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Acceptance Procedures for New and Quality Control Procedures for Existing Types of Corrosion-Resistant Reinforcing Steel

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As the Virginia Department of Transportation (VDOT) continues to move forward with implementing the use of corrosion-resistant reinforcing (CRR) bars, it is important for VDOT to have a means of characterizing the candidate bars as well as ensuring that the quality of approved CRR bars is preserved. This is vital to ensure the bars respond physically in a manner that is consistent with VDOT's expectations. The purpose of this study was to provide VDOT's Materials Division with a method/specification for evaluating CRR bars.

The study determined that visual assessment cannot be relied on to determine bar type. Further, steel fabricator markings cannot be relied on to identify the type of steel. However, when questions arise regarding the identification of bars, magnetic sorting provides a quick and easy method for differentiating between magnetic and nonmagnetic alloys. If more quantitative results are required, X-ray fluorescence provides a practical and much-needed method for positively identifying bars.

Physically, the bars differ among producers. Relative rib area should be monitored as it also varies among producers. Further, alloying changes not only the corrosion resistance but also other important properties. The results of uniaxial tensile tests showed that the stress-strain behavior, elongation, and reduction in cross-section upon fracture could vary significantly for different CRR alloys. Therefore, mechanical testing, in addition to corrosion testing, of CRR is necessary to identify the most cost-effective bars with acceptable properties.

Finally, the study determined that quality control measures need to be established to ensure VDOT receives the corrosion protection it needs. Further, care should be taken when relying upon international standards for acceptance criteria.

The report recommends that VDOT's Materials Division implement the set of test methods provided in the appendices of this report as Virginia Test Methods for CRR acceptance criteria. To simplify the implementation of CRR in Virginia and elsewhere, VDOT's Materials Division should work with the American Association of State Highway and Transportation Officials to develop a single specification for the testing and acceptance of CRR. VDOT's Materials Division should also investigate retrofitting the uniaxial tensile test equipment with a non-contact extensometer to guarantee that stress vs. strain measurements of CRR can be made and ensure the yield strength is determined.

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FINAL REPORT

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ABSTRACT

As the Virginia Department of Transportation (VDOT) continues to move forward with implementing the use of corrosion-resistant reinforcing (CRR) bars, it is important for VDOT to have a means of characterizing the candidate bars as well as ensuring that the quality of approved CRR bars is preserved. This is vital to ensure the bars respond physically in a manner that is consistent with VDOT's expectations. The purpose of this study was to provide VDOT's Materials Division with a method/specification for evaluating CRR bars.

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INTRODUCTION

The time-dependent deterioration of bridges is often related to reinforcement corrosion. This problem is so significant that in a study sponsored by the Federal Highway Administration (FHWA), Koch et al. (2002) estimated the annual direct cost of corrosion to be $8.3 billion for highway bridges. To address this problem, considerable effort has been invested in improving and implementing better concretes; however, little has been done to push the widespread implementation of corrosion-resistant reinforcement (CRR) by bridge owners even though research has shown CRR can substantially decrease reinforcement corrosion. The Virginia Department of Transportation (VDOT) through its research body, the Virginia Transportation Research Council (VTRC) (now the Virginia Center for Transportation Innovation and Research [VCTIR]) has performed numerous studies, such as those by Scully and Hurley (2007) and

Weyers et al. (2006), that indicate transitioning from traditional reinforcement to CRR is the most economical approach to mitigating reinforcement corrosion and reaching a bridge life in excess of 75 years.

On March 2, 2010, VDOT approved Instructional and Informational Memorandum No. IMM-S&B-81.4 (VDOT 2010), which detailed the sequence for the transition by VDOT from the use of galvanized or epoxy-coated reinforcement (ECR) to CRR steel bars. The memorandum also indicated that the transition period would end September 1, 2010, and full implementation would follow. The memorandum divided CRR for deck reinforcement into three classes: (1) solid stainless steel, which was governed by ASTM A955 (ASTM International [ASTM] 2010b); (2) stainless steel clad, which was governed by AASHTO MP 13 (American Association of State Highway and Transportation Officials [AASHTO] 2004); and (3) low carbon / higher chromium steel reinforcement, which was governed by ASTM A1035 (ASTM 2009c). Each of these classes was then to be used by VDOT based on the functional classification of each roadway, as indicated in Table 1.

The initial CRR transition was a substantial change for VDOT and it resulted in several lessons learned, such as how to adjust to deal with limited quantities of certain bar types and challenges in identifying bars in the field. Building on what was learned, VCTIR recently proposed refining the VDOT CRR distribution method . Although this report does not focus on this change, in general, it was proposed to categorize CRR according to corrosion resistance rather than steel type. The levels and steels associated with each level are as follows.

- *Level 1: Improved Corrosion Resistance Bars:* MMFX 2, 2101 LDX (S32101)

- *Level 2: Moderate Corrosion Resistance Bars:* Stainless Steel Clad, 2304 (S32304)

- *Level 3: High Corrosion Resistance Bars:* EnduraMet 33 (S24000), EnduraMet 32 (S24100), 304 (S30400), 316L (S31603), 316LN (S31653), 2205 (S31803).

Although the different steel types (clad vs. solid stainless, etc.) are intermixed with the proposed distribution method, each type of steel is still associated with a standard that governs the requirements for that steel. Low-carbon chromium bars, such as MMFX 2, must comply with the requirements of ASTM A1035 (ASTM 2009c). Stainless steel clad bars must comply

Table 1. VDOT Functional Classification for Use of CRR

Functional Classification	**Low Carbon / Higher Chromium**	**Stainless Clad**	**Solid Stainless**
Freeway			X
Rural Principal Arterial			X
Rural Minor Arterial		X	
Rural Collector Road	X		
Rural Local Road	X		
Urban Principal Arterial			X
Urban Minor Arterial		X	
Urban Collector Street	X		
Urban Local Street	X		

VDOT = Virginia Department of Transportation; CRR = corrosion-resistant reinforcement.

with the requirements of AASHTO designation MP 13-04 (AASHTO 2004). Solid stainless steel bars (UNS designations S24000, S24100, S30400, S31603, S31653, S31803, S32101, and S32304) must comply with the requirements of ASTM A955 (ASTM 2010b). In addition, the proposed VDOT specification requires that all Level 2 and 3 bars with a stainless steel surface be pickled and states that a bar with greater corrosion resistance can be substituted for a bar with lower corrosion resistance. These bars are then classified for use according to corrosion resistance levels, as indicated in Table 2. It is anticipated that the proposed distribution method will be put into practice near the time this report is published, although the two efforts are not dependent on each other.

Table 2. Anticipated VDOT Functional Classification for Use of CRR

Functional Classification	Level 1	Level 2	Level 3
Freeway			X
Rural Principal Arterial			X
Rural Minor Arterial		X	
Rural Collector Road	X		
Rural Local Road	X		
Urban Principal Arterial			X
Urban Minor Arterial		X	
Urban Collector Street	X		
Urban Local Street	X		

VDOT = Virginia Department of Transportation; CRR = corrosion-resistant reinforcement.

PURPOSE AND SCOPE

The purpose of this study was to establish a set of test procedures/methods that VDOT can use to characterize the response of CRR and determine each bar's key alloying elements, mechanical properties, corrosion resistance, and the steel/concrete bond. These CRR characteristics are important when evaluating new types of CRR, as well as when performing quality control checks on accepted CRR bars.

The process of establishing these test methods included reviewing the literature and determining which test provided consistent and beneficial results in a timely manner. The only limitations on the test methods to be developed were that each test had to comply with the labor and equipment requirements of VDOT's Materials Division. Different phases of the study were performed at VCTIR, VDOT's Central Office Materials Division, and Virginia Polytechnic Institute and State University.

METHODS

The process of establishing the test methods to characterize CRR included reviewing the current literature and determining which test provided consistent and beneficial results in a timely manner.

To achieve the study objective, three tasks were performed.

1. *Evaluate current reference standards*. An extensive evaluation of the following three standards was conducted: ASTM A1035 (ASTM 2004, ASTM 2007b, ASTM 2009c), ASTM A955 (ASTM 2005b, ASTM 2006c, ASTM 2009b, ASTM 2010a, ASTM 2010b), and AASHTO designation MP 13-04 (AASHTO 2004), as well as key reference documents associated with these standards, such as ASTM A276 (ASTM 2006a). Both current and historical standards were evaluated.

2. *Identify beneficial test methods for the characterization of steel*. These characterization tests include x-ray fluorescence (XRF) and magnetic property measurements, in addition to uniaxial tensile (with elongation and percent reduction in cross-section upon fracture measured), bend, and hardness testing. In addition, important features in the as-received bar finish were documented. These tests were performed on bare steel bars. The tests are relatively quick because they are not dependent on the time required for casting and curing concrete. Each test provides information on the steel itself and does not incorporate the influence associated with the concrete. The test methods identified are provided in the appendices, as detailed later.

3. *Identify beneficial test methods for the characterization of steel embedded in concrete*. These characterization tests include concrete/steel bond strength and corrosion resistance testing. In addition, important features in the as-received bar finish were documented. These tests were performed on bars embedded in concrete. They are relatively slower because they require time for the concrete to cure and, in some cases, the diffusion of chlorides into the concrete. Each test provides information on the steel when embedded in concrete. The test methods identified are provided in the appendices, as detailed later.

Several types of reinforcing steel bars, some of which were alloyed for corrosion resistance, were used in the tests. Table 3 provides an overview of which types of bars were used with each test. To help in the compilation of all of the test results, a single data sheet (Table M1 in Appendix M) was created.

Tests for Characterization of Steel

Magnetic Sorting Test

Magnetic sorting can provide a means of roughly sorting different CRR materials based on the magnetic response of the steel. This test was performed in accordance with ASTM A799 (ASTM 2009a) and ASTM A800 (ASTM 2006b). A detailed methodology for performing this test on CRR is provided in Appendix A.

X-Ray Fluorescence Test

XRF can provide a means of quickly identifying the composition of rebar in the laboratory or field. A Thermo Scientific Niton XRF Analyzer was used to test various types of

Table 3. Tests Performed on Various Types of Rebar

Rebar Type	X-Ray Fluorescence	Magnetic Sorting	Hardness Test	Uniaxial Tensile Test	Elongation	Reduction in Cross - Sectional Area	Bar Finish	Mill ID Markings	Relative Rib Area	Concrete/ Steel Bond Strength	Corrosion Resistance
2101 LDX	X	X									X
2205	X	X		X	X			X	X	X	X
2304	X	X			X		X				X
304		X									
316L Clad (NX)	X			X	X	X	X	X	X	X	X
316LN	X	X		X		X			X	X	X
ASTM A615 Grade 60				X	X	X			X	X	
ASTM A615 Grade 75	X	X		X			X		X	X	X
ASTM A615 Grade 75 w/Zn	X										X
Duracorr	X		X		X	X	X	X			X
EnduraMet 32	X	X		X	X	X		X	X	X	X
MMFX 2	X	X	X	X	X	X			X	X	X
ECR	X						X				X
Zbar	X			X			X		X	X	X

known reinforcing steel. XRF analysis was performed in accordance with the manufacturer's guidelines (Thermo 2004). The chemical composition requirement is specified for the appropriate type of steel by ASTM A955 (ASTM 2010b), ASTM A1035 (ASTM 2009c), ASTM A276 (ASTM 2006a), or AASHTO MP 13 (AASHTO 2004). A detailed methodology for performing this test on CRR is provided in Appendix B.

Hardness Test

The hardness test can be useful for quickly estimating the tensile strength of a non-austenitic steel alloy. It can also provide an indication of the resistance of the metal to surface penetration, which can be a good preliminary indicator of abrasion resistance attributable to bar-to-bar contact and the scraping of bars during bridge deck installation. This test is governed by ASTM A370 (ASTM 2008a) and ASTM E18 (ASTM 2008c) for Rockwell hardness testing of metallic materials. Tests were performed using the Rockwell hardness "C" scale and converted to the Rockwell hardness "A" scale. A detailed methodology for performing this test on CRR is provided in Appendix C.

Uniaxial Tensile Test

The uniaxial tensile test provides a significant amount of information in a single test. This test provides the engineer with the engineering stress-strain characteristics of the reinforcing steel, elongation upon fracture, and percent reduction in cross-section upon fracture. This test is performed under the guidance of ASTM A370 (ASTM 2008a) and ASTM E8 (ASTM 2008b).

An example of a stress-strain curve is provided in Figure 1. Upon completion of this test, several important steel characteristics can be determined, including the elastic modulus (E), the yield point or yield strength (f_y), the ultimate strength (f_u), the fracture strength (f_r), and the ductility. It is important to mention that, in general, the 0.2% offset method must be used to determine the yield for CRR since a distinct yield point will not usually exist.

Therefore the uniaxial test equipment must be able to measure the strain accurately, and, therefore, the extensometer is critical for these measurements. As a consequence, the test equipment must be designed in such a manner that it is not damaged if fracture occurs unexpectedly.

The uniaxial tensile tests were performed in accordance with ASTM A370. Except for the percent reduction in cross-section upon fracture, the acceptance criteria for the tensile property requirements for the appropriate type of steel are provided in ASTM A955 (ASTM 2010b), ASTM A1035 (ASTM 2009c), or AASHTO MP 13 (AASHTO 2004). The percent reduction in cross-section upon fracture requirements are provided in Appendix D.

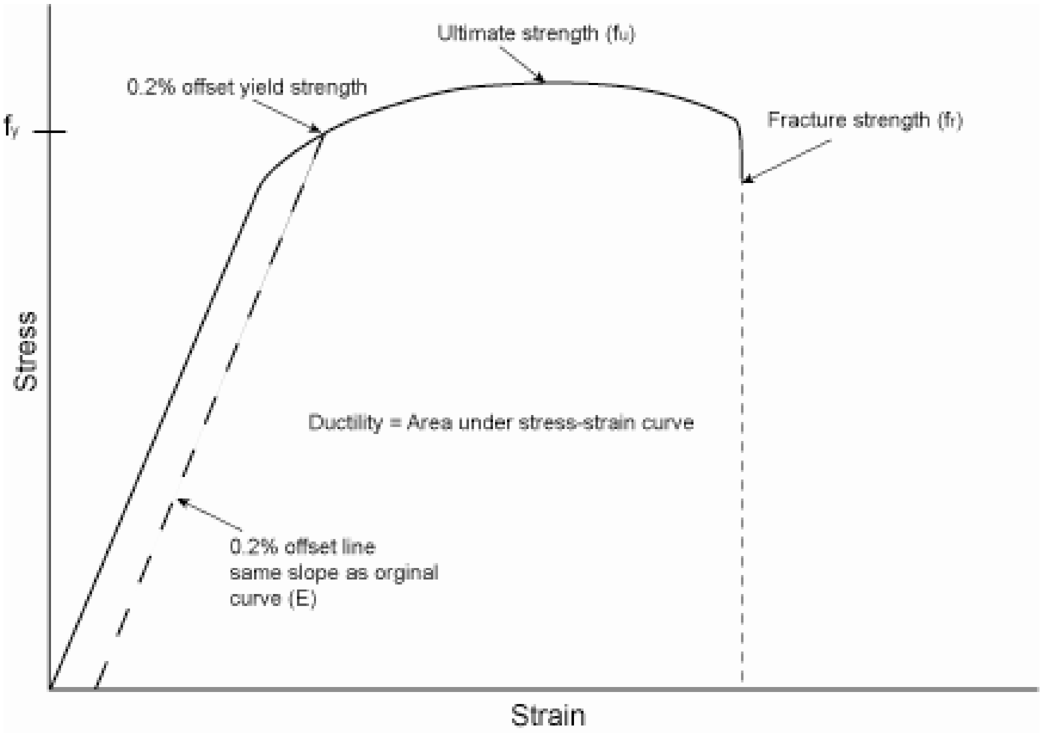


Figure 1. Illustration of different information gathered from stress-strain curve.

As-Received Bar Finish

Bar Finish

The bar finish should comply with the requirements of ASTM A955 (ASTM 2010b), ASTM A1035 (ASTM 2009c), or AASHTO MP 13 (AASHTO 2004). However, pitting of the surface attributable to corrosion should be reason for rejection of any CRR bar. In addition, stainless steel bars that require pickling should be free of corrosion. The overall surface color of the stainless steel bars can vary, but it should be uniform and free of any areas of discoloration. Finally, evaluation of the bar finish is important, especially since a “before and after” comparison will need to be made following the corrosion test. A detailed methodology for performing this test on CRR is provided in Appendix E.

Mill Identification Markings

Mill identification markings should be checked against paperwork to ensure the correct bars have been received at the jobsite. Further, bars with a stainless steel surface (ASTM A955 [ASTM 2010b] or AASHTO MP 13 [AASHTO 2004] bars) must be manufactured at a mill that is approved to produce stainless steel rebar. In the future, this process can be simplified by establishing an approved list of manufacturers and checking the mill identification marking against that list. A detailed methodology for performing this test on CRR is provided in Appendix F.

Reinforcement Rib

Two features concerning the ribs on the reinforcing steel need to be evaluated: rib spacing and rib height. If the steel is straightened from a steel coil, the ribs must be evaluated to determine if the straightening was done correctly. The cord on the rebar should not be twisted, and the rib height and spacing should comply with the requirements of the relative rib area test. The relative rib area measurements are governed by ASTM A615 (ASTM 2003). A detailed methodology for evaluating the reinforcement rib on CRR is provided in Appendix G.

Tests for Characterization of Steel Embedded in Concrete

Concrete/Steel Bond Strength Testing

In reinforced concrete structures, it is important for the load to be appropriately transferred between the steel and concrete. This load transfer is known as bond strength. To determine a suitable method the VDOT Materials Division could use to evaluate the concrete/steel bond, two types of bond strength testing were performed: (1) pullout tests and (2) beam end tests performed in accordance with ASTM A944 (ASTM 2005a). A detailed methodology for performing this test on CRR is provided in Appendix H.

Corrosion Resistance Testing

Inherent corrosion resistance is the primary reason for examining new types of alloyed reinforcing steel for bridge decks. These bars must exhibit improved corrosion resistance when embedded in concrete as compared to traditional black steel reinforcement. A detailed methodology for performing this test on CRR is provided in Appendix I.

RESULTS AND DISCUSSION

Evaluation of Current Reference Standards

ASTM A276 Chemical Composition Reference

In Section 6, under the heading “Chemical Composition,” earlier versions of ASTM A955 (ASTM 2005b, ASTM 2006c) included stainless steels complying with the chemical compositions specified in ASTM A276 (ASTM 2006a), in conjunction with those in Table 2 of the standard, as being eligible compositions for CRR candidate bars. However, in later versions of ASTM A955 (ASTM 2009b, ASTM 2010a, ASTM 2010b), this section was revised and the reference to ASTM A276 (ASTM 2006a) is no longer included. This revision decreased the number of UNS-designated stainless steel products by nearly 93%. Although not all of the steel types eliminated would be useful as rebar, the revision did eliminate some candidate bars. This change is significant to VDOT because it is important to maintain an open list of candidate materials until testing or cost has proven the bar is unacceptable as CRR. To ensure the field of candidate bars remains open and competition is maintained, ASTM A955 should include the candidate bars listed in Appendix I.

Test for Exposure to Adverse Heat Treatment

Certain stainless steels can become sensitive to intergranular attack when exposed to an unfavorable heat cycle. Other stainless steels can precipitate undesirable intermetallic phases during cooling. This can diminish the corrosion resistance of the reinforcing steel bar. A test for sensitivity to intergranular attack was required for austenitic stainless steels in earlier versions of ASTM A955 (ASTM 2005b, ASTM 2006c), but although ASTM A484 (ASTM 2011), via ASTM A276 (ASTM 2006a), requires the product to be “capable of meeting the requirement of Practice E of ASTM A262,” the test for sensitivity to intergranular attack is not required unless specified on the purchase order. For other types of stainless steels, such as duplex stainless steels, a test to detect exposure to a deleterious heat treatment cycle is not required. It is important to have a test that evaluates if the as-received material was exposed to an improper heat treatment that resulted in the stainless steel being less corrosion resistant. A description of such testing is provided in Appendix K.

