SEACON

Infravation
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D3.1 Report on field of implementation of stainless steel rebars

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1. Introduction

The SEACON project demonstrates the safe utilization of seawater and salt-contaminated aggregates (natural or recycled) for production of a sustainable concrete when combined with non-corrosive reinforcement to construct durable and economical concrete transportation infrastructures. The use of stainless steel rebars (SSR) is one of the design options considered in the project to fulfill durability requirements when chloride-contaminated raw materials are used for concrete, in order to increase sustainability issues. It is well known that SSR have higher corrosion resistance compared to traditionally used black steel bars and have been used in a large number of projects worldwide to achieve the durability performance of reinforced concrete structures, especially in chloride bearing environments or when long service lives are required (i.e. 100 years or longer). Several grades of SSR have been proposed, which are characterized by notably different chemical composition, cost and corrosion resistance performances. In this report, after a notation on the mechanism of chloride-induced corrosion of steel in concrete, a brief state-of-the art summary on the field implementation of SSR is presented. Most of the literature is related to laboratory tests studying the corrosion resistance of various grades of SSR. Significant examples of use of SSR in real structures are described and, finally, design with stainless steel reinforcement is reported. Data described in this report have been the basis for the planning of the experimental part of the SEACON project, both for lab tests and the field demonstration project (Workpackages 3 and 4).

2. Chloride-induced corrosion

Penetration of chloride ions from seawater or de-icing salts into concrete and the associated risk for reinforcement corrosion are the most frequent and cost-impacting degradation mechanisms for reinforced concrete infrastructures. Traditionally, the service life of a reinforced concrete structure exposed to the penetration of chlorides (i.e. in marine environments or where de-icing salts are used) 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 [1]. The time-evolution of a RC structure exposed to the action of chlorides under different scenarios is schematically shown in Figure 1.

Fig. 1*a* refers to a conventional structure made with essentially chloride-free concrete and exposed to chloride penetration. During the initiation period, the ingress of chloride ions into the concrete cover leads to a local breakdown of the protective passive oxide film present on the steel surface in contact with the alkaline concrete; a subsequent localized corrosion attack takes place (i.e., pitting corrosion attack) [2]. Once corrosion has initiated, a very aggressive environment is produced inside localised attacks, due to the autocatalytic mechanism of pitting corrosion, and corrosion can reach very high rates of penetration (even up to 1 mm/year) that can quickly lead to a remarkable reduction in the cross section of the rebars (Figure 2). For this reason, the propagation stage of pitting corrosion is usually neglected in the design of concrete structures exposed to aggressive chloride environments and the design life of the structure is defined only on the basis of the initiation period.

Initiation of corrosion of steel in chloride-contaminated concrete is a quite complex phenomenon, since it is influenced by many factors related to the steel and its surface conditions, to the concrete, to the steel-concrete interface and to the exposure conditions. Conventionally, a so-called *critical chloride content* or *chloride threshold value* (Cl_{th}) is considered (i.e. the corrosion initiation is considered to take place when the chloride content measured at the rebar depth, the concrete cover thickness, reaches a certain threshold value). In service life evaluations, this approach allows calculating the corrosion initiation period (and thus the expected service life) by modelling the chloride penetration through the concrete cover until Cl_{th} is reached at the steel surface. Nevertheless, this apparently simple approach does not allow neglecting the complex nature of pitting corrosion initiation. Thus, assessment of Cl_{th} under real exposure conditions is indeed rather difficult because this is affected by numerous interrelated parameters, such as: the chemical composition of steel, the pore solution chemistry, the electrochemical potential of the steel, the steel/concrete interface, the temperature, the type of steel and the surface condition of the reinforcement [2,3].

