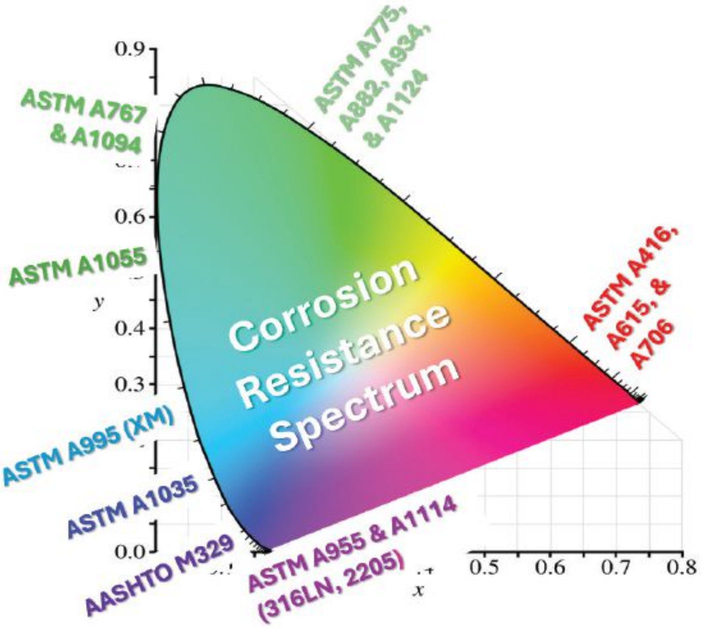
Corrosion-Resistant Steel Reinforcement for Concrete Structures: Defining Resiliency Using the Color Spectrum

by Steven Nolan, Florida Department of Transportation, Dr. Salem Faza, CMC, and Dr. Samuel McAlpine, Allium Engineering Inc.

Following the *ASPIRE*® Winter 2025 article "Corrosion-Resistant Fiber-Reinforced Polymer Reinforcement for Concrete Structures," and the *ASPIRE* Spring 2020 article "Epoxy-Coated Prestressing Steel Strand," we continue the discussion with this article about corrosion-resistant steel reinforcement. Corrosion resistance for steel reinforcement should be viewed as a spectrum of options with a broad range of durability performance resulting from an equally broad range of steel chemistry, microstructure, and coating or cladding systems.

It is worth noting that corrosion of steel bars embedded in a concrete matrix is significantly different from general steel corrosion under atmospheric conditions. The highly alkaline internal environment of a concrete member is initially compatible with conventional carbon steel bars such as those conforming to ASTM A615[1] or ASTM A709,[2] and it has contributed to the long-term success and economy of concrete structures for more than a century. However, time and exposure conditions can eventually change the internal concrete environment, significantly reducing the initially high pH (typically ranging from 12.5 to 13.5) via atmospherically induced concrete carbonation and matrix dissolution, or accelerated steel corrosion potential catalyzed by chemical ion ingress. The rate of steel reinforcement deterioration is significantly influenced by external and internal concrete conditions, exposure cycling, and—perhaps most importantly—time.

Figure 1. Comparing the relative economic and performance strengths of various types of reinforcing steel is analogous to this depiction of how visible colors of light relate to one another. The x-axis represents the indexed perception of value, and the y-axis is the life-cycle cost analysis rating. Figure: Adapted by Steven Nolan from https://commons.wikimedia.org/wiki/File:CIExy1931.svg.