AASHTO MP 13 Bend Test

ASTM A370 governs the bend test and provides an indication of the ductility of a bar. Currently, the acceptance criteria for the appropriate type of steel are specified in ASTM A955 (ASTM 2010b), ASTM A1035 (ASTM 2009c), or AASHTO MP 13 (AASHTO 2004). Although some standards allow this test to be waived if the percent of elongation for a given bar type is large enough, the bend test should always be required for clad bars. This is important because this bar is composed of an interior carbon steel core with an outer clad layer and a loss in cladding thickness during bending could be detrimental. Figure 2 shows an example of how the cladding thickness with this type of bar can vary. In addition, clad bars should be sectioned perpendicular to the bar at three locations around the bend to determine if unacceptable debonding is occurring between the clad layer and the carbon steel core. For example, Figure 3 shows an area that debonded in a bent section of the bar. To locate debonded regions, sectioning locations should be at the center of the bend and the other two locations at the quarter points of the bend. A detailed description of how to perform this test on CRR is provided in Appendix L.

Conflicts Among Test Standards

After the current standards were evaluated, it was evident that any revisions to the standards could strongly affect VDOT’s CRR selection and quality. Further, the use of CRR as specified by VDOT is governed by three standards, which could cause confusion with regard to product acceptance and quality control. However, each ASTM and AASHTO standard governing CRR has beneficial components. The tests, therefore, proposed in this report should not be considered a replacement for the tests in ASTM A1035 (ASTM 2009c), ASTM A955 (ASTM 2010b), and AASHTO designation MP 13-04 (AASHTO 2004) but should instead augment those requirements in the appropriate specification unless there is a conflict between the standard and a test listed in this report. If there is a conflict, the test listed in the report should supersede the test in the standard.

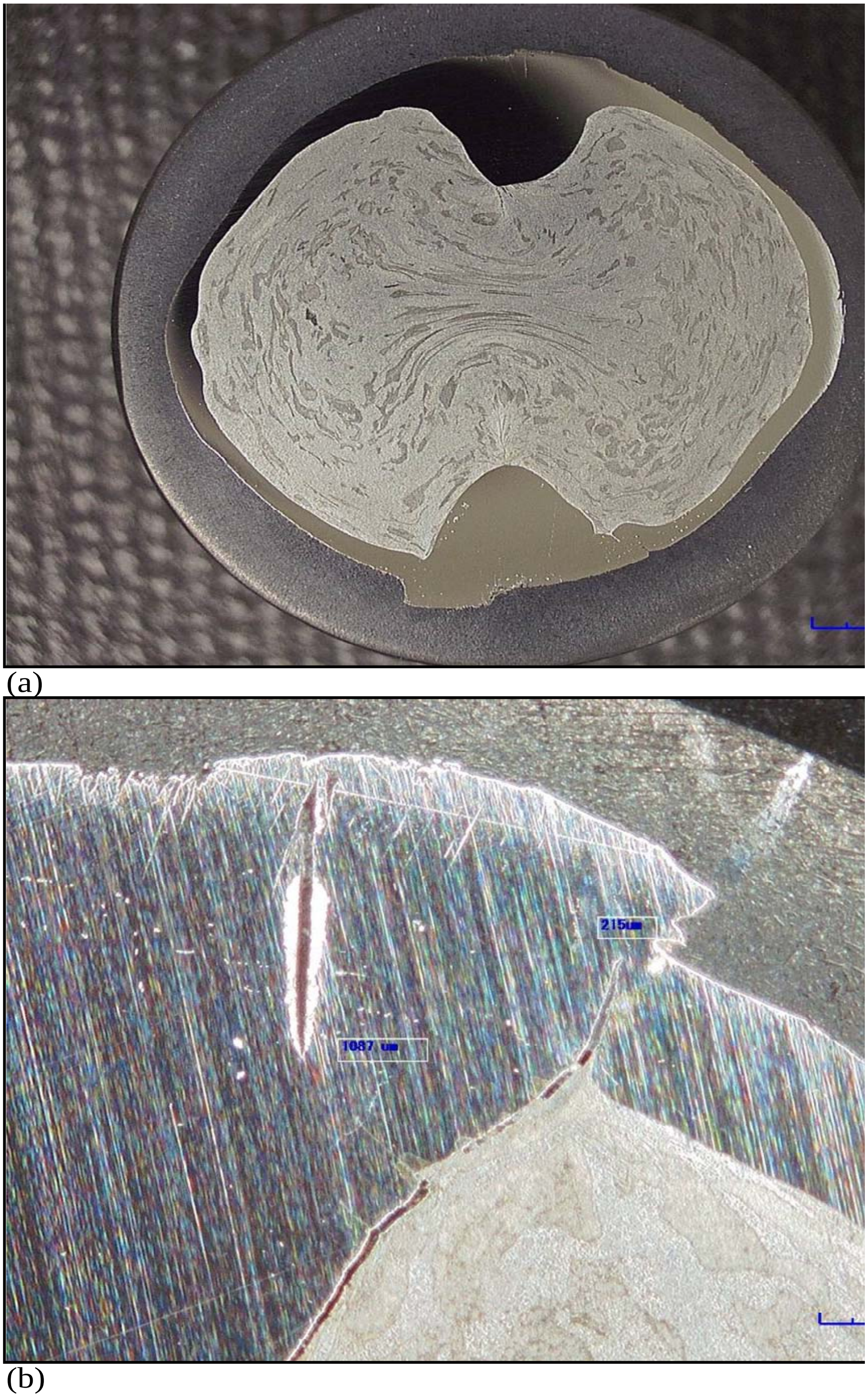


Figure 2. Sectioned clad bars showing (a) uneven cladding layer thickness and (b) regions showing incomplete cladding.

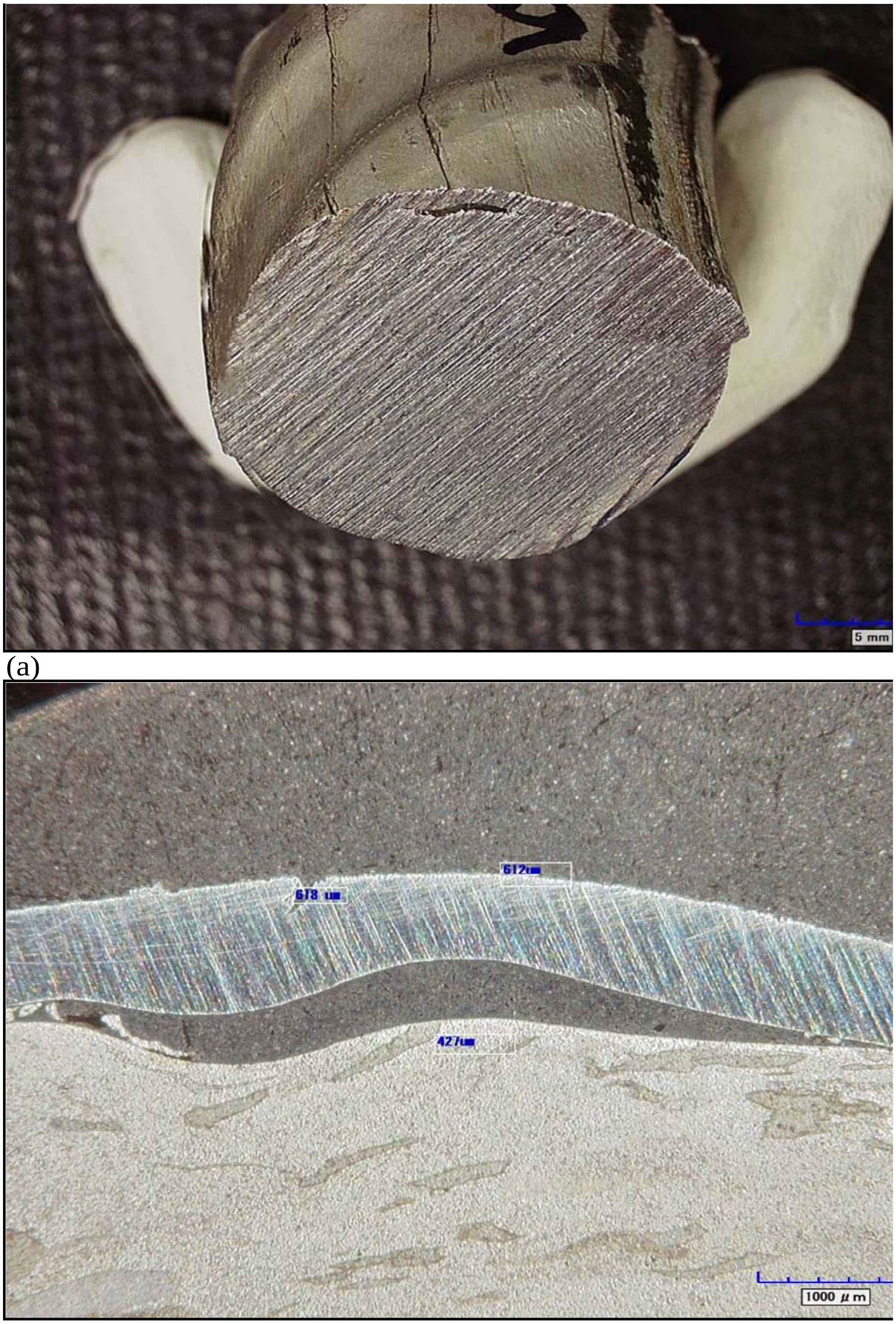


Figure 3. (a) Void located at bend section in clad bar that is visibly evident to unaided eye; (b) etched surface that clearly indicates region of separation is at interface of clad layer and carbon steel core.

Tests for Characterization of Steel

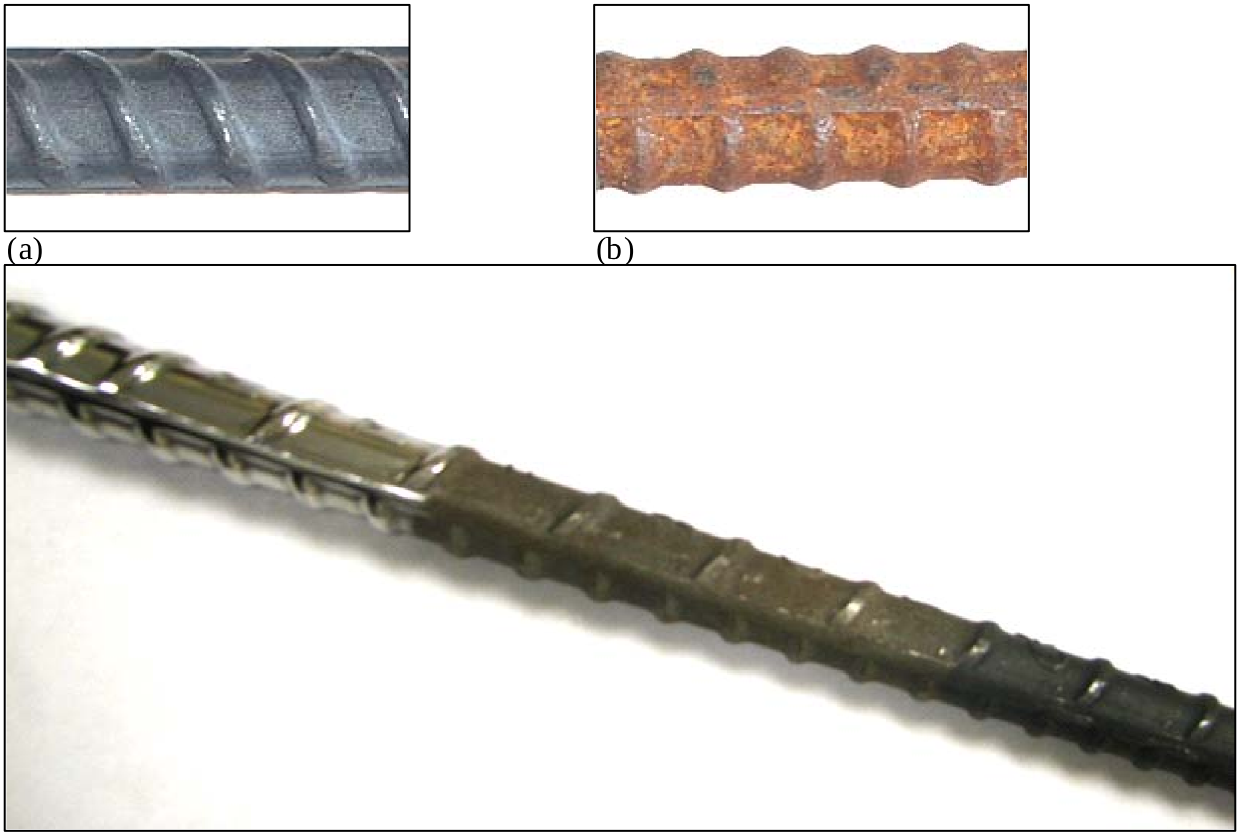
Overview of Identification of Types of Reinforcing Steel

With traditional steel reinforcement, one rebar grade with a single set of characteristics was used. Historically, when changes to the characteristics of the reinforcement occurred, such as galvanizing or coating bars with epoxy, variations in bar type could still be easily identified through visual means such as embedded marks in the steel or the different colors of coating.

As a result of VDOT's new CRR specification (VDOT 2010), a variety of steel types became available for use, as shown in Figure 4. The steel types not only differ in corrosion resistance but also have a range of properties and costs associated with alloying differences. Some CRR bars clearly look different from one another, but other bars look similar and would be difficult to distinguish from other bars. The bars in Figure 5 look similar to traditional black steel reinforcement, but the two bars on the right are alloyed for corrosion resistance. Even the surface appearance of the same type of steel can vary, as is shown in Figure 6. Figure 6a is a photograph of a sample that was submitted to VCTIR for testing, and Figure 6b is a sample of the same type of steel that was sent to the field for installation in a bridge. Figure 6c is the same type of steel shown in Figure 6a and Figure 6b, but it has been polished. Finally, even stainless steel bars can look similar, as shown in Figure 7. These two bars look similar, but their cost and properties can vary greatly because of differences in alloying. It has become clear that visual assessment is no longer a reliable method for determining the type of steel bar that is being received on a jobsite.

Figure 4. Different types of reinforcing bars that are being offered as being more corrosion resistant than traditional black steel reinforcing bars.

Figure 5. Similar looking bars, but bar on left is black steel and two bars on right are alloyed for improved corrosion resistance.



(a)

(b)

(c)

Figure 6. The three photographs show the same type of steel, but (a) is a sample that was submitted to VCTIR, (b) is a bar that was sent to field for installation in a bridge, and (c) is a bar that has been polished.

Figure 7. Two types of stainless steel reinforcement: one bar is a duplex and the other is an austenitic stainless steel.

Magnetic Sorting Test

As mentioned, CRR bars can look similar, as shown in Figure 7. Fortunately, one expensive alloy element, nickel, which is used in some stainless steel CRR bars, also promotes the formation of austenite rather than ferrite. This is also why some stainless steels are referred to as austenitic and others as ferritic stainless steels. An austenitic stainless steel generally shows a minimal attraction to a magnet, whereas a ferritic stainless steel shows a much stronger attraction. Another type of stainless steel that is used for CRR bars is the duplex bar, which has a mixture of austenite and ferrite and, therefore, usually exhibits an intermediate response to a magnet. As shown in Figure 8, the duplex stainless steel bar is raised off the table by the magnet, whereas the austenitic stainless bar remains on the table.

By using a coating thickness gage that uses magnetism to evaluate the thickness of a nonmagnetic coating that has been applied to a ferrous substrate, the magnetic characteristics of several types of CRR were collected and are listed in Table 4. Although the gage output is in

Figure 8. Two bars exposed to magnet: austenitic CRR bar (316LN) on left and duplex CRR bar (2205) on right.

Table 4. Magnetic Response of Different Types of Corrosion-Resistant Reinforcing Bars

Bar	MMFX 2	Black	2101	2304	2205	EnduraMet 32	304	316LN
Steel[a]	M, A	F, P	A, F	A, F	A, F	A	A	A
Response[b]	0.16	0.85	0.91	1.3	2.7	>25	>25	>25

[a] Steel: A = austenitic, F = ferritic, M = martensitic, and P = pearlite.

[b] Response measured using coating thickness gage, with larger values indicating greater coating thickness or less attraction between the magnet and the steel.

units of distance (i.e., coating thickness), the gage can be used to rank the CRR based on the level of attraction between the gage and the CRR when it is placed in direct contact with the CRR. Table 4 clearly shows the differences in the response of this device when austenitic versus duplex stainless steels are tested. For the 2101, 2304, and 2205 bars, the magnetic response is fair; however, for the EnduraMet 32, 304, and 316LN bars, the magnetic response is minimal. The values shown also demonstrate that this device cannot be used to differentiate between bars with the same phase(s) (e.g., two different compositions that are both austenitic). Furthermore, the device does not provide the actual chemical composition; hence, other techniques must be used if this is needed. The device does, however, provide an inexpensive and quick method for roughly sorting austenitic, ferritic, or duplex stainless steels.

X-Ray Fluorescence Test

A more accurate method for sorting CRR when compared to the magnetic sorting method is XRF. For this test, a portable XRF unit was used to evaluate several reinforcing steel bars for chemical composition. It is important to note that this device is unable to detect lighter elements, such as carbon, but can detect key heavier elements, such as chromium (Cr), nickel (Ni), molybdenum (Mo), and zinc (Zn). Figure 9 shows a bar being evaluated with the results being displayed in real time on the screen.

After the XRF device was warmed up and calibrated, which required less than 10 min, several types of candidate CRR bars were tested. The results are provided in Table 5. Alloy identification was performed within seconds; however, longer analysis times (usually less than

(a) (b)

Figure 9. Portable XRF device (a) assessing composition of bar and (b) displaying real-time results on attached screen.

Table 5. Results of XRF Analysis on Different Types of Corrosion-Resistant Reinforcing Bars

Rebar Grade	Co	Mo	Nb	Cu	Ni	Fe	Mn	Cr	Zn	Other
EnduraMet 32		0.152	0.006	0.113	0.768	69.49	12.06	17.13		V 0.111
Carbon with Zn Layer										
Outside	0.257			0.123		16.06	0.111		83.17	Zr 0.01
Inside (end shot)		0.025				98.8	0.535	0.063	0.063	
SS 316		2.24	0.033	0.397	10.31	66.61	1.6	18.35	0.029	V 0.122
SS 2304		0.254	0.017	0.221	4.24	71.25	1.52	22.09	0.057	V 0.132 Ti 0.091
SS 2205		2.56	0.016	0.238	4.57	68.54	1.88	21.78	0.03	V 0.138
SS 2101		0.179		0.317	1.05	71.22	4.94	21.89	0.027	V 0.154
Duracorr (ID as HW6015)		0.271		0.143	0.362	87.15	1.26	10.57	0.018	V 0.036
Carbon Steel		0.023		0.581	0.155	98.35	0.626	0.079		
Zbar										
Outside	0.457		0.016	0.078		12.79	0.096		71.82	Ti 14.1
Inside (end shot)		0.024		0.362		98.69	0.561	0.098		
ECR	1.02	0.045	0.008	0.893		91.49	0.476	1.94		Ti 3.98
Stainless Steel Clad Bar (NX)										
Outside (ID as SS 316)		2.04	0.01	0.323	10.01	68.65	1.38	16.9		V 0.12
Inside (end shot)		0.065		0.135	0.346	97.31	1.12	0.85		

1 min) can provide greater accuracy and are useful if the obvious identification of a single alloy is not occurring at shorter analysis times. This is significant because a reinforced concrete bridge deck requires many bars, and sometimes these bars arrive in smaller groups during different stages of construction. Moreover, if different types of bars are used to construct different parts of the bridge, the device can be used to analyze both types of bars. Even coated bars with an underlying layer of zinc, such as Zbar, can be evaluated. With the Zbar, the XRF device detected the presence of Zn through the epoxy coating, although the device will not be able to correctly analyze the composition of the steel core when analyzing zinc-coated or stainless steel clad bars. This is evident in Table 5 when the chemical composition for the outside shot, determined perpendicular to the rolling direction (as shown in Figure 9), and the inside shot, determined on the exposed cut end of the bar, are compared.

A second feature this device offers is the ability to store the data electronically and then transfer them as needed. The data shown in Table 5 were collected at the VDOT Materials Division facility in Sandston, Virginia, and then emailed for this report to VCTIR in Charlottesville, Virginia. This demonstrates the ability to share test results via email.