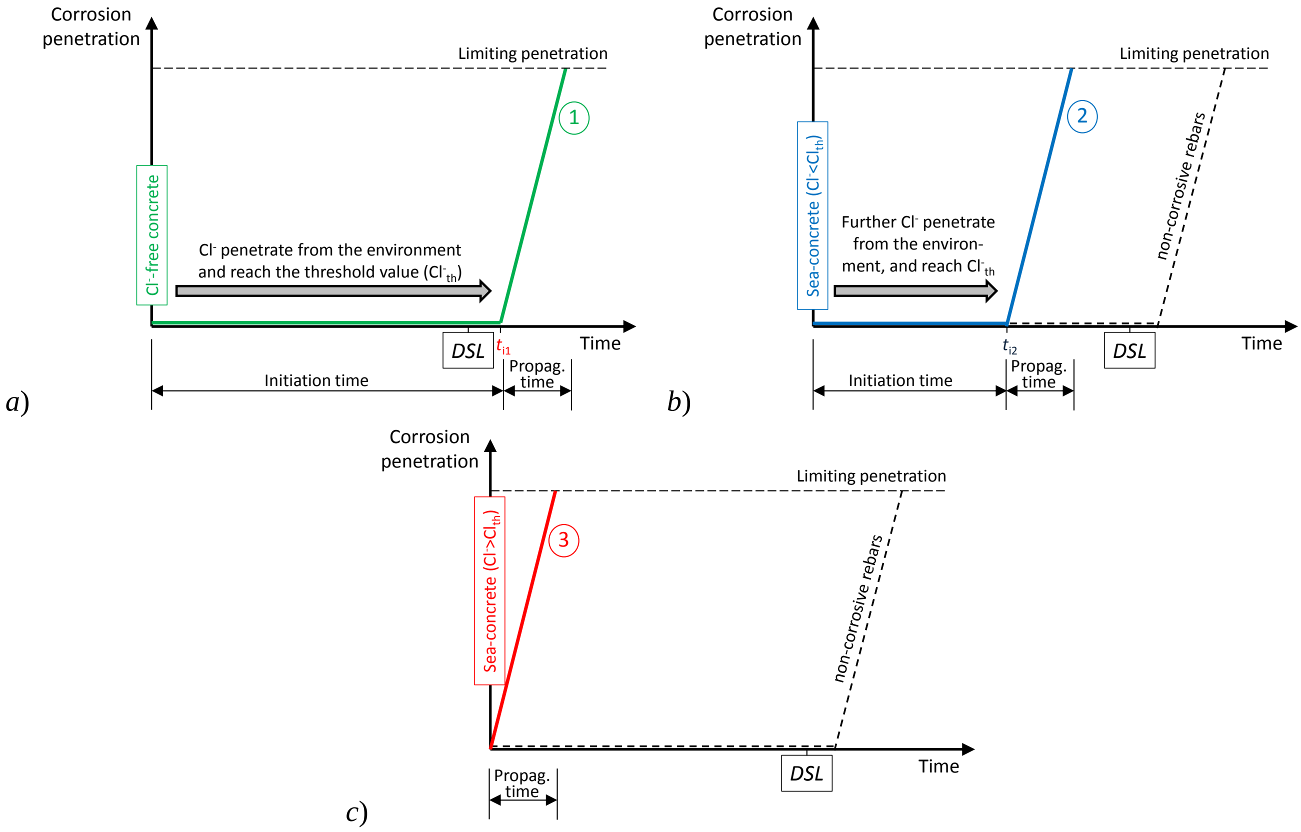

Figure 1 – Schematic time-evolution of steel corrosion in RC structures exposed to chloride penetration under different design scenarios: *a*) concrete mixed without chlorides; *b*) concrete mixed with chloride-contaminated constituents at chloride content below Cl_{th}; *c*) concrete with initial chloride content above Cl_{th} (DSL = design service life).

Figure 2 – Example of pitting corrosion of steel bars.

