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Concrete-Reinforcement Bars Made of Corrosion-Resistant Steel

Abstract: The making of building structures entails the use of concrete-reinforcement bars (also known as rebars). Elements made of reinforced concrete have proved their unquestionable usability. However, in certain cases, the traditional approach involving the use of ribbed bars made of unalloyed steels fails to provide desirable results. The extension of the service life of structures exposed to seawater or road salt is possible through the use of concrete-reinforcement bars made of corrosion-resistant steels. The study presents mechanisms triggering the corrosion of structures made of reinforced concrete, corrosion-resistant steels used in the fabrication of reinforcement bars and exemplary applications of the above-named bars.

Keywords: rebars, corrosion-resistant steels

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Introduction

The premature corrosion-triggered deterioration of the technical condition of the reinforced concrete structure of both buildings and infrastructure poses a significant both technical and economic challenge. Repairs of public transport infrastructure could entail enormous financial losses resulting, e.g. from late deliveries, and highly inconvenience daily life of the society. One of reinforced concrete structure-related characteristics is high corrosion resistance resulting from the alkalinity (basic nature) of concrete. Fluid filling concrete pores (so-called pore water) is alkaline (i.e. above 12 pH) and responsible for the passivation of rebars (reinforcement bars), usually made of unalloyed steel [1] and surrounded by (immersed in) concrete mix, as well as for the inhibition of corrosion processes. However, chemical processes occurring in the concrete mix may change its alkalinity and favour the corrosion of reinforcement steel. Apart from design and fabrication errors, the primary reasons for damage to reinforced concrete structures beyond repair include carbonatisation and chloride corrosion [1, 2].

Carbonatisation is a corrosion process occurring gradually and initiated on the outside surface of a concrete structure exposed to the effect of CO_2. Carbon dioxide (present in the air) comes into reaction with products of the hydration of clinker phases and forms calcium carbonate ($CaCO_3$). The presence of $CaCO_3$ is not, in itself, responsible for damage to concrete but it reduces its pH from approximately 13 to less than 9. The reduction of pH results in the gradual decay of a thin protective (passivation)

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layer situated on the surface of reinforcement steel. The development of the carbonatisation process is fastest under interchangeably occurring wet and dry conditions. High concrete humidity combined with the carbonatisation front (area of concrete characterised by pH < 9) reaching the level of rebars results in the fast corrosion of reinforcement steel (Fig. 1). The surface of rebars develops corrosion products having larger volume than that of a steel bar itself, which, in turn, leads to the generation of tensile stresses exceeding the strength of concrete, and, consequently, results in the formation of microcracks in concrete. As carbonatisation progresses, the concrete cover may start flaking off and, eventually, uncover rebars entirely. The corrosion of steel is additionally accelerated by the presence of chloride ions (if any) [1].

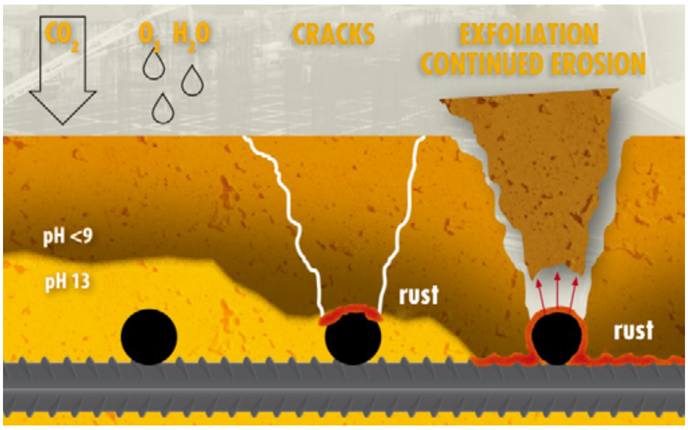

Fig. 1. Destruction of concrete through carbonatisation [1]

Chloride corrosion – among all ions, chloride ions are the fastest to penetrate the cement matrix. For this reason, the corrosion of concrete exposed to the effect of chloride solutions is characterised by fast progress. Chloride aggression decreases concrete pH and leads to the formation of expansive compounds which could trigger the cracking of concrete. Another, equally dangerous effect of chloride ions is the corrosion of reinforcement steel. The development of corrosion is very similar to the carbonatisation-triggered damage of concrete beyond repair (Fig. 2) [1]. Chloride corrosion is induced by the presence of chlorides present in seawater (structures located at/by the sea, e.g. piers), but can also be triggered by road salt used to de-ice the road surface on bridges, carparks etc. Corrosion phenomena may also occur in outside staircases or balconies of residential buildings.

