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THE DURABILITY AND SERVICE LIFE BENEFITS OF STAINLESS STEEL REBAR AND THE UNDERPINNING PROPERTIES AND FEATURES – A STAINLESS INDUSTRY PRIMER FOR OWNER'S, PLANNERS, SPECIFIERS, AND DESIGNERS ON THE TECHNICAL AND MARKET REALITIES

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Abstract: The cost of infrastructure deterioration due to chloride induced corrosion in North America is estimated as being in the billions of dollars annually. Owners, planners, specifiers, operators and designers of reinforced concrete structures faced with solving the problem of deteriorating concrete caused by chloride attack of the steel rebar from chlorides are looking for long term, low cost solutions and to solve the heavy cost burden of premature replacement of structures, excessive repair and maintenance costs, traffic congestion and reduced utilization. This paper makes the case that the unique properties of stainless steel reinforcement (SSR) are the underpinnings of the vast body of indisputable evidence pointing to SSR as being a very significant contributor to extending the service life of existing structures and enhancing the durability of new structures exposed to chloride attack. Topics dealt with include the unique mechanical properties and chemistry, and the resulting benefits, an overview of the important aspects of the ASTM standard, the evolvement of historic to the commonly used current types of SSR, an overview of various corrosion resistance test methods, research indicating the corrosion resistance of other reinforcement compared to SSR, the cost effectiveness of SSR as illustrated by life cycle costing analysis, primary users' specification formats and best practices, product applications, primary users in North America, a synopsis of the mill material supply situation, and finally an overview of the purpose and summary of the recently released ANSI / CRSI IPG4.1 document "Standard Practice for Stainless Steel Reinforcing Bar Fabrication Facilities".

1 INTRODUCTION

The depth of stainless steel rebar's alloyed chemistry in terms of metal types and quantity, the vast body of indisputable corrosion research on its superior performance, its unique mechanical properties and other features has the effect of significantly extending the service life of existing structures and enhancing the durability of new structures exposed to chloride attack.

Chloride attack of steel rebar due to man-induced sources such as road salt, or natural causes such as marine spray result in a severe deterioration or spalling of concrete structures.

This deterioration places immense pressure on infrastructure Owners and their representatives be they specifiers, designers, operators, or planners to solve the heavy cost burden of excessive repair and maintenance costs and inevitable premature replacement of structures, traffic congestion and reduced utilization.

Stainless steel rebar due to its chemistry alleviates this problem. Its durability can have the effect of extending the service life of structures to 100+ years without major repair due to the unique chemistry containing a mix of over 30% of alloys formulated to resist chloride corrosion.

Given that it is “stainless”, the corrosion resistance is proven to be “orders of magnitude” better than other products.

Because of these positive product features and the resulting benefits, there is an increasing interest in SSR on the part of Owners and their representatives tasked with managing, designing and building structures exposed to chloride induced corrosion. However, as this product is relatively new compared to conventional black bar, there is an information gap within the engineering community and beyond regarding these features which this paper seeks to close. A sampling of the material to be discussed is as follows.

The combination of enhanced mechanical properties and superior corrosion resistance properties due to its chemistry provides users with a more cost effective long term option than the status quo.

Owners are increasingly turning to SSR for their concrete structures exposed to chloride attack because of the benefits of a reduction in repair costs and extended service life resulting in the least life cycle cost.

The mix of corrosion resistant reinforcement that Owners specify has evolved to the use of more alloyed products at the expense of coated bars and other low alloy/modified carbon bars.

Additional topics to be discussed focus on providing background information for infrastructure decision makers looking to make “benchmarking comparisons” of current practices. The topics include current jurisdictions using stainless, typical SSR applications and some major North American projects using stainless, the material supply situation in North American and the suppliers, and the current leading edge fabrication practices.

2 MECHANICAL PROPERTIES AND THE BENEFITS

2.1 Mechanical Properties

The mechanical properties of SSR differ from that of conventional black steel in that it is high strength steel and it has excellent elongation. A summary of the mechanical properties of SSR is included in Table 1. The properties indicated in Table 1 are minimum values which apply to all types of SSR. The actual minimum yield of stainless steel is in excess of 80,000 psi for all types and sizes.

Table 1 *

Properties [units]	Grade 60 [420]	Grade 75 [520]
Tensile Strength Psi [MPa]	90,000 [620]	100,000 [690]
Yield Strength**, min Psi [MPa]	60,000 [420]	75,000 [520]
Elongation*** % in 8 in. [200 mm]	20	20

*Taken from ASTM A955/A955M Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. **Yield is measured by the offset method (0.2% offset) as described in Test Methods and Definitions A370. *** For all bar designation numbers.