Furthermore, it should be considered that the onset of pitting corrosion is a stochastic phenomenon, which requires that chloride threshold be defined on a statistical basis [4]. In a very approximate way, for conventional carbon steel rebars embedded in concrete structures exposed to the atmosphere, Cl_{th} values in the range of 0.4-1% by mass of binder are usually considered (although many research studies aimed at finding more refined values, e.g. depending on the type binder or concrete compaction). Cl_{th} may reach higher values if the concrete is saturated by water (e.g. in submerged structures), when the electrochemical potential of steel is depressed due to lack of oxygen. In this condition corrosion initiation is unlikely even with very high values of chloride content at the steel surface (provided the reinforced concrete is completely and permanently submerged and there are no parts of the steel bars exposed to aerated concrete, as it may occur in hollow structures).

The higher corrosion resistance of SSR compared to conventional carbon steel bars is usually expressed through proper values of Cl_{th}. Thus, the use of SSR bars may allow a prolongation of the service life of a structure when chlorides penetrate in time, as shown in Fig. 1*b*, even if some amount of chlorides are mixed in the concrete, as proposed by the SEACON project. Furthermore, SSR bars can be used to guarantee the service life requirements even when the chloride-contamination of raw materials is above the Cl_{th} of conventional carbon steel, as shown in Fig. 1*c*.

The corrosion resistance of SSR is strongly affected by the surface condition of the bars. The presence of deposits, oxides or crevice on the surface of the steel promotes the initiation of the corrosion. Pitting corrosion initiation is also promoted by an increase of the temperature.

3. Stainless steel reinforcement

3.1 SSR grades

Stainless steels are alloyed steel with chromium content of at least 10.5%, 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 applied to SSR in order to fulfill mechanical requirements for reinforcing bars.

Stainless steels are generally divided into four categories (based on the steel microstructure): martensitic, ferritic, austenitic and duplex (austenitic-ferritic). For use as reinforcing bars, however, only specific grades of austenitic and duplex stainless steel are typically used in concrete (Table 1). Traditionally, austenitic type 304L and 316L and duplex type 22-05 are commercially available. Due to the fluctuations of the cost of some alloy element, above all the cost of nickel, the use of rebars of duplex and austenitic stainless steels with low nickel and molybdenum content (in which manganese is often added in place of nickel to obtain the austenitic structure) has been proposed (Table 1) [2,5].

3.2 Corrosion resistance

As mentioned above, the corrosion resistance of SSR can be expressed though a critical chloride threshold (Cl_{th}) which depends on several factors (such as type of concrete, concrete/reinforcement interface, surface condition, temperature, etc.). In service life modelling, for each type of SSR the Cl_{th} value should be defined taking into account all the factors that affect it as well as their variability (probabilistic-based models consider probability distribution functions).

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

Steel name	*Designation*			*Microstructure*	*Main alloy elements (% by mass)*			
	EN 10088-1	*AISI*	*UNS*		*Cr*	*Ni*	*Mo*	*Other elements*
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

Unfortunately, the feedback from real structures where SSR were used is rather modest, understandably since these structures were usually built in recent years and the expected service life is rather long, due to the use of SSR. Therefore, experience on the corrosion resistance of SSR mainly derives from laboratory studies [2,5], which will be briefly summarized. In Fig. 3 an attempt has been made to depict approximate values of the range of the Cl_{th} for the different grades of SSR, based on data reported in the references [6-20]. Values reported in this figure should be assumed only as indicative values. Considering that, in real cases, chloride contents higher than 5% by mass of binder are difficult to be reached at the concrete cover depth of the steel surface, Fig. 3 has been limited to this value and values suggested in literature exceeding 5% have been identified by a rightward arrow.

