Stainless steel rebars in concrete: a asset for sustainable development

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Summary

Reinforced concrete is unfortunately subject to structural deterioration over time, under certain conditions: it is estimated that 70% of the problems affecting reinforced concrete are related to the corrosion of the carbon steel reinforcement bars which are used.

Therefore the use of high durability stainless steel rebars represents a very interesting solution for certain applications; many examples of application are now available.

Keywords: Concrete, Stainless Steels, rebars.

1. Why a stainless steel solution should be used?

1.1. The families of Stainless Steel

There are four main families of stainless steel products:

- Martensitic stainless steels: with 12% chromium content, these stainless steels combine good corrosion resistance in moderately aggressive environments with high level mechanical characteristics.
- Ferritic stainless steels: with a 17% chromium and low carbon content; these stainless steels offer an extremely good corrosion resistance in moderately aggressive environments, but only low level mechanical characteristics.
- Austenitic stainless steels: with 18% chromium and 8% nickel content; these stainless steels offer good corrosion resistance (e.g.: very good durability for bridges piers in fresh water)
- Austeno-ferritic stainless steels: with chromium content up to 28%; these stainless steels offer excellent corrosion resistance as well as excellent mechanical properties (e.g.: well suited to bridge piers in salt water).

1.2. Stainless Steel Corrosion Resistance in Concrete

1.2.1. Causes (origins) of corrosion in carbon steel reinforcing bars:

The corrosion of carbon steel reinforcing bars is a natural phenomenon, accelerated under certain conditions, which are described below.

Mortar is itself an alkaline (or basic) environment that encourages the formation of a layer of iron oxides (known as passivation) on the surface of the steel, which naturally protects the carbon steel from corrosion phenomena.

However, unfortunately, this environment does not remain chemically stable over time, and there are two "mechanisms" that will cause corrosion:

The first contributing factor which induces the corrosion process is the natural carbonation of the environment; carbonation is the reaction of the alkalines in the mortar to carbon dioxide, in the presence of water: from such reactions, the alkalinity of the concrete is reduced and the pH decreases from 12 to 8 over the years.

This carbonation reaction is the main reason for the decrease in pH; industrial pollutants (automobile air pollution, industrial pollution, and so on), for example sulphur dioxide ($SO2$), also accelerate and increase this reduction in pH.

The decrease in pH results in the destruction of the passivation layer (see the Pourbaix diagram illustrating the stability of iron oxides), which causes general corrosion of the carbon steel from pH = 9.

This decrease in pH is due to reactions that use OH- hydroxide ions:

For example, CO2gas + Ca(OH)2solid ➔ CaCO3solid + H2O.

The second factor that affects corrosion is the presence of inorganic salts, mainly chloride ions (Cl-), which increases the risk of corrosion and the corrosion rate:

- by increasing the moisture content (deliquescence).
- by increasing electric conductivity,
- but above all, by attacking the passive layer (iron oxides), thus initially causing occasional areas of corrosion (known as "pitting corrosion"), which quickly spread across the entire surface of the steel.

The chloride ions originate from two sources: Either they are already contained in the concrete components, or they originate from the outside environment (road deicing salts, sea water, and so on).

1. Chlorides in the original concrete components: concrete naturally contains the chlorides already present in its components; however, some chloride ions combine with calcium aluminate; it is these that remain free and which will become very active in the corrosion process.

The greater the amount of free chlorides in the concrete, the greater its conductivity: the quantity of chlorides in, for example, Portland concrete is estimated at 8 milligrammes / litre.

2. Chlorides originating from an external source: the quantity of chlorides in sea water is 30 grammes / litre; a certain quantity of these chlorides can diffuse into the concrete and reach the steel reinforcement where they can cause corrosion.

Due to the concept of diffusion into concrete that we have just introduced, we can understand that some of the constituent parameters of the concrete also directly or indirectly influence the corrosion process.

Consequently, the concentration of free Cl- increases, in the event of a low calcium aluminate content, or if the water / cement ratio (determining the porosity of the concrete) is low, or if silica is added to the concrete.

