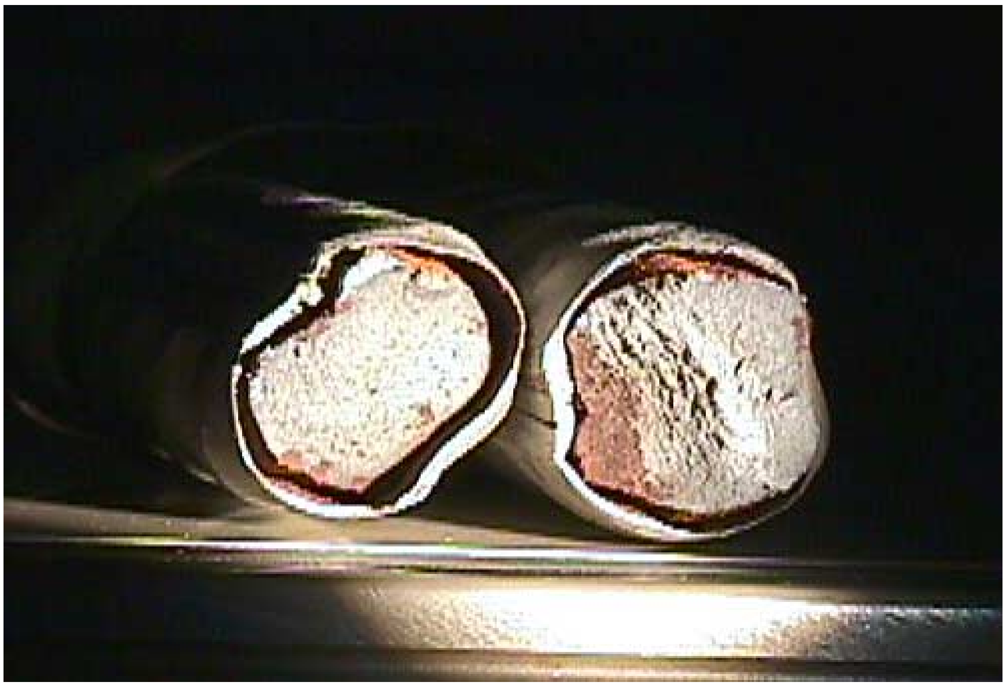
SD2000-04-F

South Dakota
Department of Transportation
Office of Research

U.S. Department of Transportation
Federal Highway Administration



Stainless Steel Clad Rebar in Bridge Decks

Study SD2000-04
Final Report

Department of Materials and Metallurgical Engineering
South Dakota School of Mines & Technology
Rapid City, SD 57701

November 2001

DISCLAIMER

ACKNOWLEDGEMENTS

This work was performed under the supervision of the SD2000-04 Technical Panel:

Mark Clausen .... FHWA
Tom Gilsrud .... Bridge Design
Todd Hertel.......................... Aberdeen Region
Brian Hines.. Research
Darin Hodges................ Materials & Surfacing
Dave Huft .... Research
Darin Larson..................... Operations Support
Paul Nelson................................ Pierre Region

The investigators wish to thank Mr. Frank Pianca of the Ontario Ministry of Transportation for providing samples of Nuovinox stainless steel clad reinforcement for laboratory testing. The work was performed in cooperation with the United States Department of Transportation Federal Highway Administration.

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
SD2000-04-F		

4. Title and Subtitle	5. Report Date
Stainless Steel Clad Rebar in Bridge Decks	November 15, 2001
	6. Performing Organization Code
7. Author(s) William M. Cross, Ed F. Duke, Jon J. Kellar, Ken N. Han, and Dan Johnston	8. Performing Organization Report No.
9. Performing Organization Name and Address South Dakota School of Mines and Technology 501 E. St. Joseph Street Rapid City, SD 57701-3995	10. Work Unit No. 11. Contract or Grant No. 310704
12. Sponsoring Agency Name and Address South Dakota Department of Transportation Office of Research 700 East Broadway Avenue Pierre, SD 57501-2586	13. Type of Report and Period Covered Final Report; March 2000 to November 2001 14. Sponsoring Agency Code HR0004

15. Supplementary Notes

An executive summary is published separately as SD2000-04-X.

16. Abstract

The corrosion resistance, mechanical properties, and cladding size and shape of a stainless steel clad (SSC) reinforcing bar (rebar) were investigated. For the mechanical property testing, the black steel core failed prior to the cladding. The mechanical properties examined were elongation, tensile strength and yield strength. The SSC rebar had greater elongation and tensile strength than the specifications, but the yield strength had a 33% probability of being less than the specification if the actual bar diameter of 0.76” was used.

The SSC rebar with end coating is estimated to give 50-60 years of life before damaging the concrete. Abrading the cladding reduced the life estimate by a few years, usually 1-5 years. Drilling a hole in the cladding, to simulate a break, significantly reduced the estimated life of the end coated SSC rebar by 15-40 years.

All samples exceeded the nominal bar size. The cladding was generally within specification, except for one failing measurement out of approximately 50 measurements. All examined samples exhibited a gap between the core and cladding. Cracking of the cladding would be similar to the corrosion test in which a hole was drilled in the cladding and would lead to a serious decrease in the life expectancy of the bridge deck compared to non-cracked clad SSC rebar. At the current time, the SSC rebar material is not recommended for use due to questions about its long-term mechanical durability.

17. Keywords	18. Distribution Statement
bridges, design and construction, testing, reinforced concrete, corrosion, bridge decks, reinforcing bars, reinforcing steel, stainless steel, corrosion resistant steel, corrosion resistance, corrosion protection, corrosion tests, mechanical properties, cladding, clad metals, tensile strength, yield strength, durability, chlorides, laboratory tests, impact tests, metal bonding, metallurgy	No restrictions. This document is available to the public from the sponsoring agency.

19. Security Classification (of this report)	20. Security Classification (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	55	

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EXECUTIVE SUMMARY

The ongoing problem of corrosion of reinforcing steel in bridge decks has been addressed in South Dakota with increased concrete cover and the use of epoxy-coated rebar (ECR). To date, these measures appear to have worked well in extending bridge deck life significantly. With the development of new materials and technologies, the potential for increasing deck life may be even greater. One of these new materials is stainless steel clad (SSC) reinforcement from Stelax, Ltd. that consists of black steel clad with 316L stainless steel during fabrication. The stainless steel cladding is much less susceptible to corrosion than black steel and may provide the means for preventing corrosion from deicing salts throughout the life of a structure.

The purpose of this research was to evaluate the potential corrosion resistance of both SSC and ECR using laboratory tests and, based on the results of these tests, design, construct and evaluate a bridge deck reinforced with SSC bars. The research was to provide information on the constructability and effectiveness of SSC bridge decks as well as performance and cost-effectiveness data on both SSC and ECR systems.

Research Objectives

Three primary objectives of this research were identified:

1) Determine the corrosion-resistance of SSC compared to ECR reinforcement as well as the mechanical properties, quality and suitability of SSC for use in bridge decks.

2) Develop design, construction, and evaluation procedures for building a bridge deck using SSC.

3) Estimate life expectancy and cost effectiveness of SSC, ECR and black steel reinforcement in South Dakota.

Thirteen tasks were outlined to achieve these objectives. The primary research tasks involved measuring the corrosion resistance of the material, determining its mechanical properties, and measuring the cladding thickness, bar size, and composition.

Mechanical Properties

For the mechanical property testing, Figure 1 shows a photograph of a tested bar. This photo indicates that the core and cladding behaved separately. The core failed prior to the cladding. The mechanical properties examined were elongation, tensile strength and yield strength. The SSC rebar had greater elongation and tensile strength than the specifications, but the yield strength had only a 67% probability of being greater than the specification if 0.76" was used as the bar diameter. The bar diameter was quite variable and could be anywhere from 0.70" to 0.78" for a bar of size #6, which should have a diameter of 0.75". For the Ontario Ministry of Transportation (MOT) #6 bar, the cladding thickness was never measured to be less than the specifications for the material.

Figure 1: Photograph of a tensile test failed SSC rebar

Corrosion Testing

Table 1 summarizes the corrosion data and gives the estimated time to failure for the concrete around the various types of rebar tested. The SSC rebar with end coating is estimated to give 50-60 years of life before damaging the concrete. Abrading the cladding reduced the life estimate by a few years, usually 1-5 years. Drilling a hole in the cladding significantly reduced the estimated life of the end coated SSC rebar by 15 to 40 years. The data in bold show those samples exhibiting sufficient life in a bridge deck.

Figure 2 shows a sample of #6 bar that was impact tested. Failure occurred at an area of corrosion within the core. The presence of corrosion within the core may indicate quality control problems in the production of this material.

Figure 3 shows a backscattered electron scanning electron microscopy (SEM0 image of the core/cladding interface. Of particular interest is the gap between the core and the cladding, which is shown in the lightest shade of gray. Table 2 shows the measured bar size, cladding thickness, and gap width for the samples. All samples exceeded the nominal bar size. The cladding was generally within the set specification, except for 1 failing measurement out of approximately 50 measurements. All examined samples exhibited a gap between the core and cladding, similar to that shown in Figure 3. This gap may be due to the sample preparation procedure, but is worrisome as the gap may lead to cracking of the cladding during use. The effect of cracking of the cladding would be similar to the corrosion test in which a hole was drilled in the cladding, and would lead to a serious decrease in the life expectancy of the bridge deck compared to non-cracked clad SSC rebar.

Table 1: Estimated Time to Concrete Failure Based On Corrosion Data

Sample Type		Time to Failure (Years)	
		High pH(12-13)	Low pH(5)
Black Steel		11	10.2
SSC Rebar	No End Coat	16	12
	Epoxy End Coat	**60**	**95**
	Stainless Spray Coat	25	11
	Mixed Weld End Coat	55	18
	T-55 Weld End Coat	55	14
	309 Weld End Coat	55	30
	No End Coat—Abraded	15	11
	No End Coat—1/16" Hole	16	12
	Epoxy End Coat—Abraded	55	**90**
	Epoxy End Coat—1/16" Hole	40	25
Time to Failure includes approximately 10-year buildup of NaCl before corrosion starts			

Figure 2: Impact-Tested #6 SSC Rebar Showing Massive Internal Corrosion

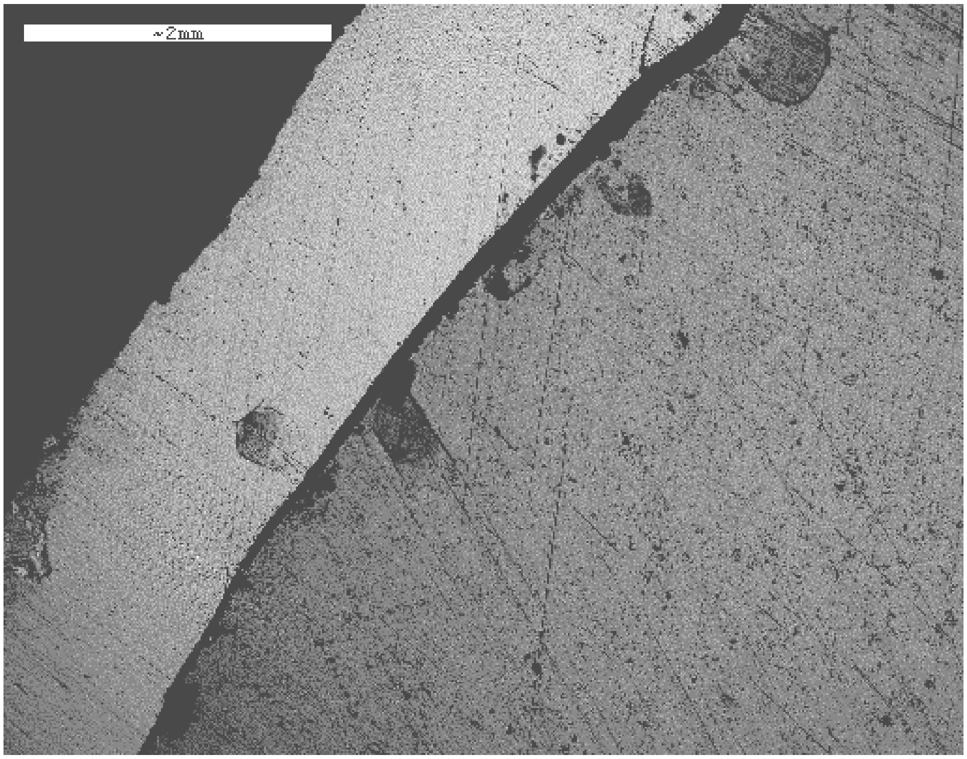

Figure 3: Backscatter SEM Image of Core/Cladding Interface

Table 2: Bar Size, Cladding Thickness and Gap Width for #10 and #6 Stainless Steel Clad Bars

Type	Bar Size	Cladding Thickness	Gap Width
#10 (1.25" nom.)	1.30" ± 0.01 (short axis) 1.40" ± 0.01 (long axis)	110 ± 20 mil	1-6 mil
#6 (0.75" nom.) Ontario	0.70" ± 0.02 (short axis) 0.78" ± 0.02 (long axis)	42 ± 5 mil 130 ± 10 mil	Not measured
#6 (0.75" nom.) Demonstration	0.78" ± 0.01 (short axis) 0.88" ± 0.01 (long axis)	45.5 ± 8 mil 53 ± 10 mil	1-6 mil

Conclusions

The material exhibited several problems that may have serious consequences in both the short- and long-term:

- *Lack of metallurgical bond between core and cladding*—This problem can lead to voids at the core-cladding interface. The full effect of these voids is hard to predict, but they could lead to premature cracking of the cladding and significantly reduce the resistance of the material to corrosion. All samples examined displayed a continuous gap at the core-cladding interface. These gaps were 30 to 150 µm (about 1-5 mils) in thickness. As the samples were cut prior to examination, the interfacial gap may be due to the cutting process. A sample was processed by cutting the cladding in one position and then pulling the cladding off with a pliers. The cladding was removed easily and the now exposed core-cladding interface indicated only 2-3 areas of core-cladding contact, making up 10-20% of the total possible contact area.