Finally, this device provides not only a list of the percentage of elements detected but also the alloy type. Excluding the Zn-coated steels in Table 5, only the Duracorr bar was incorrectly identified as HW6015, which would have a much higher Ni content than would Duracorr. However, this response from the XRF device would be an indication that the Duracorr composition is not stored in the alloy library; if the data for Duracorr are stored in the XRF device, the device should be able to identify this bar.

Hardness Test

The Rockwell hardness test is generally a quick test. One use is to approximate the tensile strength of non-austenitic steel prior to the use of the uniaxial tensile test. When used in this capacity, there will be reasonable agreement between hardness and tensile strength values for steels such as Duracorr and MMFX 2 but not for austenitic stainless steels (i.e., EnduraMet 32, Type 304 or Type 316). In Figure 10, measured values for Duracorr and MMFX 2 show good agreement with the values listed in ASTM A370 (ASTM 2008a).

The ability to correlate hardness and tensile strength is important because it provides a means of estimating the tensile strength of a bar prior to testing. This becomes even more important when consideration is given to the fact that the current uniaxial test equipment in the VDOT Materials Division Laboratory could become damaged if a test bar unexpectedly failed in tension with the extensometer attached. Since the new types of CRR do not exhibit a yield point, the extensometer must remain attached to the test bar to determine accurately the yield strength following the 0.2% offset method. Unfortunately, bars such as Duracorr and MMFX 2 exhibit higher strengths with relatively short elongations, which can result in an energetic failure, release of the bars from the wedge grips, and damage to the extensometer. However, performing a Rockwell hardness test on these or similar types of bars prior to performing a uniaxial test would provide an estimate of the tensile strength of the test bar. This value can then be used as a guide for when to remove the extensometer.

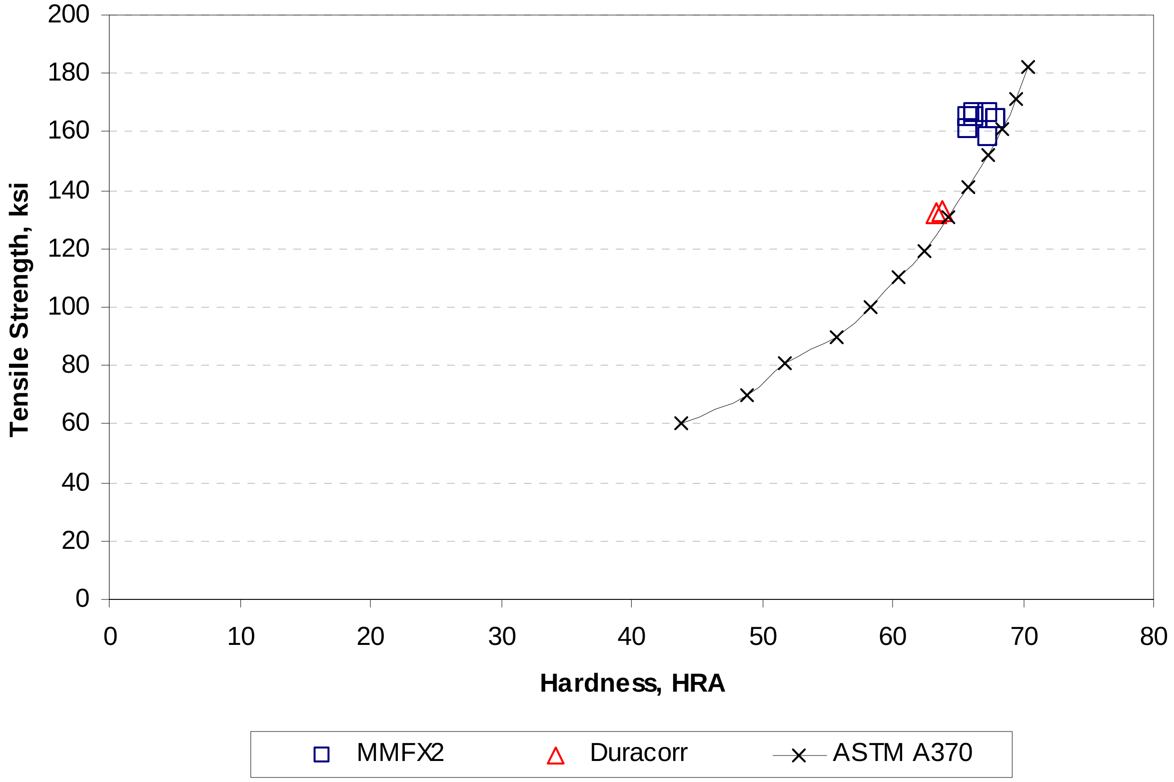


Figure 10. Comparison of Rockwell hardness values for two higher strength steels as a predictor of tensile strength (comparison data points from ASTM A370). HRA = Rockwell hardness "A" scale.

Uniaxial Tensile Test

The uniaxial tensile test is vital as the result of using different types of alloys is different steels with different stress-strain behaviors. The test results shown in Figure 11 clearly demonstrate how alloying for corrosion resistance also changes stress-strain behavior; yield strength values are provided in Table 6. Steel yield stress varied widely between bar types, with the lowest being for the No. 6 ASTM A615 Grade 60 bars (68.5 ksi) and the highest for the No. 4 MMFX bars (129.8 ksi). The only steel with a definitive yield plateau was the ASTM A615 steel; the stainless steels and MMFX 2 exhibited a gradually yielding stress-strain response. Although the elastic modulus for the stainless steels was not explicitly measured in this study, the NX and 316LN elastic moduli (i.e., slope of the linear elastic portion of the stress-strain curve) were lower than for the other steels. The MMFX 2 also exhibited the highest tensile strength of the bars tested (the Duracorr bar was not included in this group of test bars). The improved yield stress and ductility, especially that of the stainless steels, may have broader structural performance benefits beyond corrosion resistance as discussed in Sarver (2010).

During this study, uniaxial testing was also performed on different test machines at different facilities. This revealed the shortcomings of some of the test machines. When the higher strength bars, MMFX 2 and Duracorr, were tested on one test machine that uses a contact style extensometer, knowing when to remove the extensometer was a challenge. When the

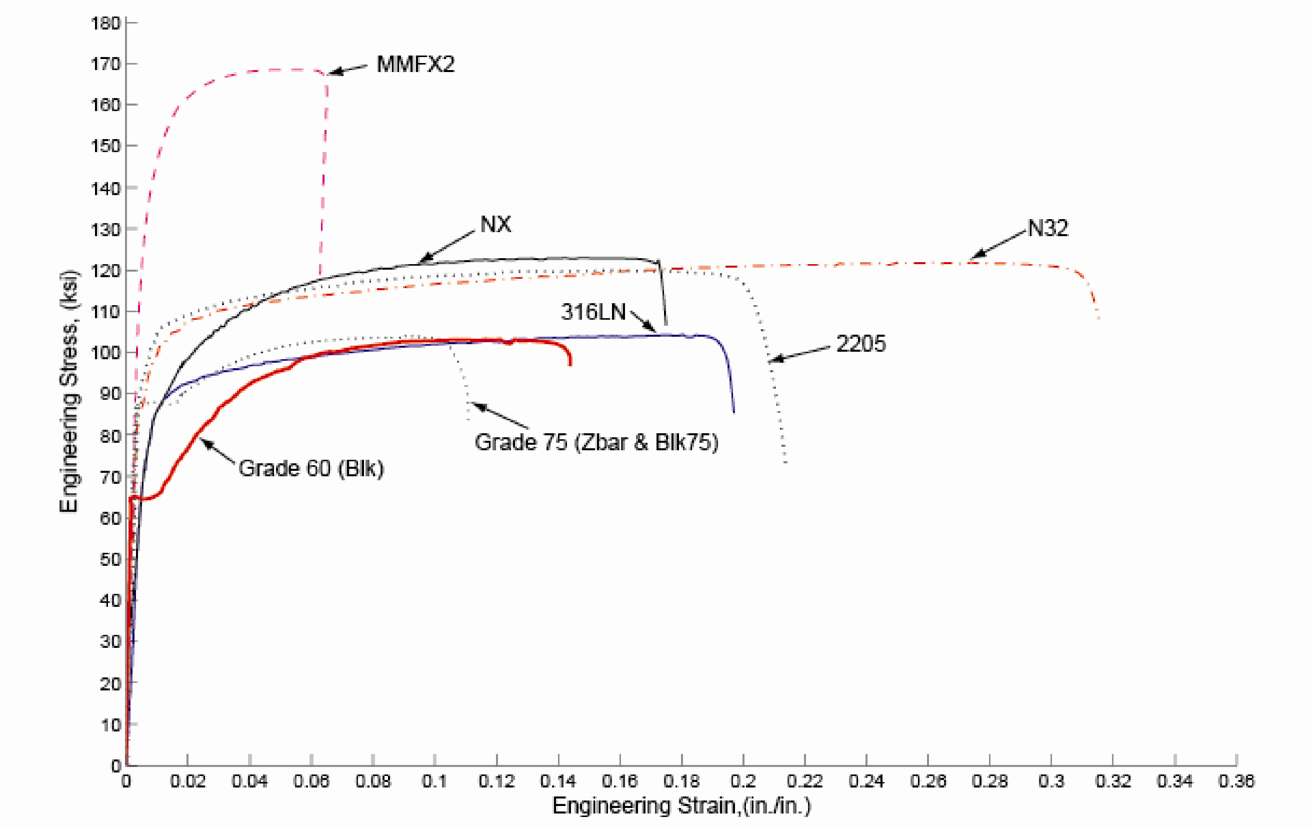


Figure 11. Comparison of uniaxial tensile test results for different types of CRR.

Table 6. Average Yield Strength Values for Selected Bars

Type	Bar Size	No. of Samples	Yield Strength (F_y), ksi
ASTM A615 Grade 60	No. 4	4	68.5
	No. 6	4	65.5
ASTM A615 Grade 75	No. 4	4	88.0
	No. 6	4	78.6
EnduraMet 32	No. 4	4	86.1
	No. 5	4	83.3
MMFX 2	No. 4	4	129.8
	No. 6	4	127.0
SS 2205	No. 5	4	85.2
	No. 6	4	82.2
SS 316LN	No. 4	4	78.5
	No. 5	4	74.8
SS Clad (NX)	No. 5	4	73.5
	No. 6	4	68.9
Zbar	No. 4	4	90.0
	No. 6	4	76.9

SS = stainless steel.

extensometer was removed too soon, the yield strength, which is an essential measurement, was not able to be determined. However, if it was left in place too long, a relatively energetic failure would occur that would necessitate recalibration and even repair of the extensometer if it was damaged. It was clear from the work that a non-contact extensometer would rectify this issue. Further, the cost of a non-contact extensometer, which is usually higher, would be recovered by the elimination of frequent repair and recalibration costs.

The elongation upon fracture can also be measured following a uniaxial tensile test. As shown in Table 7, the values varied greatly for the different CRR alloys tested, with EnduraMet 32 exhibiting the greatest elongation and MMFX 2 the smallest. It was also interesting to observe during testing that the EnduraMet 32 elongated over the entire distance between the grips in a relatively even manner, which can be seen in Figure 12.

Similar to the other steel properties, percent reduction in cross-section upon fracture greatly varies for the different CRR alloys tested, as shown in Table 8. It was interesting to notice how the order of the bars in Table 8 was different from the order given in Table 7. It was also interesting that the black steel showed the smallest change and the Duracorr the largest, as is shown in Figure 13. Figure 13 also shows how the NX bar's steel core debonded from the stainless steel clad layer during deformation, which was also observed to occur during bending.

Table 7. Percent Elongation Values for Different Types of Reinforcement

Bar	MMFX 2	Duracorr	Black Steel	NX	2304	2205	EnduraMet 32
Elongation (%)	8	10	12	19	20	28	39

Table 8. Reduction in Cross -sectional Areas for Different Types of Reinforcement

Bar Type	Black Steel	NX	EnduraMet 32	MMFX 2	316LN	Duracorr
Reduction in Cross-sectional Area (%)	7.5	21.5	35.8	38.5	48.5	52.6

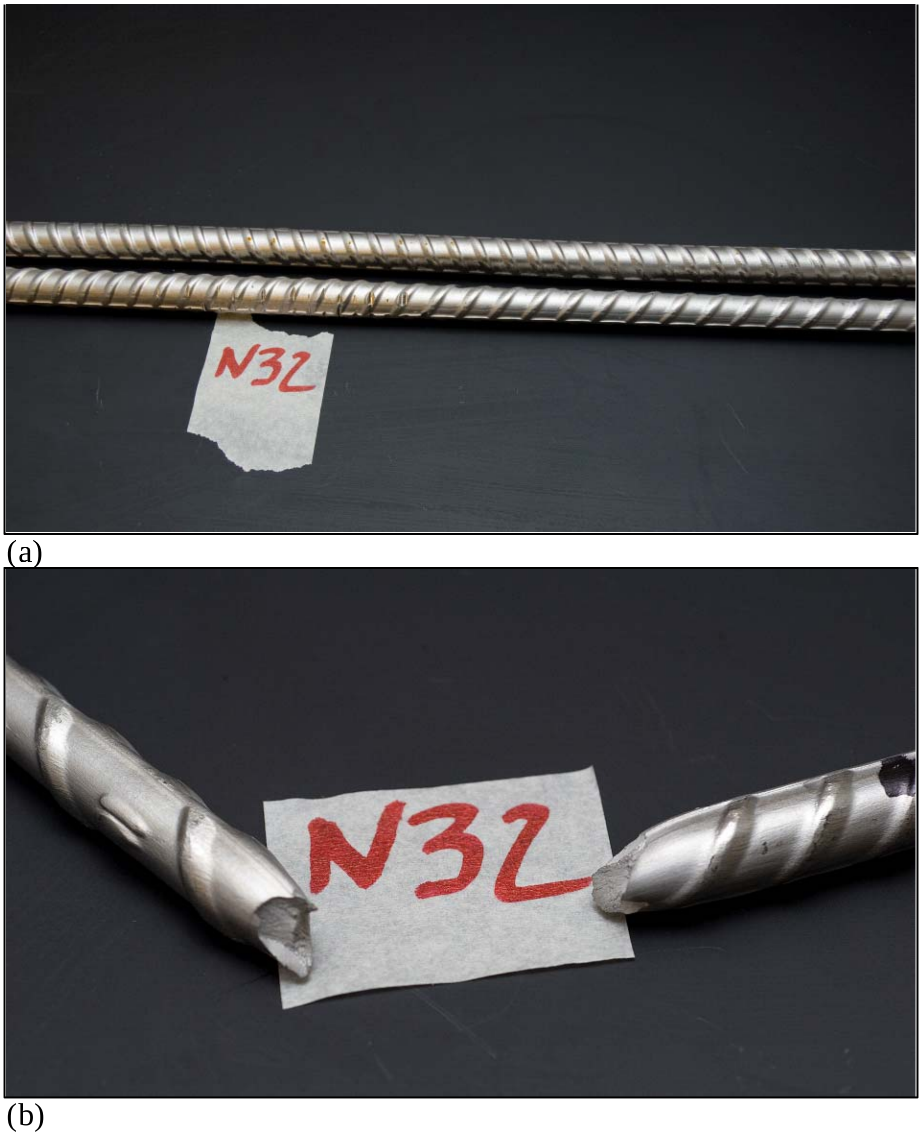
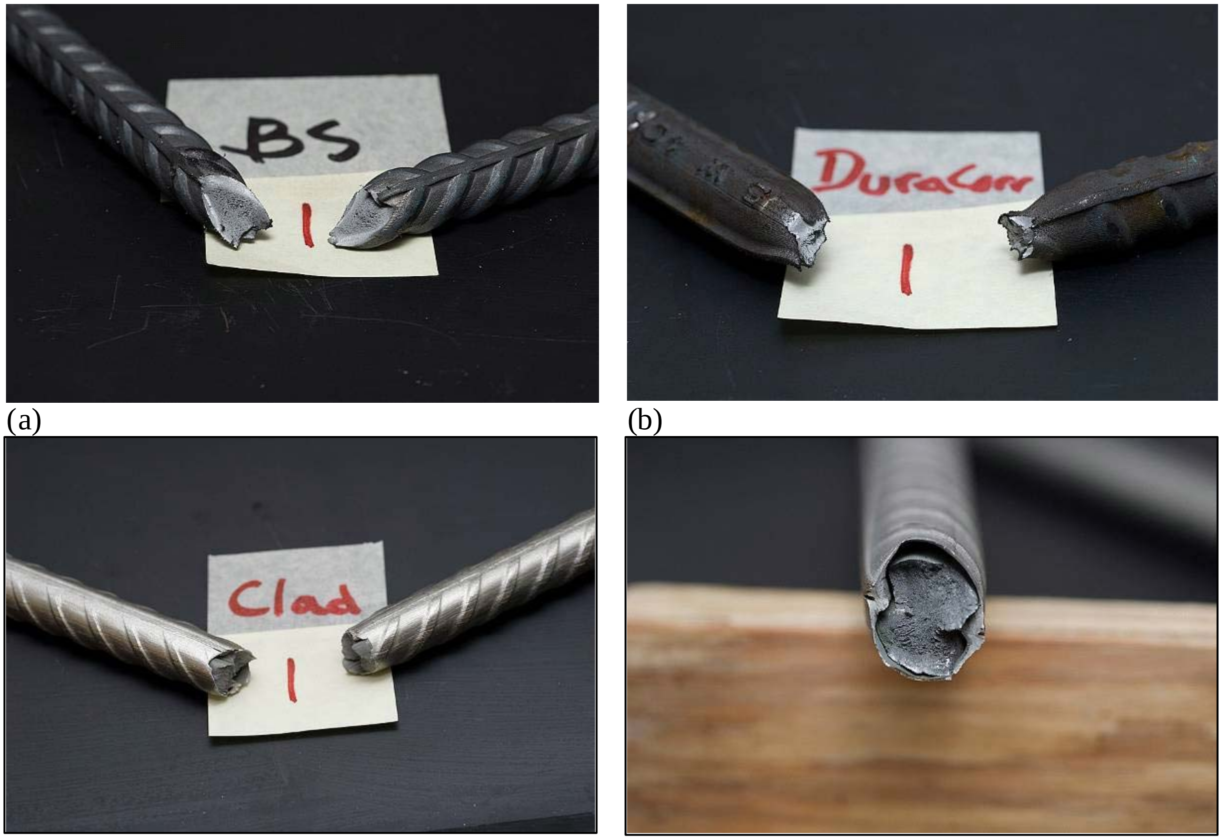


Figure 12. High elongation exhibited by EnduraMet 32. (a) Comparison of untested and tested bar showing stretched rib pattern, and (b) fairly even necking at fracture area.

As-Received Bar Finish

Bar Finish

Corrosion was present on the surface of the lower cost CRR bars; examples are shown in Figure 14. The MMFX 2, Duracorr, and NX bars exhibited corrosion along the bar surface. According to ASTM A1035 (ASTM 2009c) and AASHTO MP13 (AASHTO 2004), corrosion on the surface of CRR is acceptable; therefore, corrosion testing should include bars in a similar condition. A pinhole in the Zbar epoxy coating, shown in Figure 15, was also discovered. It is important to record these features since each could potentially reduce the corrosion resistance of the bar and reduce the life of the structure.



