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The Use of Stainless Steel as Reinforcing Bar

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The performance of reinforced concrete structures in marine environments and in environments with high levels of carbon and sulphur oxides, and chloride environments which exist on roads and bridges where de-icing salts are used, are some of the major concerns for engineers today. Steel reinforcing not protected by thick concrete covers or protected by galvanising, epoxy coatings or any other coating, of which the long-term performance is sometimes doubtful, is susceptible to corrosion and thus, spalling of the concrete.

Stainless steel offers an excellent alternative where reinforcing is subject to corrosion. Stainless steel has established itself as a corrosion resistant construction material, with a wide usage in many industries where the environmental aggressiveness is beyond any circumstances envisaged in construction. Even in the most severe construction applications stainless steel will equal or exceed the life of adjacent construction materials. The yield strength of stainless steel can be as high as 835 MPa for prestressed applications and 700 MPa for reinforcing bar.

In this paper the causes of concrete deterioration and the methods to detect concrete deterioration will be discussed. The performance of different corrosion control methods will be evaluated against each other. It is concluded in this study that the performance of stainless steel reinforcing bar is by far the best of the corrosion control methods. Although stainless steels are more expensive than any other materials in the short-term, it can be shown that stainless steels are more cost efficient over the life-cycle of the building.

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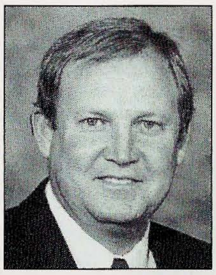

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By G J van den Berg

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The performance of reinforced concrete structures in marine environments and in environments with high levels of carbon and sulphur oxides, and chloride environments which exist on roads and bridges where de-icing salts are used are some of the major concerns for engineers today. Steel reinforcing not protected by thick concrete covers or protected by galvanising, epoxy coatings or any other coating, of which the long term performance is sometimes doubtful, is susceptible to corrosion and thus spalling of the concrete.

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INTRODUCTION

Cracking and spalling of reinforced concrete due to the corroding of steel reinforcement is today one of the major concerns for engineers in the failure of reinforced concrete to meet the design life of structures. This problem is particularly in industrial and urban environments with high levels of carbon and sulphur oxides, in chloride environments which exist on roads and bridges where de-icing salts are used and in marine locations.

According to a report by the Agricultural Department of the USA[7], 26% of the 468,095 rural bridges were classified as structurally deficient and 20% were classified as functionally obsolete. The structurally deficient bridges were either closed or restricted to lighter vehicles only because of deteriorated structural components. The average age of all United States rural bridges was found to be 36,6 years. The National Association of Counties reports in a survey that three quarters of all bridges need to be repaired or replaced at a cost of billions of dollars. This report did not take into account the bridges under State or Federal jurisdiction.

Unprotected reinforcing steel can corrode in certain environments, because moisture and oxygen penetrate the concrete through cracks and pores. This problem is accelerated in coastal areas by penetration of chloride ions from the marine environment. The ultimate effect of this penetration of moisture and chloride ions is corrosion of the reinforcing bar and thus spalling of the concrete.

In 1984 it was reported by the Federal Highway Authority,[8,10] in the United States that it has on record more than 160 000 bridges in distress due to the corrosion of reinforcing bars. This lead to large scale research into the methods of protection for new, refurbished and existing bridges. Among the techniques tried is the use of stainless steel as reinforcing bar.

A number of corrosion control methods and materials have been suggested and applied in different corrosion situations. These methods are corrosion inhibitors in the concrete, galvanising, epoxy powder coating, cathodic protection of the steel and coating of the concrete.

CAUSES OF CONCRETE DETERIORATION

It is reported[15,17] that reinforced concrete framed structures located along the Arabian Gulf seaboard show alarming degrees of concrete deterioration within a short span of 15 years. The two main causes of the concrete deterioration were found to be corrosion of reinforcing steel and expansive cracking due to sulphate attack.

The main causes for deterioration of concrete structures exposed to environmental conditions are in general attributable to corrosion of reinforcement, sulphate attack and salt weathering, early age cracking, cracking due to thermal gradients and cracking due to aggregate-cement reactivity. The single most damaging phenomenon of concrete deterioration is the corrosion of the steel reinforcement accompanied by the resulting spalling of the concrete.