It is therefore evident that in certain outside environments that are particularly exposed to chlorides (bridge piers in the sea, mountain road structures, and so on), a solution using stainless steel, which is more resistant, due to its natural passivation layer (with chromium hydroxides) than carbon steel, is advantageous.

Chloride ions and hydroxide ions therefore play a major role in the corrosion process; that is why we often speak of the permissible Cl-/OH- corrosion resistance ratio, which, for a carbon steel reinforcement, is 0.6.

Note: let us immediately mention the basic component in the corrosion resistance of stainless steel: its passive layer, which distinguishes it from other materials:
A very thin film of chromium oxide and hydroxide known as a "passive layer" is formed (on exposure to air), which protects the stainless steel from external attack and makes it corrosion resistant.
It is this passive layer, caused by the presence of chromium in stainless steels, that makes them far more corrosion resistant than carbon steel.
This layer is an intrinsic part of the material: it is its continuity.

The consequences:

The process described above explains that corrosion does not appear immediately, as it takes time for the aggressive species to diffuse into the concrete and reach the steel reinforcing bars.

As the corrosion process is induced when aggressive agents diffuse into the concrete, the porosity, and more importantly the structure of the concrete, will therefore play an important role. Note that the concrete initially has "micro" fissures which release its internal stress.

Once the corrosion process has begun, the main damage to the structure is caused by the proliferation of the corrosion products which are so considerable that they create cracks in the concrete: the volume of the iron oxides is in fact 4 to 6 times greater than the iron.

It is therefore possible to identify three phases in this corrosion process:

- an initial phase, during which the aggressive agents (chlorides and CO2) diffuse into the concrete; Fick's diffusion law can be used to estimated the initiation time,
- a corrosion period, but with a reasonable amount of corrosion product propagation (in a "free" volume at the concrete/steel interface),
- the erosion phase of the structure: fissures, delaminations, and so on.

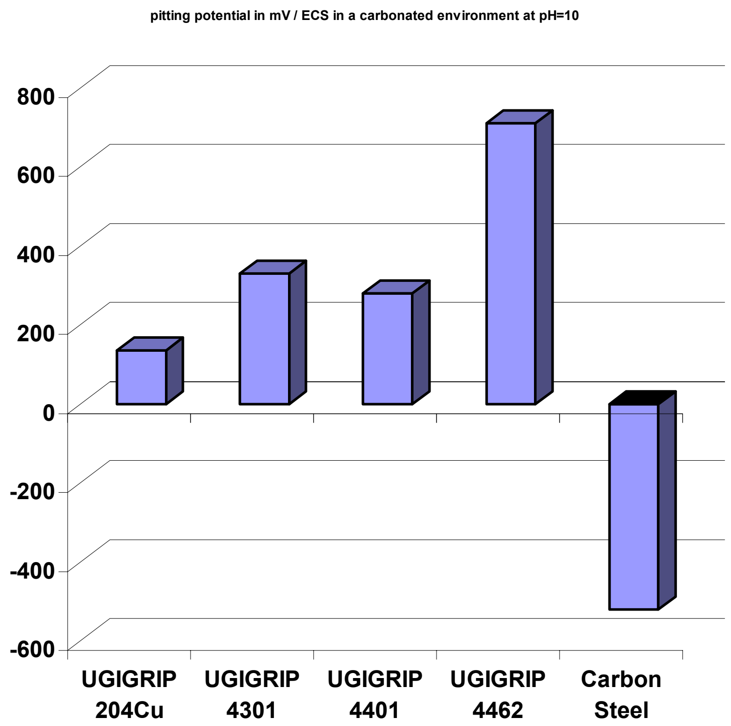
It is obvious that once the cracks in the concrete have become visible on the outside of the structure, the corrosion process accelerates, as there is no longer any barrier in the way of the aggressive agents.

1.2.2. Corrosion mechanisms of stainless steel in concrete:

Pitting corrosion is the main method of erosion of stainless steels in concrete in environments with a high chloride content.

In addition, the chloride action is more sensitive in carbonated concretes than in alkaline concretes.

However, the passivation layer of stainless steels, which is more stable than that of ordinary steel, improves their ability to withstand pitting corrosion; we will illustrate this point with examples from published documents and our own experience. They are mostly taken from accelerated corrosion tests.