2.2 ASTM A955 – the Rebar Standard

The ASTM A955/A955M Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement (“A955”) is the accepted norm for SSR which covers two types of rebar – duplex, which has a “balanced” or dual microstructure of approximately equivalent volume fractions of ferrite and austenite, and austenitic, a single phase material which is non-magnetic.

The dimensional bar profiles and grade structure (strengths) follow their respective carbon steel standards. Stainless is available in the same bar sizes as conventional reinforcing bar steel. The fabrication bend diameters also follow those of conventional reinforcing bar steel.

Where A955 diverges from carbon steel standards is the inclusion of information relating to mandatory corrosion tests, numerous types of stainless steel rebar that meet the standard, detailed chemistry data, specification of magnetic permeability requirements, surface finish and pickling guidance.

2.3 Leveraging the benefits

There are a number of ways in which these unique mechanical properties can be leveraged by the designer to reduce construction costs and provide benefits to the Owner.

Stainless steel has a modulus of elasticity within 3% of that of conventional mild steel and as such the design concepts are in line with conventional steel.

As a high strength steel at Fy = 75 ksi, there is the potential to reduce the amount of rebar steel. The Minnesota DOT mandates its engineers to design their bridge structures, particularly in the transverse deck steel, using this higher level of yield which can result in a 15% saving.

Due to its excellent bond with concrete, the development and splice length design follows that of conventional black rebar compared to coated products which require 30% more development.

Other unique properties include excellent high and low temperature mechanical properties, excellent fire resistance, high ductility, low magnetic permeability for austenitic types of stainless.

3 CHEMICAL COMPOSITION AND DURABILITY

3.1 Chemical Composition of Typical Alloys

ASTM A941 (2010b) defines stainless steel as containing a minimum chromium content of 10.5 percent, and a maximum carbon content of less than 1.20 percent. The reinforcing bars commonly used today have a carbon content of less than 0.15 percent. See Table 2.

SSR is a metal product composed of a mix of many chemical elements such as nickel, chromium, molybdenum, manganese, and carbon which comprise over 30% of the content with the balance being iron.

The alloys which had been used in the initial stages of the SSR product development for the most part included 316ln, 316l and 304. The commonly used rebar alloys today in North America in descending order of usage are 2304, XM-28, 2205, 316ln, 304 and finally 2101.

The chemical composition of four of the most common types in use is presented in Table 2.

3.2 Benefits of Chemistry

At a recent NACE conference, durability was defined as “The capability of structural systems, members and their constituent materials to meet or exceed performance requirements for a set period of time in their service environment”. [1]

Owners want their structural systems to perform better over longer periods of time in environmental conditions which have proven to be excessively harsh for conventional reinforcement steel options.

Table 2. Chemical Composition *

UNS # Type	**32304 “2304”**	**24100 “XM-28”**	**31803 “2205”**	**31653 “316ln”**
Nickel	3 - 5.5	0.5 - 2.5	4.5 - 6.5	10 - 14
Chromium	21.5 - 24.5	16.5 - 19	21 - 23	16 - 18
Molybdenum	.05 - 0.6	--	2.5 - 3.5	2 - 3
Manganese	2.5	11 - 14	2	2
Carbon	.03	0.15	.03	.03 max

* Taken from A955.

SSR is formulated to comprise specific chemical elements, and most importantly, exact quantities of these elements such as is necessary to significantly increase the durability and service life extension of structures subjected to corrosive environments, relative to that provided by conventional products.

There are numerous ways in which this durability increase manifests itself as cost reducing benefits for the Owner.

3.2.1 Cost Reductions Attributable to Chemistry

The high level of SSR durability can result in a dramatic prolongation of the useful service life eliminating an Owner’s need for new investment.

During the service life, repairs and maintenance costs will be significantly reduced.

Reducing the frequency and complexity of repairs results in a reduction in traffic congestion and user costs while increasing the utilization rate of the structure with the associated societal economic benefits.

There are a number of potential initial construction cost savings opportunities attributable singularly to the use of stainless steel rebar.

SSR is the primary corrosion resistance system. This high performance rebar product is the only protection system required. The inherent durability of SSR means that traditional secondary systems designed to protect reinforcing steel from the chlorides such as excess concrete cover, membranes, deck sealants, concrete additives are unnecessary and redundant. The “belt and suspenders” philosophy of protection duplication is unnecessary with stainless.