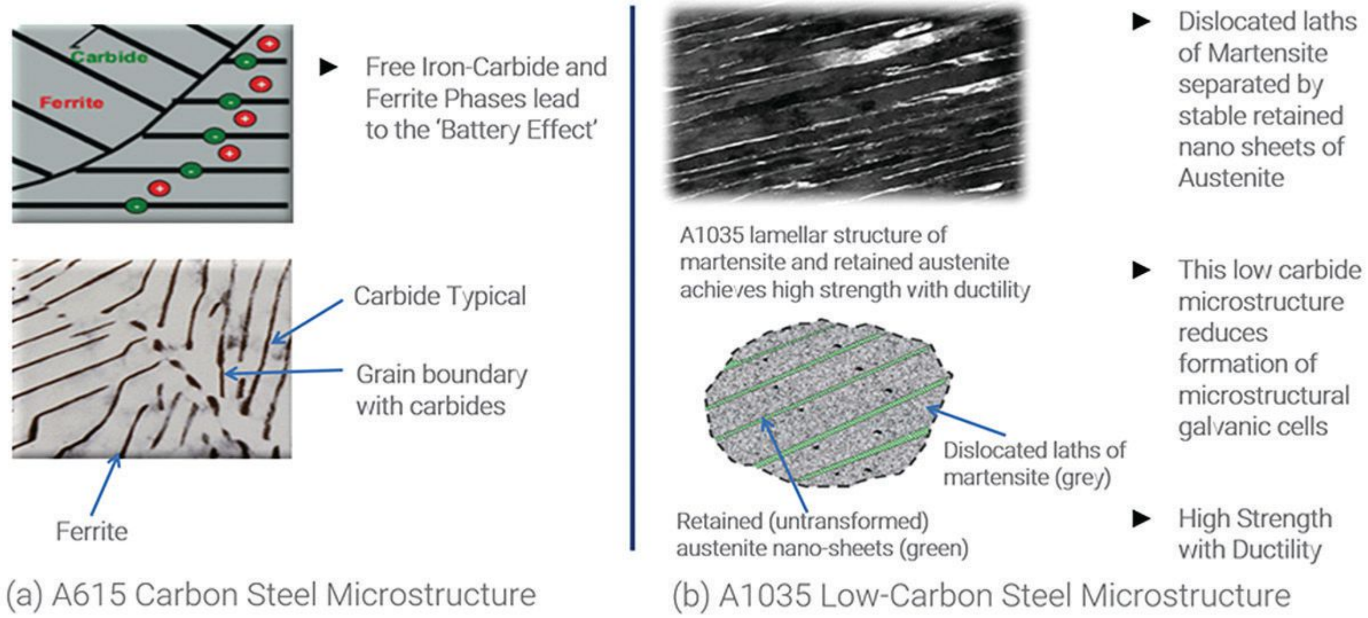
External conditions include average and extreme exposure temperatures, the pH (acidity or alkalinity) of atmospheric and surface moisture, chemical ion content (chloride and sulfate), and even microbiologically induced corrosion. Internal factors include the chemistry of the concrete binder (portland cement, pozzolans, and supplementary cementitious materials), matrix porosity and interstitial void connection structure, the degree of moisture saturation, aggregate types, and the aggregates' susceptibility to alkali reactions (alkali-aggregate reactions and alkali-silica reactions), which induce matrix cracking.

We have broadly classified steel reinforcement on a spectrum of available corrosion resistance based on coatings, constituent metallic alloy chemistry, and the crystalline microstructure created during the rolling, quenching, and tempering production processes. The color palette or nonlinear spectrum in **Fig. 1** illustrates the classification of reinforcement from "rusty red" to "shimmering violet."

On the red, or "rusty," end of this spectrum is conventional carbon steel reinforcement (ASTM A416,[3] ASTM A615,[1] and ASTM A706[4]). The violet or more "durable" end of the corrosion-resistance spectrum includes highly alloyed or duplex stainless steel (ASTM A955[5] and ASTM A1114[6]) and titanium alloy bars (ASTM B1009[7]) used for near-surface mounting.[8] In the middle of the spectrum are yellow, orange, and green zones for reinforcement with various barrier coatings or lower-alloyed steel reinforcement options such as epoxy-coated (ASTM A775,[9] ASTM A882,[10] ASTM A934,[11] and ASTM A1124[12]), galvanized (ASTM A767[13] and ASTM A1094[14]), dual-coated epoxy-zinc (ASTM A1055[15]), and low-nickel molybdenum-free austenitic stainless steel (ASTM A955[5]).

Developments over the last quarter century have introduced and refined what might be considered a "blue" zone of steel reinforcing options, including low-carbon chromium steel (ASTM A1035[16]), other lower-chromium alloyed steels (AASHTO M334[17]) and stainless clad carbon steel (AASHTO M329[18]). While the ultimate durability of a concrete structure is influenced by many factors, the selection of an appropriate reinforcement type for the intended purpose and expected service life is paramount to satisfying both resilience and sustainability objectives.

Types of corrosion-resistant steel reinforcing bars in the blue zone are not as well known among engineers as products in other zones of the spectrum. ASTM A1035 bars (ChromX 2000, 4000, and 9000 series) have a specific layered microstructure that contributes to both strength and corrosion resistance (**Fig. 2**). These bars come in a range of alloy contents and corresponding corrosion resistance, and they exhibit high tensile strengths of 100 and 120 ksi. While a 100-ksi maximum is currently permitted for design under specific conditions, such as in low-seismicity zones, in the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[19] and the American Concrete Institute's *Building Code Requirements for Structural Concrete (ACI 318-19) and Commentary (ACI 318R-19)*,[20] even the 80-ksi design limit can provide



(a) A615 Carbon Steel Microstructure (b) A1035 Low-Carbon Steel Microstructure

Figure 2. Comparison of steel microstructure for carbon steel (ASTM A615[1]) and low-carbon chromium steel (ASTM A1035[16]). Figure: CMC.

structural efficiency without compromising ductility, assuming that service limit state conditions can still be satisfied.