- *Failure to supply proper size samples and any size sample in a timely fashion*—At the outset of this project, the supplier promised to deliver 40 feet of #6 material in early April 2000, as a shipment of #6 stainless steel clad rebar was being made for the Florida DOT. Although Florida received material, SDDOT did not. The supplier then promised 40 feet of #8 size material in May. This material also was not shipped. Finally, 40 feet of #10 stainless steel clad rebar was received on June 9, 2000, far too late for much of the original planned testing to be finished by the June 23, 2000 deadline. Virginia DOT reported a similar problem that forced them to get samples from a finished bridge project in Ontario, Canada.

- *Quality control of material*—In particular, the cladding thickness varied by 30-50% (as measured by coefficient of variation). One area was found to be out of specification (less than 0.5 mm), although this may have been due to cutting the material. Furthermore, neither the #10 bar sent in June nor the demonstration piece of #6 material met the nominal size specification. The bars sent averaged about 10% greater in size than the ASTM specifications for #6 and #10 size bars. Also, conversations with the Ontario MOT indicated that it had received a mixture of 304 clad and 316L clad rebar when only the 316L clad material had been ordered. The 316L clad material is superior to the 304 in corrosion resistance but is more expensive. These concerns may be alleviated by the presence of an inspector during material production.

- *Possibility of internal corrosion*—During testing, one sample of the #6 demonstration bar was found to have a large area of internal corrosion within the black steel core. This internal corrosion did not appear to be linked to corrosion at the core-cladding interface. The internal corrosion created a weak spot that broke under an impact load of approximately 250 psi. Examination of other tested #6 samples indicated a few areas of minor internal corrosion. Internal corrosion was not observed on cut faces of the #10 material. The cause of the internal corrosion is not known at the present time. If the internal corrosion were present due to poor manufacturing, the presence of an inspector might help alleviate this problem. Also, we are currently trying to define a method by which any internal corrosion can be identified in the bar prior to placement in the bridge deck.

From a corrosion standpoint, the stainless steel clad rebar from Nuovinox/Stelax will last the required 75 years given adequate bridge maintenance and with endcapping. However, the mechanical behavior of the material over 75 years is less clear-cut. Most of the problems encountered appear to be solvable by having an inspector present during manufacturing. The one difficulty not able to be dealt with is the lack of metallurgical bond between the core and the cladding, which may lead to an interfacial gap. This gap may have severe consequences for the material's ability to last 75 years, as it may lead to cracking of the cladding and subsequent increased corrosion, causing severe cracking of the concrete and a decrease in the life of the bridge deck. Alternatively, the gap may have little if any effect on the life of the structure. Currently, the data do not exist to distinguish between these two alternatives.

Implementation Recommendations

1. Based upon this research, the use of the stainless steel clad rebar is **not** recommended. While the stainless steel clad material from Stelax, Ltd. appears to give sufficient corrosion resistance to achieve a 50-75 year life span if the ends are epoxy-coated or welded with a corrosion resistant material, the lack of metallurgical bonding between the cladding and core complicates the analysis to such an extent that the long term effects are difficult to predict. As the stability of the cladding over the life of the bridge deck can not be guaranteed, the stainless steel clad rebar should not be used. In addition, several problems with quality control of the SSC rebar again make the use of this material problematic.

2. If this material is used despite the above recommendation, an inspector should go to the manufacturing site and oversee the production of the stainless steel clad rebar for use in South Dakota bridge decks. Florida DOT did this and Virginia DOT is planning on doing this. An inspector might help alleviate some of the quality control issues mentioned previously.

3. It is recommended that alternative materials be tested for their corrosion resistance and other properties similar to the SSC rebar tested in this work. During the course of this work, several other corrosion resistant rebar materials were found and will soon be produced. In particular, a Texas company, SMI-CMC, is beginning to produce stainless steel clad rebar by the Osprey process. The Osprey process material has the advantage of creating a metallurgical bond between the stainless steel cladding and the black steel core. Also, the stainless steel can be clad at any thickness from approximately 1 mil to about 2 inches with very little variation in the film thickness. The anticipated cost for this material is about 2-5 times that of typical rebar. In addition to the Osprey process material, a California company, MMFX, is beginning production of two new types of corrosion resistant rebar material. These two material are a microcomposite steel with approximately 13% chromium and a dual-phase ferritic steel.

PROBLEM DESCRIPTION

The ongoing problem of corrosion of reinforcing steel in bridge decks has been addressed in South Dakota with increased concrete cover and the use of epoxy-coated rebars (ECR). To date, these measures appear to have worked well in extending bridge deck life significantly. With the development of new materials and technologies, the potential for increasing deck life may be even greater. One of these new materials is stainless steel clad (SSC) reinforcement from Stelax, Ltd. that consists of black steel clad with 316L stainless steel during fabrication. The stainless steel cladding is much less susceptible to corrosion than black steel and may provide the means for preventing corrosion from deicing salts throughout the life of a structure.

The literature on stainless steel corrosion identifies one ion as capable of causing pitting, stress corrosion cracking and intergranular corrosion in the 300 series of stainless steels. This ion is the chloride (Cl^-) ion. This susceptibility to chloride ion raises questions concerning the performance of SSC reinforcement over the estimated 75-year life of the proposed bridge deck. In addition, the cut bar ends have exposed black steel and will be much more likely to corrode than the rest of the bar without some form of end treatment to protect them. At the same time, questions have been raised concerning the performance of epoxy-coated reinforcement due to failures in high chloride environment within 3 years. Although the first epoxy-coated reinforcement bridge decks constructed in South Dakota exhibit no evidence of deterioration after more than twenty years, a recent attempt to evaluate their corrosion resistance in-situ was hampered by the low concentration of chloride ions at steel depth.

The purpose of this research was to evaluate the potential corrosion resistance of both SSC and ECR using laboratory tests and, based on the results of these tests, design, construct and evaluate a bridge deck reinforced with SSC bars. The research was to provide information on the constructability and effectiveness of SSC bridge decks as well as performance and cost-effectiveness data on both SSC and ECR systems.

RESEARCH OBJECTIVES

Three primary objectives of this research were identified.

1) Determine the corrosion-resistance of SSC compared to ECR reinforcement as well as the mechanical properties, quality and suitability of SSC for use in bridge decks.
2) Develop design, construction, and evaluation procedures for building a bridge deck using SSC.
3) Estimate life expectancy and cost effectiveness of SSC, ECR, and black steel reinforcement in South Dakota.

The second objective—to design, construct, and evaluate an actual bridge deck—was not pursued because the research performed to accomplish the first objective did not support the suitability of SSC in bridge decks.

TASK DESCRIPTION

This research plan was to be achieved by a team from South Dakota School of Mines and Technology and the South Dakota Department of Transportation cooperatively accomplishing the following tasks.

Task 1: Literature Search

Perform a literature search on 316L stainless steel and its use as reinforcement or as a cladding for reinforcement including a survey of any identified users of either form of stainless steel reinforcement.

Original Plan The work group at SDSM&T had primary responsibility for the review of available literature on corrosion testing of steel. This search was to be a computer-based search using the resources of the Deveraux library at SDSM&T. Once identified, the references were to be retrieved either locally or through inter-library loan. Dan Johnston of SDDOT's Office of Research was to supply available reference documents on the research topic and would attempt to obtain further information not available in the published literature, including a survey of other states including Maine, Wisconsin and New York. Prior to the beginning of this project, he had already obtained a draft specification for 316L stainless steel clad reinforcing for a bridge from Virginia DOT.

Alterations No alterations to the original plan for Task 1 were required.

Accomplishment The relevant literature was searched and more than 30 papers from the last 10 years and more than 50 including pre-1990 papers were found on the subject of stainless steel and rebar corrosion. Databases searched included the CARL (Colorado Association of Research Libraries) database and First Search. Most of this literature dealt with corrosion of either stainless steel or black steel. Only two new references to the corrosion resistance of stainless steel clad rebar were found. The first, "Performance of Corrosion Resisting Steels in Chloride-Bearing Concrete" by Rasheeduzzafar, Dakhil, Bader and Khan, ACI Materials Journal, vol. 89(5), pp 439-448, 1992, used stainless steel clad rebar in concrete samples made with 4, 8, and 32 lb/yd^3 of chloride. After 7 years of environmental exposure in eastern Saudi Arabia, no corrosion of the SSC rebar was found, and the concrete was not cracked. This behavior was much superior to black steel, galvanized steel at all chloride levels, and epoxy-coated rebar at 32 lb/yd^3 of chloride.

The second paper, "Corrosion Behavior of Stainless Steel Clad Rebar", by Cui, Sagues and Powers, was a draft obtained from Stelax, Ltd. Cui and Sagues are at the University of South Florida and Powers is with the Florida DOT. The conclusions of this Florida work are quite similar to those found here. Sound SSC has very high corrosion resistance but cladding breaks can significantly reduce the corrosion resistance. Modeling work indicated that widely spaced, sub-millimeter cladding breaks would not greatly reduce the corrosion resistance.

Task 2: Develop Work Plan

Cooperatively develop a work plan including a testing plan.

Original Plan The original work plan was based primarily upon two meetings of involved project members held December 28, 1999 and January 20, 2000 at the SDSM&T campus. Adjustments to the work plan were to be made after a review of preliminary data compiled after these meetings and after discussions with the technical panel to address any necessary modifications to the work plan.

Alterations No alterations to the original plan for Task 2 were required.

Accomplishments The work plan was developed in meetings held December 28, 1999 and January 20, 2000 on the SDSM&T campus. Adjustments to the work plan were made as described in the upcoming task descriptions.

Task 3: Meet with Technical Panel

Meet with the technical panel to discuss the project and scope of work plan.

Original Plan The research team was to meet with the technical panel to discuss the research shortly after the research contract was awarded.

Alterations No alterations to the original plan for Task 3 were required.

Accomplishments Dr. Cross met with the technical panel June 30, 2000 and discussed the project and the work plan.

Task 4: Conduct Laboratory Tests

Conduct a series of laboratory tests on SSC as outlined in the Virginia DOT draft specifications.

Original Plan Dan Johnston was to be responsible for determining the mechanical properties of the SSC material. These tests were to include determining the yield strength, tensile strength and elongation of the SSC rebar. The Virginia DOT specifications for these properties were minimum yield strength 420 MPa, minimum tensile strength 620 Mpa, and minimum elongation 9%.

The mechanical properties of the SSC rebar were to be measured by applying the procedures given in ASTM E-8. The yield strength, tensile strength and elongation were to be measured on 5 samples from 5 different bars to obtain a statistical representation of the properties. Also, the pull-out properties of the SSC rebar were to be measured.

SDSM&T was to be primarily responsible for the determination of the thickness and continuity of the cladding, and of the chemical composition of the cladding and core. These were to be determined by image analysis and SEM imaging for the thickness and continuity, and SEM elemental mapping and point analyses for the composition.

Alterations No alterations to the original plan for Task 4 were required.