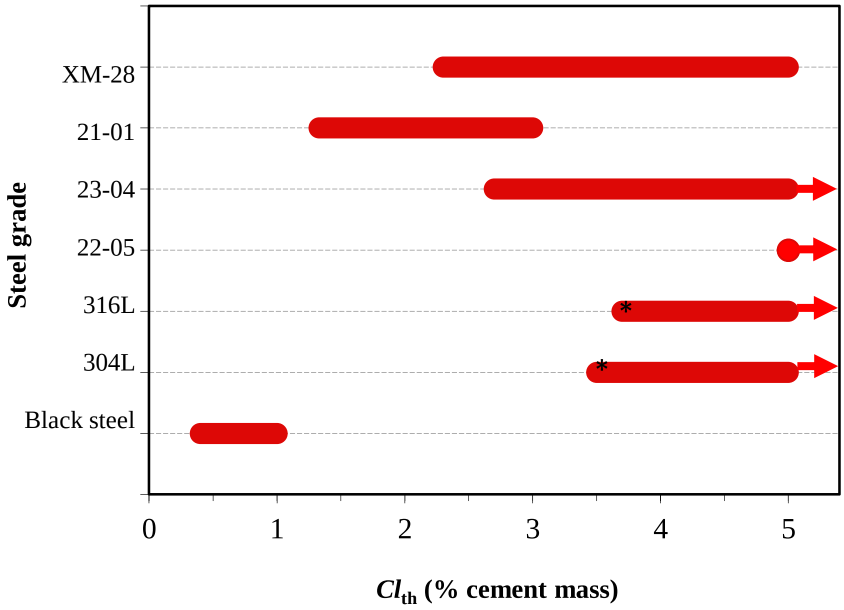

Figure 3 – Approximate values of Cl_{th} for different grades of SSR reported in refs. [6-20]. (* = min. value detected under anodic polarization [8])

Early studies were carried out in the late 1970s in the UK [6]. Tests were performed on smooth bars of austenitic stainless steels embedded in concrete prisms and beams made with 3.2% of mixed-in chloride by mass of cement, subsequently exposed to an industrial environment, and in chloride-free concrete exposed in the splash zone of a marine environment. After 22 years of exposure, no corrosion was observed on 316 (1.4401) stainless steel; on 302 (1.4310, high carbon 1.4301) stainless steel only shallow pitting attacks occurred in concrete specimen with 3.2% of chloride by mass (exposed to industrial atmosphere). Afterwards, several studies were carried out on 304L and 316L grades. No corrosion was observed in concrete with a content of chloride even higher than 5% by mass of cement [7-11]; the passive condition was preserved also at temperature values higher than 40°C [12,13]. No corrosion was observed even in carbonated concrete with 5% of chloride by mass of cement [10,12]. If an increase of the potential (i.e. an anodic polarization) was applied, a decrease in the Cl_{th} was observed. At potential of +200 mV vs SCE (that can be considered representative of the maximum potential values reached in atmospheric exposure conditions), commercial ribbed bars of 304 (1.4301) and 316 (1.4401) in mortar (in which a sulphate resistant portland cement was used) showed that corrosion could initiate at a chloride content of 3.5-5% by mass of cement (the corrosion resistance of 316 was only marginally better than for 304) [8]. A further study showed that no corrosion occur even at potential values up to +400 mV vs SCE (potential values that can be reached only in the presence of stray current) on 304L (18%Cr-10%Ni) and 316L (17%Cr-11%Ni-2%Mo) in concrete with 5% of mixed-in chloride [12]. In carbonated concrete with 5% of chloride, a rather small increase in potential of 50 mV versus the free corrosion potential was enough to initiate pitting corrosion on 304L stainless steel, showing that under this condition this very aggressive condition (5% Cl^- + carbonation) 304 SSR may be susceptible to pitting corrosion; for 316L SSR an higher anodic polarization of 150 mV was required to initiate corrosion [12].

Experimental studies showed a rather high corrosion resistance for the duplex stainless steel 22-05 (1.4462; 22%Cr-5%Ni-3%Mo). Pitting corrosion did not occur with 5% of chloride by cement mass in alkaline and carbonated concrete, even after exposure to 40°C and 95-98% R.H. [14] or increasing the potential at values higher than +400 mV vs SCE [12,15]. Indeed, this steel showed an outstanding corrosion resistance, higher than that of 304L and 316L, especially in carbonated concrete [12,15] and in presence of cracks [16].

