RESEARCH AND DEVELOPMENT

Stainless Steel Reinforcement
”State of the Art” Report
Materials and Maintenance

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STAINLESS STEEL REINFORCEMENT
“State-of-the-art” Report

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April 18, 1997

Materials and Maintenance

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STAINLESS STEEL REINFORCEMENT
STATE OF THE ART REPORT

1. Introduction

Steel reinforcement embedded in concrete will not normally corrode due to the formation of a protective ion oxide film which passivates the steel in the strongly alkaline conditions of the concrete pore water. This passivity can be destroyed by chlorides penetrating through the concrete and due to carbonation. Corrosion, which is an electrochemical process involving establishment of corroding and passive sites on the metal surface, is then initiated.

As a result of corrosion reaction rust forms and occupies a volume greater than that of the original metal. This rust occupies a volume of approximately three times that of the corroded parent steel, hence generating bursting forces which exceed the tensile strength of concrete. It is therefore causing cracking and spalling of the concrete leading to further corrosion and loss of bond between the concrete and the steel. A dangerous situation will arise where a structural member loses cross-sectional area since there will then be increasing stress on the remaining section which could possibly lead to structural failure.

Consideration of environmental and design factors will produce different solution for individual projects in order to avoid this dangerous situation. Cases that difference between normal reinforcement with high quality concrete and good cover, or, a corrosion free reinforcement system with less cover and acceptance of lower quality concrete on site, are a matter of engineering judgement.

There are several conventional options open to the designer when long life is required or corrosion is anticipated. At the head of the corrosion prevention table are good design, good site practice and quality control. Contributory to these requirements are details such as adequate concrete cover, minimal water/cement ratio, high cement content, using great care with any additives and adequate compaction.

Environmental effects are beyond design control. The ingress of salts, moisture and air and/or break down of homogeneity due to service conditions can defeat the best laid plans. In these circumstances it is necessary to look beyond the conventional acceptance of basic materials with good design and site practice. Additional protection methods are then needed. These methods include use of galvanised reinforcement, epoxy coatings, inhibitors, application of electrochemical techniques, such as cathodic protection or chloride removal. One more solution is to apply a stainless steel based reinforcement. All these alternatives have a place as design alternatives and some are now standard practice.

Stainless steel, already established as corrosion resistant material with wide usage in many industries, offers one of the most attractive technical solutions. Stainless steel was first used in quantity for reinforcement in 1967/68 in high-rise public authority housing, where Scandinavian design systems were used. Generally stainless steels are established for both conventional reinforcement in aggressive environments and for related building applications were load bearing fixtures are required. Examples of application can be found in:

* Marine structures, piers, off-shore platforms
* Bridges, viaducts, overpasses, tunnels
* Balcony fastenings
* Rock face, ground and roof anchorage's
* Support for restoration of historical buildings
* Reinforced concrete supports

Typical applications are usually where a sufficient cover cannot be obtained. An increasing amount of this material is also to be found in bridge engineering and stainless steel is generally located at structure joints or critical gaps between columns and decks. Another typical application is prefabricated wall elements where the reinforcement connects the outer and inner walls.

A specific use of stainless steel in some most aggressive exposures zones would in many cases be cost-effective for the owner. Only a small fraction of the total reinforcement, i.e. the splash zones for concrete exposed for marine or de-icing salts, would need to be replaced. In principal, stainless steel should be used in concrete which is suspected to have a high chloride content and high oxygen availability. Therefore it would be necessary to use stainless steel in submerged concrete, since there pitting corrosion is impossible and the general corrosion rate will be negligible.

Another application area of stainless steel is repair and renovation of historic buildings. The use of high strength stainless steel ribbed or plain bars has been a feature of this application, as a repair of an number of Cathedrals in the UK including Winchester and Durham.

One often stated barrier to use of stainless steel is the high cost. However the are many applications where the cost of reinforcement for the critical areas of a structure subject to corrosive conditions is a small part of the total project cost. More importantly increasing attention is being given to the concept of life cycle costing, given the experience gained with the total repair and maintenance costs of reinforced structures, through their service lives.

There are numerous examples of bridges in marine atmosphere, motorway bridges, parking decks, tunnels where sea water and de-icing salts have caused enormous cost for restoring to the designed strength requirements after relatively short period. Alarming observations of the conditions of concrete bridges at motorways and in coasted areas have been reported from for instance Norway and Sweden, most of which were built in the 60s and 70s. The costs of repairs can often be of the same order of magnitude as the original cost of the structure. In these cases, compared with the extra cost of using stainless steel rebar, this alternative shows to be cost-effective at the first replacement. Therefore, in spite of a cost premium for the stainless steel material, often 5-8 times that of mild steel, life cycle cost evaluation can show that stainless steel rebars provide the most cost-effective solution for the desired life of the construction , because of the maintenance free use.

Summarising, main advantages offered by stainless steel rebars, which will be discussed further in this report, are listed below:

* inherently good corrosion resistance, especially to chlorides
* reduced life cycle cost for the concrete structure
* good strength
* good ductility
* no coating to chip, crack or degrade
* no coating damage to repair
* no “exposed” cut-ends to coat/cover
* capable to withstanding shipping, handling, bending
* magnetic or non-magnetic depending on the alloy specified
* good high- and low-temperature mechanical properties.

2. Corrosion Environment

Concrete is formulated from a mixture of cement, aggregates, water, and often pozzolan and other admixtures as plasticisers, air entraining agents and polymers. Through the right ratio between the components a strong, durable concrete is obtained, when the cement paste reacts with water aggregates and the admixtures.

