Designing Better Built Structures, More Efficiently

Value Engineering With High-Strength and Corrosion-Resistant Rebar

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Michael W. Pompay
MMFX Steel Corporation
michael.pompay@mmfx.com
Irvine, California

MMFX STEEL TODAY'S STEEL STANDARD

Introduction

When building, improving or replacing our infrastructure, we should apply Value Engineering (VE) disciplines to build better structures, more efficiently. VE is a creative, organized effort, which analyzes the requirements of a project for the purpose of achieving the essential functions at the lowest total costs (capital, staffing, energy, maintenance) over the life of the project. This includes selecting materials that most efficiently meet the objectives of the construction project from construction through replacement. Requirements such as load capacities, service lives, maintenance and repair costs, must be taken into consideration in the design of the structure.

The use of corrosion resistant reinforcing steel bar (rebar) extends the useful life of the structure, as well as reduces maintenance and repair costs. Applying high strength steels in design can drastically reduce construction costs, including solving costly congestion issues. MMFX Technologies Corporation offers high strength and corrosion resistant reinforcing steels to the market named $MMFX_2$® and ChromX™ 4100 rebar.

Corrosion Resistance

Corrosion of steel is initiated when chlorides penetrate the concrete, which is porous, and reach the steel in sufficient concentration to initiate corrosion. This concentration is known as the Chloride Threshold (CT) of the steel. When the CT is reached, the steel begins to corrode and propagates, expanding the steel and causing the concrete to crack and spall. Figure 1 diagrams this corrosion timeline.

Figure 1. Corrosion Timeline for Concrete Reinforcement

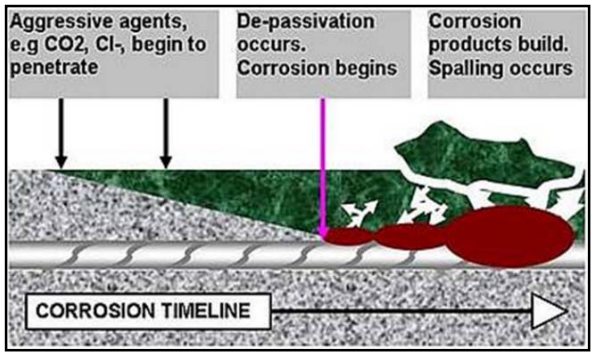


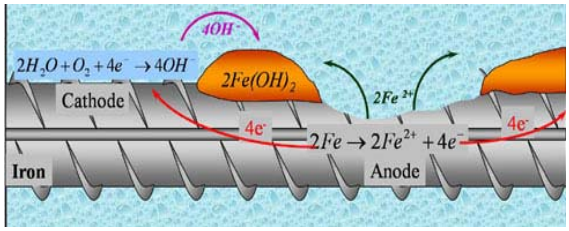
Figure 2 shows examples of a corroding bridge pile and deck. The reinforcing steel has corroded, causing the concrete to fall away, weakening the supports and substructures of the bridges.

Figure 2. Corroding Bridge Member Examples

Corrosion of the reinforcing steel is the major cause of deterioration of concrete structures and our infrastructure. The United States infrastructure is suffering significantly from the corrosion of its bridges, roadways, ports and seawalls. A 2002 study conducted by the U.S. Federal Highway Administration (FHWA) estimated the total annual cost of corrosion to be $276 billion or 3.1% of the nation's gross domestic product. The fast rate of corrosion compared to the slow rate of repair and replacement has caused cumulative deficiencies in the nation's infrastructure. Over 143,000 U.S. bridges, approximately 25% of the country's total bridges, are deemed structurally deficient or functionally obsolete. We need to change this trend and build our infrastructure to last by using better construction materials.

The corrosion resistance of $MMFX_2$ rebar is derived from the unique microstructure of the steel that is fundamentally different than standard carbon steels. Standard carbon steels consist of ferrites and carbides. When exposed to a chloride solution, the ferrites (anodes) and carbides (cathodes) establish a chemical reaction called a micro-galvanic cell that causes the breakdown of the carbides, resulting in the expansion of the steel, i.e. the corrosion of the steel. See Figure 3.