Factors affecting the cyclic penetration of chlorides include cyclic saturation and drying as well as the effect of sub-zero temperature, potentially leading to the exfoliation of the surface layer of concrete. Concrete with chemical additions is characterised by higher resistance to the corrosive effect of chlorides.

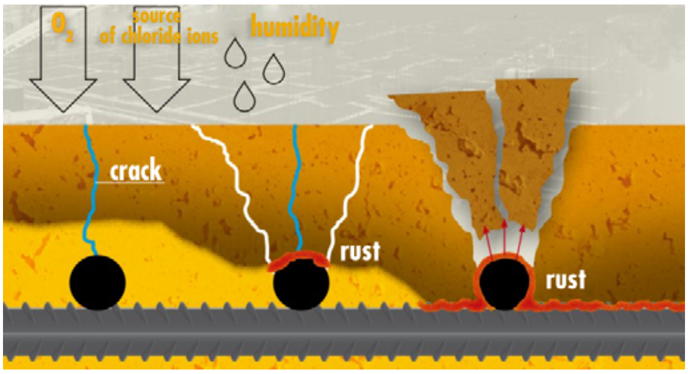

Fig. 2. Chloride corrosion-induced damage to concrete [1]

Figure 3 presents the development of chloride corrosion in stages. At the first stage, corrosion starts once chloride ions have reached rebars made of unalloyed steel (t_0). Corrosion products, occupying larger volume than steel, exert outward pressure. The cracking of concrete (t_1) that follows facilitates the further penetration of chlorides. The concrete cover cracks (peels off) (t_3) and uncovers rebars. If uncontrolled corrosion continues, the rebars are no longer able to transmit existing stresses and a given structure is damaged beyond repair (t_4) [3].

Damage to reinforced concrete structures entails costly repairs or the exchange of crucial structural elements. Increasingly often, failures can be prevented in advance by the use of stainless steel rebars, stainless-steel-clad rebars, galvanised bars or bars made of composites. On the other hand, institutions in charge of infrastructure require that more emphasis be given to calculations taking into consideration the

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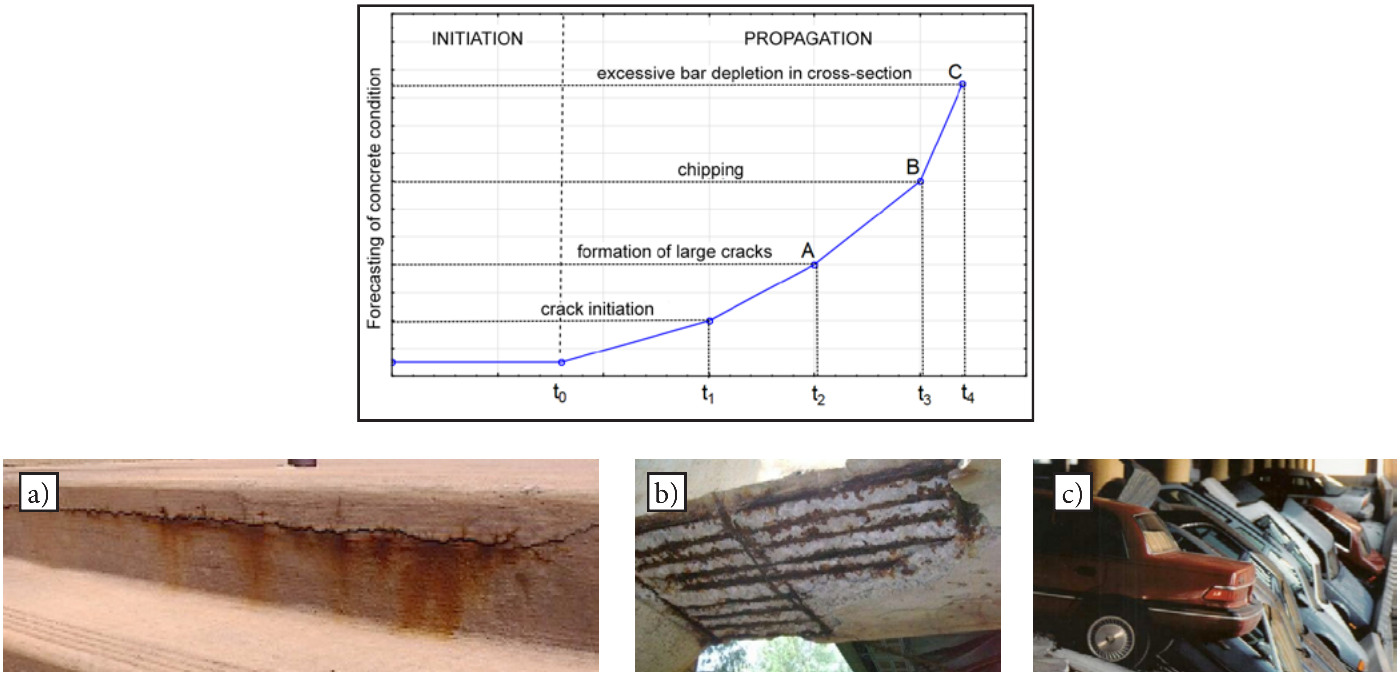