Accomplishments The mechanical properties of the SSC rebar were determined from stress-strain curves obtained according to ASTM E-8. The SSC rebar used was obtained from the Ontario Ministry of Transportation (MOT) as the material obtained from Stelax, Ltd. did not fit in the testing machine. The elongation and tensile strength were greater than the Virginia DOT specifications. The tensile modulus exceeded the specifications when the nominal diameter was utilized, but not when the measured maximum diameter was used. Similar questions concerning the mechanical properties were found by Florida and Oregon DOTs. In addition, the failure of the tested bars was examined and the cladding and core were found to fail separately and in different manners. The cladding exhibited a more brittle failure than the core and a large gap was found between the cladding and core after mechanical testing.

As the thickness and continuity of cladding and chemical composition of both the cladding and core were also a primary concern of Task 7, these results will be presented in Task 7.

Task 5: Test Corrosion Resistance

Conduct a series of statistically valid comparative tests of corrosion resistance on SSC/ECR/316L and black steel reinforcement, all both with and without defects, to determine general corrosion properties both inside and outside concrete, stress and pitting corrosion properties and end treatment effectiveness and provide recommendation for end treatment.

<u>Original Plan</u> SDSM&T was to be primarily responsible for the completion of this task. At least 4 samples of the various reinforcement materials were to be tested by polarization resistance under a variety of solution conditions to determine their corrosion resistance outside of concrete. Also, SSC was to be subjected to thermal cycling to examine the effect of thermal mismatch on this reinforcement. For in-concrete testing, mortar cubes (2" sides) were to be made containing a 1" piece of reinforcement. The corrosion behavior was to be measured using copper/copper sulfate half-cell potential measurements and linear polarization. End treatments considered were none, epoxy-coated, metallized ends, and welded stainless steel. The effectiveness of the end treatments was to be determined primarily without concrete.

The life of the reinforcement material was to be estimated by comparison with known values for black steel reinforcement and from the corrosion data obtained, particularly from polarization resistance measurements. Galvanic testing between SSC and black steel were to be performed. Also, minimum potentiostatic testing of the stainless steel clad material was to be performed to determine conditions for pitting corrosion occurrence. This was to be performed at pH13 with different chloride ion concentrations.

<u>Corrosion Testing</u>

Corrosion testing of concrete reinforcing materials goes back at least 30 years, and several test methods have been developed. For this work the corrosion testing of the various reinforcing materials was to be performed in the following manner:

Table 3: Corrosion Testing Variables

Characteristic	Values
Reinforcing Materials	SSC, ECR, Black Steel, 316L stainless steel
Stress State	Unstressed, Stressed (either bent or loaded to ultimate tensile strength)
Coating	As Received, With Hole, Abraded
Aqueous Solution pH	5, 7, 9, 11, 13—controlled by NaOH addition or by bubbling CO2 gas through solution
Solution Composition	3 % NaCl, constant ionic strength ~0.4, room temperature
Thermal Treatment	none, SSC bars will be subject to repeated thermal cycling between 273 K and 373 K to examine effect of thermal expansion mismatch
End Capping	None, Epoxy Coating, Welded Stainless Steel, Metallized End
Measurement Technique	Polarization Resistance (PR), Weight Loss

The following test cycle was envisioned. Sets of four specimens of each reinforcement were to be suspended in the test solution for 1.25 hours then removed from the solution and air-dried for 4.75 hours. These 6-hour cycles were to be repeated over a 28-day test period giving a total of 112 cycles. Polarization resistance measurements were to occur while the specimens were in solution and after 1, 7, 14, 21 and 28 days. The measured corrosion rate could then be directly related to the loss of metal and the service life of the stainless steel coating could be estimated. The test cycle was to be automatically controlled through the use of linear actuators.

As the ultimate goal of this research was to understand the corrosion behavior of reinforcements within concrete structures such as bridge decks, the SSC rebar, ECR and black steel were to be examined within cement mortars subject to corrosive environments. Cement mortar cubes were to be made according to ASTM C-109. These cubes were to be 2” on each side and have a sand-to-cement ratio of 2.75 and a water-to-cement ratio of 0.485. A 1” piece of the appropriate rebar was to be placed at the center of the cube and the sample cured according to ASTM C192. The mortar cubes were to be vacuum saturated with and placed in solutions similar to those used for direct rebar corrosion testing, then cycled into and out of solution just as the metal bars were in direct rebar corrosion testing. The method for evaluating the corrosion during testing was to be half-cell measurements performed according to ASTM C876. In this test the potential of the rebar would be measured with respect to a copper/copper sulfate half-cell.

Service Life Estimation

Service life can be estimated in two ways. First, for the stainless steel clad bars, the time for the cladding material to be corroded can be calculated as follows. From the corrosion current found by polarization resistance, the mass loss can be calculated. From this mass loss and the density of the stainless steel (~8 g/cm^3), the volumetric loss is calculated. The volumetric loss then yields a thickness loss because the size and shape of the test sample is known. As the initial thickness of the cladding will be measured, the time for complete corrosion of the cladding is found by division of the initial thickness by the rate of thickness loss.

Second, for all materials, the corrosion of the rebar and the subsequent buildup of corrosion byproducts can crack the concrete. McDonald et al. (1996) show typical values of metal loss for cracking to occur. These values range from 0.0013 to 0.038 mm, with an average of 0.014 mm. Thus, using the thickness loss, the time to cracking can be determined. Table 4 shows the current density values that give various years until failure assuming 1 mil of corrosion causes cracking

Table 4: Estimated Time to Cracking for Various Current Density and PR Values

Years required for 0.0254 mm (0.001 in) metal loss and concrete cracking	Average current densities		Average PR, $ohm*m^2$
	A/m^2	mA/ft^2	
1	0.02180	2.030	1.19
10	0.00220	0.200	11.92
50	0.00040	0.040	60.47
75	0.00029	0.027	89.4
100	0.00022	0.020	119.2

Life Cycle Cost Estimation

A life cycle cost analysis model developed as part of an FHWA research project on bridge painting was to be used to determine life cycle cost parameters for stainless steel clad, epoxy-coated and black steel reinforcement. The model is described in *Issues Impacting Bridge Painting: An Overview* by T. Bernicki et al. of Northwestern University. The model is based on computing the equivalent uniform annual cost (EUAC) and allows comparison of alternative choices on the basis of initial cost per square foot and expected life. The effects of interest rate, inflation, present and future worth and maintenance over a projected life are considered in the model and can be applied to reinforcement type with only slight modification. The best aspect of this model is its graphical output, which allows direct visual comparison of alternatives based on initial cost, required maintenance, the current interest rate, and the current rate of inflation over the projected life of each system.

Alterations Due to problems in delivery of SSC rebar to be tested, a revised testing protocol was performed to enable recommendations to be made by the deadline of the technical panel meeting of June 30, 2000. At the start of this work, the supplier was contacted and 40 feet of #6 size bar was requested. The supplier indicated that the bar would be supplied within 2-4 weeks as the supplier was finishing an order for Florida DOT of the same size and type material and that SDDOT’s 40 feet could be made at the end of the Florida DOT run. After approximately 5 weeks, the supplier was again contacted about the material. There was no #6 bar for this work; instead, the supplier was now making #8 bar and could send the required amount in about 2 weeks at the end of the current run. This material was not sent either. Finally, 40 feet of #10 bar was received on June 9, 2000. This was far too late for the original testing plan to be completed, as the tests lasted 28 days. Therefore, an accelerated program was initiated using a small amount of nominally #6 bar that had originally been intended as an illustrative piece.

The accelerated testing protocol utilized was as follows: 1” sections were cut from a piece of #6 stainless steel clad reinforcing bar given to SDDOT to demonstrate the product. Two of these sections were not end-capped, two were end-capped with an epoxy coating, and two were coated in 316L stainless steel. These sections and two pieces of #6 black bar were corrosion tested in a 3% NaCl solution at pH6 and at 60 °C. To help accelerate the corrosion, the samples were dipped into the solution for 2 hours and then removed from solution for 4 hours. This cycle was repeated continually for the duration of the test. These tests were performed for approximately 10 days to estimate the corrosion resistance of the stainless steel clad reinforcing bar.

Finally, following meeting with the technical panel in conjunction with Task 8, the researchers were requested to suspend further investigation following the completion of the experiments then being performed. Therefore, neither testing of the epoxy-coated rebar nor the in-concrete testing was performed, as the final group of experiments was the PR testing of the bars outside of concrete. Also, testing of SSC rebar was limited to pHvalues of 5 and 12.5 due to this requested suspension of work.

<u>Accomplishments</u> With epoxy end coating the estimated life of the SSC rebar in bridge decks was approximately 60-90 years, depending upon the pH. Abrasion did not significantly reduce the estimated life at either pH5 or 12.5. Welded end caps did not exhibit significantly different behavior at pH12.5, but they performed poorly at pH5. A stainless steel spray coat proved to be little more effective than no coating at all. SSC rebar with uncoated ends was not significantly superior to simply using standard black steel. Drilling a 1/16" hole in the cladding reduced the life estimate at pH12.5 by about 33% to 40 years. At pH5, the 1/16" hole in the cladding reduced the life estimate by about 75% to 25 years.

There was little difference between the predicted lives of the 316L coated rebar and the 304 coated rebar tested using the accelerated testing protocol. The 304 coated rebar did, as expected, show slightly more corrosion than the 316L stainless steel coated rebar. However, the conditions were not the same so that the accelerated testing protocol was assumed to be equivalent to the pH12.5 testing protocol to determine the life expectancy.

Task 6: Analyze Corrosion Effects

Analyze corrosion effects on all types of steel tested as well as interfacial effects on SSC and ECR using scanning electron microscopy.

<u>Original Plan</u> SDSM&T was to be primarily responsible for completion of this task. All samples were to be autopsied by SEM after treatment to determine any structural or morphological changes or by-products produced by corrosion testing. This was to include elemental mapping and visual consideration of images.

Following corrosion testing, the metal samples were to be examined by scanning electron microscopy (SEM) to investigate the effects of corrosion on the structure and composition of the metal. Digital images were to be acquired at a range of magnifications appropriate to show the surface morphology and the structure of the steel both before and after testing. In particular, the surface of the bars was to be examined before and after corrosion testing to document the extent, physical appearance and elemental composition of uncorroded and corroded surfaces. Polished cross-sections of the metal were to be prepared from samples before and after testing to determine the elemental composition, and the advance of corrosion with respect to the pre-test surface.

<u>Alterations</u> Due to the recommendations of the technical panel following receipt of the technical memorandum in Task 8, only the accelerated test protocol samples were examined by SEM.

Accomplishments Preliminary analysis of the pre-corrosion samples and some of the post-corrosion samples was performed, but as little was done prior to the decision of the technical panel to end the research project soon after the June 30, 2000 meeting, the examination of corrosion effects was stopped. Therefore, the analysis performed for this task only considers the first set of accelerated samples run under solution conditions of pH6, 3% NaCl and 60°C. The primary corrosion by-product was iron oxide as expected. No major differences were found in the composition of the core. Also some of the samples tested exhibited internal corrosion prior to testing. This is indicative of poor steel quality and would be expected to have deleterious effects on the performance of the SSC rebar.

Task 7: Evaluate Cladding Uniformity, Thickness Variability, and Deformation Effects

Provide evaluation of cladding uniformity, thickness variability and effects due to deformation profile on #4, #5 and #6 reinforcement randomly obtained.

Original Plan SDSM&T was to be primarily responsible for this task. To achieve the objectives of this research project several other test procedures needed to be performed. The stainless steel cladding needed be examined to measure the continuity, thickness and composition. These experiments were to be performed by SEM and image analysis. The composition measurement has already been described. For the continuity and thickness measurements, at least 5 pieces from 5 different SSC bars were to be obtained. The continuity was to be determined by visual examination of the image analysis and SEM images to ensure that all black steel core was covered with cladding. Thickness measurements were to be performed from the same images as continuity analysis. The cladding thickness was to be determined from at least 4 points on each image. The cladding thickness determined by SEM and image analysis was to be compared to that found by magnetic thickness gage measurements, to determine if the gage will work as a field test procedure.

Alterations Due to the recommendations of the technical panel following receipt of the technical memorandum in Task 8 and the receipt of #10 bar rather than #6 bar, the uniformity and cladding thickness were measured primarily on #10 and a demonstration piece #6 bar. As field measurements were not to be undertaken, no comparisons of thickness measurements to magnetic gage measurements were performed.

Accomplishments Pull-away of the cladding from the core and large differences in cladding thickness were found for the demonstration #6 bar. The average cladding thickness for sample 1 was 1152.5 μm (about 45.5 mil) with a coefficient of variation of 42%. The smallest thickness measured was 261 μm, about half the minimum specification. For sample 2, the average cladding thickness was 1349 μm (about 53 mil) with a coefficient of variation of 55.6%. The smallest cladding thickness measured on this sample was 550 μm. For the demonstration #6 bar, the short axis diameter was 0.778" and the long axis diameter 0.885", with a coefficient of variation of 1.5 and 3.8%, respectively. These axis diameters are both greater than the 0.75" nominal diameter for #6 bar.