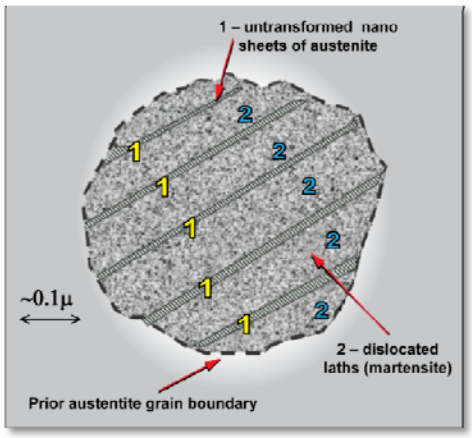
Figure 3. Corrosion of Standard Carbon Reinforcing Steel



In contrast to standard carbon steels, the $MMFX_2$ microstructure consists of dislocated laths of martensite separated by thin layers of retained austenite, and is relatively free of carbides. This martensitic, austenitic

microstructure and the minimizing of carbides in $MMFX_2$ inhibit the formation of micro-galvanic cells. Figure 4 represents a diagram of the MMFX microstructure.

Figure 4. MMFX Steel Microstructure



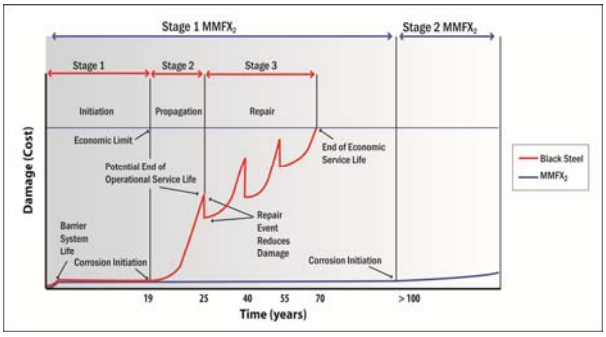
The corrosion resistance offered by this unique microstructure is twofold: 1) $MMFX_2$ steel has a CT value of four times that of standard carbon steel, which means it takes longer for corrosion to initiate; and 2) the steel corrodes at one-third the rate of standard carbon steel, which further delays the spalling of the concrete.

The corrosion resistance of $MMFX_2$ rebar has been studied, validated and measured by numerous universities, government agencies and independent testing facilities. A small selection of these studies our listed under *References* below. $MMFX_2$ rebar has been designated a Corrosion Resistant Rebar (CRR) by several state departments of transportation, ministries of transportation, and industry organizations that use the steel to extend the lives of their structures.

Economics of CRR

The corrosion cycle described above can be categorized in three stages: Initiation, Propagation and Repair. Figure 5 illustrates these stages comparing standard steel (red line) and $MMFX_2$ (blue line).

Figure 5. Service Life Timeline



Based on numerous sources and field studies, corrosion of standard steel can begin within 20 years from construction completion (See *References* below). Propagation occurs quickly and repair of the concrete is required within 25 years. The repairs can buy some time, but the underlying cause, i.e. the corrosion of the reinforcing steel, continues until the structure needs to be completely replaced.

$MMFX_2$'s higher CT value of four times that of standard steel delays corrosion initiation well beyond the projected service life of structures built using standard rebar. In addition, the steel's slower rate of corrosion further extends the service life. Studies have projected the service life of concrete structures built with $MMFX_2$ rebar to be over 100 years, based on these scientific factors and modeling of historical chloride ingress in concrete (See *References* below).

This extension of the service life and delay in the need for repairs directly reduces the maintenance and repair costs over the life of the bridge or other structure. Table 1 below compares the estimated Net Present Value (NPV) of a bridge deck made from $MMFX_2$ rebar compared to other products. The estimated costs include construction and repair costs over a 100-year target service life. $MMFX_2$ provides the lowest life cycle costs per square foot.

Table 1. Life Cycle Cost Comparisons – TCG LCCA Report (May 2012)

	Bridge	Marine Pile
Concrete Type	Bridge LP	Pile Mix LP
Minimum Cover	1.5 in.	2.0 in
Reinforcement Type	**Lifetime Cost with Repair ***	**Replacement Life**
Black Bar	$20.14	26 yr. replacement
Epoxy Coated (ECR)	$17.79	35 yr. replacement
Galvanized	$14.86	64 yr. replacement
$MMFX_2$ – Gr. 60	$14.40	> 100 yr
$MMFX_2$ – Gr. 75	$11.28	
$MMFX_2$ – Gr. 100	$8.64	
Stainless (UNS S32304)	$30.36	> 100 yr

*Net present value in US dollars per square foot, excluding traffic and road user costs incurred during repair.

$MMFX_2$ rebar was designated the lowest cost solution for corrosion based on a 75-year service life by the Virginia Transportation Research Council (VTRC). Based on the VTRC recommendation, the Virginia Department of

Transportation (VDOT) instituted its CRR policy, under which it requires the use of $MMFX_2$ or stainless steel for its bridges and highways.