Fig. 3. Stages of chloride corrosion [3]

Table 1. Structural solutions used to reinforce concrete and increase corrosion resistance in comparison with that of unalloyed steel rebars [5]

Types of reinforcement bars	Advantages	Disadvantages
Epoxy-resin-clad rebars	lower initial costs	bending may be accompanied by the formation of cracks in the cladding; special precautions required during transport and fixing
Galvanised rebars	lower initial costs, high resistance to mechanical damage	bending may be accompanied by the formation of cracks in the zinc coating, in some cases, the zinc layer could accelerate corrosion; necessity of repairing or supplementing the reinforcement surface unprotected by the zinc coating
Composite rebars	lower initial costs, high tensile strength, electromagnetic inertness, low thermal and electric conductivity, high fatigue strength (depending on fibre types), low density	lacking plasticity margin; low shear strength; low modulus of elasticity (depending on fibre types); low resistance to UV radiation; short service life of glass fibres in a wet environment; short service life of glass fibres and aramid fibres in a basic environment, high heat expansion coefficient - transversely in relation to fibres; possibly low fire resistance (depending on the type of resin and the thickness of concrete cover), high price (between 2 and 10 times more expensive than unalloyed steel rebars – depending on fibre types),
Stainless steel rebars	structures are designed in the same manner as those made using unalloyed steel bars, possibility of using along with unalloyed steel rebars, high reinforcement-related workmanship tolerance, e.g. thickness concrete cover, unnecessity of servicing and repairs, very long service life	high initial costs, yet constituting only a part of the total cost of the structure

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cost of the service life cycle of building projects as opposed to a previous approach, where only the initial investment costs were taken into consideration. Within a new approach, the total cost of an investment should also include costs of future repairs such as, for instance, the exchange of corroded or damaged elements. Table 1 presents the most popular concrete reinforcing solutions aimed at increasing the corrosion resistance of entire structures.

Figure 4 presents an example of a structure made of reinforced concrete, i.e. the Turcota spaghetti junction in Montreal, i.e. the key motorway junction between Decarie (north-south) and Ville Marie (east-west), erected in 1966. The above-named spaghetti junction is used by over 300 thousand cars every day. Presently, the reinforced concrete structure is considerably corroded, primarily by road salt. In spite of constant monitoring and repairs, some elements will have to be removed and (partly or entirely) replaced. As of today, the estimated cost amounts to 3 billion CAD. An additional sum of 254 million CAD will have to be spent to provide necessary safety until the completion of works [3, 6, 7].

Fig. 4. Turcota spaghetti junction in Montreal [6, 7]

Figure 5 presents an example of a reinforced concrete structure with visible salt water-triggered damage.

Fig. 5. Exemplary salt water-triggered damage to a reinforced concrete structure [8]

Stainless steel rebars

Although stainless steel rebars have been used in civil engineering for many years, their scope of application is not very wide. The SteelGuru web portal has estimated that, over the past three decades, the cost of replacing the corroded elements of reinforced structures in the USA alone amounted to 560 billion USD. The American Iron and Steel Institute (AISI) recommends using stainless steel rebars when erecting structures in a seaside environment as well as when building roads and bridges in a cool and temperate climate. The latter is connected with the fact that, in the above-named climate, roads are often gritted with road salt, exposing nearby steel to corrosion. Even if the external structure, e.g. of a bridge, can be protected by special anticorrosive paints, rebars, even after being immersed in concrete, are not entirely protected. The use of stainless steel rebars in the construction of roads and bridges can prove cheaper than that of unalloyed steel reinforcement bars if the entire, i.e. both investment and running costs, are taken into consideration [9].

Stainless steels are those containing a minimum of 10.5 % of chromium (PN-EN 10020 [10]). The presence of chromium enables the formation of a thin layer of stable chromium oxide on the steel surface. The layer of chromium oxide

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is passive and, in many environments, characterised by high corrosion resistance. In addition, the layer of chromium oxide is capable of "recovering" after mechanical damage to the surface, which is of particular importance in terms of reinforced concrete structures erected in the construction site. Damage to the surface, formed during transport or assembly/fixing, does not affect corrosion resistance. However, because of the necessity of maintaining required corrosion resistance, it is recommended that stainless steel rebars should not be in contact with those made of unalloyed steel. Stainless steels retain their passivity in concrete characterised by low pH and high concentration of chlorides. For this reason, such steels should be used in structures exposed to the effect of chlorides (Fig. 6).

