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STAINLESS STEEL REINFORCEMENT BAR

THE SUSTAINABLE COST EFFECTIVE CHOICE FOR CONCRETE INFRASTRUCTURE

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STAINLESS STEEL REINFORCEMENT BAR:

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(NA version)
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STAINLESS STEEL REINFORCEMENT BAR: THE SUSTAINABLE COST EFFECTIVE CHOICE FOR CONCRETE INFRASTRUCTURE

1. WHY USE STAINLESS STEEL REBAR?

Reliable, long-lasting infrastructure can have a significant impact on the quality of our daily lives. Stainless steel plays an important but often unnoticed role in infrastructure, where proper materials specification can be a decisive factor from both a sustainability and cost effectiveness perspective. Keeping reinforced concrete infrastructure in good condition is all the more critical when the design service life is extensive (over 50 years), or if the structure is exposed to increased risk of corrosion. In civil engineering, corrosion of conventional black carbon steel and coated steel reinforcement seem to be accepted as a "fait accompli". Consequently, in a relatively short span of time (i.e. <50 years) considerable sums of money are invested in protecting these types of steel reinforcement. This article aims at changing this point of view regarding steel corrosion by establishing the exceptional corrosion resistance attributes and the cost benefits of using stainless steel in concrete reinforcement.

Let us consider one of the oldest examples, the Progreso Pier, as a case-in-point. The first image dates from 1969 and shows a large jetty built on the Mexican coast in 1941. A small amount of stainless steel reinforcement was used to increase the service life of the jetty. Despite continued exposure to seawater, the pier is still functioning after eighty years. To the left of the 1941 pier, a smaller pier, built in 1969, is pictured. Stainless steel rebar was not used for this more recent pier.

The second photo dates from 2009: forty years after its construction, the smaller jetty (without stainless steel) has disappeared while the 1941 jetty is still intact. The example shows how choosing a material with a higher cost, yet more durable, offers considerable gains of longer service life, as well as in terms of almost non-existent maintenance costs. A detailed Life-Cycle Assessment (LCA)[1] deals with the environmental impact of the Progreso Pier example.

2. HOW IS STAINLESS STEEL DIFFERENT FROM CARBON STEEL?

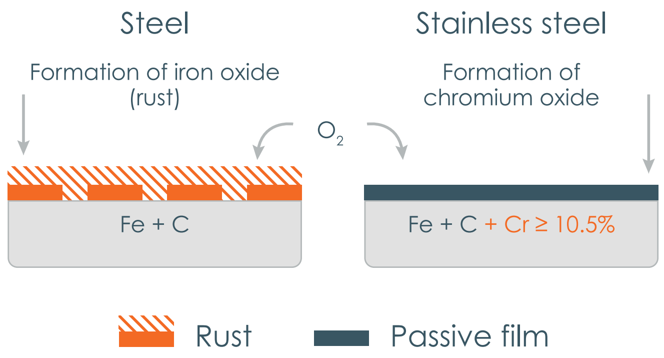
Stainless steels are iron-based alloys with a minimum chromium content (by weight) of 10.5% and a maximum of 1.2% carbon. This chromium content is the minimum necessary

The smaller jetty (without stainless steel) has disappeared while the 1941 jetty is still intact.

Progreso Pier ©Nickel Institute

©Jmagno1998, CC BY-SA 3.0, Wikimedia Commons to ensure the formation of a self-healing oxide layer – called a passive layer, which ensures the corrosion resistance of the alloy. Unlike carbon steel (often protected by coatings), the ability of stainless steel to self-passivate applies to the bulk of the alloy, not just the surface. In the event of coating damage, the exposed carbon steel will corrode. Under similar environmental and exposure circumstances, stainless steel will repair itself in the presence of oxygen.

Carbon steel versus stainless steel: exposure to oxygen



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The carbon steels used in concrete reinforcement are differentiated (only) by their level of mechanical properties in terms of yield and tensile strength. With stainless steels, on the other hand, the content of alloying elements largely influences the metallurgical structure of stainless steel and determines four families of stainless steels, each with its own mechanical, physical, and chemical characteristics:

- Martensitic stainless steels: Fe-Cr, C> 0.1% (magnetic and hardenable through heat treatment);
- Ferritic stainless steels: Fe-Cr, C <0.1% (magnetic);
- Duplex stainless steels: Fe-Cr-Ni, C<0.1%, combined austenitic-ferritic (magnetic) structure;
- Austenitic stainless steels: Fe-Cr-Ni, C <0.1% (non-magnetic).