The concrete will, to a certain degree, be porous, and the pores will contain water soluble salts among which alkaline components like sodium, potassium and calcium hydroxides are very important for the corrosion resistance of metal bars used as reinforcement of the concrete.

Initially the alkalinity of the water in the pores is dominated by the extremely soluble hydroxides of sodium and potassium resulting in a pH of 13,5. Being very reactive the strong alkalies, which are present in restricted amounts, are consumed, and the pH value decreases to 12,4. It is the pH of saturated calcium hydroxide solution.

Calcium hydroxide is present in much larger amounts than the strong alkalies, but mainly as crystals in equilibrium with the saturated solution. The crystals are an alkali reserve coming into solution in the pore water when the dissolved hydroxides reacts with carbon dioxide diffusing into the concrete from the environment under the formation of nearly insoluble calcium carbonate.

Depending on the diffusivity of carbon dioxide into the concrete full carbonation starts at the surface and protrudes into the concrete once more changing the alkalinity and the pH decreases towards slightly alkaline values of 8-9. An alkali reserve is still present, but being based mainly on nearly insoluble calcium carbonate it is not very mobile and acts mainly as a neutraliser to acid components in the environment.

The transformation of calcium hydroxide into carbonate is not detrimental to the concrete itself. It makes the concrete denser and stronger, but it changes the corrosion preventive property of the concrete through the reduction of the pH value.

At the high pH of the sound concrete carbon steels are very well protected against corrosion. The steel surface reacts with oxygen in the alkaline environment forming a very dense and diffusion tight layer of iron oxides on which further oxidation takes place at an extremely low rate. The steel passivates.

The oxide layer is very stable as long as the pH stays high, but at pH values below 10 they are not stable anymore. They become porous and do allow diffusion of oxygen to the steel surface with corrosion as the result. The steel starts rusting.

The stability of the oxide layer is also influenced by other ions than the hydroxyl ions. Especially chloride ions destabilise the iron oxide layer and initiate corrosion. The chloride ion is small and very mobile, and it penetrates the iron oxide layer in weaker points and makes it more conductive. A small amount of iron goes into solution. It is hydrolysed, and very locally the pH is lowered to a level, where the oxide stability is broken, and increased corrosion can take place.

With local active corrosion the electrochemical conditions on the steel surface change. The potential (voltage level) decreases, and a potential difference between the corroding area and the rest of the steel surface develops. Thereby the corrosion rate is drastically increased with pitting corrosion as the result.

Chlorides are nearly always present. They are contained in small amounts in the cement and in the water used for mixing of the concrete, but kept well below a certain threshold value they do not influence the passive layer formation or degradation. The detrimental chlorides most often originate from external sources like seawater, seawater spray, deicing salt, etc. The transport into the concrete is dependant on many factors. The most important concrete qualities are the porosity of the concrete and its ability to binding the chloride physically and chemically.

The transport of chlorides is a time dependant function of the environmental conditions and the design of the structure also. The mechanisms are complicated and not fully understood. It is mainly a function of chloride concentrations and the duration of wetting. Below the water level the penetration is a nearly pure diffusion process, and chlorides ingress at a constant rate into the concrete provided it is free of cracks and other inhomogeneities.

In the atmosphere frequent splashing causes water to be sucked into the concrete and chlorides may move inwards and outwards due to moisture flow and ion diffusion. In the marine environment and along roads where deicing salts are used intensively, the chloride concentration and the wetting varies considerably, and so does also the chloride penetration of the concrete.

The highest corrosion risk is usually associated with concrete which is subjected to cyclic wetting and drying. In the drying period more and more oxygen reaches the reinforcement, and the chloride threshold value decreases to a content of perhaps 0,5-1 % by weight of the cement content.

In water saturated concrete the oxygen diffusivity is extremely low which result in a high threshold value of corrosion initiation. It may easily be four times higher than under wetting/drying conditions, i.e. 2 % by weight of the cement content. If oxygen can be nearly totally excluded the chloride content may be even higher due to the fact that a corrosion attack can not take place at all.

The threshold values reported above are not related to the compaction of concrete, but experimental data indicate that there might be a considerable difference between very well compacted and insufficiently compacted concrete. It means, that a faultless layer of cement paste on the surface of embedded steel increases the threshold value.

It is a well known fact that the critical chloride concentration of passivation breakdown is pH dependant. The threshold value decreases with decreasing pH. Below pH 10 the concrete is no longer able to keep steel passive and pitting may be initiated at any chloride level., i.e. the threshold value becomes zero as a consequence of carbonation.

The carbonation process is very much dependant on the porosity of the concrete and on the water content. Under dry conditions carbon dioxide diffuses easily into a porous concrete but reacts slowly with the alkaline constituents. In water saturated concrete the diffusion rate is extremely low, and so is the carbonation rate. In between large differences in carbonation rate can be experienced. Variations from literally zero to several mm/year are experienced. Because the porosity has major influence on the carbonation rate, a high cement content, a low water/cement ratio, and addition of silica fume to the concrete have a beneficial effect.

Conclusively a high concrete quality is the best measure against corrosion of embedded steel, but it is not always enough. Carbonation and chloride ingress, which are both time dependant processes, reduces the protective proporties of the concrete, and more corrosion resistant materials than carbon steel are necessary for embedded parts, if severe damages on them and on the concrete shall be avoided or significantly delayed.

3. Stainless Steel Materials

The term stainless steel refers to a great family of metallic materials with a huge variety of physical/mechanical as well as corrosion properties. Originally the term refers to materials having a minimum content of 12% chromium, but during the recent years other materials with 10-12% chromium have appeared. Although these steels are not stainless in the classical sense they posses, however, corrosion properties better than carbon steel in many environments.