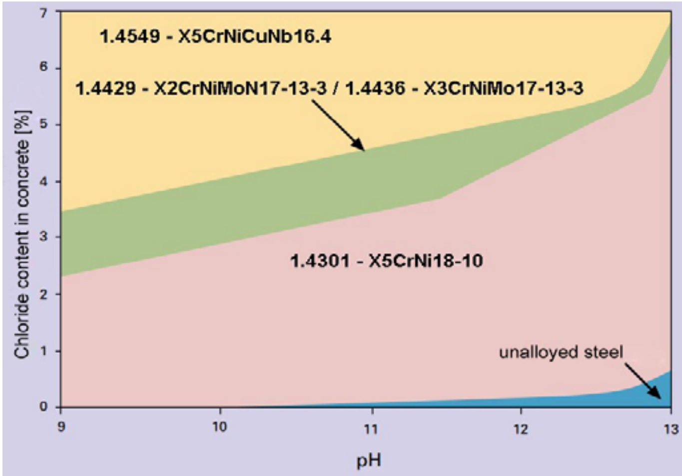

Fig. 6. Passivity of unalloyed steel and of stainless steel in concrete containing chlorides [11]

Most popular stainless steel grades used to make concrete reinforcement bars include Cr-Ni type 1.4301 austenitic steels. Recently, also dual-phase ferritic-austenitic steels such as lean duplex steel 1.4162 are enjoying growing

Table 2. Chemical composition of stainless steels used in concrete reinforcement [13]

Group of steels	Steel grade		Chemical composition									
			C max.	Si max.	Mn max.	P max.	S max.	Cr min./ max.	Ni min./ max.	Mo min./ max.	N min./ max.	Other min/ max
Austenitic	1.4301	X5CrNi 18-10	0.07	1.0	2.0	0.045	0.03	17.5 19.5	8.0 10.5	-	max 0.11	-
	1.4401	X5CrNiMo 17-12-2	0.07	1.0	2.0	0.045	0.03	16.5 18.5	10.0 13.0	2.0 2.5	max 0.11	-
	1.4429	X2CrNiMoN 17-13-2	0.03	1.0	2.0	0.045	0.015	16.5 18.5	11.0 14.0	2.5 3.0	0.12 0.22	-
	1.4436	X3CrNiMo17-13-3	0.05	1.0	2.0	0.045	0.03	16.5 18.5	10.5 13.0	2.5 3.0	max 0.11	-
	1.4529	X1NiCr-MoCuN25-20-7	0.02	0.5	1.0	0.03	0.01	19.0 21.0	24.0 26.0	6.0 7.0	0.15 0.25	Cu 0.5 1.5
	1.4571	X6CrN-iMoTi17-12-2	0.08	1.0	2.0	0.045	0.03	16.5 18.5	10.5 13.0	2.0 2.5	-	Ti x 5·C 0.7
Ferritic–austenitic	1.4162	X3CrNiMo 22-2-0	0.03	0.4	5.0	-	-	21.5	1.5	0.3	max 0.22	-
	1.4362	X2CrNiMo 23-4	0.03	1.0	2.0	0.035	0.015	22.0 24.0	3.5 5.5	0.1 0.6	0.05 0.20	-
Ferritic–austenitic Duplex	1.4462	X2CrNiMoN 22-5-3	0.03	1.0	2.0	0.035	0.015	21.0 23.0	4.5 6.5	2.5 3.5	0.10 0.22	-
Super Duplex	1.4501	X2CrN-iMoCuWN25-7-4	0.03	0.01	1.0	0.03	0.01	24.0 26.0	6.0 8.0	3.0 4.0	0.2 0.3	W 0.5-1.0 Cu 0.5-1.0

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popularity. While maintaining similar corrosion resistance, the above-named steels are characterised by significantly higher mechanical properties than, for instance, austenitic steel 1.4301. Another group of stainless steels intended for use in more demanding operating conditions includes Cr-Ni-Mo austenitic steels 1.4436 and 1.4429 as well as classical ferritic-austenitic duplex steels 1.4362 and 1.4462. Very demanding applications are addressed by high-alloy austenitic steels with an increased molybdenum content (1.4529) and dual-phase superduplex steels (1.4501), characterised by very high corrosion resistance in a chloride environment (Table 2) [12].

When selecting stainless steel, it is necessary to take into consideration its chemical composition and the operating conditions of a structure (Table 3).