Example: Ugitech internal study:

- Materials tested: Carbon steel – UGIGRIP® 204Cu or UGIGRIP® 4597 – UGIGRIP® 4301 – UGIGRIP®4401 – UGIGRIP® 4462
- Environments used: NaHCO3 0.025M + Na2CO3 0.025M + NaCl 35g/l aqueous solution, pH=10
- Tests performed: electrochemical test to determine pitting potential on a polarisation curve.
- Results:

the higher the pitting potential, the better the behaviour.

Conclusions based on these examples:

The examples studied showed that the stainless steel grades are far more resistant to chemical aggression caused by changes in the concrete (decrease in pH due to carbonation, penetration of chlorides from the outside environment).

When we consider the behaviour of different stainless steel grades, it is interesting to note the following points:

- The excellent behaviour of austeno-ferritic duplex grades (45N, etc.): in short, we can state that this is basically due to their high chromium content (22% to 25% as opposed to 17% to 20% for "conventional" austenitic steels).
- The similar behaviour of 304 and 316 grade steels in concrete: this is the opposite of what is usually observed in the case of exposure to the atmosphere (for example near the sea), where 316 grade steel is better able to withstand corrosion than 304. The result observed in basic environments is due to the nature of the ions produced by the dissolution of molybdenum and by the way in which molybdenum acts: in a saline environment, the molybdenum breaks down into cations and can trap the chloride ions and therefore prevent them from attacking the passive film; however, in an alkaline environment, the molybdenum breaks down into anionic form and cannot combine with the chlorine.

Important: the similar behaviour of 304 and 316 is only valid for basic environments such as concrete; when concrete reinforcing bars are exposed to the open air, 316 grade steel is better than 304.

1.3. The cost of Ownership:

The major objection made against the use of stainless steel rebar is the purchase cost of the material. Since the concept of sustainable development appeared and due to increasing maintenance costs, owners and investors are becoming more and more aware of the Total Cost of Ownership and are looking for long-lasting solutions. Stainless steel reinforcement therefore appears to be an interesting solution.

1.3.1. American case of highways bridges:

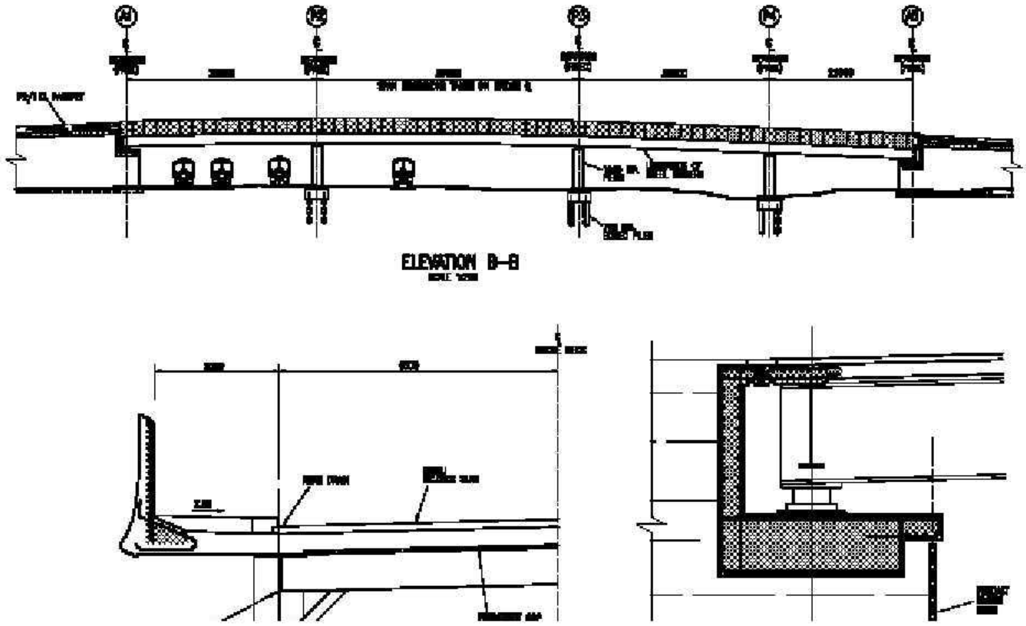
An American study on the costs of maintenance on highways bridges shows that the damages caused by the corrosion of steel rebars or steel structure cost US highways operators between 6.5 and 10 billion US dollars a year for a total of 108,000 bridges. Furthermore, the maintenance works have to be scheduled every 10 to 30 years; during these works, the installations have to be closed and the road traffic stopped: this represents an additional cost which is consistent. A greater initial investment is more cost effective over medium to longterm periods (50 to 120 years).