(a) (b) (c) (d)

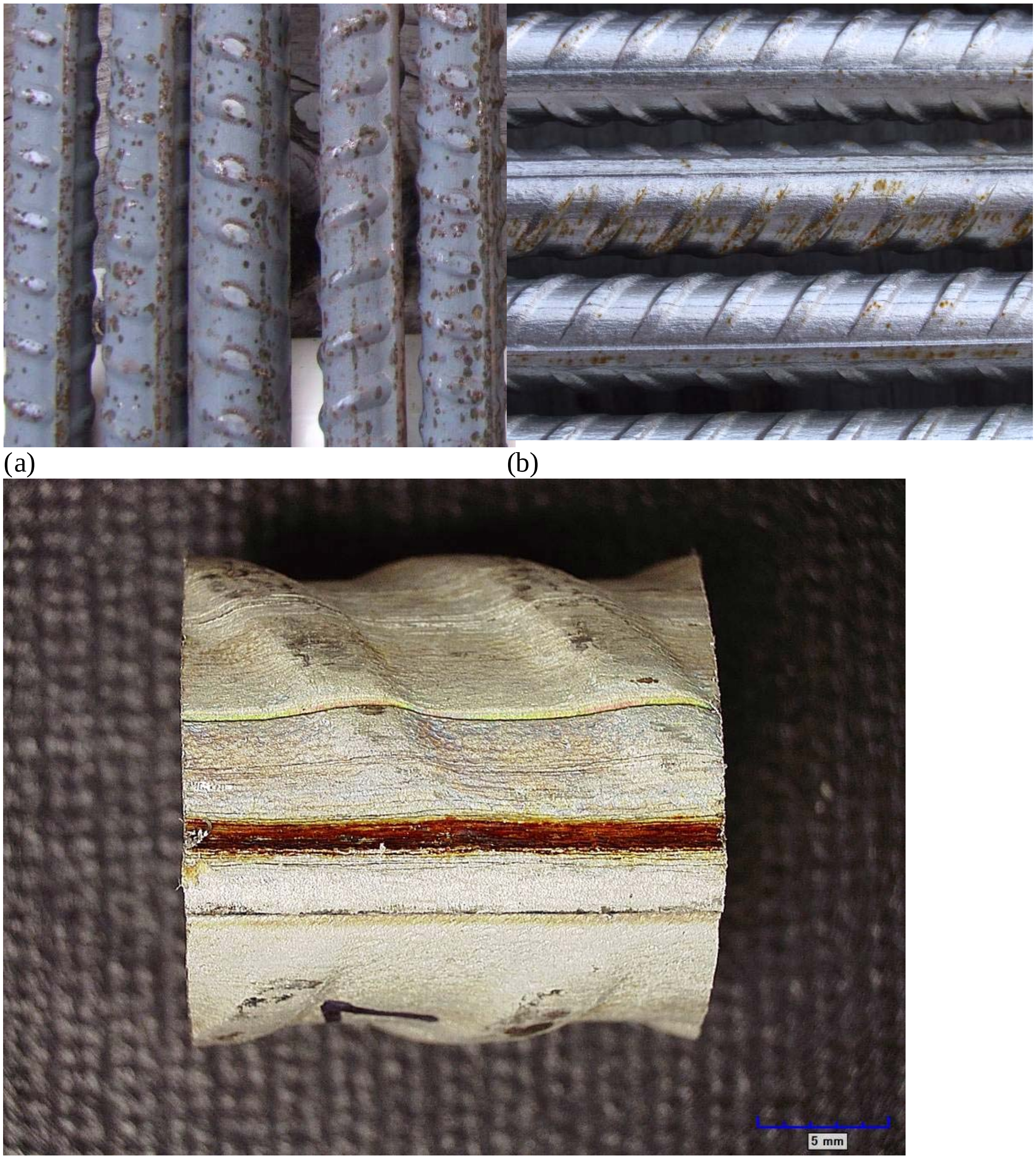
Figure 13. Evaluation of reduction in cross-sectional area with (a) black steel bar exhibiting little change in cross-sectional area, and (b) Duracorr showing high degree of necking; (c and d) stainless steel clad responded differently than other test bars, with carbon steel core debonding from stainless steel cladding.

Corrosion was not observed on the 2304 bars, but these bars were slightly bent, which is shown in Figure 16. This was most likely due to difficulties in straightening the bars. Although the curvature was small with these 3-foot samples, this curvature could become an issue with longer bar lengths and cause problems for workers laying out and tying the deck steel.

Some of the bars can also be sensitive to elevated heat cycles. It is important to evaluate the bar visually for discoloration. This is most easily seen with the stainless steel bars; some examples are shown in Figure 17. This will most likely occur because of exposure to an improper heat cycle during production or an intense heat source, such as a cutting torch.

Mill Identification Markings

Mill markings were legible for most of the bars, but the NX bars markings were faint, as shown in Figure 18. Although the MMFX 2 and Duracorr steel appeared similar based on visual inspection, the markings were different, so distinguishing between the two types of steel is possible. However, as may be seen, the mill identification markings cannot be relied upon for determining the type of steel. As shown in Figure 19, the mill identification markings are identical even though the bars are different types of stainless steel: EnduraMet 32 is an austenitic



(a) (b)

(c)

Figure 14. Appearance of surface rust on (a) Duracorr and (b and c) stainless steel clad bars.

stainless steel, and 2205 is a duplex stainless steel. It is important to recognize that bar markings indicate the bar producer and not the alloy type, and in this case, when a producer handles more than one type of stainless, the markings will be identical for all stainless bars produced. Fortunately, the magnetic and XRF methods discussed previously can be used to distinguish between these different bar types, but care is required.

Figure 15. Pinhole in Zbar coating.

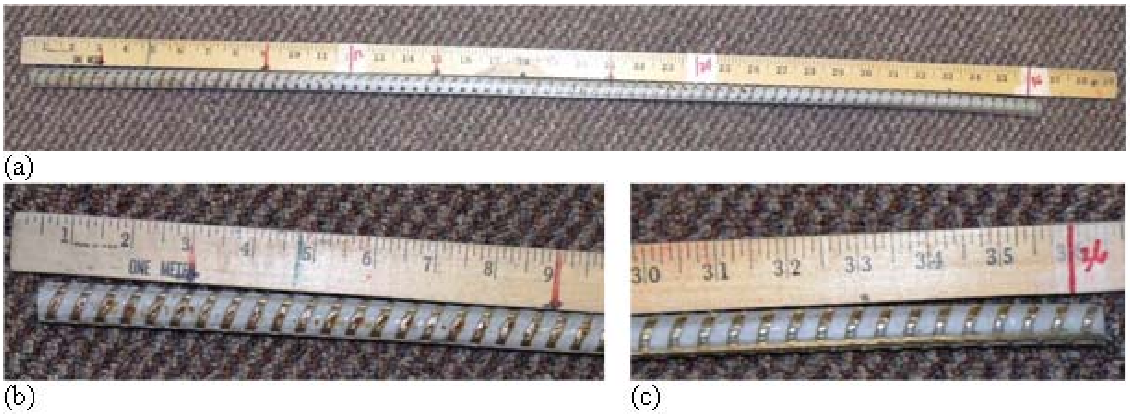


Figure 16. Slightly bent stainless steel bars: (a) overall view of bar showing middle in contact with bar with (b) left end and (c) right end deviating from ruler because of bar being slightly curved.

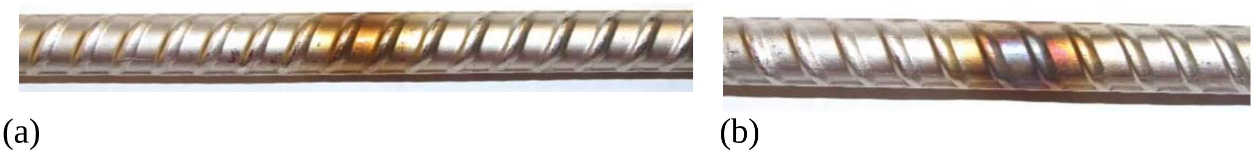


Figure 17. Area exposed to elevated heating showing (a) yellow tint and (b) deeper blue-orange tint.


(a)
(b)
(c)

Figure 18. Mill identification marks on (a) stainless steel clad, (b) MMFX 2, and (c) Duracorr bars.

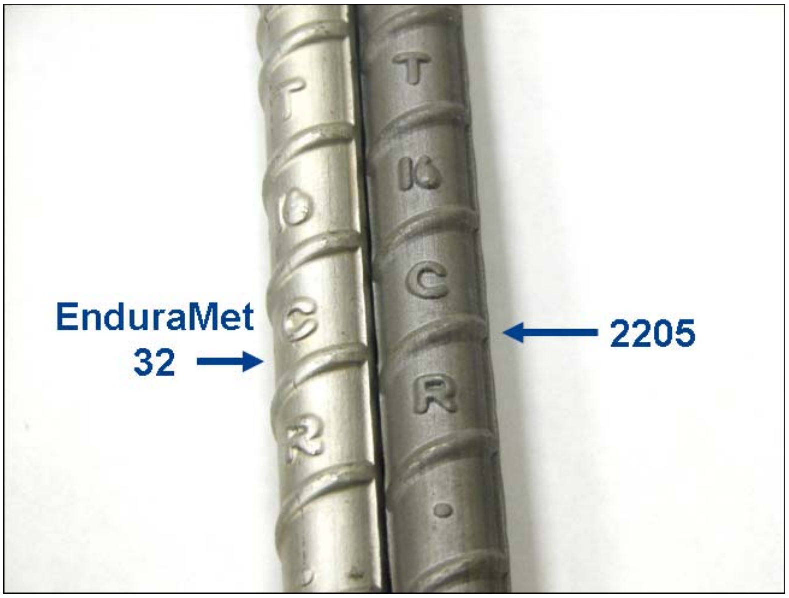


Figure 19. Same mill marking on different types of stainless steel bars.

Reinforcement Rib

The mean and coefficient of variation (COV) of the measured bar diameter, calculated cross-sectional area, and measured relative rib area (R_r) are provided in Table 9, where *n* is the number of bars in a statistical grouping. Relative rib area was highly variable among bar types, with the lowest being for the No. 5 NX with an average $R_r = 0.056$. It is hypothesized for the NX bars that the 316L cladding is not rolled as aggressively to minimize excessive thinning of or damage to the cladding during the manufacturing process, reducing the relative rib area. The Zbar relative rib area was the highest (average $R_r = 0.119$) to compensate for the expected lower bond strength between concrete and epoxy-coated steel. The high variability of relative rib area within a group, for example, the No. 4 Zbar with a COV of 0.24, is attributed to inconsistencies in the deformed bar patterns and the inherent difficulty in accurately measuring rib spacing and rib height. Full details on relative rib area measurements are provided in Sarver (2010).

Table 9. Average Bar Measurements and Relative Rib Area

Bar Type	Bar Size	No. of Samples	Diameter		Area		R_r	
			Mean, in	COV	Mean, in^2	COV	Mean	COV
ASTM A615 Grade 60	No. 4	4	0.469	0.00	0.173	0.01	0.079	0.02
	No. 6	4	0.703	0.00	0.388	0.00	0.097	0.03
ASTM A615 Grade 75	No. 4	4	0.463	0.01	0.168	0.02	0.094	0.04
	No. 6	4	0.685	0.00	0.369	0.01	0.131	0.13
EnduraMet 32	No. 4	4	0.472	0.01	0.175	0.03	0.093	0.07
	No. 5	4	0.592	0.01	0.275	0.01	0.060	0.24
MMFX 2	No. 4	4	0.469	0.02	0.173	0.03	0.083	0.18
	No. 6	4	0.710	0.00	0.395	0.01	0.108	0.13
SS 2205	No. 5	4	0.590	0.01	0.273	0.02	0.090	0.03
	No. 6	4	0.695	0.01	0.380	0.01	0.081	0.06
SS 316LN	No. 4	4	0.475	0.01	0.177	0.03	0.076	0.04
	No. 5	4	0.591	0.00	0.274	0.01	0.089	0.08
SS Clad (NX)	No. 5	4	0.654	0.01	0.335	0.03	0.056	0.10
	No. 6	4	0.763	0.01	0.458	0.01	0.063	0.09
Zbar	No. 4	4	0.470	0.00	0.173	0.01	0.110	0.24
	No. 6	4	0.714	0.00	0.400	0.01	0.119	0.08

R_r = Relative rib area, COV = coefficient of variation; SS = stainless steel.

Characterization of Steel Embedded in Concrete

Concrete/Steel Bond Strength Testing

It is clear from the thesis work by Johnson (2010) that relative rib area is the most important parameter affecting the bond strength between reinforcing steel and concrete. The dominant parameter for bond strength is the relative rebar rib area, not steel material properties or chemical composition, which is discussed in detail by Johnson (2010).

Johnson (2010) performed beam end and direct pullout tests to determine an acceptable methodology for evaluating the concrete/steel bond strength. A beam end test performed in accordance with ASTM A944-05 (ASTM 2005a) simulates the reinforcing steel bond stress state in a flexural member, e.g., a bridge deck or girder, whereas the direct pullout test does not. However, a special frame is required to provide a vertical reaction representing the tension-compression force couple in a beam and lateral reactions simulating the equilibrating shear forces in a beam.

Although the primary focus of this portion of the study was to explore the load-slip behavior between CRR bar types, the testing results made it clear that relative rib area is the most influential parameter affecting load-slip response. The link between relative rib area and bond strength is most evident with the NX bars, which had relative rib areas roughly 50% lower than that of the other bar types considered and, as a result, exhibited a “soft” load-slip response with pullout failures dominating over yielding or splitting failures as the amount of tensile force developed was relatively small. These results emphasize the importance of enforcing minimum relative rib area requirements.

Another important observation was that stainless steel had on average lower bond stiffness than ASTM A615 steel when bars with similar relative rib areas were compared. The leading hypothesis supporting this trend is that the naturally occurring self-passivating layer of chromium oxide (McGurn 1988) inhibits the mechanical bond between the steel and concrete. More research is needed to understand this phenomenon completely, as a reduction in mechanical bond can place the strain compatibility assumption used in design in jeopardy, which leads to reduced structural performance and less durability in service.

The load-slip response clearly demonstrates that the Zbar epoxy coating reduces the chemical adhesion between concrete and the reinforcing steel; however, the presence of epoxy does not influence the mechanical bond stiffness and bond strength when ASTM A615 bars with similar relative rib areas are compared. These results are consistent with previous research (Darwin 2006) and highlight the fact that ECR could still be a viable reinforcement option in bridge decks if the corrosion issues currently plaguing epoxy coatings could be mitigated.

The direct pullout test is an alternative to the beam end test. The stress state in the specimen is not consistent with flexure; however, bond-slip comparisons can still be made. This test does not require a special testing frame, only a center hole jack set against the concrete to pull the reinforcing steel. Splitting failures are common for larger bar diameters, which can make bond-slip comparisons between bars difficult if one fails in pullout and one fails in splitting. This is a disadvantage of the beam end test. In addition, splitting failures can be avoided in a direct pullout test because the bar can be located in the center of the specimen, which reduces the tensile stresses in the concrete. It is also important to note that short-bonded rebar length is essential for pullout / beam end tests to avoid yielding.

During this work, it was clear that minimum requirements for relative rib area should be clearly defined by VDOT and enforced with periodic measurements in the field. In addition, the testing guidelines described herein were developed to ensure that the assumption of strain compatibility, which forms the basis of reinforced concrete structural design, is achieved in practice. A direct pullout test is employed that can provide mechanical bond stiffness and peak bond strength without the complicated testing frame required for beam end tests and with a low probability of a concrete splitting failure. The direct pullout test does not simulate the internal stress distribution and flow of forces in a beam the same way a beam end test does; however, for relative comparisons of bond strength with consistent failure modes and simple equipment requirements, the direct pullout test is a rational compromise.

Corrosion Resistance Testing

Corrosion resistance testing was initiated using the tombstone test specimens, which tests bars embedded in concrete. Recently, 4 test specimens of the 60 total specimen population gave indications of corrosion initiation. Work has begun to autopsy those specimens, measure chloride concentration, and measure pH. The results will be reported in a subsequent study after a sufficient number of specimens have initiated corrosion.

CONCLUSIONS

- *Visual assessment cannot be relied on to determine bar type.*
- *Steel fabricator markings cannot be relied on to identify the type of steel.*
- *The purchase of new analytical equipment and the upgrading of currently owned equipment are necessary to ensure CRR is appropriately characterized in the laboratory and field.*
- *Magnetic sorting provides a quick and easy method for differentiating between magnetic and nonmagnetic alloys.*
- *XRF provides a practical method for positively identifying bars.*
- *Relative rib area needs to be monitored as it varies from producer to producer.*
- *Uniaxial tensile tests provide the stress-strain behavior and elongation and reduction in cross-section upon fracture and can vary significantly for different CRR alloys.*
- *Corrosion and mechanical testing of CRR is necessary to identify the most cost-effective bars with acceptable properties.*
- *Quality control measures need to be established to ensure VDOT receives the corrosion protection it needs.*

RECOMMENDATIONS

1. *VDOT's Materials Division should implement the set of test methods provided in the appendices of this report as Virginia Test Methods for their acceptance criteria of CRR.* The proposed tests should not be considered replacements for the tests in ASTM A1035 (ASTM 2009c), ASTM A955 (ASTM 2010b), and AASHTO designation MP 13-04 (AASHTO 2004) but should instead augment those requirements in the appropriate specification unless there is a conflict between the standard and the proposed test. If there is a conflict, the proposed test provided in this report should supersede the test in the standard.

2. *To simplify the implementation of CRR in Virginia and elsewhere, VDOT's Materials Division should work with AASHTO to develop a single specification for the testing and acceptance of CRR.*

3. *VDOT' Materials Division should investigate retrofitting the uniaxial tensile test equipment with a non-contact extensometer to guarantee stress vs. strain measurements of CRR can be made and ensure the yield strength is determined.*

BENEFITS AND IMPLEMENTATION PROSPECTS

The test methods/procedures developed in this study provide guidance on how to determine if the correct CRR steel has been received on the jobsite. Uncertainty at the jobsite because of the deck reinforcement can delay placement of the deck steel and subsequent construction of the deck. These delays can result in additional cost to the contractor and VDOT. The study results also provide guidance on which bar features must be monitored to ensure each bar is of acceptable quality. If some of the bar features discussed in the report were to be compromised, the service life of the deck could be diminished and costly repairs required. The report also provides a test method for approving new CRR bars to promote competition between CRR bars. To ensure ease of implementation, test methods have been compiled in the appendices in a manner that enables each appendix to be converted into a Virginia Test Method. Finally, the set of methods provided in the appendices provides VDOT's Materials Division with a set of test procedures that can be used to ensure that there are no losses in productivity during construction and that associated testing costs are minimized.

ACKNOWLEDGMENTS

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REFERENCES

American Association of State Highway and Transportation Officials. AASHTO MP 13M/MP 13-04: Standard Specification for Stainless Clad Deformed and Plain Round Steel Bars for Concrete Reinforcement. In *AASHTO Provisional Standards*, Washington, DC, 2004.

ArcelorMittal USA. Plate Duracorr: Life-Cycle Cost-Effective 12% Chromium Stainless Steel. http://www.arcelormittal.com/plateinformation/documents/en/Inlandflats/ProductBrochure/ARCELORMITTAL%20DURACORR.pdf. Accessed March 17, 2011.

ASTM International. ASTM A615-03: Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2003.

ASTM International. ASTM A1035: Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2004.

ASTM International. ASTM A944: Standard Test Method for Comparing Bond Strength of Steel Reinforcing Bars to Concrete Using Beam-End Specimens. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2005a.

ASTM International. ASTM A955-05: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2005b.

ASTM International. ASTM A276-06: Standard Specification for Stainless Steel Bars and Shapes. In *Annual Book of ASTM Standards*, Vol. 01.03. West Conshohocken, PA, 2006a.

ASTM International. ASTM A800-01: Standard Practice for Steel Casting, Austenitic Alloy, Estimating Ferrite Content Thereof. In *Annual Book of ASTM Standards*, Vol. 01.02. West Conshohocken, PA, 2006b.

ASTM International. ASTM A955-06a: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2006c.

ASTM International. ASTM A775-07b: Specification for Epoxy-Coated Steel Reinforcing Bars. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2007a.

ASTM International. ASTM A1035: Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2007b.

ASTM International. ASTM A370-08a: Standard Test Methods and Definitions for Mechanical Testing of Steel Products. In *Annual Book of ASTM Standards*, Vol. 01.01. West Conshohocken, PA, 2008a.

ASTM International. ASTM E8-08: Standard Test Methods for Tension Testing of Metallic Materials. In *Annual Book of ASTM Standards*, Vol. 03.01. West Conshohocken, PA, 2008b.

ASTM International. ASTM E18-08a: Standard Test Methods for Rockwell Hardness of Metallic Materials. In *Annual Book of ASTM Standards*, Vol. 03.01. West Conshohocken, PA, 2008c.

ASTM International. ASTM A799-04 Standard Practice for Steel Castings, Stainless, Instrument Calibration, for Estimating Ferrite Content. In *Annual Book of ASTM Standards*, Vol. 01.02. West Conshohocken, PA, 2009a.

ASTM International. ASTM A955-09b: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2009b.

ASTM International. ASTM A1035: Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2009c.

ASTM International. ASTM A955-10: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2010a.

ASTM International. ASTM A955-10a: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2010b.