Requirements concerning properties of stainless steel rebars are described, among other things, in the BS 6744 standard (Great Britain) [14], the ASTM A955M standard (USA) [15] and in the Z-1.4-80 technical approval (Germany) [16].

BS 6744 [14] was one of the first standards concerning rebars made of stainless steel. The above-named standard specifies requirements related to hot and cold-rolled stainless steel rebars having a yield point of up to 650 MPa. Requirements concerning the mechanical properties of stainless steels used to make reinforcement bars and related to three strength groups are presented in Table 4 4.

Presently, in Great Britain rebars are made of austenitic and ferritic-austenitic steel grades 1.4301, 1.4436, 1.4429, 1.4462, 1.4501 and 1.4529. In most cases, standard austenitic steel grades,

Table 3. Selection of stainless steel grades in relation to operating conditions [11]

Steel grade	**Operating conditions**			
	Structures or structural elements intended for long operation or poorly accessible in terms of maintenance and repairs	Structures or structural elements exposed to chlorides, protected by measures extending service life (e.g. appropriate thickness of a concrete layer, high quality of concrete, impregnated concrete surface)	Reinforcing elements or elements overlooking the surface of concrete, exposed to chlorides (e.g. pins)	Structures or structural elements exposed to chlorides, intended for shortened service life (e.g. reduction of the layer of concrete or its quality, lack of impregnated concrete surface)
1.4301	1	1	5	3
1.4436	2	2	1	1
1.4429	2	2	1	1
1.4462	2	2	1	1
1.4529	4	4	4	4
1.4501	4	4	4	4
1 – proper choice in terms of corrosion resistance and costs, 2 – higher requirements in terms of corrosion resistance, 3 – possible use in some cases after consulting a specialist in corrosion, 4 – possible use in special cases after consulting (obligation) a specialist in corrosion, 5 – improper in relation to given applications.				

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Table 4. Mechanical properties of concrete reinforcement stainless steels [14]

Steel group	Mechanical properties				Diameters [mm]
	$R_{0.2}$ [MPa]	$R_m/R_{0.2}$	A_5 [%]	A_{gt} [%]	
200	200	1.10	22	5	3÷50
500	500	1.10	14	5	6÷50
650	650	1.10	14	5	3÷25
A_{gt} – total elongation related to the maximum force; steel of group 200 is only available in the form of smooth bars					

i.e. 1.4301 or 1.4436, provide acceptable corrosion resistance. Austenitic and ferritic-austenitic steels characterised by higher corrosion resistance should be taken into consideration where there is a possibility of increasing accumulation of chlorides in concrete along with the passage of time (e.g. sea or off-shore structures, structures exposed to salt in winter). The above-named steel grades are usually available in three strength-related groups, yet only duplex steel 1.4462 is available in class 650. Rebar diameters are restricted within the range of 3 mm to 50 mm [17].

In Germany, reinforcement stainless steels are specified in an approval [16] issued by the German Institute for Building Technique (Deutsches Institut für Bautechnik) in Berlin. Until today, the use of stainless steels has been limited because of their high price. Rebars having a diameter restricted within the range of 4 mm to 14 mm are subjected to cold rolling. Available rebars include smooth or ribbed bars made of ferritic steel 1.4003, austenitic steel 1.4571 and ferritic-austenitic steel (duplex) 1.4462. Typical mechanical properties of the steels are presented in Table 5.

Where a structure is known to be exposed to highly concentrated chlorides, it is recommendable to use steel grades 1.4571 and 1.4462. Steel 1.4003 can be used where the fast carbonatisation of concrete has not worsened the mechanical properties of the entire structure. Rebars of a diameter restricted within the range of 10 mm to 40 mm are offered as hot rolled bars. Austenitic steel 1.4429 is available in various strength-related classes related to a yield point restricted within the range of 550 MPa to 880 MPa [17]. Table 6 presents the comparison of requirements for stainless steel rebars according to the Z-1.4-80 technical approval and the BS6744 standard.

In the USA, the properties of stainless steel rebars are specified in the ASTM A955M - 2018 [15] standard, containing requirements related

Table 5. Typical mechanical properties of steels used to make rebars in Germany [17]

Steel grade	Designation	As-received state	Bar diameter [mm]	R_e [N/mm²]	R_m [N/mm²]	A [%]
1.4429 austenitic	X2CrNi-MoN17-13-3	hot rolled	10 20 32 40	880 790 630 550	990 900 790 790	20 25 25 30
1.4571	X6CrN-iMoTi17-12-2	cold rolled	10[1]	456	599	39
1.4462	X2CrNi-MoN22-5-3		7[1]	870	934	13
1.4003	X2CrNi12		8[1]	518	608	16
Note: 1 available diameters restricted within the range of 6 mm to 14 mm,						