Other factors that accelerate the deterioration of concrete structures are environmental conditions which are characterized by high temperatures and humidities combined with severe ground and ambient salinity. High ambient temperatures also accelerate the chemical attack and thus the physical deterioration of the concrete.

In coastal areas concrete structures are continually exposed to frequent and persistent winds charged with sea water and sea salts. These waters and salts penetrate the concrete to cause corrosion of the steel reinforcement and thus spalling of the concrete. The ground, water and atmosphere in these coastal areas are heavily contaminated with chloride and sulphate salts.

Although the above mentioned factors are the main causes for deterioration of concrete, evidence was also found that aggregate instability and cement aggregate reaction were further causes for some cases of concrete deterioration.

Some of the minor causes or forerunner and feeder to other modes of disintegration and deterioration of concrete are early-age cracking due to plastic shrinkage, early thermal movements and subsidence stresses. These conditions facilitate the ingress of moisture, salts and sulphates into the concrete and to the steel reinforcement.

One of the major causes for concrete deterioration is concrete spalling due to inadequate cover to the steel reinforcement[17]. No cover or cover less than 10 mm was found in many structures. Many of these problems can be attributed to inadequate specifications, poor construction practices and poor supervision.

Surface mortar deterioration is caused by salt weathering and sulphate attack on vertical surfaces. The sulphate attack due to the reaction of calcium, magnesium and alkali sulphates with certain hydration products, results in a volume increase of more than twice the original volume and thus causing expansive cracking. The concrete is gradually reduced to a soft mush or to a non-cohesive granular mass which can be of considerable depth.

DETECTION OF DETERIORATED CONCRETE

It is always difficult to detect incipient spalls in walls where there is a fractured plane. One way to detect incipient spalls is to strike the concrete with a hammer or steel object. A hollow sound will emit which will clearly indicate the position of the spalled area. A modern method to detect the corrosion potential in reinforced concrete is the use of an electropotential technique where early corrosion can be located.

A long horizontal running crack along the plane of steel reinforcement is a sign of the beginning of a developing spall. The mechanical pressure exerted by the expanding volume of the corroding steel causes expansive cracking near these cracks. This will eventually lead to the creation of a fractured plane and then a spall.

CORROSION CONTROL METHODS FOR STEEL REINFORCEMENT

Galvanizing is one of the most popular methods to protect reinforcing steel in concrete exposed to marine environments. Other metallic coatings such as nickel, lead and cadmium are also being considered. Metallic coatings must have certain characteristics to be used[3]. It must be anodic to steel, its rate of self-corrosion must be a minimum, its electrochemical rest potential must remain almost constant and it must polarize anodically in the presence of uncontaminated moisture in equilibrium with concrete.

High-strength concrete can be used to increase the durability of concrete and to limit the corrosion of steel reinforcement. High-strength concrete has low permeability and penetration of chloride ions is thus reduced.

Adequate cover plays an important role in the protection of steel reinforcing. In field studies on reinforced concrete structures in the Middle East[15] it was found that optimum protection was found with a cover of approximately 32 mm to the steel reinforcement. No significant improvement was indicated for covers greater than 32 mm.

In a study by Rasheeduzzufar et al[16] on the corrosion performance of different types of steels and coatings it was concluded that galvanized and epoxy coated steels do delay the onset of corrosion to some extent but that the long term performance of these coatings is far from adequate. It was also concluded in this study that stainless steel reinforcing bars showed no sign of corrosion for even very high chloride levels.

STAINLESS STEEL REINFORCEMENT

Stainless steels offer an excellent alternative where reinforcing is subject to corrosion. Stainless steel has established itself as a corrosion resistant construction material, with a wide usage in many industries where the environmental aggressiveness is beyond any circumstances envisaged in construction. Even in the most severe construction applications stainless steel will equal or exceed the life of adjacent constructional materials. The yield strength of stainless steel can be as high as 835 MPa for prestressed applications and 700 MPa for reinforcing bar.