The stainless steel "family tree" further depends on the addition of other alloying elements, such as molybdenum, titanium, niobium, and nitrogen. Two grades of the same family can therefore exhibit roughly the same mechanical strength, while the addition of molybdenum makes a stainless steel type significantly more corrosion resistant compared to the one without molybdenum.

3. STAINLESS STEEL REINFORCEMENT BAR PROPERTIES

Two of the previously mentioned stainless steel families are particularly suitable for the use of concrete reinforcement – austenitic and duplex. In North America, the governing stainless steel reinforcement standard is ASTM A955 – Standard Specification for Deformed and Plain Stainless Steel Bars for Concrete Reinforcement.

Besides a high level of corrosion resistance, all the alloys in A955 share some common properties such as very high elongation levels (a minimum of 16% depending on the grade, which is twice as high as carbon steel rebar), enabling more complex shapes, a very high retention of strength at high temperatures (knowing that the use of duplex stainless steels – unlike austenitics – is limited to 300 °C), which adds to fire resistance, and high levels of hardness (Brinell).

ASTM A955 includes seven alloy types – three austenitic alloys and four duplex alloys. The alloys include:

Alloy type	**UNS designation**	**Type (AISI designation or common name)**	**Typical composition**				
			Cr%	**Ni%**	**Mo%**	**N%**	**Mn%**
Austenitic	S24000	XM-29	17	3	-	0.30	12
	S24100	XM-28	17	1	-	0.30	12
	S31653	316LN	16	10	2	0.12	1
Duplex	S31803	2205	22	5	2.7	0.12	1
	S32101	---	21	1.5	-	0.22	5
	S32205	2205	22	5	3	0.18	1
	S32304	2304	23	4	0.3	0.12	1.5

There are three austenitic alloys listed in A955 though UNS S24100 and UNS S31653 are the most commonly used. Austenitic steels are readily available and are noteworthy for their high corrosion resistance and ductility (the ability to be drawn). These grades contain at least 16% chromium and nickel content up to 10%. The addition of molybdenum increases the resistance to corrosion.

In addition to their corrosion resistance, due to their metallurgical structure and the resulting physical properties, these alloy types offer particular advantages for concrete reinforcement[2].

The most commonly sought physical property of the austenitic family other than corrosion resistance is a “non-magnetic” or low magnetic permeability feature. Austenitic stainless steel is known to be “non-magnetic” although they may exhibit slight magnetism if they are cold worked. These stainless steel types are therefore particularly recommended in applications such as MRI rooms in hospitals, airstrips, air traffic control towers, road toll stations, naval demagnetizing stations, etc.

This family of stainless steel possesses exceptional impact toughness at low temperatures due to the absence of a ductile-to-brittle transition temperature. As such, these austenitic alloys can be used down to -200 °C, making them ideal for applications where exposure to cold environments is the norm.

The relatively low average thermal conductivity of austenitic stainless steel at 20 °C is 15 W / m.K. provides the advantage of being three to four times less conductive than carbon steels. Stainless steel reinforcement can beneficially be used for building applications such as thermal bridge breakers, insulated walls and anchoring systems for double skin walls. The “austenitic-ferritic” or duplex stainless steels represent another family of stainless steel alloys for use as concrete reinforcement. They offer higher mechanical strength than austenitic steels. The high chromium content and lower amounts of nickel and molybdenum (compared to austenitic steels with the same level of corrosion resistance), make them attractive thanks to their excellent balance between corrosion resistance / economic value / price stability. The alloys UNS S32304 and UNS S32101 are known as “lean” duplex due to the reduction in the amount of nickel and molybdenum content relative to alloy UNS S32205 making them more economical.

In addition to its inherent material properties, an important stainless steel property to a designer is the bond between the stainless steel rebar and the concrete. The bond to concrete is very high, equivalent to that of conventional black steel. Hence, the bar lap lengths, splices and development lengths follow the same convention as with black steel. The slope that is defined by Young’s Elastic Modulus “E” is typically 29,000 ksi (200 GPa).

4. STAINLESS STEEL REBAR PRODUCT FORMS

Stainless steel reinforcement is supplied to fabricators, warehouses and distributors from the steel mills in different forms[2], similar to those of carbon steel:

- ribbed (deformed) or smooth bar in coil-form;
- ribbed (deformed) or smooth bar, supplied in maximum lengths of 12 m;
- welded wire mesh.