It is evident, that increasing the level of alloying elements, especially chromium, nickel and molybdenum, that corrosion resistance will increase. However changing the balance of the alloying elements will influence the structure as well as the other properties. Therefore members of the stainless steel family are usually grouped in groups having the same metallographic structure. In addition increasing the alloy level the cost of the material will also increase. Therefore it is important to select steel types at an alloy level which are sufficiently corrosion resistant for the job to be done and with sufficient mechanical properties and weldability.

Dealing with that many types of material the decision on which of these types of steels to depends on:

Degree of corrosion protection required

Cost aspects

Workability and application characteristics (mechanical properties, weldability).

3.1. Stainless Steel Types.

Within the area of concrete reinforcement three types of stainless steels are in question (and is available in the adequate product form). These are

ferritic
austenitic
austenitic-ferritic (duplex)

The corrosion resistance required for use in concrete is primarily resistance against localized corrosion (pitting, crevice corrosion) in chloride containing media. This resistance depends on the alloying elements of chromium, molybdenum and nitrogen. Whereas chromium is the main alloying element, molybdenum and nitrogen has more effect on the localized corrosion resistance. In order to compare stainless steel grades with different alloying, correllation of the influence of the different elements has been made resulting in the expression of pitting resistance equivalent (PREN). This expression can be considered as a relative measure of the total resistance resources for the steel grade and thus a comparable value. The expression is calculated from the content of the alloying elements in the steel grade.

For austenitic steels the expression is

PREN = %Chromium + 3,3 * %Molybdenum + 16 *%Nitrogen

For duplex steels the effect of nitrogen is considered higher resulting in the expression

PREN = %Chromium + 3,3 *%Molybdenum + 30 *%Nitrogen

Table 1 shows the composition of a range of stainless steels which are available in a product form for use as reinforcement.

The materials are arranged with increasing corrosion resistance downwards in the table and accordingly with more or less increasing cost of the materials. In general most of the stainless steels used for reinforcement is within the types 1.4301 and 1.4401. Only in extreme environments more resistant materials are considered.

Table 1. Composition of stainless steel

Steel grade	Composition						Type
	Cmax%	Cr%	Ni%	Mo%	N%	Ti%	
1.4003	0,03	11			< 0,03		ferritic
1.4016	0,08	16,5					ferritic
1.4301	0,07	18	9,5				austenitic
1.4401	0,07	17,5	12	2,2			austenitic
1.4404	0,03	17,5	13	2,2			austenitic
1.4571	0,08	17,5	13	2,2		> 5*C	austenitic
1.4429	0,03	18	13	3			austenitic
1.4362	0,03	23	4				duplex
1.4462	0,03	22	5	3			duplex

The general mechanical properties of stailess steel in the annealed condition are such that the yield strength ($R_{0,2\%}$) of ferritic and austenitic types are of the same magnitude (200-300 MPa) where as the corresponding value for duplex steels are higher (400-480 MPa). However in order to meet the requirements for use as reinforcement in concrete the strength of the steels is increased by cold working. Cold working usual results in martent-site formation in 1.4301 types whereas in 1.4401 and duplex materials this is not the case. For the austenitic types cold working results in a reduction of the elongation from 40% to 20-25%, which is beneficial for the function of the rebars in concrete.

For small dimensions (<12 mm) also warm working at reduced temperature may be used for increasing the strength resulting in mechanical properties similar to those obtained by cold working.

Another way of increasing strength is addition of nitrogen (0,15-0,2%). This is however not sufficient to reach the required strength and must therefore be combined with either cold or warm working.

The weldability of the steel types is best for the austenitic types, similar but more restricted for the duplex materials and very limited for the ferritic ones. This means that if ferritic steels are used, the connections are mainly made by binding. The weldability is discussed in more details below.

3.2 Cost aspects

Increasing alloy content results as mentioned in increased cost of materials. Therefore it is necessary to select a steel grade which is adequate for the application at the lowest cost. In order to get an idea of the cost level relative cost indices has been given below.

unalloyed		1
12% ferritic	(1.4003)	4,9
17% ferritic	(1.4016)	4,3
austenitic	(1.4301)	5,5
austenitic	(1.4401)	8-11
duplex	(1.4462)	12

Comparing the material cost of stainless steel with unalloyed steel usually results in the conclusion that stainless steel is an expensive material. On the other hand even if stainless steel is several times more expensive than unalloyed steel the additional costs of a structure are about 5 to 15%. In addition a whole life cycle calculation may prove that stainless steel is not more expensive due to the abscence of repair costs.

3.3 Welding.

Welding of reinforcement can be made by resistance welding as well as metal arc welding. As most materials used for reinforcement have their strength due to cold working, reduction of strength at the welds is possible depending of the heat input applied.

Resistance welding having generally the lowest heat input will have the least effect on the properties. On the other hand, it requires well adjusted parameters in order to obtain a mechanical connection which is able to transfer sufficient force. This is done by optimizing the electrical parameters along with the press force by the welding.

More metal arc welding methods are available but one of the most used is gas metal arc welding (MIG/MAG) which is a rational method for joining crossing rebars. Due to the above mentioned reasons it is advisable to adjust the welding parameters resulting in shortest possible welding time and the best possible gas shielding. The latter is in order to minimize oxide formation. Gas mixture used is 96% argon, 3% CO_2 and 1% hydrogen.

By welding standard austenitic types usually filler material corresponding to 1.4404 is used also when 1.4301 types are welded. Duplex types will normally require maching filler material and close control of the welding parameters.

For the austenitic types resistance welding has no detrimental effect on the tensile properties but on profiled material a reduction of fatigue properties must always be expected. The welding parameters have no influence on this within a wide spectrum of values.