1.3.2. A BSSA[1] study concerning the matter to use stainless steel characteristics in bridge's elements conception:

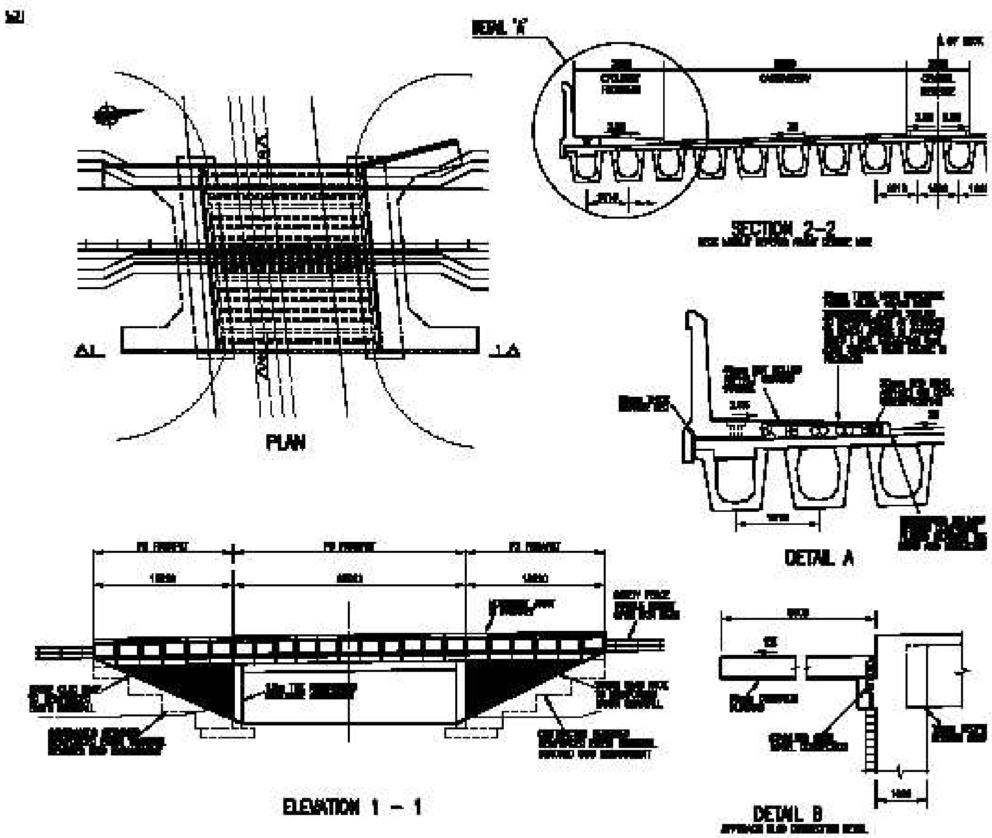
In the same way a recent study of the BSSA shows that the design and the manufacture of elements of bridges (bridge deck, parapets, piers, abutments) with stainless steel rebars are profitable.

This study compares two types of bridges:

- a multi-span bridge of 119m long and 13m wide formed from steelwork girders with in situ reinforced concrete deck carrying a 9m carriageway supported by circular reinforced concrete piers,
- a single span bridge of 25 m long and 29m wide formed by precast concrete U-beams spanning between full height abutment retaining walls.