The cladding thickness for the #10 bar was found to be 2.719 mm (about 0.11") with a coefficient of variation of 34%. The long and short axis diameters were determined to be 1.30" and 1.40", respectively. The coefficient of variation of the diameters were both less than 1%. The nominal diameter for a #10 bar is 1.25". Once again, the supplied material was slightly larger than the nominal diameter for the specified size. The #6 bar obtained from Ontario MOT did appear to be closer to the nominal size than the demonstration bar, but the bar size was variable between 0.70" and 0.78". The thinnest cladding areas always appeared at the transition point between the short axis and long axis.

Task 8: Interim Report

Submit an interim report no later than June 23, 2000 estimating SSC and concrete service life and providing a recommendation of whether SSC should be incorporated into a bridge deck including any necessary modifications to design or construction procedures as well as a preferred concrete mix design to maximize performance. If the recommendation is not to use SSC, tasks 9-11 need not be accomplished.

Original Plan This task was to be accomplished by both SDSM&T and SDDOT based on the findings in tasks 4-7. The recommended concrete mix design was to be based on a thorough literature search, laboratory testing and the preliminary results of SD2000-06 *Optimized Fly Ash Content in PCC for Structures.* Recommendations for appropriate materials for use as ties and chairs were to be included along with any construction procedure modifications required were to be included in the Technical Memorandum. Potential problems with galvanic corrosion between SSC reinforcement and any substructure steel were to be addressed to minimize these problems.

Alterations No alterations to this task were necessary.

Accomplishments An interim report was submitted on June 23, 2000 prior to the meeting with the technical panel on June 30, 2000. Following this meeting, the technical panel recommended that experimental work be suspended on this project.

Task 9: Develop Long-Term Evaluation Plan

Develop a long-term evaluation plan, including any plan notes required for installation of testing instrumentation or samples, if necessary.

Original Plan Both SDSM&T and SDDOT were to be involved in developing a long-term evaluation plan based on the in-concrete research in task 5. Proposed in-place monitoring equipment consisted of three or more system negative connections (#8 AWG wires connected to the reinforcement and strung to three access ports along the edge of the structure, depending on the deck design, with the connections coated with nonconductive epoxy) for measuring $Cu/CuSO_4$ half-cell potentials. Six probes comprising a short length of SSC #4 rebar tied to an equal length of the same size epoxy-coated or black steel (three of each) were to be installed near the surface of the deck with #8 AWG wires run from each of the bars to access ports to determine whether any galvanic corrosion was taking place. Three conductivity probes (developed as part of SD98-06 *High Performance Concrete Structures*) were also to be wired to the top mat of reinforcement to monitor concrete permeability in the deck over time.

Alterations Due to the recommendations of the technical panel following receipt of the technical memorandum in Task 8, this task was not undertaken.

Task 10: Monitor Construction

Monitor construction to observe constructability and insure any in-place monitoring equipment is properly installed.

Original Plan The constructability evaluation was to be primarily the responsibility of SDDOT, while the in-place monitoring equipment installation was to be supervised by both SDDOT and SDSM&T personnel. In addition, concrete test cylinders and beams were to be prepared during construction for measuring compressive and flexural strengths at 7, 14, 28 and 90 days. Relative humidity, temperature and wind speed were to be monitored throughout construction. Any deviations from standard construction procedures or problems with construction were to be documented.

Prior to construction, a calibrated magnetic thickness gauge was to be used to randomly sample cladding thickness on reinforcement throughout the deck area. Any reinforcement not meeting the specification minimum of 0.5 mm was to be rejected. If sufficient failures were found during the random sampling, a systematic survey of cladding thickness on all reinforcement was to be conducted to determine the actual extent of the problem.

Alterations Due to the recommendations of the technical panel following receipt of the technical memorandum in Task 8, this task was not undertaken.

Task 11: Evaluate Structure

Perform evaluation of structure during the first year after construction.

Original Plan Structural evaluation was to be performed by SDDOT. It was to include a $Cu/CuSO_4$ half-cell potential survey immediately after construction was completed and the following spring and summer. Cracking surveys were to be made as soon as practicable after construction, during midwinter and the following spring and summer. Additional surveys of either type were to be conducted as needed either by Mr. Dan Johnston or other SDDOT personnel. During this same period, conductivity and galvanic corrosion readings were to be obtained with additional readings taken on a monthly basis until August 2002.

Alterations Due to the recommendations of the technical panel following receipt of the technical memorandum in Task 8, this task was not undertaken.

Task 12: Final Report

Make an executive presentation to the SDDOT Research Review Board at the conclusion of the project.

Original Plan The research team was to make an executive presentation of the research findings, conclusions, and recommendations at the completion of this project. This presentation was to occur in Pierre, SD.

Alterations No alterations to this task were necessary.

Accomplishments An executive presentation was made to the SDDOT Research Review Board on August 17, 2000.

FINDINGS

Mechanical & Physical Properties

The mechanical properties of the SSC rebar were determined from stress-strain curves obtained according to ASTM E-8. The material tested was obtained from the Ontario Ministry of Transportation (MOT) as Stelax, Ltd. did not supply material of the proper size for mechanical property testing. Figure 4 shows a generic stress-strain curve and the definition of the specific properties found. The specifications to which the data were compared are as follows: elongation 9% minimum, yield strength 420 MPa minimum and tensile strength 620 MPa minimum.

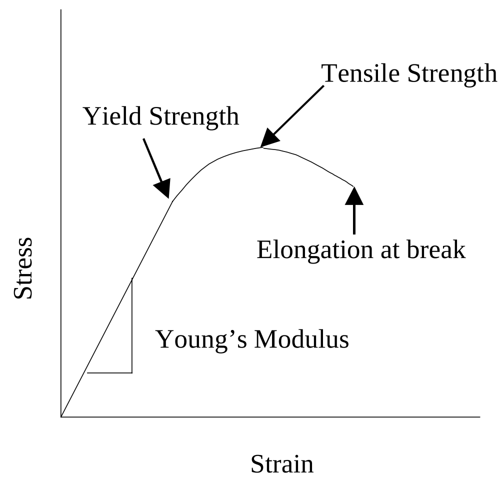

Figure 4: Typical Stress-Strain Curve with Definitions of Mechanical Properties

Table 5 contains the mechanical property data obtained from testing 12 approximately 2'-long sections of SSC rebar. To determine whether or not the material exceeded the specifications, each mean value was tested versus the specification through the use of inferential statistics. A one-sided, unknown variance test was used to evaluate whether the null hypothesis (mean≤specification) or the alternate hypothesis (mean>specification) was supported statistically. This evaluation was performed at the 95% confidence level. In Table 5, the row called 95% confidence gives these results.

For the elongation, nominal yield strength, nominal tensile strength, and 0.76" tensile strength, the mean value determined is greater than the specification. The nominal yield and tensile strengths are calculated using the nominal diameter of 0.75" for #6 rebar. As subsequent measurements (results given later) indicate that the bar is somewhat elliptical with an average diameter of ~0.76", the 0.76" yield and tensile strengths use this diameter rather than 0.75". The p-value row indicates the probability that the mean is extreme or more extreme than the observed value, assuming the null hypothesis is true. Therefore, a small p-value indicates that the observed mean is unlikely to be equal to the specification. The P-value can be thought of as the probability that the mean is equal to the specification. Thus, the 0.76" yield strength has about a 33% probability of being less than or equal to 420 MPa or, conversely, a 67% probability of being greater than 420 MPa.

Table 5: Mechanical Testing Data

Sample	Elongation (%)	Nominal Yield Strength (MPa)	Nominal Tensile Strength (MPa)	0.76" Yield Strength (MPa)	0.76" Tensile Strength (MPa)
1	19	**405.9**	624.4	**395.2**	**608.0**
2	15	429.3	671.3	**418.0**	653.7
3	15	429.3	640.0	**418.0**	623.3
4	18	429.3	640.0	**418.0**	623.3
5	22	429.3	624.4	**418.0**	**608.1**
6	21	429.3	640.0	**418.0**	623.3
7	20	432.4	640.0	421.1	623.3
8	21	437.1	640.0	425.6	623.3
9	20	437.1	655.6	425.6	638.5
10	20	429.3	655.6	**418.0**	638.5
11	20	437.1	655.6	425.6	638.5
12	20	437.1	655.6	425.6	638.5
Specification	9	420	620	420	620
Mean	19.25	430.2	645.2	**418.9**	628.3
p-Value	2.9×10^{-9}	0.0008	2.9×10^{-5}	0.3312	0.0279
95% Confidence	Mean>spec.	Mean>spec.	Mean>spec.	Mean=spec.	Mean>spec.
(Bold values indicate values lower than the minimum specification)					

Therefore, most of the mechanical properties of the SSC rebar meet the specifications. However, yield strength has a fairly high probability of being less than the specification. For instance, 7 of the 12 SSC samples tested failed the yield strength criteria when 0.76" was used as the bar diameter. Difficulties in meeting strength criteria were also reported by Oregon and Florida DOTs.

The mode of failure of the SSC rebar during tensile testing is also of interest. First, the core failed prior to the cladding. This failure produced an audible sound and led to significant deformation of the cladding prior to its failure. Figure 5 and Figure 6 show typical SSC rebar failure following tensile testing. Both Figure 5 and Figure 6 show that during testing

1) both the rebar core and the stainless steel have undergone brittle failure, and

2) the stainless steel cladding has pulled away from the black steel core.

This second point is shown by the dark ring between the cladding and core. This finding is most likely due to the cladding and core not being metallurgically bonded and therefore acting separately during loading. This may be a severe problem during use in a bridge deck as the SSC rebar will be subject to a variety of stress states and temperatures during service. Over time, gaps may develop between the core and cladding, which will cause the cladding to be unsupported and therefore forced to support much of the load the rebar is to support. This loading may eventually cause the cladding to crack, leading to a state in which the black steel core is exposed to concrete pore solution and high NaCl solutions. This would then lead to the SSC rebar exhibiting a much shorter than expected life due to the premature corrosion of the core. Examination of Figure 5 shows some corrosion between the core and cladding. The effect of breached cladding on the corrosion response of the SSC rebar is dealt with in the next section.

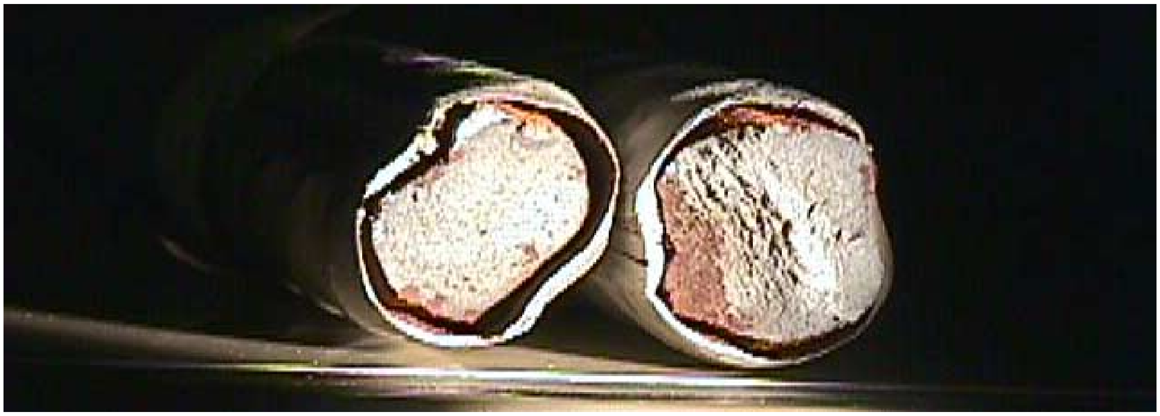

Figure 5: Photograph of Tensile Test Failed SSC Rebar

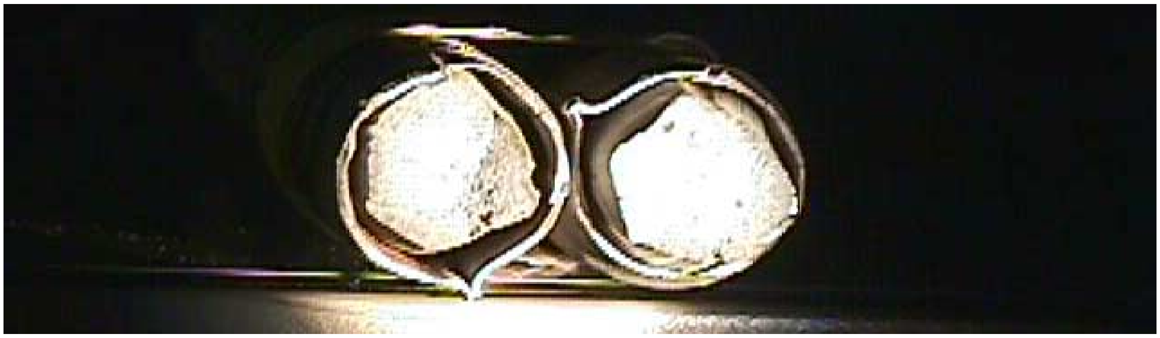

Figure 6: Photograph of Another Tensile Test Failed SSC Rebar

<u>Cladding Thickness and Continuity</u>

Samples of both #6 and #10 stainless steel clad material were examined to determine their nominal size, cladding thickness, core homogeneity and thickness of gap between core and cladding. Figure 7 shows one of the #6 samples used.

