum size lower than 0.5 mm (micro-pits), were noted on the surface of the reinforcement in three specimens (M3.5-3, M3.5-5 e M3.5-8).
In other 3 specimens the current density showed a sharp increase during the polarisation test and approached values higher than 100 mA/m^2 at the end of the 24-hour polarisation (Figure 1). This clearly indicated the onset of corrosion on these bars, which was also confirmed by the subsequent depolarisation, when the corrosion potential reached values lower than -200 mV vs SCE. Several deep corrosion attacks, of dimension higher than 0.5 mm (macro-pits), were observed on the surface of these bars. Finally, the current density of the bar embedded in one specimen (M3.5-10), during the polarisation phase showed a temporary increase, however, at the end of the 24 hours, it

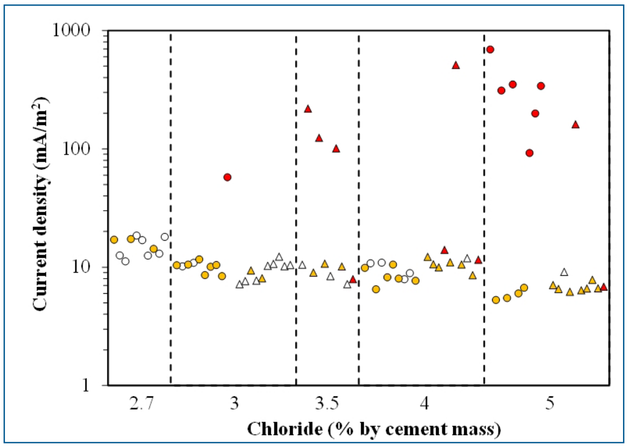

Fig. 2 – Current density measured at the end of the 24 hours of polarisation at +200 mV vs SCE on the bars in concrete (circle symbols) and mortar (triangle symbols) specimens with different chloride contents (white symbols = no corrosion observed on steel surface; red symbols = pits of dimension higher than 0.5 mm observed on steel surface; yellow symbols = small pits of dimension lower than 0.5 mm observed on steel surface).

Fig. 2 – Densità di corrente misurate al termine delle 24 ore di polarizzazione a +200 mV vs SCE sulle armature nei provini in calcestruzzo (cerchi) e in malta (triangoli) a diversi tenori di cloruri (simboli bianchi = nessun innesco di corrosione osservato sulla superficie; simboli rossi= attacchi localizzati di dimensione superiore a 0.5 mm osservati sulla superficie; simboli gialli = piccoli attacchi localizzati di dimensione inferiore a 0.5 mm osservati sulla superficie).

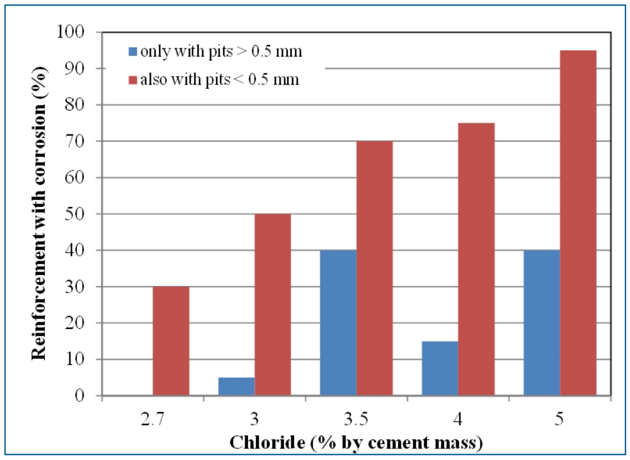

Fig. 3 – Number of bars (%) with pitting corrosion initiation after 24 hours anodic polarisation test at +200 mV vs SCE.