It should be observed that the pitting resistance equivalent index (PRE = %Cr + 3.3%Mo + 16-30%N), which is normally related to the ability of stainless steel to resist a pitting attack in neutral environments, may not be reliable in concrete. In particular the presence of molybdenum seem to have a lower effect on the corrosion resistance, as confirmed by the small differences observed between 304L (without molybdenum) and 316L; furthermore nickel has shown to give a positive effect on corrosion resistance especially in tropical environment [17,18]. In carbonated concrete (or in the presence of cracks [16]), conversely, PRE index might still be a useful ranking index.

The good corrosion resistance of stainless steels may be negatively affected by the presence of oxides produced at high temperature (i.e. mill scale or welding oxides). All of the published studies showed that high temperature oxides had a deleterious effect on the corrosion behavior of SSR. On 304L, 316L and 22-05, that resisted to corrosion initiation in alkaline concrete with chloride contents higher than 5%, pitting corrosion could also occur with a chloride content lower than 3.5% [8]. Hence, it is good practice to fully remove from the surface of the steel both the mill scale and any welding oxides.

As far as the other stainless steel types are concerned, few data are available in the literature regarding their corrosion resistance in concrete, particularly regarding low-nickel SSR recently proposed on the market. Most of the published studies merely referred to tests in solution (hence not representative of the real conditions of steel in concrete).

Duplex 23-04 showed pitting corrosion initiation in alkaline concrete with 3% of chloride by cement mass [7,19,20]. Regarding the lean duplex 21-01, cheaper than the others because nickel is replaced with manganese, a chloride threshold of 1.3% by mass of cement has been reported [11]. For XM-28, austenitic stainless steel with manganese, Cl_{th} ranged between 2.3% and 5.5% by cement mass of chlorides [19].

3.3 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 galvanized 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.

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.

The coefficient of thermal expansion of austenitic steels is higher (about $1.8 \cdot 10^{-5}$ $°C^{-1}$) than that of concrete and of the traditional carbon steel bars (about 10^{-5} $°C^{-1}$); 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. Austenitic stainless steels are generally considered non-magnetic (although cold drawing can increase the magnetic permeability) [2].

In the past, concern has been expressed concerning the risk of galvanic corrosion of black steel induced by coupling with stainless steel bars. Several studies have shown that the consequences of coupling with traditional stainless steels are modest [21,22], since galvanic action is already present between passive and active areas of black steel when pitting corrosion occurs (and, furthermore, SSR is a less efficient cathode than black steel). Thus, SSR can be used in combination with normal black steel, for instance allowing a selective utilization limited only to the more vulnerable parts of a structure, such as joints and edge beams of bridges or the splash zone of marine structures.

The use of stainless steel bars is often limited due to their high initial cost; as a matter of fact, although the cost of the material has decreased in recent years and further reductions are expected, due to new developments in production, stainless steel bars are still much more expensive than carbon steel bars. Indicatively if 1 is the cost of carbon steel bars, 304 austenitic stainless steel bars costs 6-8, and 316 and 22-05 (duplex) cost 9-10. However, it was shown that the selective use of SSR could lead to an extra initial cost of a structure of only 0.5% [23]. This additional cost should be compared to the cost of repair possibly needed in the future if carbon steel bars were used. Several authors have shown, through a life cycle cost analysis, that the use of stainless steel bars in the most exposed zones the structure can allow savings on future maintenance expenses that can be much higher than the initial increase in cost [2]. Hence, from a cost point of view, the selective use approach can be the optimal solution.

4. Applications

The first reported application of stainless steel bars dates back to 1941 for the construction of the *Progreso de Castro* Pier in Yucatán (Mexico). 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. SSR 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 special long service lives. Table 2 shows some examples of structures, built or restored in recent years, where SSR of different grades were employed [24-27]. For instance, the grade 304 was employed for the construction of *Schaffhausen Bridge* on the River Rhine in Switzerland, for which a service life of 80 years was required, whilst the steel grade 22-05 was used for the *Stonecutters Bridge* and the *Sakonnet River Bridge*.