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Table 6. Comparison of requirements related to stainless steel rebars in Europe, illustrated with an example of regulations applied in Germany and Great Britain [18]

Property	**Germany: technical approval no. Z-1.4-80**		**Great Britain BS6744**
Steel grade	1.4571		1.4301, 1.4436, 1.4362, 4.4462
Product	coil	bar	coil, bar
Yield point $R_{p0,2}$	≥510 N/mm²	≥500 N/mm²	≥500 N/mm²
Strength Rm	≥550 N/mm²	≥550 N/mm²	-
Rm/Rp0.2	≥1.08	≥1.08	≥1.1
Total elongation related to maximum load A_{gt}	≥5.5%	≥5.0%	≥5.0%
A_5	-	-	≥14%
A_{10}	≥16 %	≥ 15 %	-
Bend test	YES	YES	YES

to ribbed bars and smooth bars having a dimeter restricted within the range of 9.5 mm to 50.8 mm (2 inches). The standard defines three classes of strength related to a yield point of 420 MPa, 520 MPa and 500 MPa. The chemical composition of stainless steel should be adjusted to specific operating conditions agreed upon between the producer and the purchaser. The foregoing is important in terms of obtaining required corrosion resistance or magnetic permeability, or both these properties at the same time. It should be noted that the above-named properties are not equally provided by all grades of stainless steels [17]. The chemical compositions of stainless steel grades used when making rebars are presented in Table 7.

Stainless-steel-clad rebars

In spite of the fact that stainless-steel-clad rebars (SCRs) were developed in 1970, until today they have not been widely used in structures made of reinforced concrete. The stainless-steel-clad rebars are made during the process of rolling, where an unalloyed steel bar is provided with a 1 mm thick coating (cladding) made of stainless steel. The above-named bars are characterised by high corrosion resistance, high tensile strength and Young's modulus comparable with that of unalloyed steels. The stainless steel cladding is characterised by high resistance to scratching and adhesion, even during the bending of a bar (Fig. 7.).

Although SCRs can be bent and welded, it is recommended to protect the bar end, i.e. by putting a plastic cover on it. Otherwise, the end of a stainless-steel-clad rebar will corrode intensively (Fig. 8).

When transporting SCRs it is recommended that the bars should not be in direct contact with elements made of unalloyed steel.

Table 7. Chemical composition of stainless steels used when making rebars [19]

Designation	**Chemical composition, % by weight (max.)**									
	Grade	**C**	**Mn**	**P**	**S**	**Si**	**Cr**	**Ni**	**Mo**	**N**
S30400	304	0.08	2.0	0.045	0.03	1.0	18.0-20.0	8.0-10.5	-	0.10
S30453	304LN	0.03	2.0	0.045	0.03	1.0	18.0-20.0	8.0-11.0	-	0.10-0.16
S31603	316L	0.03	2.0	0.045	0.03	1.0	16.0-18.6	10.0-14.0	-	-
S31653	316N	0.08	2.0	0.045	0.03	1.0	16.0-18.6	10.0-14.0	2.0-3.0	0.10-0.16
S31803	2205	0.03	2.0	0.045	0.02	1.0	21.0-23.6	2.5-6.5	2.5-3.5	0.08-0.20

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Fig. 7. Stainless-steel-clad rebar [20]

Fig. 8. Protection of SCR ends with plastic covers [20]

Transport hooks or binder wire should not be made of unalloyed steel. Related tests revealed that the service life of structures made using stainless-steel-clad rebars is not shorter than that of solid rebars made of stainless steel [21].

One of SCRs manufacturers is the Stelax company (Great Britain), producing rebars under the trade name of Nuovinox. The production includes the making of an unalloyed steel bar core and a cladding. The cladding is usually made using austenitic steel 316L, but also steel 304, 316 or duplex steel 2205 can be used. Initially, a flat bar made of steel 316L is formed as a tube and subjected to plasma welding. The tube made of stainless steel has a diameter restricted within the range of approximately 100 mm to 115 mm, whereas the wall thickness is restricted within the range of 6 mm to 9 mm. Afterwards, the tube is filled with purified granulate made of unalloyed steel, subsequently and successively concentrated using a hydraulic actuator. The filled and concentrated composite tube is heated in a furnace up to a temperature of 1250°C. The process takes place in a reducing atmosphere to prevent the formation of oxides in unalloyed steel. Afterwards, the tube is subjected to 10-fold hot rolling until reaching an appropriate diameter. The hot rolling process makes it possible to obtain metallurgical bonding at an approximate depth of 5 μm and a strength of approximately 280 MPa. The final stage involves the etching and passivation of the rebar surface aimed to remove post-rolling impurities and form chromium oxides on the bar surface, increasing corrosion resistance. The thickness of the cladding is usually restricted within the range of 0.9 mm to 1.8 mm in relation to a bar diameter restricted within the range of 15.9 mm to 32.3 mm.