Fig. 3 – Numero di armature (%) con innesco della corrosione dopo le 24 ore di prova di polarizzazione anodica a +200 mV vs SCE.

was around 8 mA/m². Pits with dimension higher than 0.5 mm were observed on this bar surface.
Figure 2 summarizes the results of the anodic polarisation tests; in particular, it shows the values of current density measured at the end of the 24 hours of polarisation on the bars where corrosion did not occur (white symbols) and on the bars were macro-pits (red symbols) and micro-pits (yellow symbols) were observed. For each chloride content, results obtained on the ten replicate specimens, in concrete and in mortar, are reported. In concrete specimens with 2.7% of chlorides by cement mass the polarisation current density at the end of the 24 hours test reached values between 11 and 18 mA/m²; none of these specimens showed increase in current during the test. However on three bars micro-pits were observed (yellow symbols in Figure 2). Also at the other chloride contents it is clearly shown that micro-pits formation was not detected by the current during polarisation tests; the analysis of the current has identified only macro-pits (red symbols in Figure 2).
Figure 3 summarises the results of visual observation by showing the percentage of bars where macro-pits and micro-pits occurred (tests in mortar and concrete were considered together since no significant difference between them was noted). An increase in the percentage of reinforcement with corrosion initiation was noted increasing the chloride content by cement mass from 2.7% to 5%. It clearly appears that different percentage of reinforcement with corrosion can be obtained if only macro-pits are considered instead of all the pits (including micro-pits).
From data shown in Figure 3, the probability density function (PDF) of the critical chloride threshold, Cl_{th}, for the 1.4362 duplex stainless steel can be estimated. Figure 4 shows the frequency distribution of bars where only macro-pits were observed and of bars where both macro and micro-pits were present. Results could be fitted by a Beta PDF with the following parameters: mean value and standard deviation of 5.2% and 1.6% Cl^- by cement mass and lower and upper limits of 2.7% and 10%, considering only the number of bars with macro-pits and mean value and standard deviation of 3.2% and 1% Cl^- by cement mass and lower and upper limits of 1.5% and 7% considering the number of bars with macro and micro-pits. It can be observed that considering both macro and micro-pits led to a lower Cl_{th}. To be on the safe side, for the estimation of the critical chloride threshold PDF it is advisable to take into account any type of corrosion attack. However, the identification of the micro-pits is not an easy task. As previously observed, the current monitoring did not provide any indication of their evidence, since, at the end of the test, no significant difference was observed among bars which remained passive and bars where this type of attack occurred. Only the visual observation with the aid of a stereomicroscope allowed their detection. Conversely the detection of macro-pits can be easily carried out, since their formation was clearly identified by a current density increase during the potentiostatic test and easily detected by visual observation. Indeed the absence of any evidence of micro-pits in the trend of the polarisation current den-

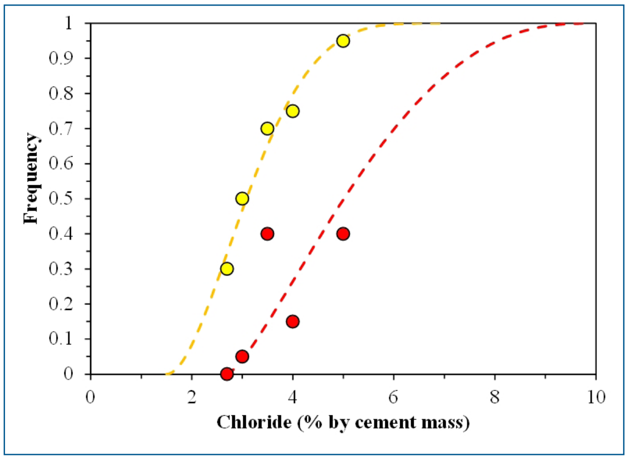

Fig. 4 – Cumulative probability distribution function (fitted by a Beta distribution) of the 1.4362 steel determined from experimental results of the anodic polarisation tests at +200 mV vs SCE (indicated with the points in figure) considering only macro-pits (in red) and also micro-pits (in yellow).