4. Structural properties of stainless steel related for application in concrete

Mechanical and physical properties are very important in order to evaluate the ability of any material to withstand the expected loads during the designed service life.

As mentioned previously stainless steel is a family of steels with different compositions having characteristic microstructures and properties, including austenitic, ferritic and martensitic, and also duplex steels. Depending of the manufacturing procedures, the mechanical properties regarding strength, may differ.

Processes such as pickling and neutralisation, roller design, stress-strain degree and straightening influence the strength of stainless steels. These conditions may be considered when the mechanical properties of different grades of stainless steel are compared.

Additionally the strength of stainless steel is influenced by the material composition and by the microstructure.

4.1. Mechanical properties of stainless steel for application in concrete

The mechanical properties usually considered are: yield stress, tensile stress and elongation. The typical values of these stress parameters for austenitic and duplex stainless steel are shown in table 2.

Table 2. Mechanical properties of stainless steels used for rebars

Type	Yiels strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Magnetic
Austenitic	205-575	490-860	30-60	No*
Duplex	330-550	570-1000	25-40	Yes

* Austenitic alloys can becomne magnetic if cold-worked

The strength of the austenitic types are further increased by cold work, for example when shaping the ribbed profile of the rebar.

Table 3 shows some typical values of strengths for the Danish manufactured austenitic stainless steel ribbed bars of the grades 304 and 316. These bars which are cold rolled weldable austenitic steel have dimensions from 4-16 mm.

Table 3. Mechanical properties of cold rolled austenitic stainless steel manufactured in Denmark

Steel Type	Surface Shape	Deformation degree %	Yield Strength MPa	Tensile Strength MPa	Elongation %
AISI 304	smooth	19	565	745	36
AISI 304	profile	19	710	815	19
AISI 316	smooth	19	610	730	29

AISI 316	profile	19	710	795	15

For application in concrete, stainless steels can be produced as ribbed bars within the normal range of strength and deformability requirements. Such bars can be welded as a part of normal construction practice. One of the initial problems in producing stainless steel reinforcement was that the yield strength of “as rolled” bars were approximately the same as those for mild steel. Therefore no ferritic or austenitic standard steel in the normal as rolled condition would have sufficient strength.

As these steels had a metallurgical structure incapable of being hardened significantly by heat treatment other methods of increasing strength had to be pursued. Subsequent treatment, either special heat treatment or cold and warm working will enable high yield reinforcement strengths to be reached. These processes are however complicated and increase the high material cost of stainless steel.

Acceptable high yield reinforcing bar strengths can be obtained from austenitic stainless steels. For example in the UK a number of steel grades exist which fulfil the basic property requirements for British Standard reinforcing steels. British Standard, (BS 6744, 1986) specifies austenitic stainless hot rolled or cold worked deformed steel bars. Table 4 shows typical properties for steel grade 316.

Table 4. Mechanical properties of stainless reinforcing steels in UK and steel maker information

Steel Grade	Chemical Composition	Condition	Bar size	Yield Stress	Tensile Stress	Elongation
			mm	MPa	MPa	%
316 1.4401 austenitic	X5CrNiMo 17-12-2	* warm worked	10 20 32 40	865 745 620 550	1000 880 775 685	20 25 25 25
		+ as rolled	25	279	579	52
		+ cold twisted	20	660	780	28

* minimum values + values of specific specimens

In Germany bars of 10 to 40 mm are offered in the hot rolled condition. For austenitic steel, grade of 1,4429 with 16,5-18,5 % Cr, 10,0-13,0% Ni, 2-3% Mo and 0,2% N a yield stress of 550-880 MPa mm^{-2} can be reached. Another typical values for the German stainless steel grades are shown in table 5.

Table 5. Mechanical properties of stainless reinforcing steels in Germany and steel maker information

Steel Grade	Chemical Composition	Condition	Bar size	Yield Stress	Tensile Stress	Elongation
			mm	MPa	MPa	%
1.4429 austenitic	X2CrNiMoN 17-13-3	hot rolled ++	10 20 32 40	880 790 630 550	990 900 790 790	20 25 25 30
1.4571 austenitic	X2CrNiMoN 22-5-3	cold rolled **	10*	456	599	39
			7*	870	934	13
			8*	518	608	16
1.4003 ferritic	X2CrNi 12	hot rolled +		350	490	25

* 6-14 mmm is possible + no reinforcing steel
** values of specific specimens ++ minimum values

The application of these steel types in Germany has up to now been limited because of the high price.

In comparison with austenitic stainless steels, duplex steels have even better mechanical strength properties. For example, the Italian duplex steel of grade 1.4462 (X2CrNiMoN 22-5) as cold rolled, has a yield stress of 950 MPa, tensile stress of 1059 MPa and elongation of 14 % for 10 mm bars. Another Italian duplex steel of grade 1.4362 (X2CrNiN 23-4), as rolled, has a yield stress of 485 MPa, tensile stress of 668 MPa for 18 mm bars.

Owing to their excellent mechanical properties in the as-rolled conditions, duplex steel are of interest as material for reinforcement.

Stainless steel has also other properties which are different to conventional steels. At low temperatures, even down to minus 196 °C, the strength properties are maintained or improved and the elongation remains good. Also at high temperatures the strength remains good up to 800 °C.

Finally it can be concluded that that the ductility of stainless steel always exceeds that of conventional bars. Stainless steel also offer the option of significantly higher strengths of around twice those of normal steels.

4.2. Physical properties of stainless steel for application in concrete

The most important physical properties of stainless steel considered in relation to application in concrete are: density, thermal conductivity, coefficient of thermal expansion and magnetic permeability.