In comparison with epoxy resin-covered bars, SCRs are characterised by higher resistance to mechanical damage; the thickness of the epoxy coating being approximately 0.25 mm. The stainless steel cladding is thicker and harder. Because of the fact that the unalloyed steel granulate is a cheap by-product and constitutes approximately 77% of the weight of SCRs, whereas the stainless steel cladding constitutes the remaining part, the cost of making an entire bar is lower than that of stainless steel solid bars. The price of SCRs (cladding made of steel 316L) amounts to approximately 1.32 USD/kg, i.e. approximately a third of the price of solid bars. Other, i.e. transport and assembly/fixing-related costs amount to approximately 2.20 USD/kg. Stainless-steel-clad rebars can also be supplied with a cladding made of steel 304L or 3Cr12, making the final price of the bars even lower.

Taking the above-named characteristics of SCRs, and their price in particular, it can be seen that the stainless-steel-clad rebars constitute an interesting alternative to stainless steel solid bars or bars protected with epoxy

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resin. It is expected that the service live of reinforced concrete structures made using SCRs can amount to between 75 years and 100 years. The restricted use of the above-named solution has been connected, among other things, with few research-related tests concerning the properties of such bars [20]. Figure 9 presents the simultaneous application of stainless steel bars and stainless-steel-clad rebars.

Fig. 9. Exemplary use of stainless steel bars and SCRs in one structure [22]

The above-presented solution was used in the bridge (I-94) over the Galien river in Berrien (county of Michigan). The solution involved the use of solid bars having a diameter of 9.6 mm and SCRs having a diameter of 15.8 mm. Stainless-steel-clad rebars (SCRs) were, following related recommendation, protected using plastic covers.

Exemplary applications of stainless steel rebars

An important issue, affecting the use of stainless steels in the form of rebars, is the appropriate identification of areas in the structure at the highest risk of being exposed to corrosion triggered by the high concentration of chlorides, followed by the precise identification of elements at the highest risk of corrosion-related exposure [12]. Stainless steel bars are used in:

- structures operated in corrosive environments, such as [3]
  - seawater, particularly in a hot climate (bridges, piers, docks, anchors of lamp posts, railings, breakwaters etc.)
  - road salt (bridges, overpasses and junctions, roofed or underground carparks),
- water treatment reservoirs,
- water desalination systems,
- structures intended for very long operation, such as
  - vintage buildings,
  - nuclear waste storage facilities,
- structures operated in unknown environments, where
  - periodic inspections are impossible to perform,
  - repairs are very expensive or nearly impossible,
- structures, where the use of ferritic bars is impossible:
  - power engineering objects (switching stations, transforming stations),
  - airports (air traffic service-related buildings, radar stations, control towers),
  - research establishments and laboratories,
  - hospitals,
  - military objects.

In terms of practice, the ultimate decision to use stainless steel rebars should be preceded by the detailed technical and economic analysis of the entire undertaking. Related calculations should concern total costs incurred throughout the service life of the entire structure. As regards road infrastructure, the analysis should include costs connected with repairs resulting from the use of road salt. As to bridges (depending on the complexity of their design), the application of rebars made of stainless steels increases the total investment cost by between 1% and 15% [23]. Although initial costs are important, the calculation of costs related to the entire service life is crucial for the determination of investment and running costs of the structure. Figure 10 presents the actual comparison of costs incurred during the making and operation of a bridge in Öland (Sweden). The costs

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of the construction and operation of the bridge made using stainless steels 316 and 304 should remain constant, i.e. without additional maintenance (repair) costs for 120 years. It is expected that a structure made of concrete reinforced with unalloyed steel should require repairs after between 18 years and 23 years.

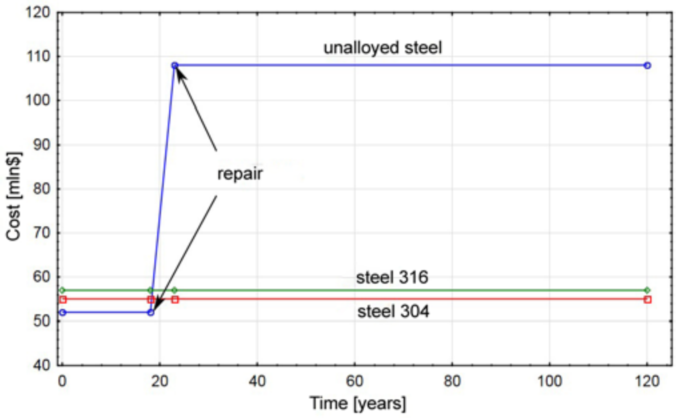

Fig. 10. Service life of the entire structure exemplified by the bridge in Öland (Sweden) [24]

Detailed calculations concerning the costs borne during the service life cycle of a bridge in Schaffhausen in Switzerland revealed that the use of stainless steel grade 304 decreased the above-named costs by 14% in comparison with solutions based on rebars made of unalloyed steel and bars coated with epoxy resin [24].