CLASSIFICATION OF STAINLESS STEELS

A wide range of stainless steels, which are iron based alloys containing at least 11% chromium with an upper limit of 30% for practical considerations, are utilized, especially for their resistance to corrosion, in a wide range of environments. Chromium is not the only alloying element which is used to produce the different types and grades of stainless steels. To enhance the corrosion resistance, and to resist more aggressive corrosion conditions, the chromium contents are increased and additional alloying elements are added, mainly nickel and molybdenum. Other elements, such as carbon, manganese, silicon, copper, titanium, niobium, nitrogen, sulphur, selenium and aluminium may also be used, not only to increase the corrosion resistance and heat resistance but also to influence the crystal structure, the mechanical properties and hence the formability, machinability and weldability.[20,21]

The classification of the different types of stainless steels is based on the crystal structure which is developed within the steel, due to both the chemical composition and thermal treatment. Although stainless steels are classified into austenitic, ferritic, martensitic, duplex and precipitation hardening stainless steels, only the first two will be discussed as they are the two which can commonly be used as reinforcing bar in concrete.

Austenitic Stainless Steels

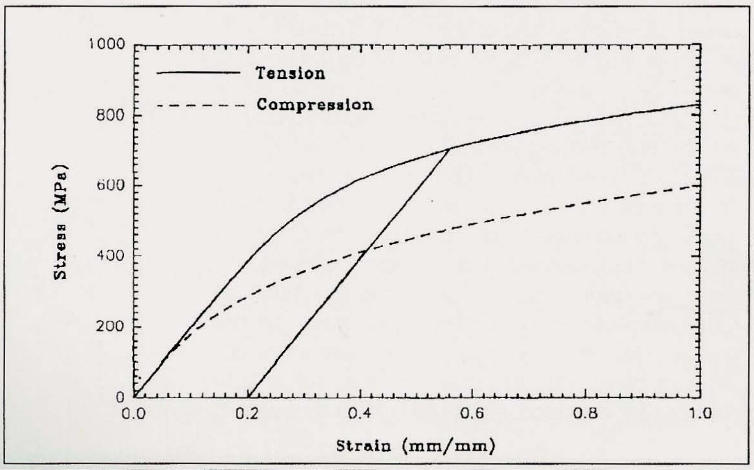
The American Iron and Steel Institute (AISI) Type 200- and 300-series are austenitic stainless steels. The two types that are used in reinforced concrete are AISI Type 304 and 316. The formation and stabilisation of the austenitic crystal structure, over a wide range of chromium contents and temperatures, are promoted by the amount of nickel (6 - 20%) in the austenitic stainless steels. In the 200-series some of the nickel is replaced by manganese in the ratio of two parts of manganese for each part of nickel. The austenitic stainless steels have a high level of corrosion resistance in a wide variety of aggressive conditions, as well as a good high temperature strength, a high resistance against scaling at high temperatures and excellent toughness and ductility down to very low (cryogenic) temperatures.

Stainless steel Type 304 is commonly available and is used in a wide range of applications. Although stainless steel Type 304 is less corrosion resistant than Type 316, it has a wider field of application as it is more price competitive. Stainless steel Type 304 has a corrosion resistance in industrial areas where there is a combination of moisture, carbonaceous and other pollutants.

Ferritic Stainless Steels

Some of the AISI Type 400-series are ferritic stainless steels. Type 3CR12 corrosion resisting steel, a 12% chromium steel, is a modified AISI Type 409 steel, developed by the specialty steel producing company, Columbus Stainless, to overcome the weldability problems of plain chromium ferritic stainless steels. Type 3CR12 steel has sufficient chromium to impact a useful, cost effective level of corrosion resistance. Further development of these steels as reinforcing bar is necessary to enable the engineer to use these steels with confidence.

Figure 1: Stress Strain Curves for Stainless Steel Type 304



MECHANICAL PROPERTIES

The mechanical properties of Type 304 stainless steel and Type 3CR12 corrosion resisting steel have been established at the Rand Afrikaans University by uniaxial tensile and compression tests. These tests were carried out in accordance with the procedures outlined by the ASTM Standard A370 - 77[2], BS18[5] and by a method described by Parks[12] for compression tests. The mechanical properties of these two steels are given in Table 1 and in Figures 1 and 2.