ASTM International. ASTM A484-11: Standard Specification for General Requirements for Stainless Steel Bars, Billets, and Forgings. In *Annual Book of ASTM Standards*, Vol. 01.03. West Conshohocken, PA, 2011.

Darwin, D. *Evaluation of Bond Strength of ZBAR Multiple Coated Steel Reinforcing Bars.* University of Kansas Center for Research, Inc., Lawrence, 2006.

Johnson, J. *Bond Strength of Corrosion Resistant Steel Reinforcement in Concrete*. CE/VPI-ST-10/06. Virginia Tech, Blacksburg, 2010.

Koch, G.H., Brongers, M.P.H., Thompson, N.G., Virmani, Y.P., and Payer, J.H. *Corrosion Cost and Preventative Strategies in the United States.* FHWA-RD-01-156. Federal Highway Administration, McLean, VA, 2002.

McGurn, J.F. *Stainless Steel Reinforcing Bars in Concrete*. Nickel Development Institute, Toronto, Ontario, Canada, 1988.

Presuel-Moreno, F., Scully, J.R., and Sharp. S.R. *Identification of Commercially Available Alloys for Corrosion-Resistant Metallic Reinforcement and Test Methods for Evaluating Corrosion-Resistant Reinforcement.* FHWA/VTRC 08-R21. Virginia Transportation Research Council, Charlottesville, 2008.

Sarver, B. *Mechanical and Geometric Properties of Corrosion Resistant Reinforcing Steel in Concrete*. CE/VPI-ST-10/07. Virginia Tech, Blacksburg, 2010.

Scully, J.R., and Hurley, M.F. *Investigation of the Corrosion Propagation Characteristics of New Metallic Reinforcing Bars*. VTRC 07-CR9. Virginia Transportation Research Council, Charlottesville, 2007.

Thermo Fisher Scientific. *Nitro Data Transfer Software XL3T\PManuals.* Version 6.5.5 Billerika, MA, 2004

Virginia Department of Transportation, Structure and Bridge Divison. *Corrosion Resistant Reinforcing Steels.* IIM-S&B-81.4. http://www.virginiadot.org/business/bridge-ii-memoranda-index.asp. Accessed March 25, 2010.

Weyers,R.E., Sprinkel, M.M., and Brown, M.C. *Summary Report on the Performance of Epoxy-Coated Reinforcing Steel in Virginia.* FHWA/VTRC 06-R29. Virginia Transportation Research Council, Charlottesville, 2006.

APPENDIX A: MAGNETIC SORTING TEST

1. Scope
    1.1. This method covers the procedures to be used in determining and establishing the magnetic response of the candidate reinforcement by comparing the response of known and CRR candidate samples.

2. Reference Documents
    2.1. ASTM International. ASTM A800-01: Standard Practice for Steel Casting, Austenitic Alloy, Estimating Ferrite Content Thereof. In *Annual Book of ASTM Standards*, Vol. 01.02. West Conshohocken, PA, 2006.
    2.2. ASTM International. ASTM A799-04: Standard Practice for Steel Castings, Stainless, Instrument Calibration, for Estimating Ferrite Content. In *Annual Book of ASTM Standards*, Vol. 01.02. West Conshohocken, PA, 2009.

3. Test Apparatus
    3.1. For this test, a conventional magnet, an Elcometer, and a James Instruments R-Meter (C-4956) are required. Other ferrite content meters or gages can also be used for this work, such as one that relies on magnetic permeability (e.g., FERITSCOPE®) or a permanent reference magnet (e.g., Severn or Tinsley gage). In addition, more advanced equipment that conforms to the requirements of ASTM A799 and ASTM A800 is acceptable.

4. Test Specimens
    4.1. The test surface should be free of corrosion and debris and reasonably smooth.
    4.2. In addition to the candidate bars, standard test samples will include 316LN, 2205, and MMFX 2 No. 5 steel bars.

5. Procedure
    5.1. Although ASTM A800 was developed to estimate the ferrite content of steel castings, this standard can be used for reference purposes. However, it is important to recognize that some deviation from this standard will be required since rebar is a rolled product and the diameter of the material can be relatively small. During the test, a conventional magnet, Elcometer, and R-Meter are used to compare the magnetic response of the CRR candidate samples against some known standards.
        5.1.1. Conventional magnet
            5.1.1.1. The conventional magnet will be used to compare qualitatively the force required to pull the magnet off a CRR candidate sample vs. three known samples. Place the magnet on each of the known samples and then remove the magnet. The force required to remove the magnet should be as follows:

                316LN Stainless steel = None
                2205 = Medium
                MMFX 2 = Strong.

                Place the magnet on the CRR candidate sample and determine if the force to remove the magnet is none, medium, or strong. Record this value. Repeat this procedure on the remaining CRR candidate bar samples.

5.1.2. Elcometer

5.1.2.1. Calibrate the meter in accordance with the manufacturer’s recommendations. Place the squared end of a standard bar sample in the test jig, which is shown in Figure A1. Measure the pulloff values in accordance with the procedure outlined by the manufacturer. Record the value indicated on the Elcometer gage. Repeat this procedure for the remaining standard and CRR candidate bar samples.

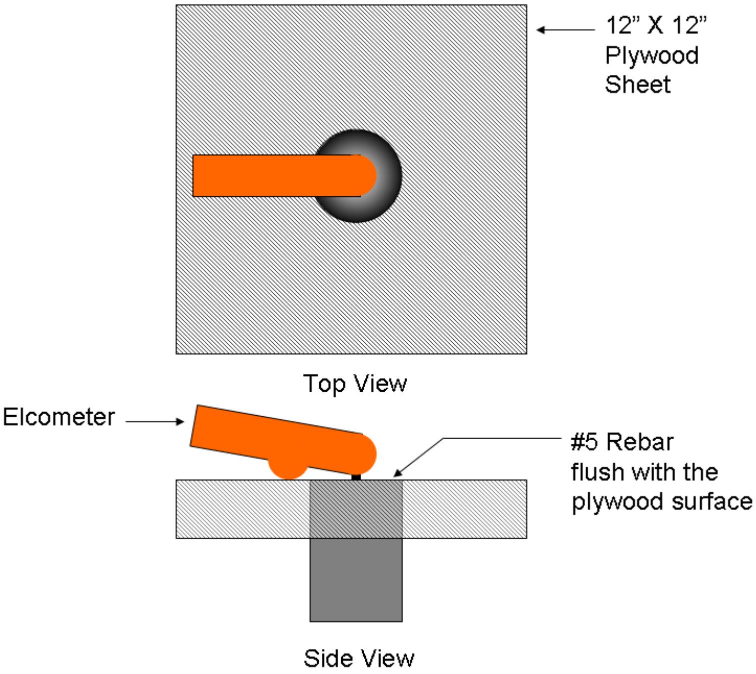

Figure A1. Illustration of magnetic measurement using the Elcometer.

5.1.3. R-Meter

5.1.3.1. Calibrate the meter in accordance with the manufacturer’s recommendations. Place wood spacer blocks adjacent to the rebar and the concrete spacer on top of the standard bars, as shown in Figure A2. Align the measurement head so that it is parallel with the reinforcing bar being evaluated. While monitoring the battery quantity scale, move the measurement head left and right until the maximum value is indicated. Measure and record the values indicated on the battery quantity scale. Repeat this procedure for the remaining standard and CRR candidate bar samples.

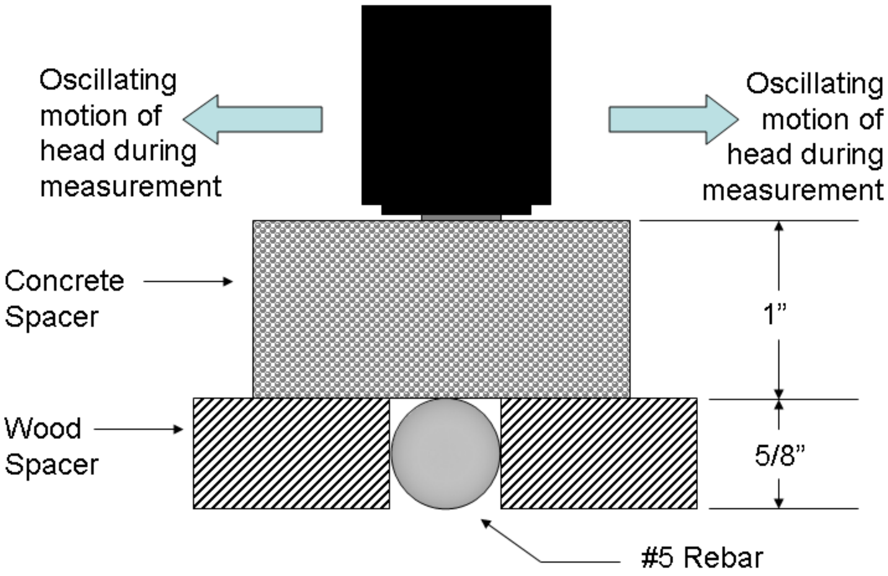

Figure A2. Illustration of magnetic measurement using an R-Meter.

6. Report
   6.1. Conventional magnet
      6.1.1. Comparing the standard and CRR candidate samples, report for each standard and CRR candidate sample the force required to remove the magnet as none, medium, or strong. Results from this test should be recorded on Table M1 in Appendix M.

   6.2. Elcometer
      6.2.1. Comparing the standard and CRR candidate samples, report for each standard and CRR candidate sample the value indicated on the Elcometer gage. Results from this test should be recorded on Table M1 in Appendix M.

   6.3. R-Meter
      6.3.1. Comparing the standard and CRR candidate sample, report for each standard and CRR candidate sample the value indicated on the R-Meter. Results from this test should be recorded on Table M1 in Appendix M.

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APPENDIX B: X-RAY FLUORESCENCE TEST

1. Scope
   1.1. This method covers the procedures to be used in establishing the detectable chemical composition of the candidate reinforcement by using a field ready handheld X-ray fluorescence device.

2. Reference Documents
   2.1. Manufacturer's guidelines.

3. Test Apparatus
   3.1. For this test, a commercially produced field ready handheld X-ray fluorescence device is required. Metal coupons of known composition are also required to ensure proper calibration.

4. Test Specimens
   4.1. The test surface should be free of corrosion and debris and reasonably clean.
   4.2. In addition to the candidate bars, standard test samples will include 316LN, 2205, and MMFX 2 No. 5 steel bars.

5. Procedure
   5.1. The total test time (warm-up + calibration) is less than 10 minutes.
   5.2. The test is performed in accordance with the manufacturer's guidelines.
   5.3. Turn on the x-ray fluorescence analyzer.
   5.4. Allow 5 minutes for the XRF unit to warm up.
   5.5. Perform checks.
      5.5.1. If XRF checks, proceed with analysis.
      5.5.2. If not, calibrate instrument and recheck.
   5.6. Alloy identification should occur within seconds of initiating analysis.
   5.7. Longer analysis time is needed for greater accuracy.

6. Calculations
   6.1. Calculations are not required.

7. Report
   7.1. The XRF instrument will provide alloy type, percent confidence of alloy ID, list of percent elements detected, and confidence limit per element detected. The chemical composition should be checked against the values listed in Table J2 in Appendix J. Verification that this test has been performed should be recorded on Table M1 in Appendix M.

APPENDIX C: HARDNESS TEST

1. Scope
    1.1. This method covers the procedures to be used in determining the hardness of candidate reinforcement bars.

2. Reference Documents
    2.1. ASTM International. ASTM A370-08a: Standard Test Methods and Definitions for Mechanical Testing of Steel Products. In *Annual Book of ASTM Standards*, Vol. 01.01. West Conshohocken, PA, 2008.
    2.2. ASTM International. ASTM E18-08a: Standard Test Methods for Rockwell Hardness of Metallic Materials. In *Annual Book of ASTM Standards*, Vol. 03.01. West Conshohocken, PA, 2008.

3. Test Apparatus
    3.1. The test apparatus shall comply with the requirements of ASTM A370 and ASTM E18.

4. Test Specimens
    4.1. Test specimens shall be No. 4, 5, or 6 bar sizes, approximately 2 inches long.

5. Procedure
    5.1. Hardness testing will be performed in accordance with ASTM A370 and ASTM E18. For this test, hardness testing will follow the Rockwell hardness test method. The test will be performed using the Rockwell C scale, with a 150-kgf load, and diamond penetrator, as discussed in ASTM A370. This test requires very little material for testing and is relatively quick, but it should not be performed on thin layer specimens (see ASTM E18, Annex A5, for thickness guidelines). Further, although portable hardness test equipment is available for field-testing, this document assumes hardness testing will be performed in the laboratory using a stationary Rockwell hardness tester. Measurements will include 10 values gathered from the surface parallel to the rolling direction of the bar and 10 values perpendicular to the rolling direction of the bar.

6. Calculations
    6.1. Calculations will be performed in accordance with ASTM A370 and ASTM E18.

7. Report
        7.1.1. Reporting will be performed in accordance with ASTM A370 and ASTM E18. The mean, median, and standard deviation of each group of hardness values should be recorded along with the approximate tensile strength shown in Table 2 of ASTM A370. Results from this test should be recorded on Table M1 in Appendix M.

APPENDIX D: UNIAXIAL TENSILE TESTING (WITH ELONGATION AND PERCENT REDUCTION IN CROSS-SECTIONAL AREA UPON FRACTURE MEASURED)

1. Scope
    1.1. This method covers the procedures to be used in determining and establishing uniaxial tensile testing response and the elongation and reduction in cross-sectional area upon fracture of the candidate reinforcement.

2. Reference Documents
    2.1. American Association of State Highway and Transportation Officials. AASHTO MP 13M/MP 13-04: Standard Specification for Stainless Clad Deformed and Plain Round Steel Bars for Concrete Reinforcement. In *AASHTO Provisional Standards,* Washington, DC, 2004
    2.2. ASTM International. ASTM A370-08a: Standard Test Methods and Definitions for Mechanical Testing of Steel Products. In *Annual Book of ASTM Standards,* Vol. 01.01. West Conshohocken, PA, 2008.
    2.3. ASTM International. ASTM A615-03: Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards,* Vol. 01.04. West Conshohocken, PA, 2003.
    2.4. ASTM International. ASTM A955-10a: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards,* Vol. 01.04. West Conshohocken, PA, 2010.
    2.5. ASTM International. ASTM A1035: Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards,* Vol. 01.04. West Conshohocken, PA, 2009.

3. Test Apparatus
    3.1. The test apparatus shall comply with the requirements of ASTM A370.

4. Test Specimens
    4.1. Test specimens shall be No. 4, 5, or 6 bars, with each bar having a length of 3 feet.

5. Procedure
    5.1. During uniaxial tensile testing, each steel type will be evaluated in accordance with ASTM A370 and a comparison will be made to carbon steel reinforcement. It is important to note that the resultant values can vary, as shown in Table D1. Therefore, it is important that the appropriate criteria and standard be applied for acceptance. Some example uniaxial tensile test values are shown in Table D2, and elongation upon fracture example values are shown in Table D3. The composition of the candidate reinforcing bar will be used to determine which ASTM or AASHTO standard governs the uniaxial tensile testing and elongation acceptance criteria for a particular candidate bar. The composition will be based on the values supplied by the producer, which will have been confirmed using XRF.

Table D1. Some observed minimum and maximum strength and elongation values for various types of CRR bars

Description	Minimum Value Recorded	Maximum Value Recorded
Yield strength (ksi)	73	132
Ultimate strength (ksi)	93	161
Elongation (%)	8	39

Table D2. Different uniaxial test acceptance values for different bar types based on ASTM A615 (ASTM 2003), A955 (ASTM 2010a), and A1035 (ASTM 2009c).

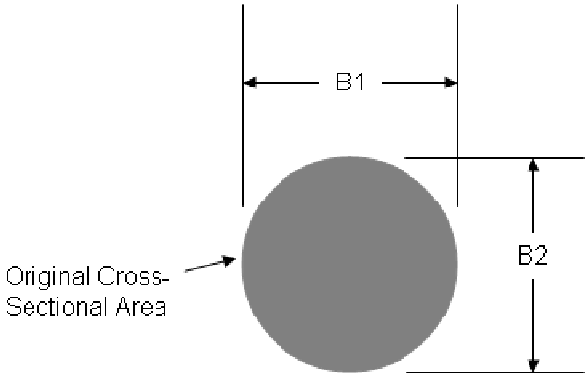
Description	Grade 40[a,b]	Grade 60 [a,b]	Grade 75 [a,b]	Other[c]
Tensile strength, minimum, ksi	70	90	100	150
Yield strength, minimum, ksi	40	60	75	100
[a]ASTM A615. [b]ASTM A955. [c]ASTM A1035.				

Table D3. Different elongation test acceptance values for different bar types and bar sizes based on ASTM A615 (ASTM 2003), A955 (ASTM 2010a), and A1035 (ASTM 2009c).

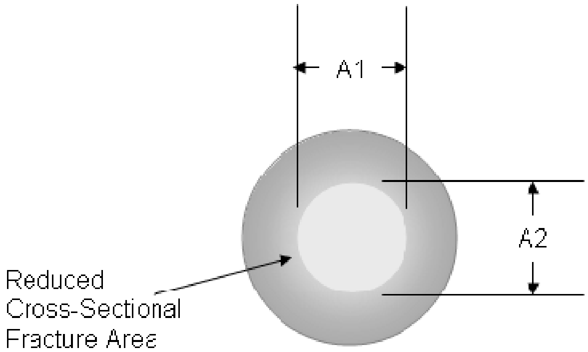
	Elongation in 8 inches, %			
Bar No.	Grade 40 [a,b]	Grade 60	Grade 75 [a,b]	Other[c]
3	11	9 [a,b]	…	7
4, 5	12	9 [a,b]	…	7
6	12	9 [a,b]	7	7
7, 8	…	8[a] / 9[b]	7	7
9, 10, 11	…	7 [a] / 8[b]	6	7
14, 18	…	7 [a,b]	6	6
[a]ASTM A615. [b]ASTM A955. [c]ASTM A1035.				

6. Calculations
   6.1. Calculations will be reported in accordance with ASTM A370.
   6.2. Percent reduction in cross-sectional area at location of fracture can be calculated as follows (see Figure D1):
      6.2.1. Make two perpendicular measurements of the diameter of the untested bar. Average these two measurements and record them as B_{ave}. After testing the bar, make two perpendicular measurements of the diameter of the bar at the fracture location (either half of the bar can be used). Average these two measurements and record them as A_{ave}. The following simplified equation can be used to calculate percent reduction in cross-sectional area.

$$\text{\% Reduction in Area } = \left[1 - \frac{(A_{ave})^2}{(B_{ave})^2}\right](100)$$



CRR Before Testing



CRR After Testing

Figure D1. Illustration for calculation of percent reduction in cross-sectional area.

7. Report
    - 7.1.1. Record the yield strength, tensile strength, percent elongation, and percent reduction in cross-sectional area at the location of fracture. Results from this test should be recorded on Table M1 in Appendix M.

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APPENDIX E: BAR FINISH

1. Scope
   1.1. This method covers the procedures to be used to visually evaluate the bar finish of candidate reinforcement bars.
      1.1.1. This is to be performed before and after corrosion testing.
      1.1.2. This is to be performed if a bar is considered questionable.

2. Reference Documents
   2.1. American Association of State Highway and Transportation Officials. AASHTO MP 13M/MP 13-04: Standard Specification for Stainless Clad Deformed and Plain Round Steel Bars for Concrete Reinforcement. In *AASHTO Provisional Standards,* Washington, DC, 2004.
   2.2. ASTM International. ASTM A955-10a: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards,* Vol. 01.04. West Conshohocken, PA, 2010.
   2.3. ASTM International. ASTM A1035: Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards,* Vol. 01.04. West Conshohocken, PA, 2009.

3. Test Apparatus
   3.1. The apparatus required shall consist of a digital camera, digital calipers, and a ruler.

4. Test Specimens
   4.1. Test specimens shall be representative samples of No. 4, 5, or 6 bars.

5. Procedure
   5.1. A visual evaluation of the bar finish will be performed and documented using digital photography. The surface evaluation process will document visual features such as the bar tint and any signs of corrosion and/or pits. If corrosion and/or pitting is observed, measurements should be made to document the size of these features. In addition, notes should be made on the uniformity of the bar diameter and if the bars are straight or retain some curvature following the straightening process.
   5.2. Extreme bar tint (example shown in Figure E1) or corrosion pitting should be sufficient reason for rejection of the bar as CRR and should be noted on Table M1 in Appendix M.
      5.2.1. Extreme bar tint could occur at a single location on an individual bar or be seen as a difference in tint between a group of bars.
      5.2.2. If bar tint is of concern, the results of “Test for Exposure to Adverse Heat Treatment” in Appendix K should be reviewed to determine if the steel has been subjected to an improper heat cycle.