Fig. 4 – Funzione di distribuzione cumulativa di probabilità (interpolata con una distribuzione di tipo Beta) dell'acciaio 1.4362 determinata a partire dai risultati delle prove di polarizzazione potenziostatica a +200 mV vs SCE (indicati in figura con i punti) considerando solo i macro-pits (in rosso) e comprendendo anche i micro-pits (in giallo).

sity makes the evaluation of results of the proposed test somewhat complicated. Further tests have been planned in order to investigate the possibility of solving this problem, by evaluating the role of testing parameters (e.g. the duration of polarisation and the size of specimen).
Although some aspects of the anodic polarisation test proposed in this work still need to be clarified, it can be observed that it allowed the determination of the probability density function of Cl_{th} that can be used as input parameter in performance-based models. However, it has also to be considered that this PDF is the result of an accelerated test, which is only valid in the test conditions (a temperate climate and atmospheric as well as splash conditions). In order that the results of this test could be used to predict the reinforcement behaviour in all exposure conditions, they should be modified, e.g. through appropriate corrective coefficients, k_i, which take into account that the results are obtained by means of an accelerated test and the role of different parameters that can affect the critical chloride threshold (for instance the real characteristics of the concrete, the environmental exposure conditions and the surface condition of the reinforcement):

$$Cl_{th} = k_1 \cdot k_2 \cdot \ldots \cdot k_n \cdot Cl_{th,test}$$

Experimental tests are ongoing to investigate these issues.

CONCLUSIONS

A polarisation test was applied to mortar and concrete specimens with mixed-in chloride to estimate the critical chloride threshold of duplex stainless steel 1.4362. A potential of +200 mV vs SCE was applied to sets of ten reinforced specimens in order to simulate atmospheric exposure conditions.
Results showed that by simply monitoring the current density it was not possible to detect corrosion initiation on the bars, whilst a careful visual observation was necessary. By considering only specimens which showed corrosion initiation by the increase in polarisation current, which was associated to corrosion attacks clearly visible at the naked eyes, the probability distribution of the critical chloride threshold was overestimated. By fitting results of all the bars with corrosion attack a probability distribution of the critical chloride threshold could be obtained according to a beta distribution function. This could be representative of the probability density function of chloride threshold for this steel in atmospheric zone of structure exposed to temperate marine environments.

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Progettazione prestazionale di strutture in C.A. con armature in acciaio inossidabile

Parole chiave: Corrosione - Acciaio inossidabile - Modellazione

L'impiego di armature in acciaio inossidabile può essere una strategia efficace per garantire la durabilità delle strutture in calcestruzzo armato esposte in ambienti aggressivi, in particolare in presenza di cloruri, oppure per le quali è richiesta una vita di servizio molto lunga. A fronte di un maggiore investimento iniziale, l'uso di barre d'armatura d'acciaio inossidabile può consentire un notevole risparmio nell'arco del ciclo di vita di servizio della struttura. Per valutare quantitativamente i vantaggi legati all'uso di queste armature è fondamentale considerare il loro contributo nel determinare la vita di servizio di una struttura. A questo scopo sono disponibili dei modelli di calcolo per la valutazione della vita di servizio di una struttura in calcestruzzo armato basati su approcci prestazionali probabilistici. Il modello di calcolo più diffuso è il "Model code for service life design", proposto dalla Federazione Internazionale del Calcestruzzo *(fib)*. Questo modello, sebbene in linea di principio possa essere applicato anche quando sono impiegate armature in acciaio inossidabile, non contiene indicazioni specifiche a riguardo. Al momento, quindi, la sua applicazione alle strutture con armature in acciaio inossidabile richiede le competenze di esperti che possano definire dei valori ragionevoli per i parametri di progetto e, in particolare, per il tenore critico di cloruri necessario per l'innesco. Questo parametro non è di facile determinazione, perché influenzato da numerosi fattori e, inoltre, al momento non esiste una metodologia di prova standardizzata. È, quindi, sentita la necessità di sviluppare una prova sperimentale che consenta la valutazione di questo parametro.
Questa nota riporta i risultati preliminari, realizzati sulle armature in acciaio inossidabile austeno-ferritico di tipo 1.4362, di una procedura di prova proposta per la determinazione della distribuzione di probabilità del tenore critico di cloruri in funzione dell'ambiente di esposizione. Una prova di polarizzazione anodica a +200 mV vs SCE è stata applicata a una serie di 10 provini con cloruri aggiunti in fase di getto. I risultati della prova di polarizzazione potentiostatica hanno permesso di determinare la distribuzione del tenore critico di cloruri per questo acciaio per strutture operanti in ambiente marino temperato ed esposte all'atmosfera.