In table 6 typical values of these parameters for different types of stainless steel, namely austenitic, ferritic, martensitic and duplex steels are collected.

Table 6. Physical properties of stainless steel

	Density g/cm^3	**Thermal conductivity W/m · °C**	**Specific heat J/g · ^{o}C**	**Coefficient of thermal expansion cm/cm · ^{o}C**	**Magnetic**
Ferritic steel	7,7	23	0.46	11-10^{-6}	yes
Austenitic steel	7,8-8,0	12-15	0.44	17-10^{-6}	no
Martensitic steel	7,7	23	0.46	12-10^{-6}	yes
Duplex steel	7,7	20	0.44	12-10^{-6}	yes

The following comments in relation to these parameters are of importance:

Coefficient of thermal expansion:
Coefficient of thermal expansion of ferritic steel and concrete are more or less the same (1,2 and 1,1 * 10^{-5} °C respectively). In comparison, the coefficient of thermal expansion of austenitic stainless steel is higher (1,7 * 10^{-5} °C).

If the concrete structure with austenitic reinforcement is exposed to high temperatures (for instance in connection with the fire), tensile stress will be produced in the uncracked concrete as a consequence of the different thermal coefficient of steel and concrete. This may in theory cause some defects in the contact zone and expansion cracking, particularly in heavy reinforced sections. However, there is no practical evidence of laboratory results supporting this assumption.

Generally at higher temperatures the strength remains good up to 800 °C. At low temperatures down to minus 196 °C, the strength properties are maintained or improved and the elongation remains good.

Magnetic permeability:
Austenitic stainless steels have low magnetic permeabilities compared to other ferrous reinforcement products. In particular the more highly alloyed grades, e.g. 316 with nitrogen addition are effectively non-magnetic. The use of these steels are suited to applications where the field interference effects associated with conventional reinforcement structures cannot be tolerated, e.g. housing of electronic equipment. Another known application areas are: transformer bases, medical buildings where magnetic scanners are used and runway calibration pads for aircraft instrumentation.

5. Corrosion resistance of stainless steel in concrete

Stainless steels develop a natural passivity also in neutral and acid media, but chlorides can induce pitting corrosion, depending on the alloy content and the pH of the solution. The chloride tolerance increases with increasing pH and several investigations have confirmed that stainless steel is much superior to mild steel in its ability to resist chloride initiated corrosion when embedded in concrete.

So far most of the stainless steel used as reinforcement has been of the austenitic types (AISI 304 and 316), which are most readily available and have been shown to have 5-10 times higher chloride tolerance compared to mild steel reinforcement.

The lower alloyed ferritic stainless steels are less resistant to chlorides, but they can be delivered with higher strength and their response to mechanical loading is very similar to that of mild steel. They are not so readily weldable as the other types.

The duplex types of stainless steels are generally more expensive than other of the above types, but they combine good mechanical properties with excellent corrosion resistance.

The corrosion resistance of stainless steels is lowered by welding and by contamination with iron deposits from tools used in handling.

The main characteristic of these three groups of stainless steel can be summarised as follows:

Austenitic stainless steels: High corrosion resistance and also easily formed and welded

Ferritic and martensitic stainless steels: Good corrosion resistance, easily formed, difficult to weld. Martensitic steels are hardenable due to higher carbon contents.

Duplex stainless steels: High corrosion resistance, good weldability, high mechanical strength

5.1. Stainless steel reinforcement in contact with black steel reinforcement in concrete

It seems to be a fact, that most of civil engineers have an unfounded fear of using stainless steel and black steel together in the same concrete structure. In Denmark, FORCE Institute (The former Danish Corrosion Centre) has given advice to more than 100 clients on the use of stainless steel in concrete. Nearly always the clients had to be convince, that it is in the fact good and safe practice to use stainless steel in the most chloride exposed concrete, with the stainless steel in good - often welded - connection with the black steel in the main reinforcement.

Stainless steel freely exposed to seawater may, if in galvanic contact with less noble metal such as black steel, initiate a rapid galvanic type of corrosion of the less noble metal. The otherwise slow cathodic oxygen reduction at the stainless steel surface is catalysed by a bacterial slime, which forms after a few weeks in seawater.

When cast into concrete, however, the cathodic oxygen reaction is a very slow process, since then no such catalytical activity take place at stainless steel surface. Research project conducted at FORCE Institute has indicated that the cathodic reaction is inhibited on stainless steel embedded in concrete, as compared to the cathodic reaction on ordinary steel reinforcement in galvanic contact with corroding black steel.

As a consequence, connections between stainless steel and ordinary steel will not promote galvanic corrosion. As far as corrosion of the stainless steel is concerned, a galvanic connection between stainless- and ordinary reinforcement would also result in partial cathodic protection of the stainless steel, as a consequence of the lower passive potential of the black steel.
Stainless steel is therefore an excellent material to use for all components, which are only partially embedded in concrete, especially connected to the reinforcement. Examples are blots, binders, ladder rungs, inserts, electrical connectors, sanitary piping and bushings.

The fact that stainless steel is far less effective cathode in concrete than the ordinary steel gives also possibility for application in the traditional repairs projects. When a part of the corroded reinforcement, e.g. close to concrete cover shall be replaced, it is advantageous to use stainless steel in stead of black steel. Because of being a poor cathode the stainless steel will minimise eventual problems which could occur in neighbouring corroding and passive areas after the repair.