It can be observed, from Table 2, that stainless steel rebars are usually utilized 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 SSR 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 SSR were used for the new reinforced concrete walls. SSR 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, SSR can be beneficial in those repair cases where carbon steel bars have 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. 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.

For some structures, a huge amount of SSR has been used; for instance, for the construction of the *Macau bridge*, which is an ongoing construction project consisting of a series of bridges and tunnels crossing the Lingdingyang channel which will connect Hong Kong, Macau and Zhuhai, the use of approximately 15000 tons of SSR has been reported. In several structures to limit the required amount of SSR and, hence, to limit the entire cost of a structure, SSR have been adopted 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. In this regard, the *Stonecutters Bridge*, which connects Nam Wan Kok, Tsing Yi Island and Stonecutters Island is an example; built in 2009, the duplex steel 22-05 has been selected for the tower to provide the required combination of strength and corrosion resistance through the entire service life of 120 years [28]. Finally, it can be observed in Table 2 that, SSR are usually used to guarantee long service lives, i.e. around 100 years; often the indications on the required service life are lacking or service lives 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.

Table 2 – Examples of application of different grades of SSR (un = unknown).

Type of SSR	Structure	Location	Date	SL (years)	Ref.
304 304L 304LN	Bridge on I-696	Detroit, Michigan, USA	1984	un	[24]
	Schaffhausen bridge	River Rhine, Switzerland	1995	80	[25]
	Guildhall	East London	2000	750	[2]
316 316L 316LN	Underpass	Newcastle, Tyneside, UK	1995	un	[24]
	Broadmeadow Bridge	Dublin, Ireland	2003	un	[25]
	Gladstone Bridge	Queensland, Australia		un	[26]
	Bridge	Ajax, Ontario, Canada	1998	un	[24]
	Thorold Tunnel	Ontario, Canada	2004	un	[24]
21-01	Gateway Bridge	South-east Queensland, Australia	2011	300	[25]
	Buddhist Temple	Thailand	2013	300	[25]
	Junction Värtan	Stockholm, Sweden	2015	un	[25]
22-05	Ramp for Garden State Parkway	New Jersey, USA	1998	un	[24]
	Haynes Inlet Slough Bridge	Oregon, USA	2004	120	[25]
	Belt Parkway Bridge	Brooklyn, USA	2004	100	[24]
	Driscoll Bridge	New Jersey, USA	2004	un	[24]
	Siena Footbridge	Siena, Italy	2006	120	[24]
	Stonecutters Bridge	Hong Kong, China	2009	120	[25]
	Sea wall construction	Arabian Gulf	2009	un	[24]
	Little Bay Bridge	Newington, New Hampshire, USA	2011	un	[27]
	Sakonnet River Bridge	Rhode Island, USA	2012	un	[24]
	Hurdman Bridge	Ontario, Canada	2014	un	[25]
	Bayonne Breakwater	Bayonne, France	2014	un	[25]
	Burgoyne Bridge	St. Catharine’s, Ontario, Canada	2016	un	[27]
23-04	Cameron Heights Dr. Bridge	Edmonton, Alberta, Canada	2010	un	[24]
	S. Saskatchewan River Bridge, Medicine Hat	Alberta, Canada	2011	un	[24]
	Caminada Bay Bridge	Louisiana, USA	2011	un	[27]
	Hastings Bridge	Minnesota, USA	2012	100+	[25]
	Riverwalk	Brisbane, Australia	2013	100	[25]
	Allt Chonoglias Bridge	Scotland, UK	2013	120	[25]
	Coastal Protection	Cromer, UK	2014	50	[25]
	Kenaston Overpas	Winnipeg, Manitoba, Canada	2014	un	[24]
	Daniel Hoan Bridge	Milwaukee, Wisconsin, USA	2014	un	[27]
	Macau Bridge	Hong Kong - Zhuhai - China	2016	120	[25]
	New Champlain Bridge	Montreal, Canada	2016	un	[25]
XM-28	Light rail transit	Edmonton, Alberta, Canada	2012	un	[27]
	Osborne Bridge	Winnipeg, Manitoba, Canada	2012	un	[27]
	Pulasky skyway	Newark, Jersey City, USA	2014	un	[27]
	Kosciuszko Bridge	New York City, USA	2019	un	[27]