5. CORROSION OF REBAR IN CONCRETE

Under normal conditions, carbon steel reinforcement, covered by compact and non-cracked concrete is naturally protected from corrosion by the creation on the steel surface of a protective layer of Fe_2O_3CaO, called the passivation layer.

This layer is formed by the interaction of lime - released by calcium silicates – with iron oxide. The presence of lime maintains the basicity of the environment surrounding the rebar (hydration of the cement produces an alkaline interstitial solution of high pH: 12 to 13).

Stainless steel rebar

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The reinforcement is protected as long as the pH of the environment stays between 9 and 13.5.

Two main phenomena[3] can under certain conditions destroy this protection and initiate corrosion of the concrete reinforcement:

- carbonation of the surrounding concrete by adsorption (surface fixation) of carbon dioxide contained in the atmosphere. The alkaline medium is gradually modified by the neutralization of the alkalinity of the cement to reach a pH of the order of 9, no longer ensuring the protection of the carbon steel reinforcement and leading to depassivation of the steel (destruction of the passivation layer), which causes oxidation on the reinforcement surface;
- penetration of chloride ions into the reinforcement area of either carbon steel reinforcement or coated steel products. This happens more or less rapidly, depending on ambient humidity, porosity of the concrete and presence of cracks which promote diffusion of aggressive gases or liquids. The corrosion of the steel starts as soon as the chloride content in the reinforcement area reaches a certain depassivation threshold. This threshold is a function of the pH of the interstitial solution and of the oxygen content in the reinforcement area; it is of the order of 0.4% of the weight of the cement and is reached more quickly if the concrete is carbonated.

6. EFFECTS OF REBAR CORROSION

As corrosion of carbon steel reinforcement develops, swelling within the concrete of the surface oxide products at the bar surface causes very high internal pressure on the concrete (iron oxides take up more volume than steel, generating stresses in the concrete which can exceed the concrete's tensile strength). The result is a deterioration of the external appearance of the structure: initially the appearance of rust staining on the concrete surface, followed by local cracking and spalling, leading possibly to exposed reinforcement. Also, the reinforcement's effective cross section is reduced which adversely affects adhesion to the concrete and very likely the integrity of the structure.

Generally, in less aggressive environments, the recommended concrete cover and properties (compactness, homogeneity, resistance) are sufficient to guarantee the natural protection of the reinforcing steel during the expected service life of the structure. However, concrete cover defects, poorly vibrated concrete (resulting in excessive porosity), or very aggressive environments risk leading to premature degradation of the reinforcing steel.

The main reason for recommending stainless steel in corrosive environments is stainless steel's corrosion resistance and therefore its durability. A technical evaluation of the Progreso Pier[4] structure did not detect any cracking or spalling as described above and typical of the degradation

Corrosion of reinforced concrete following the use of deicing salts

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Repair of the central pier of a highway bridge

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of traditional carbon steel reinforced concrete. Given the reduced susceptibility of stainless steel to corrosion compared to carbon steel, there was no evidence of significant corrosion products, nor the kind of deterioration as seen with carbon steel[5].

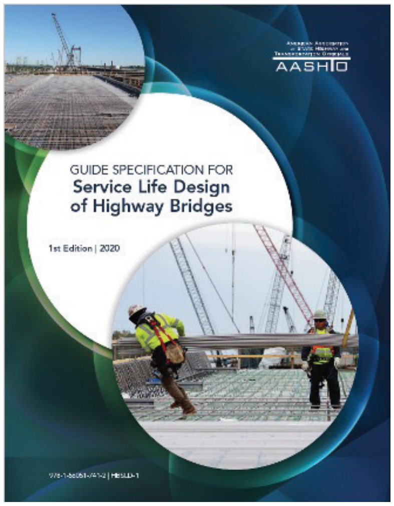
7. CONTACT BETWEEN STAINLESS STEEL AND CARBON STEEL

Field experiments involving the mixed use of stainless steel and carbon steel have shown that from a corrosion point of view, there is no risk to consider. When it comes to repair work, in a field situation of adjacent top and bottom layers of existing carbon steel reinforcement in concrete, the combination of the existing corroding carbon steel and replacing the other carbon layer with new stainless steel is more beneficial than replacing the existing corroding carbon steel reinforcement layer with new carbon steel reinforcement. In the latter case, contact between new reinforcements (made of carbon steel) and parts that are already partially corroded would constitute a greater risk of corrosion (because of the distinct galvanic potential between corroding and freshly produced carbon steel). The increase in the corrosion rate of carbon steel due to galvanic coupling with stainless steel will be significantly lower than in the case of carbon steel[6].