It is important to note that the owner does not have to wait the full service life in order to realize the cost benefits offered by $MMFX_2$ rebar. Significant savings are realized upon the first repair of a structure built with standard rebar, which can be required in as early as 20 – 25 years from construction. While a structure built with $MMFX_2$ rebar would not require a repair for 100 years.

As Table 1 above indicates, the life cycle cost savings is further increased when design engineers take advantage of $MMFX_2$ rebar's higher strength. See "*High Strength*" below.

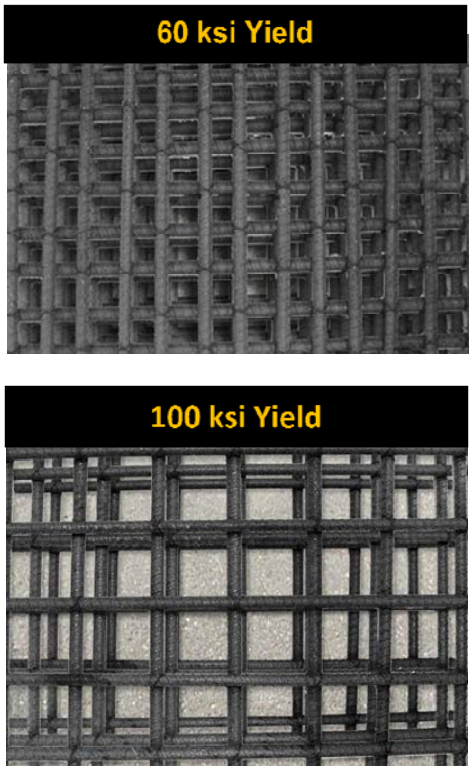
High Strength

Both $MMFX_2$ and ChromX 4100 rebar provide over 690 MPa yield strengths allowing for efficient designs and construction of bridges. The savings derived from designing with High Strength Steel (HSS) grades not only result from the direct reduction in the amount of steel needed, but also the reductions in the fabrication and placement of that steel, the transportation and pouring of the concrete, and other construction costs, such as crane time, couplers, and excavation, depending on the given design alternative selected. In addition, high strength steel designs can solve rebar congestion issues, improving constructability, and shorting construction timelines. Lastly, the availability of these high strength steels gives engineers the freedom to design innovative structures that would not otherwise be possible with standard grade steels.

The construction industry standards accommodate high strength rebar designs that allow owners and engineers to realize these benefits today. The American Concrete Institute (ACI) and the International Commercial Code (ICC) include high strength concrete reinforcing designs up to 100 ksi / 690 MPa. In addition, the American Association of State Highway and Transportation Officials (AASHTO) issued the 2013 Load and Resistance Factor Design (LRFD) Bridge Design Specifications that allows bridges to be designed using high strength reinforcing steels up to 100 ksi / 690 MPa.

Figure 6 compares mat foundation designs at 100 versus 60 ksi (690 versus 420 MPa). The high strength design opens the spacing between bars, relieving the rebar congestion and allowing the concrete to flow for better coverage. Design engineers have also been able to thin mat foundations saving significant costs and time in excavation.

Figure 6. High Strength Mat Foundation Design Comparison



To illustrate and exemplify the savings potential, Table 2 summarizes a quantified comparison of a mat foundation Grade 100 design compared to a Grade 60 design. The analysis is based on a specific mat foundation design and uses today's U.S. cost factors for materials and labor. In this case, the high strength design resulted in 40% less steel and a reduction in the mat thickness by two and half feet.

Table 2. High Strength Steel Mat Foundation Design Comparison

SUMMARY OF DESIGN COMPARISON Mat Foundation Example 5/30/2014	Grade 60 Black Bar	Grade 100 ChromX 4100	Added Cost / (Savings)
Construction Costs			
Rebar Quantities (Tons)	2,000	1,200	**(800)**
Steel Related Costs	$2,370,000	$2,022,000	**($348,000)**
Concrete Costs	$3,334,682	$2,249,935	**($1,084,747)**
Other Construction Expenses:			
Excavation	$317,377	$253,791	**($63,585)**
Total Construction Costs =	**$6,022,059**	**$4,525,726**	**($1,496,333)**
% Savings =			**-25%**
Other VE Considerations			
Number of Trucks	2,396	1,900	**(496)**
Construction Time (in hours)	366	229	**(137)**
Construction Time Savings =			**-37%**

Per the example above, ChromX 4100 is estimated to provide a savings of 25% in costs, as well as a 37% decrease in construction time.