5.2. Reported corrosion resistance of stainless steel reinforcement

A number of corrosion tests have been made with stainless steel rebars, both on laboratory scale as well as in simulated and natural seawater environments. The following tests have been conducted:

* electrochemical tests involving metal/solution electrolyte or metal/concrete electrolyte systems

* accelerated laboratory tests carried out on reinforcement concrete specimens (the usual methods adopted are partial immersion of specimens in salt solutions or by intermittent exposure to salt spray)

* long term site exposure tests of reinforced concrete specimens

In order to make results better known, a few of the most important tests will be reviewed in the following.

5.2.1. Test in UK carried out by Building Research Establishment (BER) and reported by Treadaway, Cox and Brown : "Durability of corrosion resisting steels in concrete" (see enclosed list of literature).

This extensive test includes ten years study of variety of stainless steels, such as the ferritic types 405 (X6CrAl13), 430 (X5Cr17) and the austenitic types 304 (X5CrNi 18-10), 315 (-) 316 (X5CrNiMo 17-12-2). These steels types were compared with unalloyed, weathering and galvanised steel using exposure and laboratory testing. The surface conditions of the stainless steel was "descaled". The steels were used as reinforcement for small prisms fabricated with various qualities of concrete cast to different thickness. The concrete cover was 10 and 20 mm. A wide range of chlorides (between 0 and 3,2 mass%) were added to the concrete and the specimens, after curing, were exposed to natural environments.

The durability of the reinforcement was estimated by measurement of the development of concrete cracking, weight loss and extend of pitting.

The results indicated that weathering and galvanised steels are unsuitable for use as corrosion resistant reinforcement in heavily chloride contaminated concrete. It appears that the additional corrosion resistance of ferritic stainless steels is an advantage in comparison with unalloyed steel when embedded in concretes containing low chloride levels. At high chloride levels the ferritic steels suffered severe pitting attack which was concentrated at a few points on the surface. When the cover was reduced then the corrosion intensity increased. The strongest effects occurred at isolated points, when carbonation had reached the steel surface.

All the austenitic steels showed very high corrosion resistance in all environments tested. No serious corrosion was observed on any of the bars. Ideally, the molybdenum-bearing alloys should be used in chloride contaminated conditions to minimise the risks of corrosion, especially with the combination of high chloride contents and carbonation to the full depth of cover.

5.2.2. Test in UK carried out by the Building Research Establishment (BRE) and Nickel Development Institute (NIDI), reported by Flint and Cox: " The resistance of stainless steel, partly embedded in concrete, to corrosion by seawater" (see enclosed list of literature).

Another investigation of similar nature has been carried out by BRE and NIDI. The main purpose of this test was to determine the susceptibility to crevice corrosion, partly embedded in concrete. The project was initiated in view of the massive concrete constructions which were envisaged for the North Sea. Test bars of stainless steel type 316 and mild steel were cast into concrete cubes of 100 mm side, spaced 3 mm from each other. Bars were protruding from on side at different lengths. The samples were immersed fully or partially into natural seawater of the south coast of Great Britain for periods of 1,3,5,7 and 12,5 years, after which time concrete was removed and bars examined with respect to corrosion attack and mechanical strength.

Mild steel specimens suffered some corrosion after one year, more pronounced on longer protruding bars. Corrosion became more serious with time.

Stainless steel (316) specimens showed excellent corrosion resistance during the whole test period. Bars having small areas outside the concrete suffered no corrosion, even after 12,5 years. More protruding bars showed some local corrosion, although insufficient to affect strength or ductility. Crevice corrosion on bars partly embedded in concrete was observed on one of the 42 specimens after more than 12 years of exposure. The results shown by the 316 material were even better than expected in this environment, which was considered to be the effect of a beneficial influence from the concrete.

5.2.3. Test in Denmark reported by Sørensen, Jensen and Maahn: "The corrosion properties of stainless steel reinforcement" (see enclosed list of literature).

This project is carried out by the Danish Corrosion Centre (now part of the FORCE Institute). Electrochemical investigations (potentiodynamic and potentiostatic polarisation) have been carried out on rebars of mild and stainless steel (type 304 and 316), with and without welds (resistance and MIG/MAG welding) in mortar samples. The stainless steels were cold-rolled. The particular aspect of welding was included since welds of stainless steel may be subject to the reduced corrosion resistance, unless the weld can be cleaned by pickling or other means.

The effect of mixed-in-chloride (0-8 mass% Cl^- by weight of cement) as well as ingress of chloride was investigated.

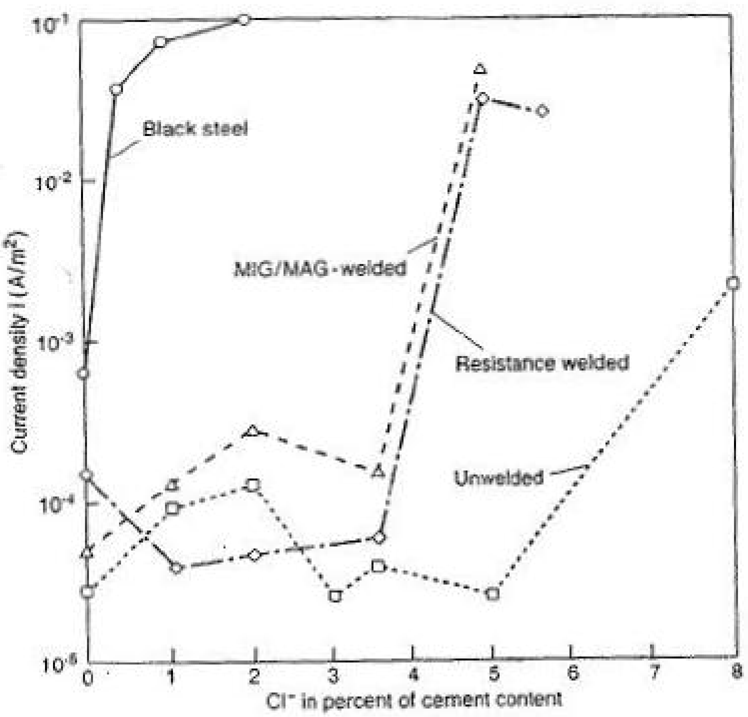

Figure 1

Figure 1 gives the results of the potentiodynamic polarization to 0 mV for AISI 304 and black steel. It may be seen that samples with overcritical chloride concentration can easily be distinguished from samples with sub-critical concentrations, as the difference in average corrosion rate was approximately two orders of magnitude.