Perhaps the least-known product type in the blue zone is stainless steel–clad reinforcement. This is a metallic composite material that combines a corrosion-resistant outer layer of high-chromium and nickel stainless steel alloy (such as UNS S31653) with a carbon steel core (equivalent to ASTM A615[1]). This type of reinforcement was introduced to North America in 2001 from the United Kingdom; a newer generation and domestically manufactured version that meets AASHTO M329[18] and U.S. federally funded procurement sourcing restrictions is now available.[21] The corrosion-resistance of stainless steel–clad reinforcement[22] is comparable to that of solid stainless steel (ASTM A955[5]), provided that the metallurgically bonded coating remains unbreeched, whereas the bulk mechanical properties and structural design are comparable to conventional carbon steel reinforcement (**Fig. 3**). Compared with solid stainless steel reinforcement, stainless steel–clad reinforcement is substantially less expensive to produce and has a significantly lower global warming potential (GWP). There is a minor risk of some localized corrosion at the cut bar ends or in isolated spots subjected to extreme impacts during construction, if those areas are not subsequently sealed appropriately. This risk demotes stainless steel–clad reinforcement from a potential violet status to blue; however, when robust quality control is in place at the jobsite, this type of reinforcement may warrant an indigo status.

Production of the current version of stainless steel–clad reinforcement differs significantly from production of the earlier U.K.-based product line for the patented composite steel. Production of the former version involved filling a stainless steel tube with carbon steel (either shavings or a solid billet), sealing the end of the tube, and hot-rolling the composite piece into deformed steel reinforcement. For the current version, a U.S.-based company has developed a novel manufacturing approach using laser deposition to build up a metallurgically bonded stainless steel layer on the outside of a carbon steel billet, thereby creating a composite stainless steel–clad billet, which can then be hot-rolled into deformed stainless steel–clad reinforcement at commercial steel reinforcing bar rolling mills. Initial installations of this stainless steel–clad reinforcement are underway in California and Florida after successful completion of the National Cooperative Highway Research Program Innovations Deserving Exploratory Analysis Project 240.[23] This material is a cost-effective and scalable option, especially for highly aggressive environments resulting from deicing or marine salt exposure,[24] with the advantage of using familiar structural design practice and having ductility equivalent to that of ASTM A615 reinforcement.

Conclusion

A spectrum of steel reinforcement options is commercially available and standardized in the United States. Given the broad range of options, design professionals are obliged to familiarize themselves with both the benefits and limitations of each product type to best serve their client-owner interests and be good stewards of our concrete infrastructure. In the context of national and international cement and concrete road maps for decarbonization by 2050,[25–28] resilience (durability, robustness, and self-healing), and sustainability (GWP, adaptability, and reuse), design guidance should be refined to balance both economic and environmental costs. Here, the use of corrosion-resistant steel reinforcement along with smart concrete choices may be a pivotal advancement as we all strive to be environmental stewards.

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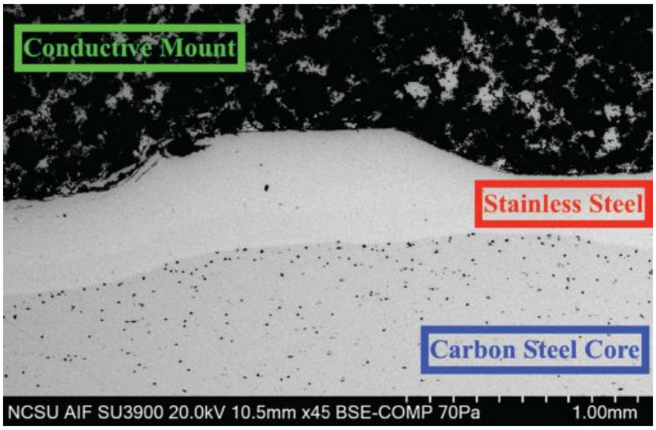
Figure 3. Electron microscope image of a longitudinal cross section of a stainless steel–clad reinforcing bar. The cladding is shown across a surface deformation. Photo: Allium Engineering Inc.



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Steven Nolan is a senior structures design engineer for the Florida Department of Transportation in Tallahassee. Dr. Salem Faza is the engineering manager at CMC. Dr. Samuel McAlpine is the cofounder and CTO of Allium Engineering Inc.