Figure 7: Cut Surface a #6 SSC Bar

Large differences in cladding thickness are evident from Figure 7. In addition, some pull away of the cladding from the core is also evident. The cladding thickness was measured using image analysis. For one sample, 27 measurements were taken; for the second sample, 15 measurements were obtained. The average cladding thickness for sample 1 was 1152.5 μm (about 45.5 mil) with a coefficient of variation of 42%. The smallest thickness measured was 261 μm, about half the minimum specification. For sample 2, the average cladding thickness was 1349 μm (about 53 mil) with a coefficient of variation of 55.6%. The smallest cladding thickness measured on this sample was 550 μm.

The grain size was found to be about 160 μm (about 6.3 mils) for both the central and edge areas of the core. However, the coefficient of variation in both areas was very high (about 25%), indicating some heterogeneity of the core material. The total diameter of the SSC material was measured on both the short and long axes, as the bars were slightly ellipsoidal in cross-section. For the #6 bar, the short axis diameter was 0.778" and the long axis diameter 0.885", with a coefficient of variation of 1.5 and 3.8%, respectively. These axis diameters are both greater than the 0.75" nominal diameter for #6 bar.

Excepting the grain size measurements, the same measurements were made on the #10 size bar. Figure 21 shows a photograph of the #10 bar after sectioning and impact testing. The cladding thickness for the #10 bar was found to be 2.719 mm (about 0.11"), with a coefficient of variation of 34%. The long and short axis diameters were determined to be 1.30" and 1.40", respectively. The coefficient of variation of the diameters were both less than 1%. The nominal diameter for a #10 bar is 1.25". Once again, the supplied material was slightly larger than the nominal diameter for the specified size.

Table 6 shows a compilation of the bar size, cladding thickness and gap width for the samples tested. The #6 bar obtained from Ontario MOT does appear to be closer to the nominal size than the demonstration bar, but the bar size is variable, as the average diameters are 0.70" for the short axis and 0.78" for the long axis. Also, for the Ontario MOT #6 bar, the cladding was never measured to be less than the specifications for the material. The thinnest cladding areas always appeared at the transition point between the short axis and long axis.

Table 6: Bar Size, Cladding Thickness, and Gap Width for #10 and #6 Stainless Steel Clad Bars

Type	Bar Size	Cladding Thickness	Gap Width
#10 (1.25" nom.)	1.30" ± 0.01 (short axis) 1.40" ± 0.01 (long axis)	0.11" ± 0.02	1-6 mil
#6 (0.75" nom.) Ontario	0.70" ± 0.02 (short axis) 0.78" ± 0.02 (long axis)	42 ± 5 mil 130 ± 10 mil	Not measured
#6 (0.75" nom.) Demonstration	0.78" ± 0.01 (short axis) 0.88" ± 0.01 (long axis)	45.5 ± 8 mil 53 ± 10 mil	1-6 mil

The cladding composition for the #6 (demonstration) and #10 bar were measured by quantitative SEM. The #6 Ontario MOT bar was not measured for composition for this work. However, Ontario MOT did measure the composition of some of their bars. Initially, the bars sent were found to be 304 stainless steel, but were replaced by 316 clad SSC rebar. From the SEM composition data in Table 7, the demonstration bar is clearly 304L stainless steel as evidenced by the lack of molybdenum in the #6 bar cladding. The #10 bar was found to be 316L stainless steel. Interestingly, the corrosion behavior was not much different for the #6 and #10 bars, which was not expected given the conditions used in the corrosion tests, where the 316L should outperform the 304L. This may be due to the carbide inclusions observed in the SEM work.

Table 7: Cladding Composition

Sample	Ni	Mn	Cr	Mo	Fe
316L Specs	10-15 %	2 % max	16-18 %	2-3 %	Bal.
304L Specs	8-13 %	2 % max	18-20 %	0 %	Bal
#6 Bar	11.1 %	1.3 %	18 %	0 %	~70 %
#10 Bar	10 %	1.2 %	17.1 %	2.3 %	~67 %
#10 bar also contained about 2.5% Si					

Corrosion Testing

Due to problems in delivery of SSC rebar to be tested, a revised testing protocol was devised to enable recommendations to be made by the deadline of the technical panel meeting of June 30, 2000. As no other sample was available, a test sample of SSC rebar that had been given by Stelax, Ltd. to SDDOT as a demonstration piece was used for initial corrosion testing. This piece was supposed to be clad with 316 stainless steel. Subsequent analysis indicated that this sample was actually clad in type 304 stainless. Substitution of 304 for 316 stainless steel was also found by the Ontario Ministry of Transportation (MOT) in Canada when using SSC rebar for a bridge deck. The Ontario MOT also supplied SDDOT with samples of #6 size SSC rebar for mechanical testing, as the #10 size bar would not work in the SDDOT testing machines.

<u>Description of Polarization Resistance Tests</u>

Polarization resistance (PR) testing of metals to determine their corrosion resistance is a well-established practice with roots going back nearly 50 years. PR testing has proven to be the most useful method for determining corrosion rates in both research and practical application areas. PR testing is fast (usually only a few minutes per test), highly sensitive, and nondestructive. Thus, repeated tests can be performed on the same sample and acceleration methods are often unnecessary.

The rebar samples (both unclad and stainless steel clad) were cut into 1-inch long sections by RPM and Associates using a chop saw. The cut samples were examined for any surface irregularities caused by the cutting process and, when found, these irregularities were removed by grinding. Next, the flat section of the cladding surface (see Figure 7 and Figure 20) was located and a 5/8” diameter hole was drilled partway into the cladding (Figure 8). The cladding was not drilled completely through in this case, to minimize any possible problems that might be caused by internal galvanic interactions at the core/cladding interface.

Once these holes were drilled in the cladding, an electrical connection was made to the cladding by inserting a prepared wire into the hole. The connecting wire was prepared from plastic-coated 14-gauge stranded (20 strands) copper wire. This wire was soldered to a 16 mm long by 5/8” diameter brass linoleum nail (Elco Industries, Goodlettsville, TN) using No. 5 lead-free solder (Oatey, Cleveland OH). Figure 9 shows the wire/nail assembly. The wire/nail assembly was fixed to the rebar sample by placing the nail tip in the cladding hole and giving the nail head 2-3 taps with a hammer to fix the nail in the hole.

After all the samples had electrical connections, the connections were sealed so that water would not get into the hole and alter the corrosion behavior. Sealing was done by applying a two-part plumbing/marine epoxy (Ace Hardware, Oak Brook IL) to the junction, around the wire, and onto a small portion of the flat cladding area. The epoxy was allowed to cure for at least 24 hours before the rebar was subject to corrosion testing. Figure 10 shows examples of the electrical connections attached to rebar samples. Once all the samples had sealed electrical connections, corrosion testing was begun.

RPM and Associates (Rapid City) built a multiple sample corrosion testing apparatus (Figure 12) with large capacity for this project. This apparatus allowed for 60 tests to be run simultaneously and for the samples to be cycled in and out of the corrosion solution for any desired time period. Plastic sheeting was used to prevent ambient dust from entering the test area and contaminating the test solutions.

To begin testing, samples had to be suspended above the test solution. This was done by tying a piece of 20-pound test nylon fishing line tightly around the cladding. Four samples were placed in each test solution, and were hung at different height levels. Corrosion of the test samples occurred as described in Task 5 and in the corrosion testing section of the Findings and Conclusions section.

Corrosion testing was performed at the end of the in-solution portion of the test cycle. The bucket with its four samples was carried to the room in which the potentiostat was located (Figure 13). A glass cell was used to hold the counter (platinum mesh) and reference (saturated calomel) electrodes. No capillary holder for the reference electrode was necessary as the solution conductivity was very large due to the NaCl concentration. The test sample (working electrode) was suspended in the glass cell (see Figure 11) and the glass cell was placed into the test solution. Thus, each electrode was approximately the same distance apart for every corrosion test performed. All three electrodes were connected to the potentiostat and the system was given a few minutes to come to rest. After the rest potential was obtained, the polarization resistance test protocol was begun, and the polarization resistance curves were obtained. This procedure was followed for all samples on which polarization testing was performed.

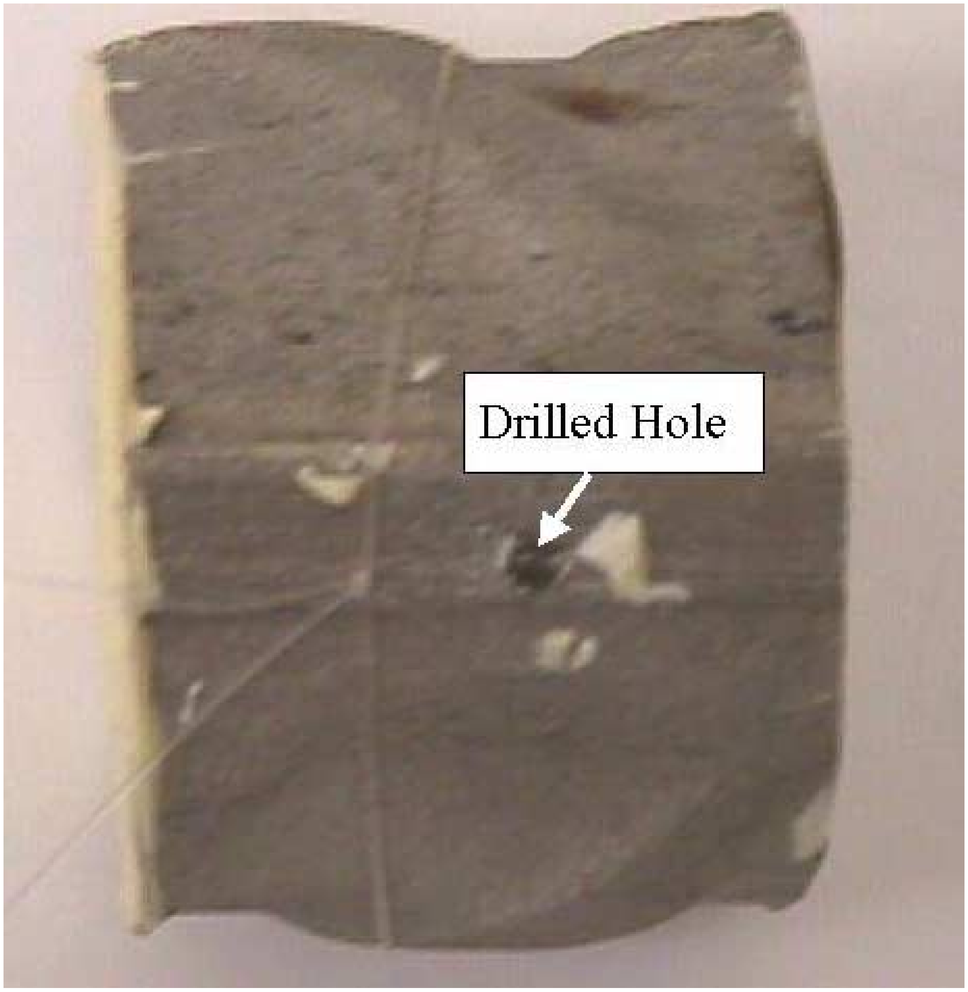

Figure 8: Stainless Steel Clad Rebar Showing Hole Drilled in Flat Portion of Cladding

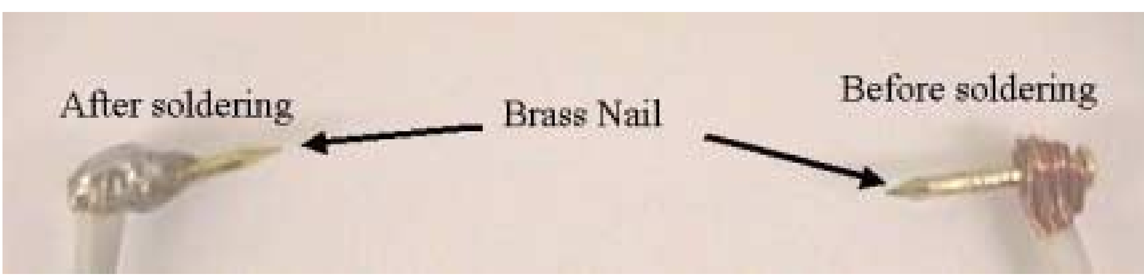

Figure 9: Wire/Nail Assembly Before and After Soldering.