Full VE Comparisons (HSS & CRR)

To illustrate the value engineering potential of $MMFX_2$ rebar with both its corrosion resistance and high strength properties, Table 3 provides a comparison of $MMFX_2$ rebar to epoxy-coated rebar (ECR) using a specific seawall example of a Grade 600 design versus a Grade 460 design, respectively. The design engineers elected to only design up to 600 MPa for this seawall application. Again, U.S. cost factors of materials and labor were used for this comparison.

Per the example below in Table 3, $MMFX_2$ rebar is estimated to provide an upfront construction cost savings of 4% and a 20% reduction in construction time. Further, the high strength redesign reduced the thickness of the wall by 10%, saving valuable real estate along the canal.

In addition, $MMFX_2$ rebar provides over 100 years of service life in concrete compared to only 34 years estimated for ECR. $MMFX_2$'s corrosion resistance is estimated to reduce the life cycle costs over a 100-year service life by 28% for a total savings of approximately $29 million.

Table 3. HSS & CRR Seawall Design Comparison

SUMMARY OF DESIGN COMPARISON **Seawall Example - Metric** **7/29/2014**	**Grade 460** **ECR**	**Grade 600** **MMFX2**	**Added Cost /** **(Savings)**
Construction Costs			
Rebar Quantities (metric tons)	20,000	15,333	**(4,667)**
Steel Related Costs	$37,670,000	$38,847,000	**$1,177,000**
Concrete Costs	$37,970,323	$34,173,290	**($3,797,032)**
Other Construction Expenses:			
Excavation	$3,043,591	$2,739,232	**($304,359)**
Total Construction Costs =	**$78,683,914**	**$75,759,523**	**($2,924,391)**
% Savings =			**-4%**
Other VE Considerations			
Number of Trucks	22,448	20,107	**(2,342)**
Construction Time (in hours)	2,924	2,338	**(586)**
Construction Time Savings =			**-20%**
Service Life & LCCA			
Service Life	34	101	**67**
NPV of Repairs	$25,911,409	$0	**($25,911,409)**
Total Life Cycle Costs	$104,595,323	$75,759,523	**($28,835,800)**
Life Cycle Cost Analysis Savings =			**-28%**

Again, the savings in repair costs are realized upon the initial repair of the ECR structure, which is estimated to be within 34 years of construction. These initial repair costs alone are estimated at a net present value of $9.7 million. Combined with the estimated upfront construction cost savings from the high strength design, the total savings realized from using $MMFX_2$ rebar is over $12.5 million within the first 34 years, with many more subsequent repairs scheduled for the ECR structure.

Logistics

The corrosion resistant property of $MMFX_2$ rebar comes from the microstructure of the steel, not a coating; therefore, there are no special handling requirements. $MMFX_2$ can be handled similarly to standard carbon steels. This is in contrast to products that purport to derive their corrosion protection from a coating or stainless steels that have special handling requirements, as well as added quality control procedures that increase construction time and costs. In addition, there is no risk of damaging the coating or protective layer as there is with a coated product, which would undermine that product's corrosion protection.

Both $MMFX_2$ and ChromX 4100 rebar provide the high strength yields of 100 ksi / 690 MPa with maintained ductility, so the rebar can be cut and bent on standard fabrication equipment just like standard carbon 60 ksi / 420 MPa rebar. There is also no preheating or other special fabrication procedures required.

Applications

MMFX steels have been used in:

- Bridges, highways, and roads
- Seawalls
- Ports, piers and marinas
- Canals and waterways
- Dams and spillways
- Water management and containment structures
- Many other applications

$MMFX_2$ rebar is sold under the ASTM A1035 (Grades 100 [690] and 120 [830]) and AASHTO MP 18 (Grade 100 [690]) specifications. ChromX™ 4100 is also available at these grades, but with a modified chemistry designed for a lower cost where corrosion is less of a concern.

Conclusion

MMFX steels are:

- High-strength
- Corrosion-resistant
- Easy to handle with no special handling or fabrication requirements

Utilizing high strength steel designs allows for substantial cost savings in both dollars and time. The corrosion resistance of $MMFX_2$ rebar provides additional cost savings throughout the life of the structure compared to structures built with standard steel. This savings is realized from the first repair and increases with each subsequent repair required for the standard steel structure.

Both $MMFX_2$ and ChromX 4100 rebar are essential tools for applying Value Engineering to designs, resulting in efficiently built, better constructed and longer lasting structures.

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