8. REDUCTION OF CONCRETE COVER

The corrosion resistance of stainless steels compared to carbon steels offers opportunities to reduce the concrete cover (which no longer needs to incorporate a corrosion allowance). In Europe, standardization work on Eurocode 2 relating to concrete structures take durability into account by relying on the notion of exposure classes. These classes reflect the effects due to the environment to which the concrete and its reinforcing steel will be exposed during service life[2].

Guide specifications for service life design of highway bridges



AASHTO

GUIDE SPECIFICATION FOR
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The Eurocode 2 recommendations about concrete cover are innovative. They enable optimizing the amount of cover if stainless steel is used for reinforcement. The use of stainless steel rebar thus makes it possible to reduce concrete cover by 25 mm, for example, for concrete in marine environments exposed to attacks from sea salt in tidal zones and designed for a service life of 100 years. The reduction of cover would require less concrete and thus offers weight savings as well as design optimization.

In 2020, AASHTO released the first edition of its "Guide Specification for Service Life Design of Highway bridges". The Guide focuses on the relationship between designing for durability by selecting appropriate protection strategies for the defined exposure environment, and the effect on the service life of bridges.

In this study, the use of stainless steel reinforcement is presented as being the "best" corrosion resistant reinforcement protection strategy. This conclusion is evident from the study as *only this material* can be combined with any of the five concrete mix designs, including the lowest quality concrete mix, and the least level of concrete cover relative to other types of reinforcement.

The primary conclusions regarding the use of stainless steel are:

- Stainless steel is considered the upper bound on reinforcement protection;
- With the use of stainless steel, the quality of the concrete mix and the amount of concrete cover can be significantly reduced relative to other types of reinforcement.

9. TOTAL COST OF OWNERSHIP

The analysis of the total cost of ownership of infrastructure helps to determine the most economical material to use in the ensuing construction. In almost all investment decisions, the material selected for a given application is based solely on the initial purchase price. Over time, the emphasis has shifted more to the belief that the lowest cost material may not be the most economical choice over the long term while considering the additional costs, due to installation, regular maintenance, or even replacement and premature decommissioning of the structure. The cost of downtime (scheduled or not) to industry (loss of manufacturing time, wages) and to society (idling vehicles, environmental impact) denoted as "user costs" must also be included. Stated otherwise, an extensive full-service life cost profile analysis should be performed which includes the impact of the service life extension of more durable materials such as stainless steel, and the avoided costs of maintenance, repair, and user costs.

For most civil engineering projects, a complete substitution of steel rebar by stainless steel rebar is not justified. A small proportion of stainless steel rebar is sufficient to significantly extend the durability of the structure. Finally, only those reinforced concrete structures for which maximum durability is desired (such as heritage structures) and/or on which any maintenance or repair work is impossible, or if it is difficult to carry out, or for which it is impossible to interrupt traffic for repairs would benefit from the use of stainless steel rebar. Reference[3] proposes a series of hypotheses of substitution by stainless steel and the associated overall costs.

As an example, the Swiss Schaffhausen Bridge[7] can be cited. This bridge over the Rhine was inaugurated in 1995. Due to concerns about road salt splash, duplex grade Type 2205 (UNS S32205)/1.4462 was used for the reinforcements of the lower part (7.6 m) of the pylon reinforcement. The longitudinal beams were constructed using Type 304 (UNS30400)/1.4301 stainless steel for the concrete reinforcement, totaling just 15 tonnes of stainless steel. This choice added less than 1% to the total initial cost. In the areas specifically concerned, stainless steel was chosen instead of carbon steel, or even an alternative solution with epoxy coated carbon steel rebar. These two – cheaper upfront – options, would have required renovation work every 25 years, while stainless steel rebar enables the bridge to survive without these operations strongly impacting its reliability and availability.

10. RECENT EXAMPLES OF STAINLESS STEEL REBAR USE

The new 3.4 km long Champlain Bridge located in Montreal[8] was inaugurated in 2019. It is an important road axis for residents and businesses transporting more than 50 million vehicles each year. The original 1962 structure was not adequately designed to withstand the

Bridge over the Rhine in Schaffhausen

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Samuel de Champlain bridge in Montreal

© Infrastructure Canada

severe conditions of de-icing salts, requiring frequent repairs. Traffic disruptions were frequent and long, causing significant delays for local residents and frequently stopped trucks. It had become clear that these problems had their origin in the choice of materials that were ill-suited for the actual exposure conditions.