Less concrete cover will lighten the support structures reducing initial structure cost. In the case of bridge rehabilitation, reducing concrete cover and therefore “dead” load will allow the structure to take on more “live” truck load.

The Michigan DOT and the New York DOT both have policies of reducing cover with stainless.

In the New York State DOT bridge design manual [2], Section 5.1.1 of the a 1” reduction of concrete cover and slab thickness for bridge decks is allowed only when constructed with stainless steel rebar. Section

15.12.4 indicates that the cost of stainless will be offset to a degree by the reduction in thickness of the slab and reduction in the foundation cost owing to the reduced dead load. The designer is reminded that reinforcement is a small percentage of the overall cost when deciding the type of reinforcement to use.

Reduced cover means lighter structures may be more earthquake resistant and less costly. And, less cover is associated with smaller crack widths.

Though the effort to reduce deck cracking is encouraged, the owner could be less sensitive to cracking with stainless given its excellent corrosion resistance.

The replacement of coated products relieves the Owner of the cost burden of a coating quality assurance program and removes the risk and associated costs of a coating failure.

3.3 Corrosion Resistance Measured

Corrosion of steel is an electrochemical process, involving both chemical reactions and electronic/ionic current within the corrosion cell. The cell consists of a cathode and an anode that are electrically connected to one another in an electrolyte solution through which "corrosive" ions may travel. The assessment of a material's corrosion resistance is quantified by researchers in a laboratory simulation of a field corrosion environment by measuring the rate of flow of electrons usually in the presence of chlorides from the anode to the cathode. For more details, refer to WJE, Corrosion Resistant Reinforcement: Summary of Test Methods. [3]

The types of metal corrosion test methods and parameters measured are numerous. Commonly used corrosion assessment methods are chloride thresholds, corrosion potentials, corrosion current densities, macrocell, and linear polarization to name a few.

A review of the published corrosion resistant research reveals the essential point that regardless of the level or rate of corrosion resistance that is captured in the tests, the bottom line is that SSR's chemistry places it orders of magnitude better than competing reinforcement products.

3.3.1 Representative Corrosion Research

A scan of a sample of published corrosion research on steel reinforcement is presented as evidence of the superior corrosion resistance of SSR relative to other concrete reinforcement products, with a focus on alloyed materials.

According to the U.S. Department of Transportation, given the "uncertainties regarding the long term performance of epoxy coated reinforcements", in 2009 the Federal Highways Administration ("FHWA") released a comprehensive study [4] of the corrosion resistance of various steel alloys. It indicated that while some alloyed products were classified as "Improved Performers" relative to black bar, it concluded that only with SSR can a service life of 75 to 100 years for major structures be confidently achieved.

In a paper published in the ACI Materials Journal in 2009 [5] comparing critical chloride thresholds at cracks in simulated bridge deck specimens for black, galvanized and stainless steel bars, the average time to corrosion for conventional black steel was 2.3 years compared to 5 years for galvanized bars. The stainless steel did not corrode in the study.

The University of Kansas Center for Research ("University") developed the Rapid Macrocell test which is the corrosion test in the stainless rebar standard A955. Rebar must pass these tests to comply with this standard. The test involves subjecting the steel to 15 weeks of exposure to chloride attack. To pass the test the steel bar samples must exhibit an average corrosion rate below 0.25μm/yr.

The University has Macrocell tested various types of stainless steel rebar as well as ASTM A1035, a low alloyed bar. The stainless steel rebar product UNS S24100, also known as XM-28, which is at the lower end of the SSR corrosion resistant spectrum, out performs MMFX by a very wide margin.

Comparing the results of the two University research papers reveals that according to a November 2010 test paper [6], alloy Enduramet 32 (an XM-28 brand name) did not corrode during the 15 week test. Rebar A1035 (MMFX) following the same test procedure in a second paper [7] in November 2010, recorded an average corrosion rate of 20μm/yr. This puts the A1035 corrosion rate at “orders of magnitude” greater than that of stainless. Note that the stainless did not corrode!

Research was conducted by the National Research Council (“NRC”) in Ottawa into the corrosion resistance of ASTM A1035 bars relative to stainless. In their 2009 paper [8] the rate of corrosion for stainless type 2205 is 50 times less than the A1035 product at a 3% chloride level. The second study by the NRC [9] was published in November 2012. It provided chloride thresholds for a range of steel rebar types. The threshold data shows that for stainless types 2205 and 2304, it takes 16 times and 12 times more chloride respectively to initiate corrosion relative to A1035.