5. Service-life design with SSR

The choice of the stainless steel grade for a specific application in the past has often been made through empirical criteria or practical codes developed by producers and public or private institutions (e.g. the Technical Center on Consulting for Cement and Concrete, Switzerland [29]). Few European Standards and Design Codes provide information, which are often limited, for the durability design with stainless steel reinforcement. For instance, the BS 6744 Standard [30] provides general guidance related with the suitability of different grades (e.g. the stainless steel of grades 1.4301, 1.4436, 1.4429, 1.4462, 1.4529 and 1.4501) for a range of service conditions. In particular, the suitability of a specific grade is simply indicated by ranking (from 1 to 5) for the different combinations of exposure conditions and service life duration. According to the Eurocode

2 the use of stainless steel bars would allow to reduce the minimum value of the concrete cover thickness to guarantee a certain service life as a function of the environmental exposure conditions; this may lead to additional economic advantages. The reduction of the concrete cover when stainless steel bars are used instead of carbon steel bars is, however, demanded by each country and, in many National standards no values are provided. Furthermore, available standards do not take into consideration new types of stainless steel recently proposed on the marked (such as low nickel grades). The Recommendations for Design and Construction of Concrete Structures Using Stainless Steel Bars, developed in 2009 by the Japan Society of Civil Engineers (JSCE) consider the use of three different types of SSR, 304, 316 and 410, and suggest a corrosion verification of SSR, in order that concrete structures in which SSR are used maintain the required performances through their design service life. The verification for the resistance to corrosion of SSR bars due to the penetration of chloride ions may be conducted by confirming that the ratio of the design chloride ion concentration at the surface of the bar to the threshold chloride concentration for the SSR, multiplied by a safety factor, is not more than 1. Values of the critical chloride concentrations for the three types of SSR are provided in the Recommendations.

Today, performance-based service life design approaches are available which allow quantifying the service life of a structure as a function of the environment, the performance of materials used and design details. These models would be valid tools for the design with SSR since they could allow assessing the benefits in relation to the whole life cycle costs. For instance, modelling the environmental actions, the concrete requirements, the concrete cover thickness and the possible use of specific grades of SSR could be analyzed, so that the structure guarantees, with a target probability, the required performances during the entire service life. Among the models proposed in the recent years, the “Model Code for Service Life Design”, issued by the International Federation for Structural Concrete (*fib*) in 2006, is often considered one of the most authoritative. This approach includes a probabilistic performance-based approach for the modelling of the effects of the environment on the structure and the calculation of the probability that a pre-defined limit state, which corresponds to an undesired event (e.g. initiation of corrosion, cracking or spalling of concrete cover), will occur. As an example, Figure 4 shows the results of probabilistic evaluations carried out on a structural element made with a water/cement ratio of 0.45 and a portland cement (migration chloride diffusion coefficient equal to $6.5 \cdot 10^{-12}$ m^2/s), exposed in the splash zone of a temperate climate with an average annual temperature of 20°C (e.g., the coast of Mediterranean Sea) and a surface chloride concentration of 5% by mass of cement. A comparison, in terms of probability of initiation of corrosion, among carbon steel and different types of stainless steel can be made. For carbon steel, for the critical chloride threshold the distribution suggests by the model was taken into account. For the stainless steel bars, the probability density functions were determined from the literature data previously shown.

The modelling allows evaluating the probability of failure, p_f, i.e., the probability of occurrence of initiation of corrosion at the end of the design service life of 100 years, as a function of the mean value of the concrete cover thickness (Figure 4*a*). Once the target probability is chosen, the combinations between type of reinforcement and concrete cover thickness which guarantee the durability requirements can be evaluated. For instance for a serviceability limit state, as the initiation of corrosion, a value of 10% for the target probability is considered suitable. In the example shown in Figure 4*a* it can be observed that several combinations may guarantee the service life of 100 years; for instance the XM-28 in combination with a minimum concrete cover thickness of 70 mm or the 23-04 together with a concrete cover thickness of 45 mm. The other stainless steel showed to be suitable in this case and allowed a further reduction of the concrete cover thickness.