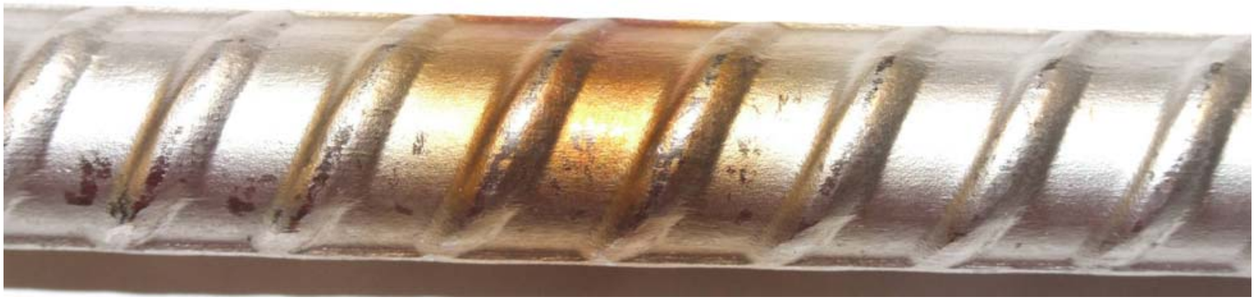

Figure E1. Bar exhibiting discoloration because of exposure to improper heat cycle.

6. Calculations
   6.1. Calculations are not required.

7. Report
   7.1. Reporting should include observations of corrosion, variations in bar tint, bar uniformity, and straightness. Results from this test should be recorded on Table M1 in Appendix M.

APPENDIX F: MILL IDENTIFICATION MARKINGS

1. Scope
   1.1. This method covers the procedures to be used to record the mill identification markings of candidate reinforcement bars.

2. Referenced Documents
   2.1. American Association of State Highway and Transportation Officials. AASHTO MP 13M/MP 13-04: Standard Specification for Stainless Clad Deformed and Plain Round Steel Bars for Concrete Reinforcement. In *AASHTO Provisional Standards.* Washington, DC, 2004.
   2.2. ASTM International. ASTM A955-10a: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2010.
   2.3. ASTM International. ASTM A276-06: Standard Specification for Stainless Steel Bars and Shapes. In *Annual Book of ASTM Standards*, Vol. 01.03. West Conshohocken, PA, 2006.

3. Test Apparatus
   3.1. The apparatus required shall consist of a digital camera and data sheet.

4. Test Specimens
   4.1. Test specimens shall be representative samples of No. 4, 5, or 6 bars.

5. Procedure
   5.1. The mill identification markings should be located.
      5.1.1. If the reinforcement is a candidate CRR bar, recording of mill identification markings should be done both electronically (digital camera) and on a data sheet use for logging mill identification markings. The data sheet should include the file name for the electronic image to allow for ease of sharing this image if future questions from the field arise.
   5.2. For bars with a stainless steel surface (ASTM A955, ASTM A276, or AASHTO MP 13 type bars), verify that the bars are manufactured at a mill that is approved to produce stainless steel rebar.

6. Calculations
   6.1. Calculations are not required.

7. Report
   7.1. Confirm that this test has been performed by recording it on Table M1 in Appendix M.

APPENDIX G: RELATIVE RIB AREA

1. Scope
   1.1. This method covers the procedures to be used to measure and record the relative rib area of candidate reinforcement bars.

2. Referenced Documents
   2.1. American Association of State Highway and Transportation Officials. AASHTO MP 13M/MP 13-04: Standard Specification for Stainless Clad Deformed and Plain Round Steel Bars for Concrete Reinforcement. In *AASHTO Provisional Standards.,* Washington, DC, 2004.
   2.2. ASTM International. ASTM A615-03: Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards,* Vol. 01.04. West Conshohocken, PA, 2003.
   2.3. ASTM International. ASTM A955-10a: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards,* Vol. 01.04. West Conshohocken, PA, 2010.
   2.4. ASTM International. ASTM A1035: Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards,* Vol. 01.04. West Conshohocken, PA, 2009.

3. Test Apparatus
   3.1. The apparatus required shall consist of a digital caliper with depth gage.

4. Test Specimens
   4.1. Test specimens shall be representative samples of No. 4, 5, or 6 bars.

5. Procedure
   5.1. The relative rib area should be measured and compared to the minimum required by ASTM A615, ASTM A955, ASTM A1035, or AASHTO MP 13 bars, as governed by the composition of the bar, based on x-ray fluorescence testing or the manufacturer's reported chemical composition. Equation G1 should be used to calculate the relative rib area using the features shown in Figure G1.

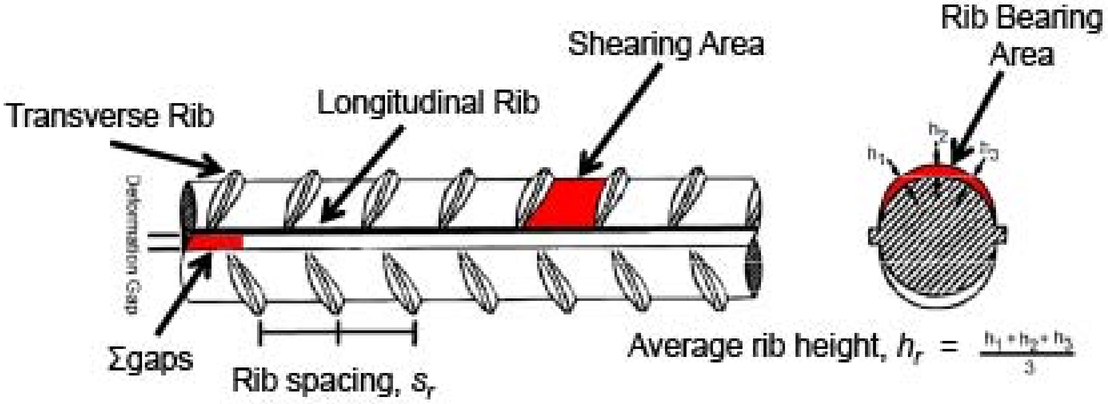

Figure G1. Relative rib area bar features.

6. Calculations

6.1. Equation G1 is used for relative rib area (R_r) calculations.

$$R_r = \frac{h_r}{s_r}\left(1 - \frac{\sum gaps}{p}\right) \qquad \text{[Eq. G1]}$$

Where: h_r = average rib height
s_r = average rib spacing
Σgaps = sum of the gaps between ends of transverse ribs
p = perimeter (= diameter (φ) × π)

7. Report

7.1. Results from this test should be recorded on Table M1 in Appendix M.

APPENDIX H: BOND STRENGTH TESTING PROCEDURE

1. Scope
   1.1. The testing guidelines described herein were developed to ensure that the assumption of strain compatibility, which forms the basis of reinforced concrete structural design, is achieved in practice. A direct pullout test is employed that can provide mechanical bond stiffness and peak bond strength without the complicated testing frame required for beam end tests and with a low probability of a concrete splitting failure. The direct pullout test does not simulate the internal stress distribution and flow of forces in a beam the same way a beam end test does; however, for relative comparisons of bond strength with consistent failure modes with simple equipment requirements, the direct pullout test is a rational compromise.

2. Referenced Documents
   2.1. ASTM International. ASTM A615-03: Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards,* Vol. 01.04. West Conshohocken, PA, 2003.
   2.2. ASTM International. ASTM C39-10: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. In *Annual Book of ASTM Standards*, Vol. 04.02. West Conshohocken, PA, 2010.
   2.3. ASTM International. ASTM C143-10a: Standard Test Method for Slump of Hydraulic Cement Concrete. In *Annual Book of ASTM Standards,* Vol. 04.02. West Conshohocken, PA, 2007.
   2.4. ASTM International. ASTM C192-07: Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. In *Annual Book of ASTM Standards*, Vol. 04.02. West Conshohocken, PA, 2007.
   2.5. ASTM International. ASTM C231-10: Standard Test Method for Air Content of Freshly Mixed Concrete by the Pressure Method. In *Annual Book of ASTM Standards*, Vol. 04.02. West Conshohocken, PA, 2010.
   2.6. ASTM International. ASTM C511-09: Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes. In *Annual Book of ASTM Standards*, Vol. 04.02. West Conshohocken, PA, 2009.

3. Test Apparatus
   3.1. *Molds*. One type of mold is required that produces a concrete specimen with out-to-out dimensions of 10 inches by 10 inches by H, where H is the height of the specimen, which can vary based on the embedded length of the bar, L_e, as shown in Figure H1.
   3.2. *Measuring apparatus.* An apparatus shall be provided for measuring the movement of the bar at the unloaded end of the specimen. A dial gauge with an accuracy of ±0.0005 inch is recommended. The dial gauge should be attached to the concrete specimen to obtain a relative measurement between the concrete and bar.
   3.3. *Testing apparatus.* A center hole jack with gripping ring shall bear flat on the top surface of the specimen. Blocking that elevates the specimen off the laboratory floor is required to accommodate the dial gauge, as shown in Figure H2.

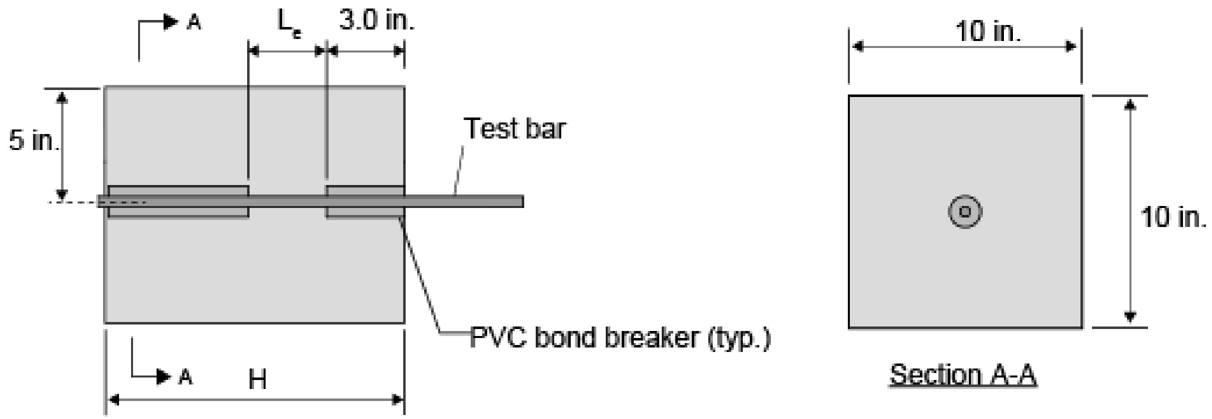

Figure H1. Specimen dimensions and details.

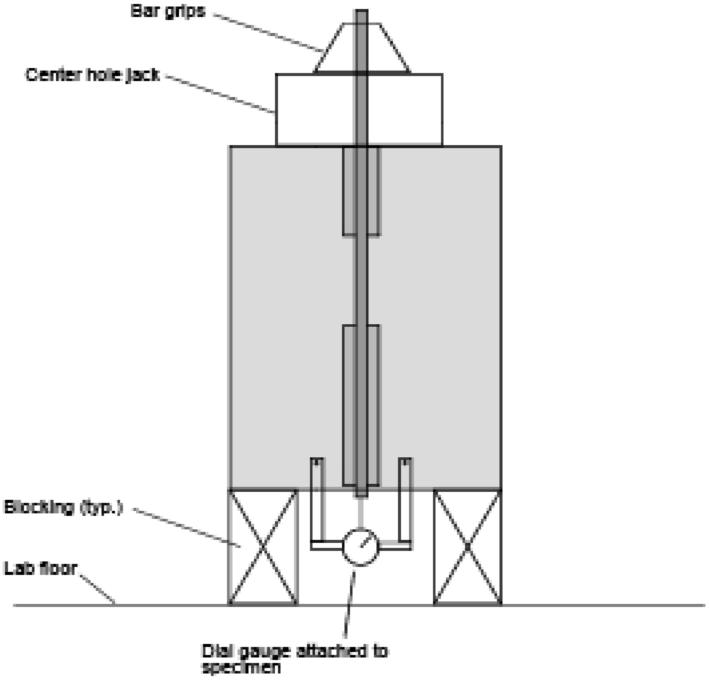

Figure H2. Direct pullout test setup.

4. Test Specimens
   4.1. Test quantity
      4.1.1. Six specimens shall constitute a set of test specimens.
   4.2. Bonded length
      4.2.1. The bar bonded length, L_e, shall be 4 inches for Nos. 4, 5, and 6 bars. For other bar diameters, L_e shall be established by testing.
   4.3. Fabrication
      4.3.1. A bar shall be oriented vertically and centered in the concrete specimen. The length of the bar extending from the top of the specimen shall be sufficient to accommodate the center hole jack and grips. The bar shall extend to the bottom

surface of the specimen. A 3-inch-long piece of PVC pipe shall be placed around the bar at the top surface. A PVC pipe shall encase the bar from the lower extent of the bonded bar to the bottom of the specimen. The bar shall be centered in the PVC pipe, and the PVC pipe diameter shall be sufficiently large to avoid contact with the bar. The joint shall be sealed with duct tape at the protrusion of the bonded bar length to prevent concrete infiltration.

4.4. Mixing concrete

4.4.1. The concrete shall be batched, machine mixed, molded, and cured in accordance with the applicable portions of ASTM C192. Immediately after mixing, the slump of each batch of concrete shall be measured in accordance with ASTM C143. The air content of the freshly mixed concrete shall be determined in accordance with ASTM C231.

4.5. Casting specimens

4.5.1. Prior to casting the test specimens, coat the inside surfaces of the molds with a thin film of mineral oil, petroleum jelly, or stearic acid paste. Place the concrete in the mold and provide internal vibration by means of a laboratory type, low amplitude high-frequency vibrator. After the concrete is consolidated, strike off the top surface with a trowel and protect against evaporation and moisture loss by one of the acceptable methods described in ASTM C192. Make at least three standard 4 inch by 8 inch control cylinders from each batch of concrete for determining compressive strength tested in accordance with ASTM C39.

4.6. Curing specimens

4.6.1. Remove the molds from the specimens not earlier than 20 hours after casting. Take extreme care to prevent striking or otherwise disturbing the reinforcing bars. Immediately after removing the molds, cure the specimens in a room in accordance with ASTM C511 until the time of the test. Test the specimens at an age of 28 days.

5. Procedure

5.1. Load application

5.1.1. Apply the tensile load to the reinforcing bar at a rate not greater than 5,000 lbf/min.

5.2. Data recording

5.2.1. Read and record the applied load and the dial gage at a sufficient number of intervals throughout the test to provide at least 15 readings before the bar has yielded or pulled out. Terminate the test when (1) the yield point of the reinforcing bar has been reached, (2) the concrete splits, or (3) a slippage of at least 0.10 inch has occurred at the unloaded end.

6. Calculations

6.1. None.

7. Report

7.1. Pass/fail criteria

7.1.1. The tested bar is considered acceptable if (1) the average peak load of the specimen group is greater than or equal to the peak load established for an ASTM A615 Grade 60 bar, and (2) the average unloaded end bar slip of the specimen group at peak load is less than or equal to the end slip at peak load established for an ASTM A615 Grade 60 bar. The baseline ASTM A615 Grade 60 peak load and slip values shall be determined from tests where L_e and the concrete 28-day compressive strength, $f'c$, are consistent with the specimens under consideration.

7.2. Results from this test should be recorded on Table M1 in Appendix M.

APPENDIX I: CORROSION RESISTANCE TESTING

1. Scope
   1.1. This method covers the procedures to be used in determining the corrosion resistance of candidate rebar.
   1.2. The Florida tombstone test provides a means of comparing the corrosion resistance of different types of steel reinforcement. The following test procedure describes how to evaluate and compare the relative corrosion resistance of different types of reinforcement.

2. Referenced Documents
   2.1. ASTM International. ASTM A615-03: Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2003.
   2.2. ASTM International. ASTM C39-10: Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens. In *Annual Book of ASTM Standards*, Vol. 04.02. West Conshohocken, PA, 2010.
   2.3. ASTM International. ASTM C138-10b Standard Test Method for Density (Unit Weight), Yield, and Air Content (Gravimetric) of Concrete. In *Annual Book of ASTM Standards*, Vol. 04.02. West Conshohocken, PA, 2010.
   2.4. ASTM International. ASTM C192-07: Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory. In *Annual Book of ASTM Standards*, Vol. 04.02. West Conshohocken, PA, 2007
   2.5. ASTM International. ASTM C876-09: Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete. In *Annual Book of ASTM Standards*, Vol. 03.02. West Conshohocken, PA, 2009.
   2.6. Virginia Department of Transportation. Virginia Test Method 112: Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration. http://www.virginiadot.org/business/resources/Materials/bu-mat-VTMs.pdf. Richmond, 2007.
   2.7. Hartt, W.H., Powers, R.G., Lysogorski, D.K., Liroux, V., and Virmani, Y.P. *Corrosion Resistant Alloys for Reinforced Concrete*. FHWA-HRT-07-039. Federal Highway Administration, Turner-Fairbank Highway Research Center, McLean, VA, 2007.

3. Test Apparatus
   3.1. To perform this test, several types of reinforcement will be embedded in tombstone specimens and immersed in cyclical saltwater ponding tanks while a data acquisition system (DAS) gathers macro-current measurements. Figure I1 is a photograph of the test system.
   3.2. Saltwater test solution
      3.2.1. The saltwater test solution is a 3% by weight sodium chloride solution. The solution volume needed depends on the size of the immersion tank. To calculate the quantity of a saltwater solution required, the bottom 6 inches of the tombstone specimens plus the height of the sample booster must be considered in conjunction with the other two dimensions of the ponding tank.

Figure I1. Tombstone test setup: 3% saltwater storage tank in lower left corner, with tombstone immersion tanks adjacent to saltwater storage tank and data acquisition system above tombstone tanks (top of picture).

3.3. Immersion tanks

  3.3.1. A suitable immersion tank will most likely be a fiberglass or plastic tank that is resistant to sodium chloride solution and has favorable impact resistance or can be easily repaired if a specimen strikes the tank. For example, the two VCTIR fiberglass tanks (shown in Figure I1) are 28 by 30 by 48 inches and hold 30 specimens each.

3.4. Sample spacers

  3.4.1. The sample spacer provides a means of adding stability to specimens since the height of the specimen is much greater than the width. This item is not required for testing but should be considered to reduce the chance of damaging the specimens. The spacer must be resistant to saltwater and moisture. An example is shown in Figure I3.

  3.4.2. Sample booster

    3.4.2.1. The sample booster provides a means of lifting specimens out of residual saltwater during dry periods of the wet/dry exposure cycle. It must be resistant to saltwater and moisture and also impact resistant or easily repaired if the specimen should strike the booster material. An example of a sample booster is shown in Figure I2 and Figure I3.

3.5. Data acquisition system

  3.5.1. The DAS will be used to monitor the voltage across a 1-ohm resistor on each block. Therefore, it is important that the DAS have sufficient channels for the number of tombstones being tested. In addition, the DAS must have high impedance terminals and for DC voltage measurement a maximum resolution of 1 μV at 20 mV and measurement accuracy integral time 1.67 ms ± (0.1% of rdg + 25 digits) at 20 mV, all at standard operating conditions. Further, based on the experience of VCTIR, a web browser monitoring and control system can provide an added benefit of not requiring proprietary software that might limit the number of computers that can access the data because of a limit in the number of site licenses.