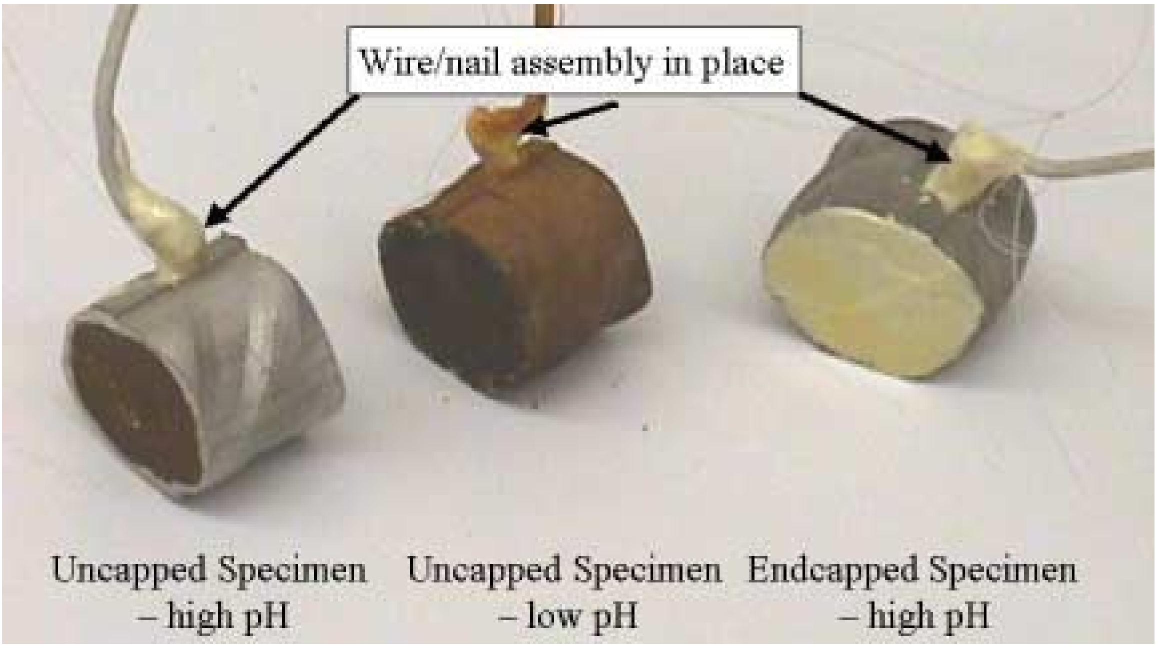

Figure 10: Test Samples of Stainless Steel Clad Rebar with Wire/Nail Assembly in Place

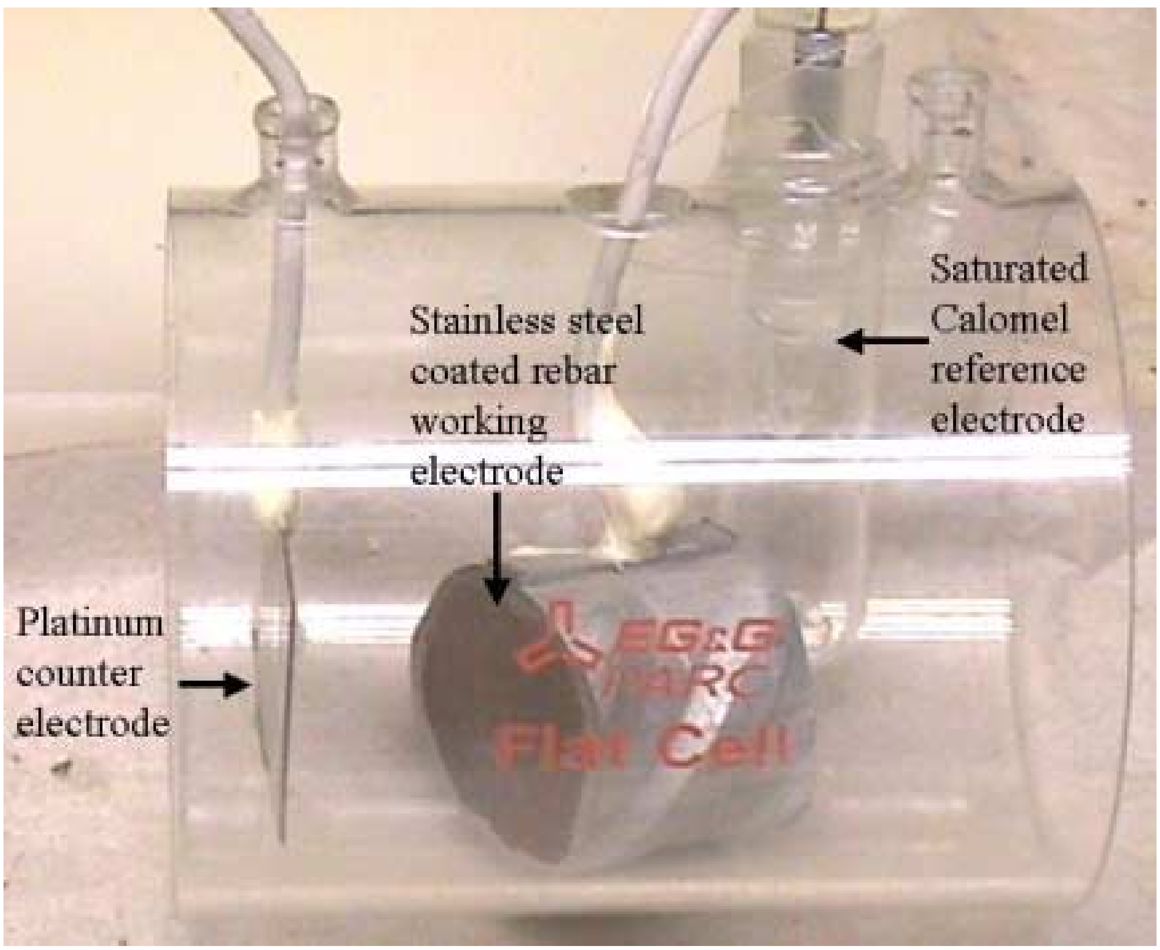

Figure 11: Electrochemical Cell with Electrodes in Place

Figure 12: Apparatus for Conducting Multiple Corrosion Tests Simultaneously

Figure 13: Potentiostat

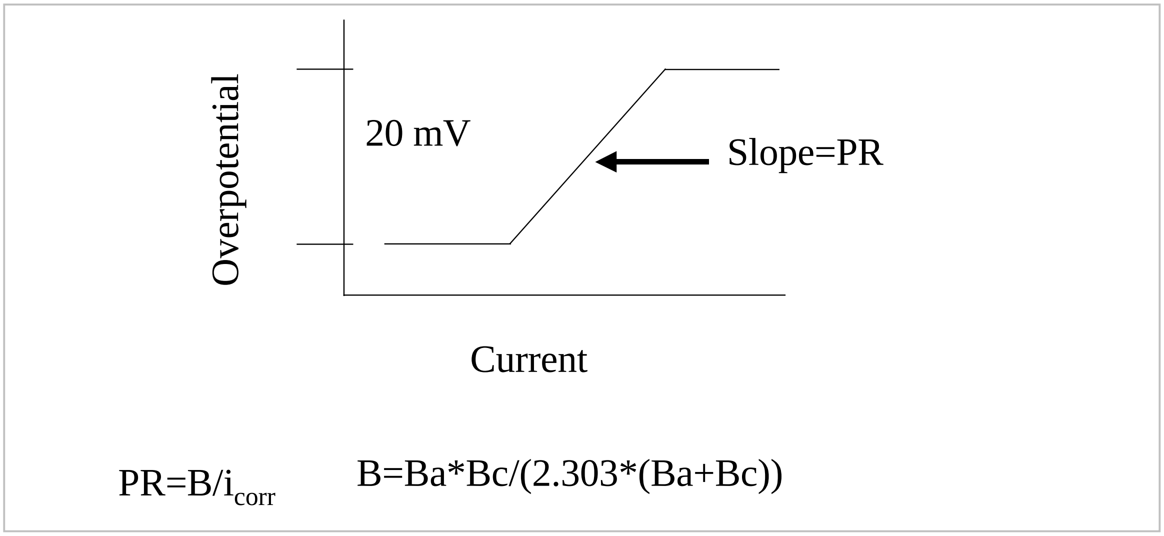

Figure 14: Expected Polarization Resistance Behavior

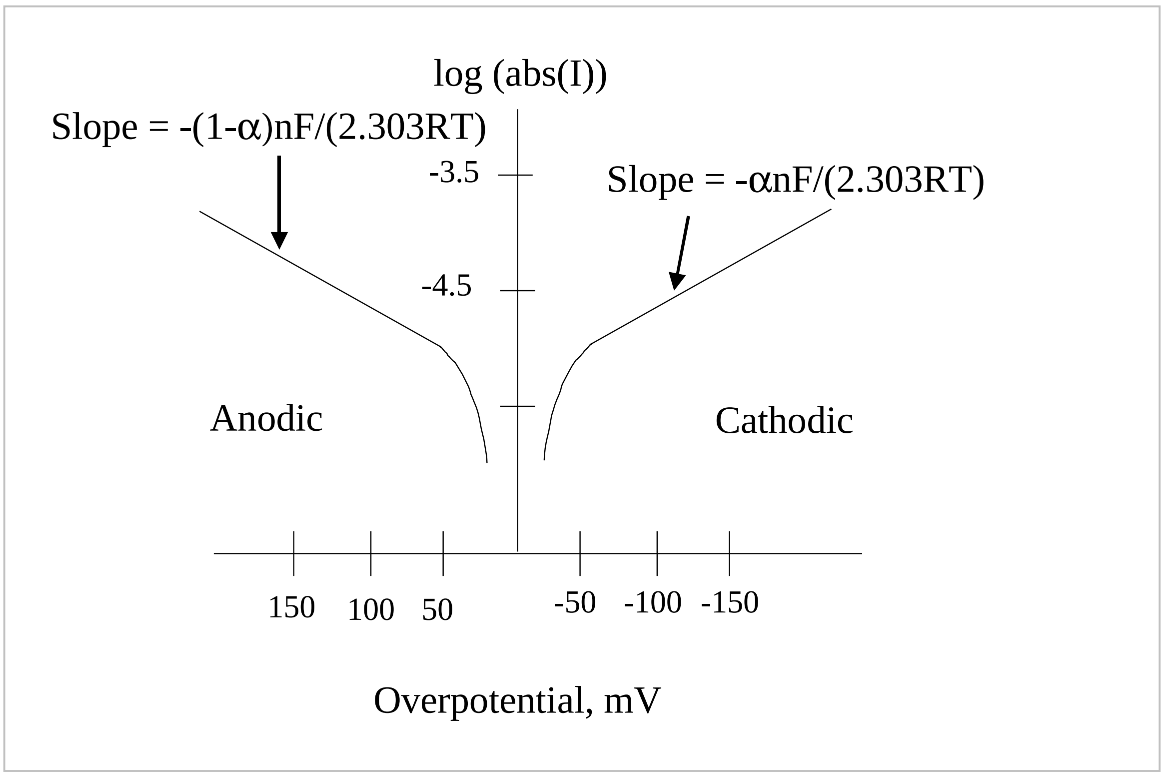

Figure 15: Expected Tafel Plot Showing Tafel Slopes Equivalent to 1/Ba and 1/Bc

PR testing is a common method for measuring the corrosion rates of many metallic materials, and has previously been applied to rebar. In PR testing, a small bias of 20 mV is placed on the working electrode sample. The slope of the potential versus current graph gives the polarization resistance, which can be related to the corrosion current (and hence rate of corrosion) as shown in Figure 14.

The Tafel slopes, Ba and Bc, are needed for this calculation. The Tafel slopes (Figure 15) are found from large biases (also called overpotentials) placed on the sample. For most materials, a linear region exists in the plot of log current versus overpotential; this is the Tafel region. The values for Ba and Bc can be found from the anodic and cathodic Tafel slopes.