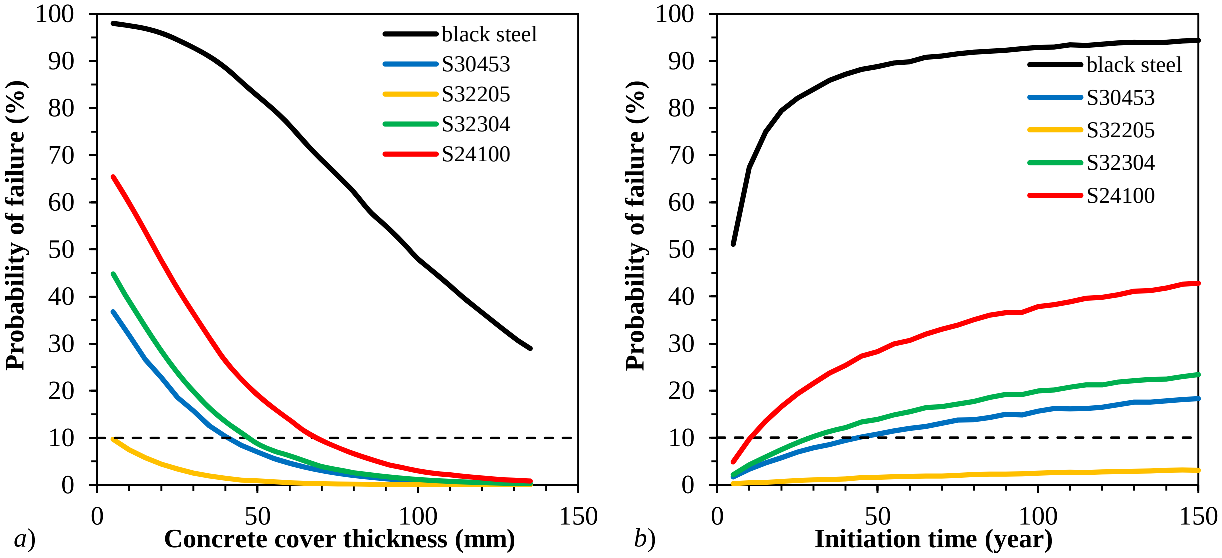

Figure 4 - Mean concrete cover thickness to guarantee a service life of 100 years (*a*) and initiation time (*b*) for a RC element exposed in the splash zone, as a function of the probability of failure and the type of bar (average annual temperature of 20°C; portland cement and water/cement ratio of 0.45)

This approach would also allow evaluating the service life which can be guaranteed with a certain concrete cover thickness. For instance, Figure 4*b* shows the probability of failure as a function of the service life for the different types of rebar, assuming a concrete cover thickness of 45 mm (which is a typical value for the splash zone, suggested for instance by Eurocode 2) [20].

6. Concluding remarks

SSR bars have been widely used worldwide both for the construction of new structures and infrastructures and the repair of existing structures. Today a range of stainless steel grades is commercially available which provide different corrosion resistance and costs. From the analysis of the results of laboratory studies, indicative values for the chloride threshold of the different grades have been deduced. All types of SSR are able to significantly increase the chloride threshold compared to conventional carbon steel bars, and it seems they could be suitable to be used in combination with concrete with contaminated raw materials, where the chloride content (for instance when seawater is used as mixing water) should not exceed 1% by mass of cement. The selection of a specific grade of stainless steel in association with SEACON, will also depend on the further chloride penetration of chloride expected during the design service life. Data described in this report, in combination with the results of the experimental tests carried out within the project, will be used for the selection of the suitable type of stainless steel for specific applications on the basis of the service life design and life-cycle assessment.

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