Figure I2. Close-up of 1" plastic square tube that functions as a sample booster

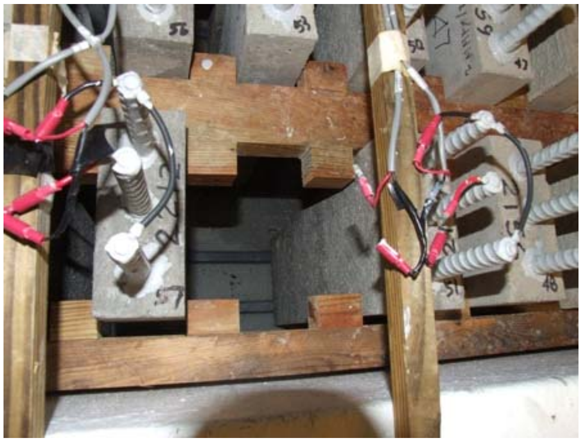

Figure I3. Picture of sample spacers (upper wooden slots) and sample boosters (lower plastic rails)

4. Test Specimens:
   4.1. The rebar tested will include, in addition to the candidate bar specimens, test specimens with types 316LN, 2205, and MMFX 2 No. 5 steel bars with each bar being in an as-received condition. Each test specimen, or tombstone, will have a single type of reinforcing steel embedded in a concrete block that complies with the VDOT A4 concrete specification except that the concrete will not contain pozzolanic materials. In addition, the course aggregate will be composed of 50% each of No. 4 and 3/8 inch aggregates sieved out of No. 68 aggregates. This is considered an A-4 Post and Rail mixture. The tombstone specimens have dimensions (shown in Figure I4) that will ensure rapid corrosion test results for an embedded steel type test. After the tombstone specimens have been cast and cured for 28 days (in accordance with VDOT protocol), the exposed ends of the bars will be cleaned to expose the base metal, and after the electrical connections are made, a two-part epoxy, such as a 100% solids high-build epoxy such as EP-3T, will be applied to the bars and top of the specimens. The bars embedded in concrete, as shown in Figure I4, with the exposed bar ends connected and epoxy applied, is considered a "Test Specimen," which is also known as a Florida tombstone test specimen or simply a tombstone.

5. Procedure
   5.1. Tombstone concrete mixture design
      5.1.1. The concrete used for the tombstone specimens shall comply with the requirements of a VDOT A4 mixture design.
   5.2. Tombstone molds
      5.2.1. An illustration of a tombstone mold is shown in Figure I5. These molds have two regions. The upper mold region does not receive concrete and is used to align and secure the bars prior to casting. The lower mold region is where the concrete is placed to embed the steel bars.

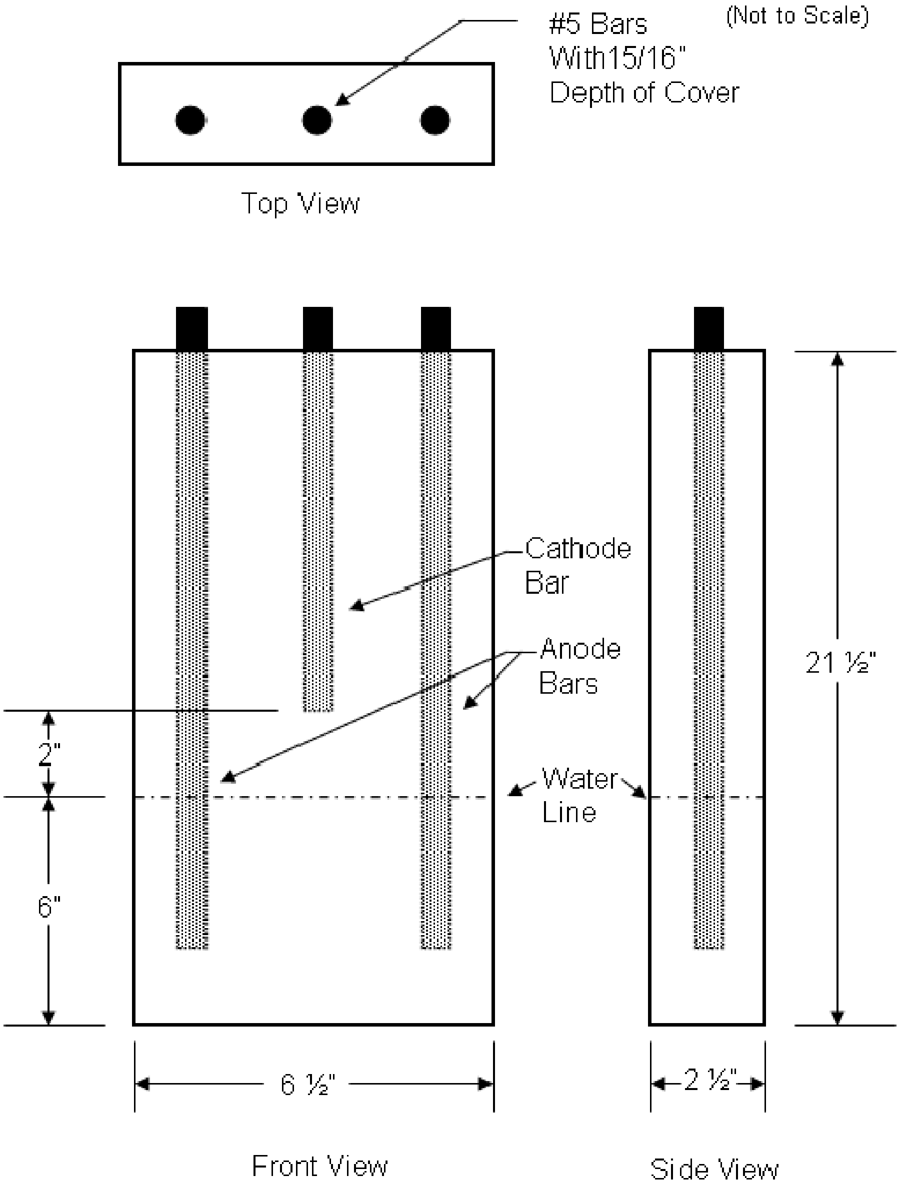

Figure I4. Illustration of tombstone specimens with sample dimensions.

5.3. Casting tombstone

- 5.3.1. Place a single type of reinforcing steel in the tombstone molds, adjust the bar heights to ensure the concrete cover will be consistent, and cover all bolt hardware and exposed form edges with tape, as shown in Figure I6.
- 5.3.2. Mix and cast concrete specimens in accordance with ASTM C138, ASTM C192, and standard VDOT protocol. The concrete can be placed in a single lift and consolidated by vibrating the entire form. In addition to casting tombstone specimens, 4-inch-cylinder specimens should be cast for 28-day compressive strength (ASTM C39) and permeability (VTM 112) testing to confirm the concrete quality. After casting, specimens should be allowed to cure properly before any additional work is performed on the specimens.

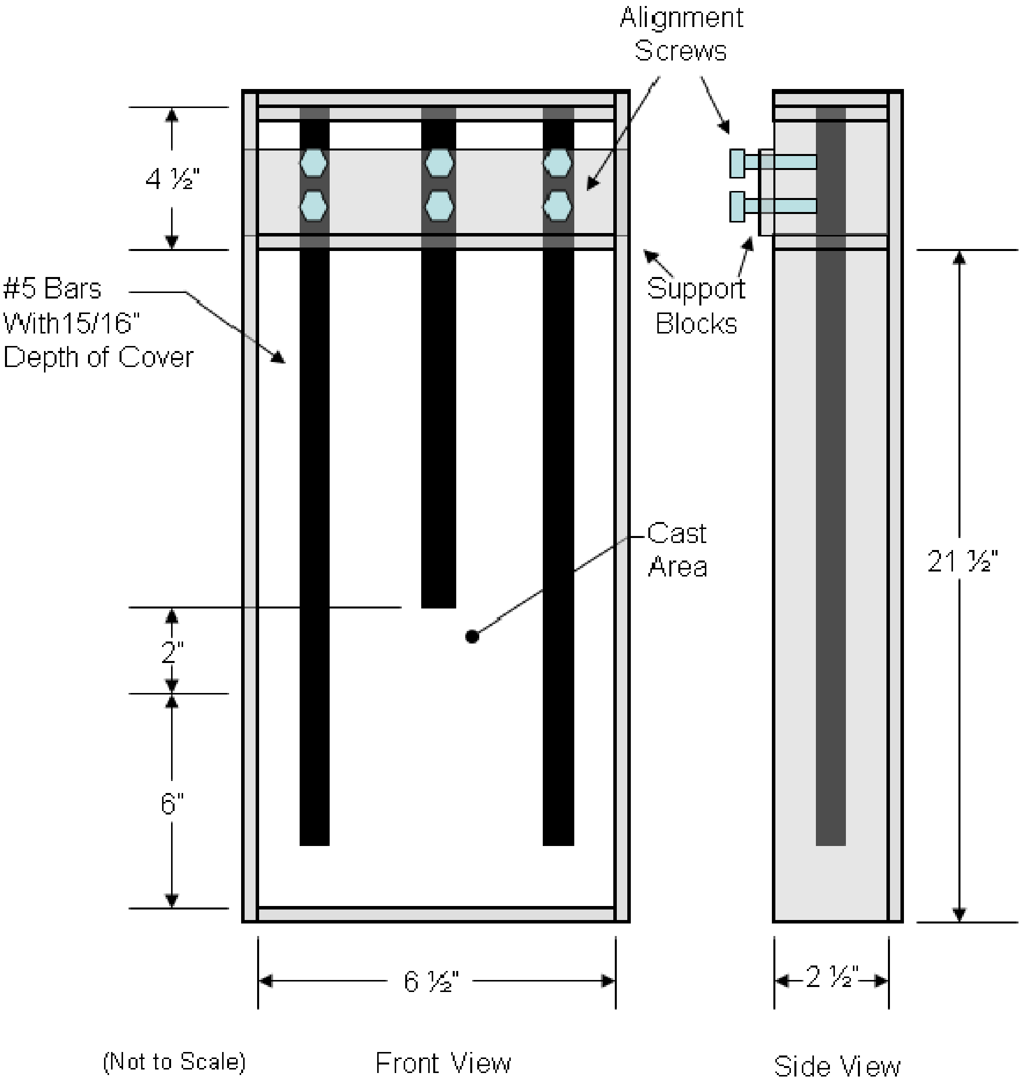

Figure I5. Illustration of forms used to cast tombstone specimens.

Figure I6. Photograph of tombstone molds that are ready for concrete casting phase.

5.4. Connections and wiring

5.4.1. After the specimens have properly cured, remove them from the curing room and clean the exposed bar ends to remove any rust and ensure a quality electrical contact between the rebar and the wire. To make a connection between embedded rebars, stranded copper wire (size range of No. 10 through No. 16) will be used. Solderless connectors will be used to couple the blocks to the DAS (examples are shown in Figure I7) and to connect the wire to each rebar. A rivet will be used to join the solderless connector and the rebar. A hole, slightly larger than the rivet, is drilled into the end of each piece of rebar, and the rivet is used to secure the solderless connector to the rebar. The size of the rivet is not as important as the fit between the rivet and the ring style solderless connector. VCTIR has successfully used a size 3/16-inch rivet, which is shown in Figure I8. A 1-ohm resistor is placed in series between the electrically connected anode bars and cathode bar, as shown in Figure I9.

Figure I7. Examples of solderless connectors that can be used

Figure I8. A 3/16" rivet positioned through a ring style solderless connector, which will be used to connect the wires to each rebar specimen

5.5. Place in tank

5.5.1. With the sample boosters and spacers placed appropriately, carefully lower each tombstone specimen into the immersion tank. If several tombstone specimens are cast, it is advantageous to mark the top of each specimen with a unique marking or to create a key above the immersion tank to help in identifying each specimen.

5.6. Connect leads

5.6.1. The distance between each tombstone and the data acquisition system is measured and two lead wires are cut and uniquely labeled. One wire from each pair is then connected on each side of the resistor and then wired to either the positive or the negative pole of the DAS.

5.7. Initial immersion test cycle

5.7.1. During the first immersion cycle (3 days ponded, 4 days dry), pond the samples in water (no salt). The water level in the tank should be 6 inches from the bottom of the specimen. During this first cycle, check for leaks, faulty wire connections, computer or data acquisition hardware/software issues, and any other potential equipment-related problem.

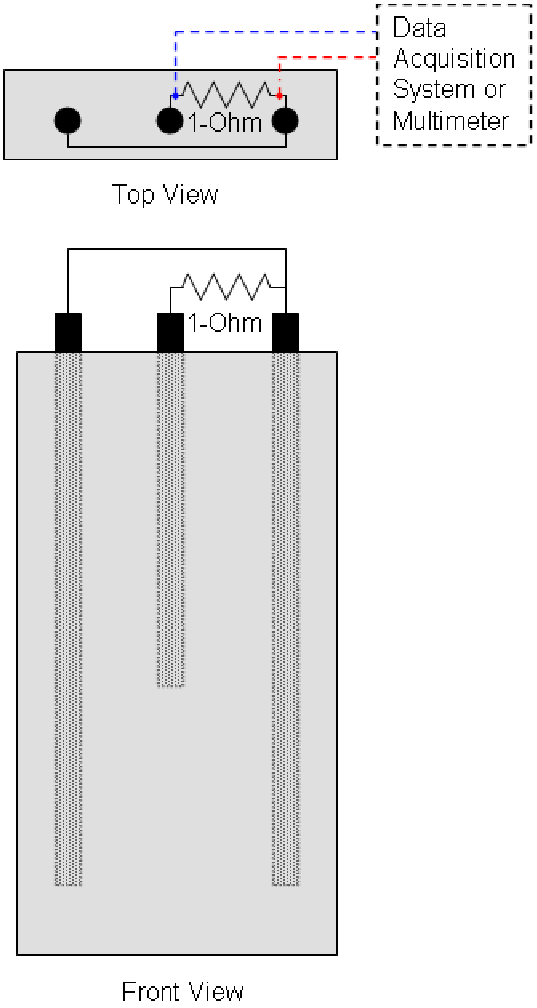

Figure I9. Illustration of tombstone wire connections.

5.8. Saltwater ponding

5.8.1. During immersion test cycle 2 and until the test is completed, use the 3% saltwater solution. The saltwater level in the tank should be 6 inches from the bottom of the specimen. The test cycle is 3 days ponded with saltwater and 4 days dry. Terminate the test process upon detection of concrete cracking or visible corrosion product bleed-out or if half-cell values more negative than –0.35 V vs. CSE are detected, as discussed in Section 6.

6. Data Analysis and Calculations

6.1. Monitor macro-current using DAS and compare values to previous values to determine if macro-current is trending away from zero, which is an indication of macro-current activity. Activity is typically indicated by macro-current activity greater than 0.01 mA (or 0.01 mV measured across a 1-ohm resistor).

6.2. After macro-current activity is detected, begin monitoring half-cell current using a voltmeter.

- 6.2.1. Using a silver / silver chloride electrode, place the electrode in the tank. Measure voltage in accordance with ASTM, with the silver / silver chloride electrode being used in place of copper / copper sulfate (CSE).
- 6.2.2. The electrode should not be left in the tank for a prolonged period of time.
  - 6.2.2.1. Measured values should be evaluated as follows:
    - 6.2.2.1.1. Measurement more positive than -0.20 V vs. CSE = Low Probability of Corrosion
    - 6.2.2.1.2. -0.20 to -0.35 V vs. CSE = Uncertain Probability of Corrosion
    - 6.2.2.1.3. Measurement more negative than -0.35 V vs. CSE = High Probability of Corrosion.
- 6.2.3. Terminate exposure if the half-cell value is more negative than -0.35 V vs. CSE and record macro-cell and half-cell values upon termination. Begin autopsy.

6.3. Autopsy specimens and visually evaluate bar condition.

- 6.3.1. Gather concrete sample for total chloride analysis.
- 6.3.2. Gather sample for concrete pH analysis.
- 6.3.3. Compare % corroded surface area to qualifier bar values.
- 6.3.4. Record if pits are evident and depth of pits.
- 6.3.5. Record any other unusual observations.

7. Report

7.1. Record all data on Table I1 and rank each bar according to the [Cl]/[OH] ratio.

7.2. Bar acceptance is based on ranking in accordance with the following:

- 7.2.1. Bars that rank the same as or worse than carbon steel are considered a **LEVEL 0 Bar (No Corrosion Resistance).**
- 7.2.2. Bars that rank better than carbon steel and similar to ASTM A1035 bars in Table I1 are considered a **LEVEL 1 CRR** (**Improved Corrosion Resistance).**
- 7.2.3. Bars that rank similar to a duplex stainless steel in Table I1 but worse than a 316LN stainless steel are considered a **LEVEL 2 CRR (Moderate Corrosion Resistance Bars).**
- 7.2.4. Bars that rank similar to a 316LN stainless steel in Table I1 are considered a **LEVEL 3 CRR (High Corrosion Resistance).**

Table I1. Summary of Tombstone Test Data

Bar Type	Start Test, Date	Half-Cell Exceeds Threshold		Micro-Current Exceeds Threshold		% Surface Area Corroded	No. of Pits	Average Pit Depth, mm	Chloride Concentration, lb/yd^3	pH Value	[Cl]/OH Value	Rank, 1 = best
		Date	Value	Date	Value							
Carbon Steel												
ASTM A1035												
Duplex SS												
SS 316LN												
Test Bar 1												
Test Bar 2												
Test Bar 3												
Test Bar 4												
Etc.												

SS = stainless steel.

APPENDIX J: DESCRIPTION OF CANDIDATE CRR STEELS

1. Scope
    1.1. Several types of alloyed steels are eligible for candidacy as CRR bars. The chemical composition for a candidate reinforcing steel bar should comply with one of the chemical compositions listed in ASTM A276, ASTM A955, or ASTM A1035. Testing should be done in accordance with ASTM A751. After the matching composition is identified in ASTM A276, ASTM A955, ASTM A1035, or Table J2, the bar should be described using the description provided in Table J1. Table J3 provides a list of the abbreviations used in Table J2 and the associated element. The column "Steel Type" indicates which types of steel phases are present, but it does not include any heat-treating information that might be important, such as if the martensite has been tempered.

Table J1. Alloy description, type, and grade.

Description	Common Name	Steel Type[a] (Reference[b])	Description	Common Name	Steel Type[a] (Reference[b])	Description	Common Name	Steel Type[a] (Reference[b])
ASTM A1035	MMFX 2	A, M (Pre)	S30815	---	A (276)	S32101	---	A, F (276)
S41003	Duracorr	F, M (Arc)	S30900	309	A (276)	S32205	---	A, F (276)
N08367	---	A (276)	S30908	309S	A (276)	S32304	---	A, F (276)
N08700	---	A (276)	S30940	309Cb	A (276)	S32506	---	A, F (276)
S20100	201	A (276)	S31000	310	A (276)	S32550	---	A, F (276)
S20161	---	A (276)	S31008	310S	A (276)	S32760	---	A, F (276)
S20162	---	A (276)	S31040	310Cb	A (276)	S40500	405	F (276)
S20200	202	A (276)	S31254	---	A (276)	S40976	---	F (276)
S20500	205	A (276)	S31400	314	A (276)	S42900	429	F (276)
S20910	XM-19	A (276)	S31600	316	A (276)	S43000	430	F (276)
S21800	---	A (276)	S31603	316L	A (276)	S44400	444	F (276)
S21900	XM-10	A (276)	S31635	316Cb	A (276)	S44600	446	F (276)
S21904	XM-11	A (276)	S31651	316N	A (276)	S44627	XM-27	F
S24000	XM-29	A (276)	S31653	316LN	A (276)	S44700	---	F
S24100	XM-28	A (276)	S31654	---	A (276)	S44800	---	F
S28200	---	A (276)	S31700	317	A (276)	S40300	403	M (276)
S30200	302	A (276)	S31725	---	A (276)	S41000	410	M (276)
S30400	304	A (276)	S31726	---	A (276)	S41040	XM-30	M (276)
S30403	304L	A (276)	S31727	---	A (276)	S41400	414	M (276)
S30451	304N	A (276)	S32053	---	A (276)	S41425	---	M (276)
S30452	XM-21	A (276)	S32100	321	A (276)	S41500	---	M (276)
S30453	304LN	A (276)	S32654	---	A (276)	S42000	420	M (276)
S30454	---	A (276)	S34565	---	A (276)	S42010	---	M (276)
S30453	304LN	A (276)	S34700	347	A (276)	S43100	431	M (276)
S30454	---	A (276)	S34800	348	A (276)	S44002	440A	M (276)
S30500	305	A (276)	S31100	XM-26	A, F (276)	S44003	440B	M (276)
S30800	308	A (276)	S31803	---	A, F (276)	S44004	440C	M (276)

[a] Steel Type: A = austenitic, F = ferritic, M = martensitic.