Clearly, there are differences in corrosion resistance of different types of steel rebar depending on the chemistry. It is also evident that stainless is a far superior product relative to other commercially available rebar.

An important point to note on this type of corrosion resistant research is that various methods to accelerate the results are used by testing at chloride levels much higher than that found in the field.

While it is generally accepted that stainless is the best at resisting the chlorides, the engineer needs to match the type of reinforcement to the service life requirements and the environment.

3.3.2 Progreso : 75+ Years of Evidence

The port city of Progreso, in the Mexican state of Yucatán, is home to the longest pier in the world. The pier was built between 1937 and 1941 and was the first concrete structure in the world constructed with SSR. Despite the relatively poor grade of concrete used, the pier has withstood the harsh marine environment and has been in continuous service for over 75 years without any major repair or routine maintenance activities. Florida DOT engineers attest to these facts.

4 HIGH PERFORMANCE PRODUCT

The unique mechanical properties of a high strength steel product with 20%+ elongation coupled with the superior corrosion resistance properties providing an unmatched extended service life of structures without major repair definitely put SSR in the category of a HIGH PERFORMANCE product.

5 COST EFFECTIVENESS – LIFE CYCLE COSTING

Life-cycle cost (LCC**)** is an analytical tool to determine the most cost-effective option among different competing alternatives to build and maintain a structure or component (bridge deck) during a pre-determined structure service life.

For a new bridge structure, in addition to the initial construction cost, LCC takes into account all the Owner’s costs over the service life related to future activities, including future periodic maintenance and rehabilitation repairs, user costs, and reduced capacity utilization. All the costs are discounted at the Owner’s discount rate and totaled to a present-day value known as net present value (NPV).

The evidence is clear : based on the significantly enhanced durability of SSR, the avoidance of repairs and maintenance attributable to the use of SSR results in the least total cost over the service life of the structure, that is, the least LCC. An assessment of the LCC of the Progreso Pier mentioned previously is referenced herein. [10]

The NYSDOT provides evidence of the positive impacts of using the LCC tool. They conducted their own independent research and analysis which was used to demonstrate savings with SSR.

The DOT published two studies on the subject of life cycle costing of bridges which were based on their own cost data and experiences.

The first study was titled “Improving Tomorrow’s Infrastructure : Extending the Life of Concrete Structures with Solid Stainless Steel Reinforcing Bar”. [11]

The paper looked at the comparative life cycle costs using different types of reinforcement for bridge rehabilitation and for the construction of a new bridge. The conclusions of this study was that the life cycle cost saving of using stainless steel rebar for bridge deck rehabilitations was 20% with respect to the next best alternative. For the construction of a new bridge which involves a much larger scale investment than bridge rehabs, the savings on a LCC basis was 9% for the stainless case.

The second paper published by the NYSDOT titled “Use of Advanced Materials to Extend Bridge Life and Reduce Initial Cost : A Case Study of Three Projects In New York City” [12] studied the savings that could result from a reduction in concrete cover. It concluded that the incremental initial construction cost was “trivial” with stainless and the LCC savings were 10% relative to next best alternative. The paper cites three examples of bridge projects in New York where the use of stainless steel rebar resulted in net project savings not otherwise achievable.

Note that the avoidance of user costs associated with traffic congestion during repairs have not been accounted for in the NYSDOT analysis which can be a major additional cost saving in favour of the stainless option.

In conclusion, the use of SSR will likely result in the least life cycle cost of both rehabilitation and major projects.

6 PRICING

Pricing is always a consideration. While I will not talk about actual prices, I can say that prices in general have come down due to volume effects from the historical high point when SSR was a “specialty/niche” product. So enquire about actual pricing from a knowledgeable source such as a fabricator of SSR.

SSR may cost more than conventional rebar but it works! Consumers face a range of price/quality options for any product or service. Normally, quality and price are directly proportional. The rebar market is the same – less costly and less effective rebar is available, but the Owner looking for excellent durability and an extended service life without repair will be disappointed without stainless steel.

7 SPECIFICATION – BEST PRACTICES

There is a growing trend in North American among Owners and engineers to primarily rely upon alloyed materials rather than conventional or coated materials given their lower rates of corrosion resistance and durability uncertainty due to the fragility of the coating materials.

A corrosion resistant reinforcement specification format is emerging which allocates alloyed reinforcement products on the basis of their corrosion resistance to specific roadway classes as defined by the level of strategic importance and/or traffic volume.

Two good examples of Agencies adopting this format are the Virginia Department of Transportation and the Vermont Agency of Transportation.