The corrosion attack on stainless steel was more localised than on black steel. The critical chloride concentration for rebars embedded in chloride containing mortar was more than ten times higher for stainless than for black steel. However, the corrosion properties of the Cr-Ni-Mo-steel were marginally better than for Cr-Ni-steel.

Welding reduced the critical chloride concentration to 1/3-2/3 of that of the unwelded steels due to combined effect of oxidation and insufficient compaction of concrete around the weld. Deposits of each kind act as a starting point for corrosion attack. After depassivation the stainless steels show a slower reaction rate than the mild steel. Also the cathodic reaction rate seemed to be inhibited on stainless steel compared to mild steel.

The results of this test suggest that austenitic stainless steel bars without molybdenum are sufficiently resistant and therefore suitable for application in chloride environments.

5.2.4. Test in Middle East reported by Rasheeduzzafar, Dhakil, Bader and Khan: Performance of corrosion resisting steels in chloride -bearing concrete (see enclosed list of literature).

Stainless lad reinforcing steels of type 304 (X5CrNi 18-10) and unalloyed galvanised and epoxy coated steels have been evaluated in a 7-year exposure programme for corrosion resistance performance in chloride-bearing concretes. The two variables studied were reinforcing material and chloride content in concrete. Bars were cast in prismatic specimens of 0,45 water-cement ratio good-quality concrete containing three chloride levels: 0.6, 1.2 and 4.8 mass% by weight of cement . The specimens were exposed to the environment of Eastern Saudi Arabia.

The results show that unalloyed steel bars had suffered severe corrosion for all three chloride levels with significant loss of section and rib degradation for 1.2 and 4.8 % chloride-bearing concretes. The use of galvanised steel in concretes with high levels of chlorides merely delays concrete failure. Epoxy-coated bars performed exceedingly well as corrosion resistance steel in 0.6 and 1.2 % chloride concretes as no corrosion and concrete cracking were observed. For the 4.8 % chloride concrete significant corrosion was observed on the substrate steel under the coating. These results indicate that epoxy barrier coating may have a finite tolerance limit for chlorides.

Among corrosion-resisting steels, the best durability performance was exhibited by the stainless steel reinforcing bars. After 7 years of exposure in 4.8 % chloride concrete, no sign of corrosion was observed on any of the bars tested.

5.2.5. Investigations in Italy reported by Pastore, Pedeferri, Bertolini and Bolzoni: "Corrosion behaviour of a duplex stainless steel in concrete" (see enclosed list of literature):

Electrochemical tests (monitoring of free corrosion potential, measuring of the corrosion rate using the linear polarisation method and potentiostatic tests) have been carried out to study the corrosion behaviour of traditional austenitic steel types 304 and 316 and the duplex stainless steel X2CrNiN 23-4 in chloride contaminated concrete with up to 3 % of chlorides Of the cement weight. The tests were conducted on reinforced concrete slabs exposed to open air. The concrete (w/c = 0.5 and 400 kg/m^3 OPC) was of good quality. The stainless steel was as-rolled.

All steel types were in the passive state for the whole range of chloride content considered and there was no substantial difference in their corrosion behaviour. The results of potentiostatic test confirm the passive state even at +400 mV with respect to an activated titanium reference electrode.

5.2.6. Test in Germany reported by Nürnberger, Beul and Onuseit: “Corrosion behaviour of welded stainless reinforced steel in concrete” (see enclosed list of literature).

Concrete elements with cold deformed ribbed bars were exposed in open air for up to 2.5 years. The welded materials consisted of unalloyed and stainless steels 1.4003, 1.4462 and 1.4571. There was no treatment of the weld. The concrete types used were a medium normal weight concrete and two qualities of lightweight concrete. The reinforcing bars had a cover of 1.5 and 2.5 cm. In one part of the specimen 1.0 and 2.5 mass% chloride related weight of cement was mixed in the fresh concrete. Some elements were additionally carbonated.

Figure 2 shows the results of this test by means of corrosion degrees based on pitting depth and loss of weight.

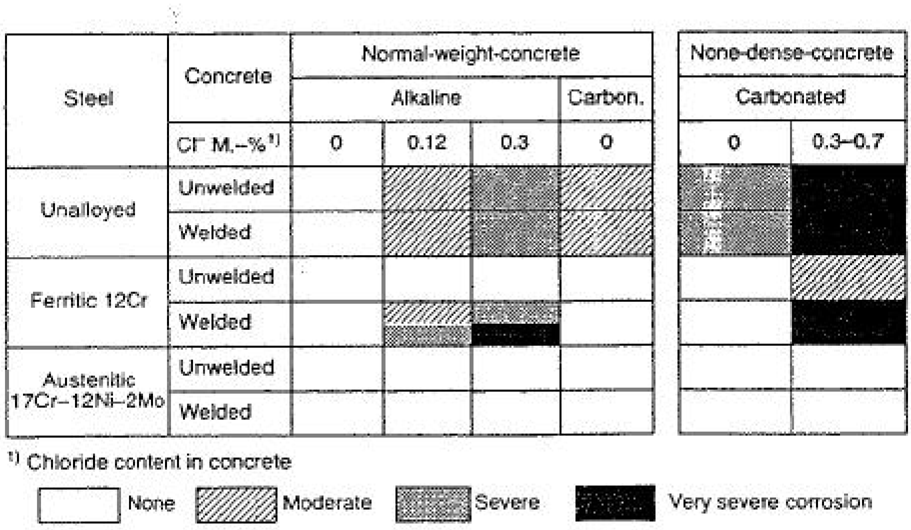

Figure 2

The obtained results with ferritic, austenitic and unalloyed steels can be summarised as follows:

* Unalloyed steel corroded in carbonated and/or in chloride contaminated concrete. The strongest attack occurred in carbonated plus chloride-contaminated concrete.

* The unwelded ferritic chromium steel 1.4003 showed a distinctly better behaviour than unalloyed steel. In carbonated concrete and in chloride-contaminated, alkaline normal-weight concrete no attack took place. Nevertheless, in chloride-contaminated concrete, carbonated concrete as for the unwelded steel a reduced pitting corrosion can occur.

* For the welded steel within the weld line chlorides produced locally distinct pitting corrosion. The depth of pitting increased with increasing chloride content and was more pronounced in chloride-containing carbonated concrete. For the ferritic chromium steel the pitting at weld lines was deeper than for unalloyed steel, but the overall general corrosion (loss of weight) was significantly smaller.

* In all test conditions no corrosion appeared with austenitic steel 1.4571 and the ferritic-austenitic steel 1.4462 whether in the unwelded or welded states.

6. References of application of stainless steel reinforcement

A number of specific examples of applications where stainless steel reinforcement has been used for both conventional concrete structures and for general supports are listed below. This list is not presented in the chronological- but in the random order. It shall be emphasised that stainless steel has been used in many further projects, which names are not available for the authors of this report.

Examples of constructions with stainless steel reinforcement:

* Bridge Deck Reinforcement, Trenton, New Jersey,
* Rock Anchors A55, North Wales,
* Foundation Supports, Mansion House, London,
* Scarborough Spa, marine application
* Val de Grace, rebar MRI application
* Sydney Opera House, promenade, marine application,
* Manchester Airport, dowels/slab,
* Tie bars with couplers, bridge strengthening
* Emmanuel College, Cambridge - posttensioned bars
* Thames Bank at Wapping, brick faced precast concrete panels
* M4 Motorway Reconstruction- Slough/Maidenhead/Berkshire, bridge repair
* Mersey Tunnel, replacement of corroded reinforcement
* Cambridge University/Bio-Technology Laboratory, precast facade panel and basement
* Guidhall Yard East, conservation of the historic building
* St. Paul’s Cathedral, conservation of historic building
* Bridge on Highway 407, Toronto, Ontario, reinforcement in bridge deck and reinforcing bar in the parapet wall.
* Oland Bridge, Sweden, replacement of the corroded reinforcement

*   Great Belt Connection, Denmark, some parts which need to protrude from the surface of the concrete, e.g. earthing rods and wires for making other electrical connections to reinforcement.

7. Conclusions

The following general conclusion can be drawn based on the information collected in this report:

* Due to the excellent mechanical and corrosion properties, stainless steel can be recommended for special application in reinforced concrete structures.

* Extensive long term test, some up to 24 years, have shown that stainless steel offers excellent resistance to corrosion in concrete structures exposed to chlorides from seawater and de-icing salts. Depending on the actual corrosion attack, austenitic or ferritic as well as duplex steels can be used. The corrosion resistance increases in the sequence:

unalloyed	
ferritic	e.g. Cr12....Cr17
austenitic	e.g. CrNi 18-10
austenitic	e.g. CrNiMo 17-2-2
duplex	e.g. CrNiN 23-4
duplex	e.g. CrNiMoN 22-5-3

* The corrosion properties appear to be extremely dependent on the state of the steel surface. In particular, all scale and temper colours can aggravate pitting corrosion and therefore the usual welding procedures will lead to a significant reduction in the corrosion resistance.

* Stainless steels are resistant in carbonated concrete but may suffer pitting corrosion in chloride contaminated concrete. The intensity of pitting corrosion increase with increasing chloride content. Carbonation of the concrete leads to a significant reduction in the critical chloride concentration for pitting initiation.

* Austenitic stainless steel of type CrNiMo 17-12-2 have an excellent corrosion resistant both in carbonated and in chloride contaminated concrete. These properties are also maintained at very high chloride levels and when these steel types are welded. Austenitic stainless steel of type CrNi 18-10 may be satisfactory in many cases.

* To take a full advantage of this material it should be used in cold workhardened condition to increase its strength and reduce dimensions and cost. At the same time the possibility of reducing of concrete cover could be considered.

* The duplex steels offer even better properties. These materials may provide a suitable solution to the problem of concrete structures requiring rebars with high mechanical strength and good corrosion resistance.

* Although the initial cost of stainless steel is significantly higher than that of conventional products (mild steel), their use can often be justified on a life cycle costing basis. It is because the above mentioned properties of stainless steel can exclude steel corrosion in reinforced concrete for long periods of service.

* Typical applications where total maintenance costs (repairs, accesss, cost of closure) predicate the use of stainless steels include: rapairs involving low concrete cover, marine structures, splash and damage areas of road bridgework, coastal applications. In addition, stainless steels should find wide application for load bearing building components such as dowel boors, rock anchors and masonry reinforcement.

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