Montreal's seasonal temperatures can vary up to 60 °C, resulting in extreme freeze-thaw cycles and the need to use de-icing salt to keep the bridge open in winter. Faced with these conditions, Infrastructure Canada did not want to repeat the low reliability of the previous bridge and set the design life at 125 years. To guarantee this service life, high-performance construction materials were necessary, including the choice of concrete reinforcement. Corrosion modeling concluded that stainless steel reinforcement would significantly outperform carbon steel or even galvanized steel, which was also considered. Infrastructure Canada aimed at achieving a design life without replacement of specific bridge components for 125 years and without major planned repairs. Such a design life could only be ensured by the use of stainless steel rebar and which provided benefits in terms of overall cost.

The economic benefits are expressed as a sharp reduction in traffic delays associated with road works if non-stainless rebar had been used. In addition, uninterrupted access to an accessible road for decades to come dramatically increased the capacity for private vehicle and commercial truck traffic, generating substantial economic benefits for the local economy.

The condition of "no replacement" for 125 years without major repairs has been specified for the most exposed areas of the bridge, including the road deck. A total of 17,000 tonnes of ASTM A955 Type 2304 (UNS S32304) stainless steel reinforcement was used in the precast and in situ cast parts of the deck, including approaches, abutments, and all surfaces around expansion joints.

In the new San Giorgio Bridge in Genoa[9], designed by Renzo Piano and inaugurated in 2020, stainless steel reinforcement not only guarantees mechanical strength, but also corrosion resistance, thus ensuring the durability of the bridge and user safety. After the partial collapse of the Morandi Bridge (its predecessor) in 2018, stainless steel was specified - from a corrosion point of view – at the design stage, in the most critical areas. For example, stainless steel rebar was specified for the pedestrian bridges zone, and positioned next to steel rebar, which is located closer to the bridge deck core.

Stainless steel thus acts as a protection against corrosion and cracking or spalling of the structure elements most exposed to atmospheric agents; in fact, in very aggressive environmental conditions, such as marine and port structures, it is necessary to use materials with specific characteristics. In the absence of stainless steel, external agents would

San Giorgio bridge in Genoa

© Inossidabile n° 220 – Centro Inox

Repair of the Northern Breakwater of the port of Bayonne

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trigger the corrosion of the carbon steel reinforcement, leading to an increase of its volume, causing the concrete to crack over time and the structure to deteriorate further. Type 304L (UNS30403)/1.4307 stainless steel reinforcement of different diameters was positioned at the outer surfaces of the concrete structure, in the sections of the structure which have a thinner concrete cover and are therefore inevitably more exposed to the corrosion from the external environment.

Stainless steel provides significant savings in maintenance costs for bridges like this one which are exposed to aggressive environments. Stainless steel is therefore proving to be the most economical solution in the long term. Other relevant characteristics of stainless steel reinforcement which led to its recommendation in this specific setting (marine port) are high mechanical strength, high ductility and excellent energy absorption capacity during seismic events.

Maritime ports are an area where infrastructure is particularly affected by the risk of corrosion. Maintenance costs should include not only the loss of business, but also the business risk posed to shipping lines by delays and lack of mooring space. Each port has its specificities to manage: layout, type of activity (marina, tanker, bulk, container, cruise ships, etc.), condition (aging, recent). It turns out that maintenance is complicated and expensive and that preventive maintenance software is rather simple and dependent on the data provided. The notion of life cycle cost does not seem to be included, which is why stainless steel reinforcement needs to be brought to the attention of specifiers of concrete port structures. In France, two examples of coastal infrastructure can be cited: the Bayonne breakwater, restored in 2008 and the extension of the port area of Monaco (in progress). The Spanish Technical Association for Ports and Coasts deals with the choice of materials in this area[10].

11. CONCLUSIONS

The examples of the use of stainless steel rebar for reinforced concrete structures prove that the right choice of construction materials can increase the service life of infrastructure while offering savings in terms of maintenance. In a context where the environmental and economic impacts are becoming more and more important, growth of stainless steel rebar seems inevitable.

The experience with carbon steel and stainless steel rebar has also clarified some misconceptions about stainless steels:

- Stainless steels should only be used in critical areas of the structure. The quantity of stainless steel rebar in a concrete structure rarely exceeds 5%;
- The cost effect of using stainless steel on the project is small;
- Carbon steel and stainless steel rebar are compatible, i.e. they do not cause galvanic corrosion (also called bi-metallic corrosion) to occur.

Beyond the very comprehensive book[3], references [11] and [12] offer a range of information and examples about stainless steel reinforcements.

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