All Tafel and PR measurements were taken on an EG&G Princeton Applied Research Model 273 A potentiostat/galvanostat (shown in Figure 13). A saturated calomel electrode was used as the reference electrode and a platinum mesh was used as the counter electrode.

The samples were tested in the same solutions in which they were corroded, except that the measurements were all made at room temperature. The PR slope was then converted to corrosion current i_{corr} and finally into amount per year of corrosion by the equation:

$$R(mm/year) = \frac{0.00327 \bullet i_{corr} \bullet MW}{n \bullet \rho}$$

where

MW is the molecular weight of iron (55.85 g/mole);

n is the number of electrons transferred (for iron and steel corrosion this is usually 2); and

ρ is the density of the material, about 7.8-8.0 g/cm^3.

Previous research has indicated that about 0.0254 mm of corrosion is required to begin to affect the surrounding concrete.

<u>Corrosion Testing Results</u>

Table 8 shows the results for the initial accelerated SSC rebar testing at 60 °C. Because PR values are inversely correlated to the corrosion rate, samples with larger PR values exhibit less corrosion. Examination of Table 8 shows that all samples increase in loss with time for about 4 days then seem to plateau after about 6 days (Figure 16).

Table 8 can be interpreted in the following manner. The left-hand columns specify the sample number and day of testing. The remaining columns contain the polarization resistance (PR) and the estimated rate of loss for the specific rebar/end treatment. Thus, on the second day of testing, the first sample of black steel had a PR of 142.3 and an estimated loss rate of 3.03 mm/year, while the SSC rebar with no end coat had PR=685.6 and an estimated loss rate of 0.57 mm/year. Thus, on the second day, the SSC rebar corrosion rate was 1/5 to 1/6 times that of the black steel.

Table 8: Initial Accelerated Corrosion Data

Sample	Day	Black Bar		SSC Bar No End Coat		SSC Bar with Epoxy End Coat		SSC Bar with Stainless Coat	
		PR, ohm*A	Loss, mm/yr	PR, ohm*A	Loss, mm/yr	PR, ohm*A	Loss, Mm/yr	PR, ohm*A	Loss, mm/yr
1	1	338.6	1.19	4006	0.099	28552	0.0136	2540*	0.152*
1	2	142.3	3.03	685.6	0.57	14473	0.0268	390.2*	0.585*
1	3	66.1	6.33	281.2	1.39	8064.8	0.0480	698.9*	0.564*
1	4	61.4	6.61	235.8	1.70	4276.5	0.0908	1320*	0.293*
1	5	72.3	5.62	512.5	0.78	1723.8	0.2323	1179*	0.329*
1	6	111.2	3.68	187.0	2.09	2103.9	0.1844	1084*	0.357*
1	7	128.0	3.03	260.5	1.49	2061.7	0.1910	869.7*	0.445*
1	8	125.3	3.13	293.7	1.33	933.3^	0.418^	1280*	0.302*
2	2	111.9	3.80	439.8	0.93	55900	0.0037	2460	0.1578
2	3	77.4	5.39	234.8	1.69	10378	0.0374	2843	0.1363
2	4	66.6	6.36	213.0	1.96	2746.4	0.1410	3336	0.1161
2	5	80.6	4.92	348.4	1.11	966.6^	0.403^	3023	0.1281
2	6	104.3	3.83	130.4	3.13	949.3^	0.410^	2557	0.1513
2	7	140.7	2.76	83.7	4.77	820.9^	0.472^	3667	0.1056
2	8	66.4	5.87	240.3	1.63	490.3^	0.795^	2995	0.1294
A is the area in cm^2, ^ indicates probable disbondment of the epoxy coating * indicates a crack in the original coating leading to differences in corrosion behavior									

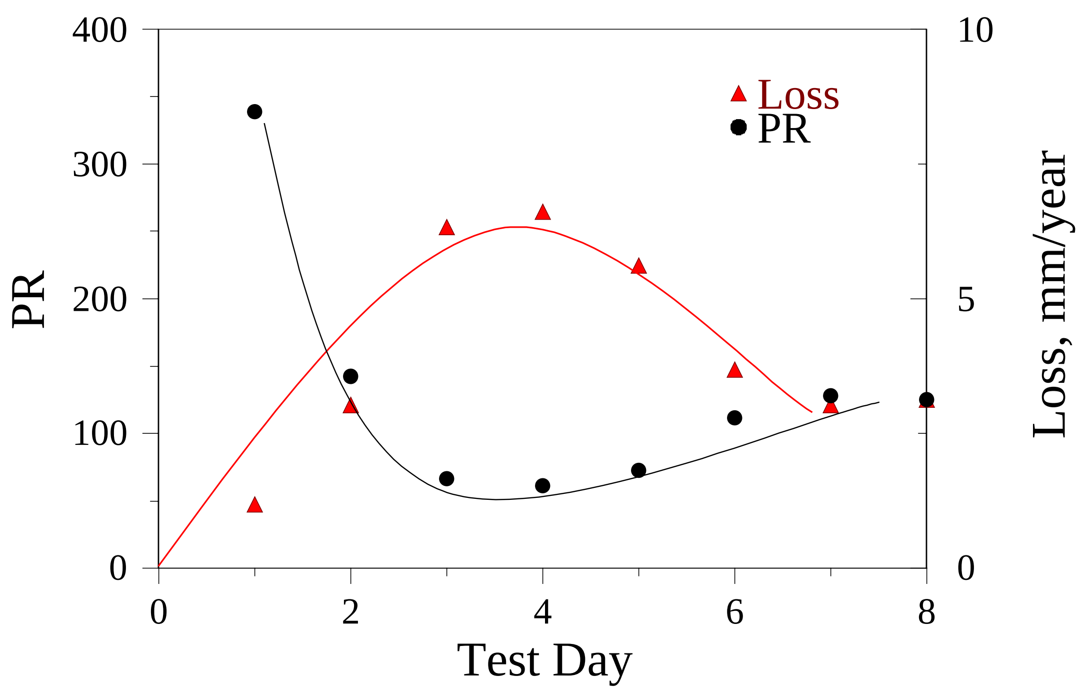

Figure 16: Graph of Corrosion Data for Black Steel Rebar During Accelerated Corrosion Testing

As the data in Table 8 and Figure 16 are for accelerated corrosion conditions, they cannot be directly used to estimate the time required to lose 0.0254 mm, the amount which would affect the concrete. If even the lowest rate were used, the bridge would begin to fail after 1 year.

A better way of interpreting these numbers is to compute a ratio the SSC rebar data to the black steel data. Under normal conditions black steel will last about one year before cracking the concrete. Therefore, the ratio of corrosion rates of the SSC rebar and the black steel will provide an estimate of the number of years to concrete damage when SSC rebar is used (Table 9). Due to the small amount of sample available, only three types of samples were examined:

- SSC rebar with no end treatment, which exposes the core to the corroding solution (3% NaCl, pH6 and 60 °C)
- SSC with epoxy-coated end-treatment to limit the exposure to the cladding
- SSC with stainless steel end coating. The particular stainless steel coating method used made a relatively porous coating through which solution could penetrate. Also, the coating was observed to be cracked in some cases.

For the uncoated SSC rebar, the samples appeared to be about 2-5 times better than black steel. Epoxy coating the ends resulted in an increase in the improvement over black steel of about 30-70 times better. The epoxy end-coating eventually disbonded from the SSC rebar causing the corrosion behavior to approach that of the SSC rebar without endcoating. The disbonded epoxy coating was slightly better than the uncoated piece, most likely due to problems with solution ingress and perhaps some of the epoxy still adhering to the SSC rebar. The stainless steel coating worked approximately the same as the epoxy-coated end (see sample 2) when no cracks were formed. When the coating was cracked, the corrosion resistance was about the same as the debonded epoxy sample, about 10 times that of the black steel.

Table 9: Comparison of Time to Concrete Failure for SSC and Black Steel Under Accelerated Corrosion

	Estimated Years to Concrete Failure	
Sample	**Sample 1**	**Sample 2**
Black Steel	11	11
SSC Uncoated	13.5	11.9
SSC Epoxy-coated	47.1	78.7
SSC Epoxy-coated, After Disbondment	20.0	18.0
SSC Stainless Coated	21.0	46.1

This data indicates that the SSC rebar (in this case 304 stainless clad rebar), should last 50-70 years in a bridge deck before concrete damage occurs. This figure comes from the corrosion resistance given above and the estimation that approximately 10 years is necessary for the buildup of salts in the concrete to induce corrosion.

Following receipt of the #10 bar from Stelax, Ltd., testing was begun on the original test matrix. The series of tests performed used pHvalues of 5 and 12, 3% NaCl and room temperature. Samples were prepared from #6 black steel and #10 SSC rebar. The SSC rebar was used with no end treatment, epoxy-coated ends and a variety of welded and spray coated treatments. In particular, 316 stainless steel spray coating such as that used in the initial experimentation, a T-55 weld material, which is a Ni-Fe alloy with 55% Ni, a 309 stainless steel weld material and a mixed weld of the end treatment used by the manufacturer and a T-55 weld material on the other end. The epoxy-coated and uncoated SSC rebar samples also had their cladding abraded by brushing with a Dremel hard-wire tool brush and had a 1/16" hole drilled through the cladding into the core. In all cases, four samples of each type were tested simultaneously for each combination of pHand end treatment/cladding treatment.

Table 10 shows the final results for this corrosion testing. The polarization resistance and loss data are the mean of the four replicate samples and are for the testing after 28 days cyclic treatment—1.5 hours in solution 4.5 hours drying, four times per day for 28 days. As the highest pHtested was 12 (pH13 was unable to be maintained probably due to buffering from ions in the tap water) the observed loss is somewhat greater than that found by McDonald at pH13, about 0.0254 mm/year. However, similar to the initial testing, the method of ratioing the SSC rebar samples to the black steel sample is a good method of comparing the data.

From Table 10, the best end treatment method over the 28-day test is epoxy end coating. The epoxy used in this work was a marine epoxy made to cure and be used underwater, so it is expected to have very good resistance to water penetration. Water penetration may lead to cathodic disbondment of epoxies similar to the result seen for the initial testing at 60 °C. The results with epoxy at pH12 were similar to the initial accelerated corrosion tests at pH6 and 60 °C; the epoxy end coated material was 55 times better than the black steel. The epoxy-coated SSC rebar was 40-70 times better than the black steel in the initial testing (Table 9). At pH5, the black steel corrosion is about 5 times faster than at pH12. The epoxy end coated SSC rebar improves its corrosion resistance at pH5 by about a factor of 2, due to the susceptibility of epoxy to alkaline induced degradation at high pH. Therefore, the epoxy-coated rebar is 600 times better than black steel at pH5 and about 115 times better than the black steel at pH12. The epoxy-coated steel should therefore last more than 100 years at pH5 assuming that cathodic disbondment does not occur.

Abrading the stainless steel cladding slightly increases the corrosion of the epoxy-coated SSC rebar. This is probably due to the type of brush used for performing the abrasion. A carbon steel Dremel brush was used. The brush may have left behind some small particles that could serve as loci for corrosion to occur.

When a 1/16" hole was drilled into the cladding, the epoxy end coated material corrosion was severely affected, as expected. At pH12, the presence of a hole increased the corrosion rate by about a factor of 2. The corrosion rate increased by a factor of about 9 for pH5 testing. At pH5 there was no difference between the PR value at 14 days and 28 days. This indicates that the hole drilled in the cladding had probably filled with corrosion by-products, leading to a diffusion controlled process and a steady state corrosion rate.

When no end coating of the SSC rebar was performed, the results again resembled those from the previous testing. At pH12, the SSC rebar was about 6 times better than the black steel, whereas it was 2-5 times better in the initial testing. There was little difference in the superiority of the SSC rebar at pH5 when compared to pH12. The corrosion behavior was also little effected by the drilling of a 1/16” hole or abrading the cladding. In all these cases the SSC rebar was 3-6 times better than black steel under the same conditions.

For the spray coated and weld end capped SSC rebar, the spray coated material corroded at essentially the same rate as the SSC rebar without any end coating. Therefore, spray coating is ineffective as a corrosion inhibitor.

The mixed weld (stainless steel and T-55), the T-55 welded and 309 stainless end capped material inhibited corrosion and was slightly worse than the epoxy-coated material at pH12 and significantly worse than the epoxy-coated material at pH5. At pH12, the estimated life of the weld end capped SSC rebar was 40-50 years. The estimated life at pH5 is about 10 years, given that the black steel corrodes about 5 times faster at pH5.

Following the completion of the testing, the results of which are presented in Table 10, this task was ended as directed by the technical panel during the meeting of June 30, 2000.