Multi-span bridge



Single Span bridge with precast concrete U-beams

Four exposure conditions in accordance with BA 84/02 section 3:

- Category U for new structures where stainless steel is not considerer appropriate;
- Category A for New structures where stainless steel is appropriate for the complete replacement of reinforcement in structure, superstructure and deck slab, except foundations or piles;
- Category B for new structures where stainless steel is appropriate for the partial replacement of reinforcement in structure elements exposed to seawater;
- Category C for new structures where stainless steel is appropriate for the partial replacement of reinforcement in structure elements exposed to chlorides from road de-icing salts.

Four stainless steels grades: 1.4301 (304), 1.4429 (High proof 316), 1.4436 (316 with high Mo), 1.4462 (Duplex) and two levels of steel strength : InE500 and InE650.

This study shows that the use of standard stainless steel reinforcement 1.4301 under InE500 and InE650 conditions allows a gain of weight between 4,5% and 37% on the elements, for overcosts from 0,2% to 6,5% (according to the level of replacement) on the total cost of a bridge compared to a carbon steel reinforcement.

2. Advantages of stainless steel rebars

Stainless steel reinforcement presents numerous advantages:

- Enhance fire and earthquake resistance.

- Significantly improve the durability of the installation, which can be guaranteed up to 120 years (e.g. highway bridge in Oregon), thanks to enhanced corrosion resistance.

- Reduce the reinforcement cross-section and therefore the weight of the structure, thanks to greater mechanical properties.

- No particular implementation problems (folding, welding).

3. Some examples of application

Avalanche protection structures in the Val-d'Arly gorges (Savoie, France),

Civil engineering work for widening a road over a river in the Czech Republic.

Some photos of the Czech Republic works

4. Standards (By Aldo Bennani and François Moulinier)

There is a reference standard for the stainless steel reinforcement bars in concrete in American standards. In Europe, national standards are in place, for instance:

BS 6744 in UK

ISO/TC 17/ SC 16 N 486 and 487 in Norway

NF XP 35 014 in France (since 2003)

In other European countries, either the standardisation is in progress, or local practices do not require a standard.

We will quickly survey the state of the standardisation in 3 countries during the presentation: UK where the standard is the oldest, hence a reference, and linked with many recommendations; France where it is very fresh; Italy where works are going forward.

In the UK , stainless steel has been used for reinforcement since 1930's, before any standards were in place. The technical report n°51 lists many examples of use; from these examples, the BRE (Building Research Establishment – Pedeferri) has published a very complete study which stresses the advantages of the use of stainless steel for rebar. After the publication of the BS 6744, more recently, the Highways Agency has published a guide book for the use of stainless steel rebar for civil engineering applications .

In France, a particular effort has been made in order to facilitate the comprehension and the use of the standard by the professionals of the building and construction: suitable vocabulary, boards built according to the same frame as those already existing for carbon steels, annexes summarizing the possibilities and the conditions of use. Some particularities have to be underscored: there are some references to particularly advantageous grades. The high value yield strength has been introduced in order to significantly reduce the diameters of the bars. The standard is mentioned in the DTU 21; at the same time, an on-going process in order to quote this standard in the "leaflets 65 A & 65 B" of the SETRA (guidance for working)

In Italy, stainless steels for rebar have been used for about 10 years; as their use is not covered by any standard, they are included inside the frame of the carbon steels standards (D.M. 09/01/96 AND DM 16/01/96). They have mainly been used in particularly hard conditions imposed by a specific environment (necessity to combine marine corrosion resistance with use in seismic zones, restoration of works of art, securing and perpetuating structures, etc...); hence, they have been recognized and appreciated for their ductility and mechanical properties in general. The competent ministry, together with the involved partners, is working at the publication of a new decree which would be a compromise between a "standard" product (carbon steel with an unique tensile strength 450 MPa) and a "personalized" product, such as stainless steel, which should be used for particular applications or in niche markets.

5. References

[1] BSSA Study : British Stainless Steel Association : Stainless Steel reinforcement cost analysis tool prepared by Ove Arup & Partners Ltd for BSSA members Acerinox, Ugitech S.A. (Arvelor), Arminox, Avesta Polarit, Cogne, The Nickel Development (NiDI) and Valbruna.