The Virginia specification [13] defines three classes of roadway, Classes 1, 2 and 3 in ascending order of strategic importance -- Class 3 is Freeways, Rural and Urban Principal Arterial Highways. SSR is specified for all three Classes whereas less corrosion resistant materials are relegated strictly to Class 1, Rural and Collector Local Roads. These roads have less traffic, and therefore are less economically/strategically important to the Virginian network. No coated products are permitted.

The Vermont format [14] defines three classes of roadway, Levels I, II and III in ascending order of strategic importance. Thus Level III is for Interstate and National Highway Structures, and sites where construction or maintenance will be is challenging. This level requires "Exceptional Corrosion Resistance" and thus specifies SSR. Level I on the other hand requires "Limited Corrosion Resistance" and is required for low volume roads defined as Unpaved Roads with ADT≤400 or Components with a Design Life of 30 yrs. or less. For this Level, a coated product is permitted.

8 APPLICATIONS

Stainless steel rebar is being used where an effective corrosion resistant rebar is required in the following general applications :

- Highway Infrastructure
- Marine Infrastructure
- Pre-assembled cages for CIP end uses
- Precast end uses

Fabricated rebar is supplied either directly to the field for cast-in-place (CIP) applications or to pre-casters for precast applications such as deck panels or other bridge elements, or in the form of welded pre-assembled rebar cages.

8.1 Highway Infrastructure

The primary use of SSR is for highway infrastructure applications where deterioration due to corrosion defines the service condition. The highway elements where SSR is most often specified are as follows :

- Decks and deck panels
- Barrier walls, curbs, sidewalks, medians
- Deck joint block outs
- Abutment roof slabs
- Approach slabs and wing walls
- Bridge piers and pier caps
- Highway load transfer dowels

A summary of some recent major North American projects using stainless steel reinforcement is presented in Table 2.

Table 2. Snapshot of Some Major SSR Projects

Project	Owner	SSR [tonnes]	SSR Type

Champlain	Canada	15,000	2304
Stillwater	MN DOT	5,400	2304
Gardiner	Toronto	5,000+	2205
Pulaski	PANYNJ	5,000	XM-28
Calgary Ring Road	AB Trans	5,000	2304
Hoan	Wis DOT	4,500	2304
Bonner	NC DOT	3,200	XM-28
I-74 Mississippi	Iowa DOT	2,500	2304
Edmonton LRT	Edmonton	1,200	XM-28

8.2 Primary Areas of Usage

The main geographical areas of use are the higher elevation areas as well as the Northern regions of the U.S.A., practically all of Canada and coastal regions in North America.

Within the highway and marine infrastructure markets, the primary users are departments of transportation (DOT) at the various jurisdictional levels (provincial, state, city, county, etc.) and port authorities. An abridged list of State DOT's using SSR include NY, NJ, RI, VT, NH, VA, MD, NC, MN, WI, UT, IA. The primary Canadian governmental users are BC, AB, SK, MB (City of Winnipeg), ON, NB, Transport Canada.

9 MATERIAL AVAILABILITY

There is no lack of product supply. In fact the opposite is the case.

There are three mills producing stainless steel reinforcement located in the U.S. and various European mills as well. The U.S. mills, namely Carpenter, NAS and Outokumpu, meet the "Buy America" requirement that the rebar be manufactured from ingots melted in the U.S. and that the bars be rolled State-side.

The current global total in place capacity to produce SSR is estimated at approximately 150,000 tonnes which is far in excess of the current market size.

10 FABRICATION PRACTICES

The contamination of SSR with black carbon can affect product performance. As such, the industry has developed a standard to eliminate the possibility of contamination of the SSR with black carbon during the various fabrication processes. The document was developed by the Concrete Reinforcing Steel Institute ("CRSI") and approved by ANSI. This ANSI CRSI IPG4.1 document is titled "Standard Practice for Stainless Steel Reinforcing Bar Fabrication Facilities".

The main provisions are that SSR is to be fabricated in a dedicated facility and that all contact points during storage, fabrication, handling or shipping will be with materials that do not impart any carbon steel contamination to the stainless product. Other key provisions are material acceptance and rejection criteria.

11 CONCLUSIONS

SSR is a high performance cost effective product which should be part of the consideration when Owners are confronted with constructing infrastructure in a corrosive environment. Furthermore, with the current drive for longer service lives free of major corrosion induced repair, the use of SSR certainly applies for all infrastructure applications and especially for major bridge structures where the 100 year service life is becoming the norm.

For more information, please feel free to contact the author at rhuza@salitsteel.com.

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