The most famous structure made using stainless steel rebars is the pier in Progreso de Castro in Yucatán (Mexico), built in the years 1937-1941 (Fig. 11). The pier is 1752 metres long and 9.5 metres wide. The construction "absorbed" 220 tons of rebars having a diameter of 30 mm and made of steel 304 [25].

Fig. 11. Pier in Progreso de Castro in Yucatán (Mexico) built in the years 1937-1941 [26]

The second example of a structure built using bars made of stainless steel is the Hong Kong-Zhuhai-Macau Bridge (Fig. 12), one of the largest in the world. The expected service life without repairs amounts to 120 years. For this reason, the reinforcement of the structure in its critical areas, i.e. primarily in the zones permanently exposed to the effect of seawater, was made of stainless steel. The construction of the bridge involved the use of 15 thousand tons of stainless steel [3, 27].

Fig. 12. Hong Kong-Zhuhai-Macau Bridge [28]

The third example is the Stonecutters Bridge in Hong Kong, i.e. the world's second longest suspended bridge with the main span having a length of 1018 m. The entire length of the bridge amounts to 1600 m. The pillars of the bridge are 298 metres high and have been reinforced using 1600 tons of stainless steel in the area of the spans and 2800 tons of stainless steel in the bridge footing foundation [3, 29].

Fig. Stonecutters Bridge in Hong Kong [30]

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Table 8 presents other examples concerning the use of bars made of stainless steel.

Summary

Increasingly high investors' demands concerning the reduction of running costs make designers and contractors search for alternatives to commonly used solutions. One of the methods making it possible to extend the service life of structures made of reinforced concrete is the use of bars made of stainless steels or stainless-steel-clad bars instead of using reinforcement bars made of unalloyed steel. Both of the above-named solutions enable the aforesaid extension at a slight increase in investment expenses. However, designers should precisely specify where rebars characterised by high corrosion resistance should be placed. It is not technically or economically justified to make the entire structure using corrosion-resistant bars. Such bars should be used in areas directly exposed to the effect of seawater or road salt. The above-presented solution also seems attractive as regards the renovation of vintage buildings or buildings, the servicing of which could be significantly impeded or even impossible in the future. A limitation related to the use of corrosion-resistant bars is their price

Table 8. Exemplary use of rebars made of stainless steel [3, 19, 25]

Country	Structure
Australia	Christ Church, Newcastle Opera, Sydney
Denmark	Great Belt Bridge, Great Belt underground in Copenhagen
France	repair of the sea bank, Bayonne
Hong Kong	Shenzhen Western Corridor Bridge
Ireland	Broadmeadow Bridge, Dublin
Canada	bridge deck on highway 407
Qatar	Museum of Islamic Arts, Doha Terminal Ras Laffan, Pearl Island, Doha
Oman	Sohar Port, Liwa
USA	bridge deck in Trenton, New Jersey bridge deck in Detroit, Michigan bridge between the Garden State Parkway and New Jersey most over the Flathead river , Glacier National Park – Montana garage at the Boston airport Haynes Inlet Slough Bridge, Oregon Mast Belt Parkway, Brooklyn
Switzerland	bridge in Schaffhausen
Sweden	bridge in Öland
Great Britain	Biotechnology Laboratory at Cambridge University foundations of the Mansion House, London restoration of Guildhall Yard East; London Mersey tunnel connecting the Wirral Peninsula with Liverpool; bridge on motorway M4 Manchester Airport road crossing, Newcastle restoration of St. Paul's Cathedral, London Thames Bank, London
United Arab Emirates	Sheikh Zayed Bridge, Abu Dhabi Jebel Ali Free Zone, Dubai

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as well as a small number of regulations and standards concerned with this structural element. It should be noted that paragraph 4.3 of Eurocode 2 [30], describing requirements related to the service life of structures made of reinforced concrete, contains a clearly formulated regulation about the possibility of reducing the minimum concrete cover where reinforcement bars made of stainless steel have been used [31]. The foregoing raises hopes that stainless-steel-clad rebars will enjoy growing popularity also in Poland.

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