[b] Reference: 276 = ASTM A276 (ASTM, 2006); Pre = Presuel-Moreno et al., 2008; Arc = ArcelorMittal USA, 2011.

Table J2. Alloy description and chemical composition (all alloy compositions are based on values listed in ASTM A276 [ASTM 2006] unless indicated in “Other Elements” column).

Description UNS No. (Reference[a])	Alloy, wt. %									
	Cr	Ni	Mo	Mn	Si	C	N	P	S	Other Elements (Alloy Composition Reference[a])
ASTM A1035	8.0-10.9	---	---	1.5	0.5	0.15	0.05	0.035	0.045	--- {1035}
S40976	10.5-11.7	0.75-1.00	---	1	1	0.03	0.04	0.04	0.03	Cb 10X(C+N)-0.80
S41003	11.0-12.5	1	0.20-0.30	1.5	0.7	0.025	0.03	0.04	0.015	--- {Arc}
S41040	11.0-13.0	---	---	1	1	0.18	---	0.04	0.03	Cb 0.05-0.30
S40300	11.5-13.0	---	---	1	0.5	0.015	---	0.04	0.03	---
S41000	11.5-13.5	---	---	1	1	0.08-0.15	---	0.4	0.03	---
S41400	11.5-13.5	1.25-2.50	---	1	1	0.15	---	0.04	0.03	---
S41500	11.5-14.0	3.5-5.5	0.50-1.00	0.50-1.00	0.6	0.05	---	0.03	0.03	---
S40500	11.5-14.5	0.5	---	1	1	0.08	----	0.04	0.03	Al 0.10-0.30
S42000	12.0-14.0	---	---	1	1	0.15 Min	---	0.04	0.03	---
S41425	12.0-15.0	4.0-7.0	1.50-2.00	0.50-1.00	0.5	0.05	0.06-0.12	0.02	0.005	Cu 0.30
S42010	13.5-15.0	0.35-0.85	0.40-0.85	1	1	0.15-0.30	---	0.04	0.03	---
S42900	14.0-16.0	---	---	1	1	0.12	---	0.04	0.03	---
S43100	15.0-17.0	1.25-2.50	---	1	1	0.2	---	0.04	0.03	---
S20161	15.0-18.0	4.0-6.0	---	4.0-6.0	3.0-4.0	0.15	0.08-0.20	0.045	0.03	---
S44002	16.0-18.0	---	0.75	1	1	0.60-0.75	---	0.04	0.03	---
S44003	16.0-18.0	---	0.75	1	1	0.75-0.95	---	0.04	0.03	---
S44004	16.0-18.0	---	0.75	1	1	0.95-1.20	---	0.04	0.03	---
S43000	16.0-18.0	---	---	1	1	0.12	---	0.04	0.03	---
S31653	16.0-18.0	10.0-13.0	2.00-3.00	2	1	0.03	0.10-0.16	0.045	0.03	--- {955}
S31654	16.0-18.0	10.0-13.0	2.00-3.00	2	1	0.03	0.16-0.30	0.045	0.03	---
S31600	16.0-18.0	10.0-14.0	2.00-3.00	2	1	0.08	---	0.045	0.03	---
S31603	16.0-18.0	10.0-14.0	2.00-3.00	2	1	0.03	---	0.045	0.03	--- {955}
S31635	16.0-18.0	10.0-14.0	2.00-3.00	2	1	0.08	0.1	0.045	0.03	Ti 5X(C+N)-0.70
S31640	16.0-18.0	10.0-14.0	2.00-3.00	2	1	0.08	0.1	0.045	0.03	Cb 10XC-1.10
S31651	16.0-18.0	10.0-14.0	2.00-3.00	2	1	0.08	0.10-0.16	0.045	0.03	---
S20100	16.0-18.0	3.5-5.5	---	5.5-7.5	1	0.15	0.25	0.06	0.03	---
S21800	16.0-18.0	8.0-9.0	---	7.0-9.0	3.5-4.5	0.1	0.08-0.18	0.06	0.03	---
S20500	16.5-18.0	1.0-1.7	---	14.0-15.5	1	0.12-0.25	0.32-0.40	0.06	0.03	---
S24100	16.5-19.0	0.50-2.50	---	11.0-14.0	1	0.15	0.20-0.45	0.045	0.03	--- {955}
S20162	16.5-21.0	6.0-10.0	0.50-2.50	4.0-8.0	2.5-4.5	0.15	0.05-0.25	0.04	0.04	---
S28200	17.0-19.0	---	0.75-1.25	17.0-19.0	1	0.15	0.40-0.60	0.045	0.03	Cu 0.75–1.25
S30500	17.0-19.0	11.0-13.0	---	2	1	0.12	---	0.045	0.03	---

Description UNS No. (Reference[a])	Alloy, wt. %									
	Cr	**Ni**	**Mo**	**Mn**	**Si**	**C**	**N**	**P**	**S**	**Other Elements (Alloy Composition Reference[a])**
S24000	17.0-19.0	2.3-3.7	---	11.5-14.5	1	0.08	0.20-0.40	0.06	0.03	--- {955}
S20200	17.0-19.0	4.0-6.0	---	7.5-10.0	1	0.15	0.25	0.06	0.03	---
S30200	17.0-19.0	8.0-10.0	---	2	1	0.15	0.1	0.045	0.03	---
S32100	17.0-19.0	9.0-12.0	---	2	1	0.08	---	0.045	0.03	Ti 5X(C+N)-0.70
S34700	17.0-19.0	9.0-12.0	---	2	1	0.08	---	0.045	0.03	Cb 10XC-1.10
S34800	17.0-19.0	9.0-12.0	---	2	1	0.08	---	0.045	0.03	Cb 10XC-1.10 Ta 0.10 Co 0.20
S31726	17.0-20.0	14.5-17.5	4.0-5.0	2	1	0.03	0.10-0.20	0.045	0.03	---
S31727	17.5-19.0	14.5-16.5	3.8-4.5	1	1	0.03	0.15-0.21	0.03	0.03	Cu 2.8-4.0
S44400	17.5-19.5	1	1.75-2.50	1	1	0.025	0.035	0.04	0.03	Ti+Cb 0.20+4X(C+N)-0.80
S31700	18.0-20.0	11.0-15.0	3.0-4.0	2	1	0.08	0.1	0.045	0.03	---
S31725	18.0-20.0	13.5-17.5	4.0-5.0	2	1	0.03	0.2	0.045	0.03	---
S30452	18.0-20.0	8.0-10.0	---	2	1	0.08	0.16-0.30	0.045	0.03	---
S30400	18.0-20.0	8.0-11.0	---	2	1	0.08	---	0.045	0.03	--- {955}
S30451	18.0-20.0	8.0-11.0	---	2	1	0.08	0.10-0.16	0.045	0.03	---
S30453	18.0-20.0	8.0-11.0	---	2	1	0.03	0.10-0.16	0.045	0.03	---
S30454	18.0-20.0	8.0-11.0	---	2	1	0.03	0.16-0.30	0.045	0.03	---
S30403	18.0-20.0	8.0-12.0	---	2	1	0.03	---	0.045	0.03	---
S30800	19.0-21.0	10.0-12.0	---	2	1	0.08	---	0.045	0.03	---
S21900	19.0-21.5	5.5-7.5	---	8.0-10.0	1	0.08	0.15-0.40	0.045	0.03	---
S21904	19.0-21.5	5.5-7.5	---	8.0-10.0	1	0.04	0.15-0.40	0.045	0.03	---
N08700	19.0–23.0	24.0–26.0	4.3–5.0	2	1	0.04	---	0.04	0.03	Cu 0.50 Nb 8X3 C min 0.40 max
S31254	19.5-20.5	17.5-18.5	6.0-6.5	1	0.8	0.02	0.18-0.22	0.03	0.01	Cu 0.50-1.00
S30815	20.0-22.0	10.0-12.0	---	0.8	1.40-2.00	0.05-0.10	0.14-0.20	0.04	0.03	Ce 0.03-0.08
N08367	20.0-22.0	23.5-25.5	6.0–7.0	2	1	0.03	0.18–0.25	0.04	0.03	Cu 0.75
S20910	20.5-23.5	11.5-13.5	1.50-3.00	4.0-6.0	1	0.06	0.20-0.40	0.045	0.03	Nb 0.10–0.30, V 0.10–0.30
S32101	21.0-22.0	1.35-1.70	0.10-0.80	4.0-6.0	1	0.04	0.20-0.25	0.04	0.03	Cu 0.10-0.80
S31803	21.0-23.0	4.5-6.5	2.5-3.5	2	1	0.03	0.08-0.20	0.03	0.02	--- {955}
S32304	21.5-24.5	3.0-5.5	0.05-0.60	2.5	1	0.03	0.05-0.20	0.04	0.03	Cu 0.05-0.60
S32205	22.0-23.0	4.5-6.5	3.0-3.5	2	1	0.03	0.14-0.20	0.03	0.02	---
S30900	22.0-24.0	12.0-15.0	---	2	1	0.2	---	0.045	0.03	---
S30908	22.0-24.0	12.0-15.0	---	2	1	0.08	---	0.045	0.03	---
S30940	22.0-24.0	12.0-16.0	---	2	1	0.08	---	0.045	0.03	Cb 10X C-1.10
S32053	22.0-24.0	24.0-26.0	5.0-6.0	1	1	0.03	0.17-0.22	0.03	0.01	---
S32565	23.0-25.0	16.0-18.0	4.0-5.0	5.0-7.0	1	0.3	0.40-0.60	0.03	0.01	Cb 0.10
S31400	23.0-26.0	19.0-22.0	---	2	1.50-3.00	0.25	---	0.045	0.03	---
S44600	23.0-27.0	0.75	---	1.5	1	0.2	0.25	0.04	0.03.	---

Description UNS No. (Reference[a])	**Alloy, wt. %**									
	Cr	**Ni**	**Mo**	**Mn**	**Si**	**C**	**N**	**P**	**S**	**Other Elements (Alloy Composition Reference[a])**
S32654	24.0-25.0	21.0-23.0	7.0-8.0	2.0-4.0	0.5	0.02	0.45-0.55	0.03	0.005	Cu 0.30-0.60
S31000	24.0-26.0	19.0-22.0	---	2	1.5	0.25	---	0.045	0.3	---
S31008	24.0-26.0	19.0-22.0	---	2	1.5	0.08	---	0.045	0.03	---
S31040	24.0-26.0	19.0-22.0	---	2	1.5	0.08	---	0.045	0.03	Cb 10XC-1.10
S32506	24.0-26.0	5.5-7.2	3.0-3.5	1	0.9	0.03	0.08-0.20	0.04	0.015	W 0.05-0.30
S32760	24.0-26.0	6.0-8.0	3.0-4.0	1	1	0.03	0.20-0.30	0.03	0.01	Cu 0.50-1.00 W 0.50-1.00 %Cr + 3.3X %Mo + 16X %N $\geq$ 40
S32550	24.0-27.0	4.5-6.5	2.9-3.9	1.5	1	0.04	0.10-0.25	0.04	0.03	Cu 1.5-2.50
S31100	25.0-27.0	6.0-7.0	---	1	1	0.06	---	0.045	0.03	Ti 0.25
S44627	25.0-27.5	0.5	0.75-1.50	0.4	0.4	0.01	0.015	0.02	0.02	Cu 0.20 Cb 0.05-0.20 Ni+Cu 0.50%max
S44700	28.0-30.0	0.15	3.5-4.2	0.3	0.2	0.01	0.02	0.025	0.02	C+N 0.025 Cu 0.15
S44800	28.0-30.0	2.00-2.50	3.5-4.2	0.3	0.2	0.01	0.02	0.025	0.02	C+N 0.025 Cu 0.15

[a] Alloy Composition Reference: {1035} = ASTM A1035 (ASTM 2009; {955} = ASTM A955 (ASTM 2010); and {Arc}= ArcelorMittal USA, 2011.

Table J3. Abbreviations and associated elements.

Abbreviation	Element
Al	Aluminum
C	Carbon
Ce	Cerium
Co	Cobalt
Cr	Chromium
Cu	Copper
Mn	Manganese
Mo	Molybdenum
Ni	Nickel
Nb (Cb)	Niobium (Columbium, original name)
N	Nitrogen
P	Phosphorus
Si	Silicon
S	Sulfur
Ta	Tantalum
Ti	Titanium
V	Vanadium
W	Tungsten

2. Referenced Documents

2.1. ASTM International. ASTM A276-06: Standard Specification for Stainless Steel Bars and Shapes. In *Annual Book of ASTM Standards*, Vol. 01.03. West Conshohocken, PA, 2006

2.2. ASTM International. ASTM A955-10a: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2010

2.3. ASTM International. ASTM A1035: Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2009

2.4. ASTM International. ASTM A751: Standard Test Methods, Practices, and Terminology for Chemical Analysis of Steel Products. In *Annual Book of ASTM Standards*, Vol. 01.03. West Conshohocken, PA, 2008.

2.5. ArcelorMittal USA. Plate Duracorr: Life-Cycle Cost-Effective 12% Chromium Stainless Steel. http://www.arcelormittal.com/plateinformation/documents/en/Inlandflats/ProductBrochure/ARCELORMITTAL%20DURACORR.pdf. Accessed March 17, 2011.

2.6. Presuel-Moreno, F., Scully, J.R., and Sharp, S.R. Identification of Commercially Available Alloys for Corrosion-Resistant Metallic Reinforcement and Test Methods for Evaluating Corrosion-Resistant Reinforcement. FHWA/VTRC 08-R21. Virginia Transportation Research Council, Charlottesville, 2008.

APPENDIX K: SENSITIVITY TO INTERGRANULAR ATTACK

1. Scope
    1.1. This method covers the procedures to be used to evaluate the sensitivity of CRR to intergranular attack in austenitic or ferritic stainless steels or the formation of a detrimental intermetallic phase in a duplex stainless steel. It is important to note that these tests evaluate certain detrimental effects that can occur in stainless steels that could reduce the functional life of the steel. These tests, however, are not designed for estimating the service life of CRR embedded in concrete.

2. Referenced Documents
    2.1. ASTM International. ASTM A262-10: Standard Practices for Detecting Susceptibility to Intergranular Attack in Austenitic Stainless Steels. In *Annual Book of ASTM Standards*, Vol. 01.03. West Conshohocken, PA, 2010.
    7.2. ASTM International. ASTM A763-93(2009): Standard Practices for Detecting Susceptibility to Intergranular Attack in Ferritic Stainless Steels. In *Annual Book of ASTM Standards*, Vol. 01.03. West Conshohocken, PA, 2009.
    2.2. ASTM International. ASTM A923-08: Standard Test Methods for Detecting Detrimental Intermetallic Phase in Duplex Austenitic/Ferritic Stainless Steels. In *Annual Book of ASTM Standards*, Vol. 01.03. West Conshohocken, PA, 2008.

3. Test Apparatus
    3.1. For austenitic stainless steel, guidance is provided in ASTM A262.
    3.2. For ferritic stainless steels, guidance is provided in ASTM A763.
    3.3. For ferritic-austenitic (duplex) stainless steels, guidance is provided in ASTM A923.

4. Test Specimens
    4.1. For austenitic stainless steel, guidance is provided in ASTM A262.
    4.2. For ferritic stainless steels, guidance is provided in ASTM A763.
    4.3. For ferritic-austenitic (duplex) stainless steels, guidance is provided in ASTM A923.

5. Procedure
    5.1. Testing should be conducted according to the type of stainless steel as follows:
        5.1.1. Austenitic stainless steels shall be tested in accordance with Practice E, in conjunction with Practice A, of Specification ASTM A262.
        5.1.2. Ferritic stainless steels shall be tested in accordance with Practice Y or Z, in conjunction with Practice W, of Specification ASTM A763. The stainless steel UNS designation and Table 2 in ASTM A763 shall be used to determine the best test practice, Y or Z.
        5.1.3. Ferritic-austenitic (duplex) stainless steels shall be tested in accordance with Test Method C, in conjunction with Test Method A, of Specification ASTM A923.

6. Calculations
    6.1. For austenitic stainless steel, guidance is provided in ASTM A262.
    6.2. For ferritic stainless steels, guidance is provided in ASTM A763.
    6.3. For ferritic-austenitic (duplex) stainless steels, guidance is provided in ASTM A923.

7. Report
    7.1. For austenitic stainless steel, guidance is provided in ASTM A262. Results from this test should be recorded on Table M1.
    7.2. For ferritic stainless steels, guidance is provided in ASTM A763. Results from this test should be recorded on Table M1.
    7.3. For ferritic-austenitic (duplex) stainless steels, guidance is provided in ASTM A923. Results from this test should be recorded on Table M1.

APPENDIX L: BEND TEST

1. Scope
    1.1. This method specifies the procedures to be used for evaluating candidate bars for bend test acceptance.

2. Reference Documents
    2.1. American Association of State Highway and Transportation Officials. AASHTO MP 13M/MP 13-04: Standard Specification for Stainless Clad Deformed and Plain Round Steel Bars for Concrete Reinforcement. In *AASHTO Provisional Standards.* Washington, DC, 2004.
    2.2. ASTM International. ASTM A370-08a: Standard Test Methods and Definitions for Mechanical Testing of Steel Products. In *Annual Book of ASTM Standards*, Vol. 01.01. West Conshohocken, PA, 2008.
    2.3. ASTM International. ASTM A615-03: Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2003.
    2.4. ASTM International. ASTM A955-10a: Standard Specification for Deformed and Plain Stainless-Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2010.
    2.5. ASTM International. ASTM A1035: Standard Specification for Deformed and Plain, Low-carbon, Chromium, Steel Bars for Concrete Reinforcement. In *Annual Book of ASTM Standards*, Vol. 01.04. West Conshohocken, PA, 2009.

3. Test Apparatus
    3.1. The test apparatus shall comply with the requirements of ASTM A370.

4. Test Specimens
    4.1. Test specimens shall be No. 4, 5, or 6 bars, with each bar having a length of 3 feet.

5. Procedure
    5.1. During bend testing, each steel type will be evaluated in accordance with ASTM A370 and when appropriate ASTM A615, ASTM A955, ASTM A1035, and AASHTO MP 13M/MP13-04. It is important to note that the resultant values can vary. Therefore, the appropriate criteria and standard must be applied for acceptance. Some example values are shown in Table L1. The composition of the candidate reinforcing bar will be used to determine which ASTM or AASHTO standard governs the bend testing acceptance criteria for the particular candidate bar. The composition will be based on the values supplied by the producer, which will have been confirmed using XRF.
    5.2. Upon completion of bend testing on AASHTO MP13 bars, the bars will be sectioned perpendicular to the bar at three locations around the bend to determine if unacceptable debonding has occurred between the clad layer and the carbon steel core. These sectioning locations should be at the center of the bend and the other two locations at the quarter points of the bend. After sectioning, both faces should be examined for voids between the clad layer and carbon steel core.

Table L1. Different bend test acceptance values for different bar types and sizes based on ASTM A615 (ASTM 2003), A955 (ASTM 2010a), and A1035 (ASTM 2009c).

Bar Designation No.	Pin Diameter			
	Grade 40[a,b]	**Grade 60[a,b]**	**Grade 75[a,b]**	**Other[c]**
3, 4, 5	31⁄2 d	31⁄2 d	---	31⁄2 d
6	5d	5d	5d	5d
7, 8	---	5d	5d	5d
9, 10, 11	---	7d	7d	7d
14, 18(90°)	---	9d	9d	9d
Test bends 180° unless noted otherwise; d = nominal diameter of specimen.				
[a] ASTM A615. [b] ASTM A955. [c] ASTM A1035.				

6. Calculations

6.1. Calculations will be performed in accordance with ASTM A370.

7. Report

7.1. Reporting will be performed in accordance with ASTM A370. Results from this test should be recorded on Table M1 in Appendix M.

APPENDIX M: BLANK SUMMARY DATA SHEET

Table M1. Summary of Test Data

Bar Type	Magnetic Properties	XRF Spectrum Gathered	Uniaxial Tensile Test	Bend Test	Hardness Test	Developmental Length Testing	Bar Finish	Corrosion Resistance Level (1–3)	Sensitivity to Intergranular Attack	Acceptable as CRR Yes/No
ASTM A1035										
Duplex SS										
316LN SS										