Type 304 and 316 stainless steels are the two stainless steels that are readily available on the market. Type 405 and 430 stainless steels are ferritic stainless steels that are not readily available and which are not that corrosion resistant in high chloride environments.[4] The mechanical properties of Type 304 and 316 stainless steels are given in Table 2 as given by data sheets of the producers.[18,24] It is not stated whether these mechanical properties are for tension or compression. The mechanical properties may vary with the thickness of the material.

TABLE 1. EXPERIMENTAL MECHANICAL PROPERTIES OF CERTAIN STAINLESS STEELS

PROPERTY	TYPE 304		TYPE 3CR12	
	LT	LC	LT	LC
E_o (GPA)	195,4	196,6	188,8	218,6
F_y (MPa)	704,9	415,3	668,9	707,0
F_p (MPa)	444,3	172,2	298,0	307,0
F_u (MPa)	844,3	-	841,0	-
Elongation (%)	40,0	-	18,3	-

LC - Longitudinal Compression

LT - Longitudinal Tension

E_o - Initial Elastic Modulus

F_y - Yield Strength

F_p - Proportional Limit

F_u - Ultimate Strength

TABLE 2. MECHANICAL PROPERTIES OF CERTAIN STAINLESS STEELS

PROPERTY	TYPE 304	TYPE 316
	LT	LT
Yeild Strength F_y (MPa)	684	828
Ultimate Strength F_u(MPa)	916	928
Elongation (%)	23	20

COMPARISON OF CRACK WIDTHS

In a recent study[13,14] a comparison of crack widths was made between beams reinforced with high yield strength carbon steel and Type 304 stainless steel reinforcing bar. The test beams were loaded in a four point load configuration to facilitate a region of constant bending moment. Crack widths were measured in this region of constant moment.

The experimental crack widths were compared with two theoretical crack width equations that are used by BS8110[6] and ACI 318M-89[1,9] design specifications. A detailed discussion of the experimental procedure and the application of the above mentioned equations can be referred to in Reference 13.

A comparison of the crack widths between the beams reinforced with high yield strength carbon steel and Type 304 stainless steel reinforcing bar is given in Figures 3 and 4. A comparison is also made of the experimental crack widths and the two theoretical crack width equations.

It can be seen from Figures 3 and 4 that the experimental crack widths for the high yield strength carbon steel and Type 304 stainless steel correspond well with the theoretical design equations except for stainless steel above the proportional limit which is in the region of 0,01% strain. Above the proportional limit the beam reinforced with stainless steel shows an increase in crack width. This is to be expected because stainless steels show gradual yielding behaviour. In the inelastic region the stress is no longer proportional to the strain. In comparison to carbon steel an increase in strain is experienced in this region resulting in larger crack widths.

LIFE STYLE COSTING

The concept of life cycle costing is nothing new and has been used in the planning of the reliability and maintenance of complicated engineering systems in military defence, airlines, railways, offshore platforms, nuclear power stations and many other types of structures[22]. The application of the life cycle cost can be taken from the extremely basic, the arithmic calculation of original cost of various options against the likely replacement cost and frequency over the anticipated life of the installation, to the extremely complex, involving maintenance cost, loss of production during downtime, financial incentives and calculation of future costs.

The life cycle costing analysis used in the marketing of stainless steel is based on comparing stainless steels with other materials. It is convenient and efficient to use a computer program, particularly when many different alternatives and consequences are considered. A computer program to evaluate the life cycle cost of a structure has been developed at the Rand Afrikaans University and has been used with success internationally.[11,23]

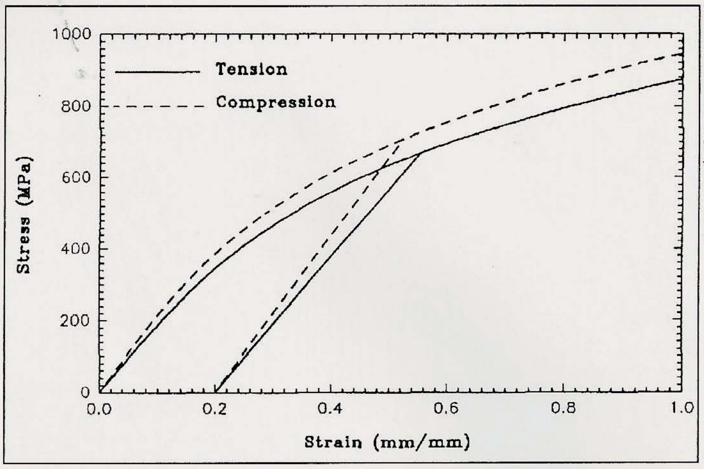


Figure 2: Stress Strain Curves for Type 3CR12 Steel

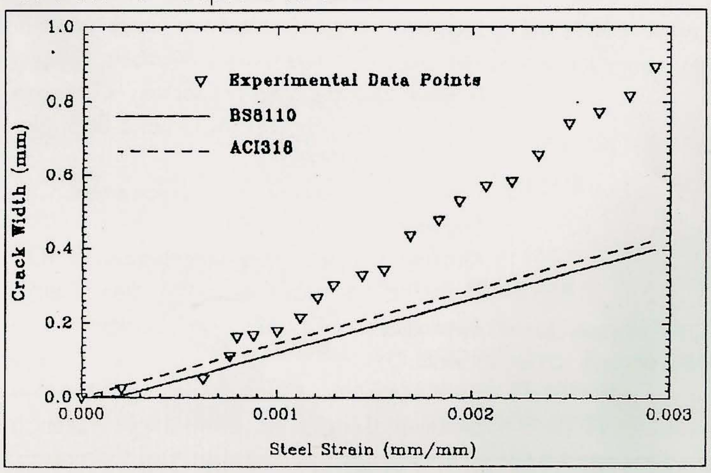
When doing a life cycle cost of a structure it is important and critical to put values on the following: The risk if the structure fails, the cost of down time if the structure fails or has to be replaced, the difficulty of access for maintenance once installed and the likelihood of successful in situ maintenance being achieved. In a study where Type 3CR12 was used as an alternative in structural applications[19] it was judged in all the instances that the costs of maintenance and/or replacement were lower than that of other materials over the life of the structure.

CONCLUSIONS

Cracking and spalling of reinforced concrete due to corroding reinforcement is today one of the major concerns for engineers. The mechanical properties of stainless steels are such that less steel can be used in reinforced concrete structures leading to a smaller difference in the increased costs of stainless steel. Stainless steel should be considered as an alternative to galvanized, epoxy coated or other method of coating, of which the long term performance is sometimes doubtful.

Because stainless steels show gradually yielding behaviour it is expected that concrete structures reinforced with stainless steel reinforcing bar will lead to larger crack widths. This is not serious for most structures in moderate to mildly severe conditions. Where conditions are severe the right stainless steel should be chosen for the specific condition.

Figure 3: Experimental Crack Widths for Beam with Type 304 Stainless Steel Reinforcing Bar



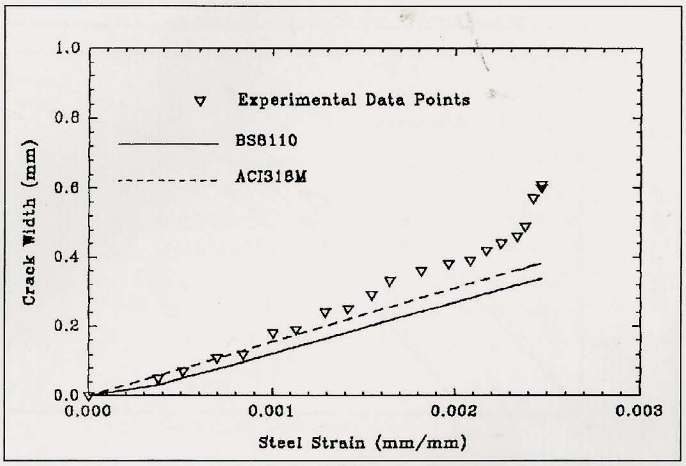


Figure 4: Experimental Crack Width for Beam with High Tensile Reinforceing Bar

The life cycle costing method should be used more widely as a management tool to evaluate the true cost effectiveness of stainless steels in a wider variety of structural applications. When evaluating the life cycle cost of a structure it can be shown that by using stainless steel reinforcing bar as an alternative the structure will be more economical.

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