Table 10: 28-Day Corrosion Testing Data at Room Temperature and 3% NaCl

Type	Conditions	PR (ohm*A)	Loss (mm/year)	Better Than Black
Black Steel	pH12	790.4	0.694	--
	pH5	128.5	3.64	--
SSC Epoxy End	pH12	43635	0.0126	55x
	pH5	77530	0.00603	600x
	pH12—abraded	35690	0.0154	45x
	pH5—abraded	51410	0.0091	403x
	pH12—hole	21856	0.0251	28x
	pH5—hole	8695	0.0538	68x
SSC No End Coat	pH12	4733	0.1159	6x
	pH5	692	0.6758	5.4x
	pH12—hole	7267	0.1152	6x
	pH5—hole	723	0.6466	5.6x
	pH12—abraded	2327	0.2357	2.9x
	pH5—abraded	697	0.6728	5.4x
SSC Spray Coat	pH12	1200	0.4569	1.5x
	pH5	579	0.8078	4.5x
SSC Mixed Weld	pH12	18500	0.0161	43x
	pH5	2600	0.1000	36x
SSC T-55 Weld	pH12	17350	0.0165	42x
	pH5	1500	0.2000	18x
SSC 309 Weld	pH12	18600	0.0160	43x
	pH5	6950	0.0420	87x

To summarize the corrosion testing data, SSC rebar without end treatment is expected to last approximately 6 years at pH12 and 2 years at pH5 after the chloride ion content of the concrete has risen enough to activate corrosion. The use of marine epoxy for end coating increased the expected life to approximately 60 years at pH12 and 95 years at pH5. Abrading the cladding or drilling a hole in the cladding had little effect on the behavior of the material with uncoated ends.

For the epoxy end coated SSC rebar, abrasion slightly reduced the corrosion resistance, probably due to the type of material used for abrasion. Drilling a hole in the cladding with epoxy end coating significantly reduced the corrosion resistance of the epoxy-coated SSC rebar. This highlights the possible problem with the lack of metallurgical bonding. As the lack of metallurgical bonding may result in cracks in the cladding over the life of the bridge deck, these cracks could cause increased corrosion and significantly decrease the life of the bridge deck. The amount of life span reduction for the bridge deck is difficult to predict as it depends upon the time to cracking of the cladding, which is not known.

Compared to SSC rebar with no end coating, weld end caps increased the corrosion resistance of the SSC rebar to about 45 years (from 6 years) at pH12 and to 5-10 years (from 2 years) at pH5.

Stainless steel spray coating yielded no improvement over using no end cap. Table 11 summarizes the results found in this task.

Table 11: Summary of Estimated Time to Concrete Failure from Corrosion Data

Sample Type		High pH(12-13) Time to failure in years	Low pH(5) Time to failure in years
Black Steel		11	10.2
SSC Rebar	No End Coat	16	12
	Epoxy End Coat	60	95
	Stainless Spray Coat	25	11
	Mixed Weld End Coat	55	18
	T-55 Weld End Coat	55	14
	309 Weld End Coat	55	30
	No End Coat—Abraded	15	11
	No End Coat—1/16” Hole	16	12
	Epoxy End Coat—Abraded	55	90
	Epoxy End Coat—1/16” Hole	40	25
Time to failure Includes approximate 10-year buildup of NaCl before corrosion starts			

Corrosion Effects Examination

Preliminary analysis of the pre-corrosion samples and some of the post-corrosion samples was performed, but as little was done prior to the decision of the technical panel to end the research project soon after the June 30, 2000 meeting, the examination of corrosion effects was stopped. Therefore, the analysis performed for this task only considers the first set of accelerated sample run under solution conditions of pH6, 3% NaCl and 60°C.

Figure 17: Uncoated SSC Rebar After 8 Days at pH6, 60˚C

Figure 18: Uncoated SSC Rebar After 8 Days at pH6, 60˚C, Other Side Of Sample from Figure 17

Figure 19: Cross Section of Stainless Steel Coated SSC Rebar Tested 8 Days at pH6, 60˚C

Figure 17 through Figure 19 show photographs of the SSC rebar after the initial corrosion testing. The primary corrosion by-product was iron oxide, as expected.

No major differences were found in the composition of the core, but a small amount of a minor constituent could cause this and would be difficult to observe in the SEM. Although the cross-section of the stainless steel coated SSC rebar did not show any internal corrosion, some of the test pieces did show internal corrosion and corrosion at the core/cladding interface.

Figure 19Figure 20 shows a sample with internal corrosion found after impact testing. Impact testing was performed to assess the stability of the core/cladding interface to stress. Impact testing caused the cladding to pull away from the core in some areas. Because the sample was from the demonstration material, the internal corrosion may have been caused by procedures different from the manufacturer's standard operating procedure.

Figure 21 through Figure 23 show SEM micrographs of the core and cladding of various #6 and #12 samples. Figure 21 shows the core and cladding of a #6 sample. The image was collected in backscatter mode to better differentiate between the phases. The lighter color is due to the average elemental weight being less due to the greater amount of chromium compared to Ni. A small gap is seen between the core and cladding in this sample. Figure 22 through Figure 24 show SEM micrographs of the specimen shown in Figure 19. Figure 22 shows the broken cladding, which appears to have failed in a ductile manner. Figure 23 shows the area of internal corrosion. This area was found to be primarily composed of iron and oxygen. Figure 24 shows the unoxidized core region and appears quite different in form from the oxidized core region. The white spots are believed to be carbide inclusions and may lead to the black areas in Figure 26 and Figure 27.

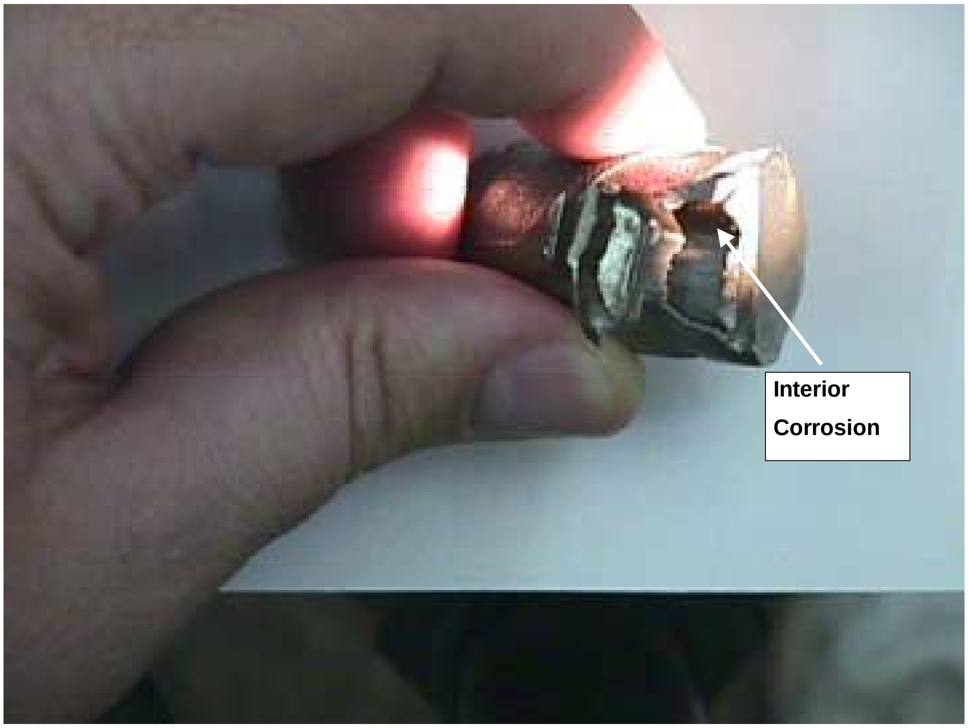

Figure 20: Impact-Tested #6 SSC Rebar Showing Massive Internal Corrosion

Figure 21: #10 SSC Rebar After Impact Testing

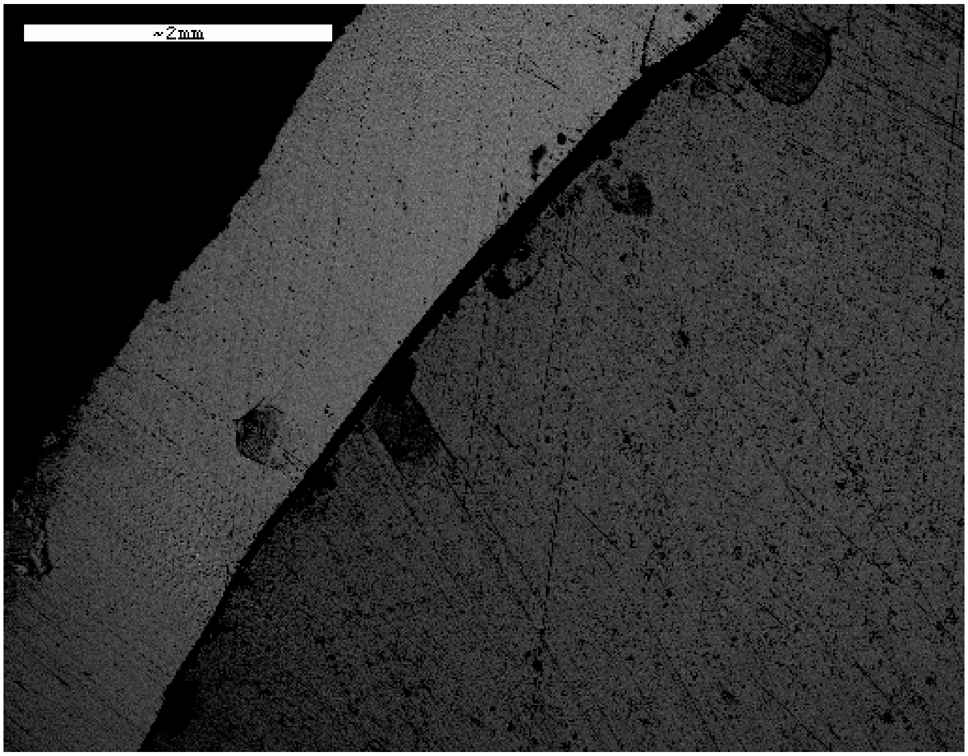

Figure 22: Backscattered SEM Image of the Core/Cladding Interface and Gap

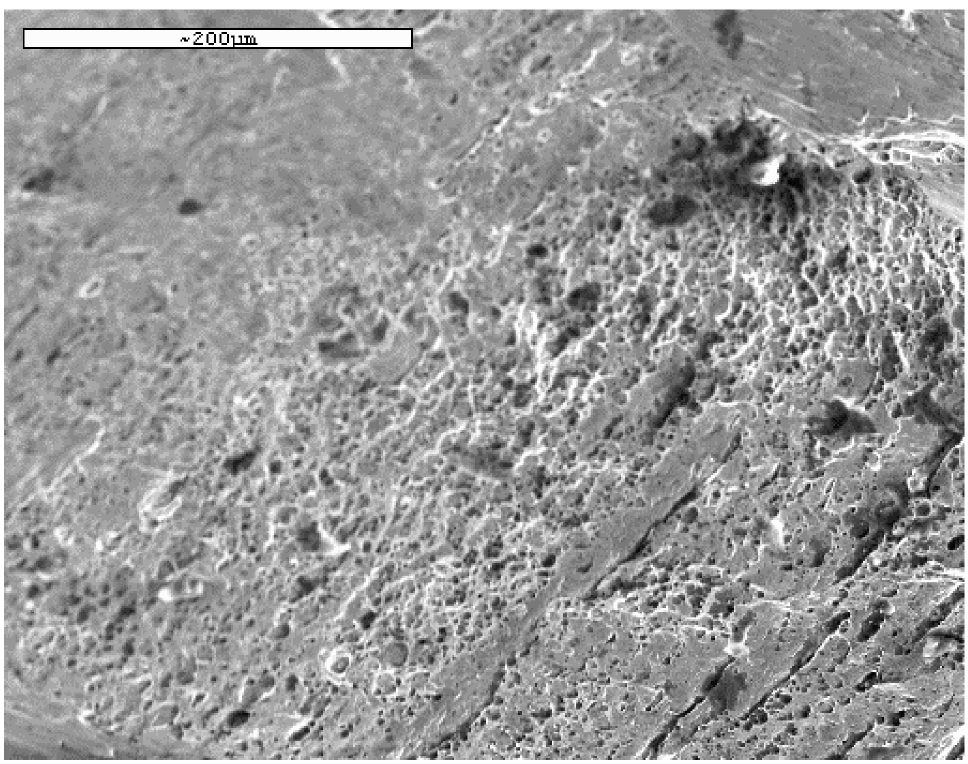

Figure 23: SEM Micrograph of Cladding of Impacted #6 Sample, Same Sample as Figure 20

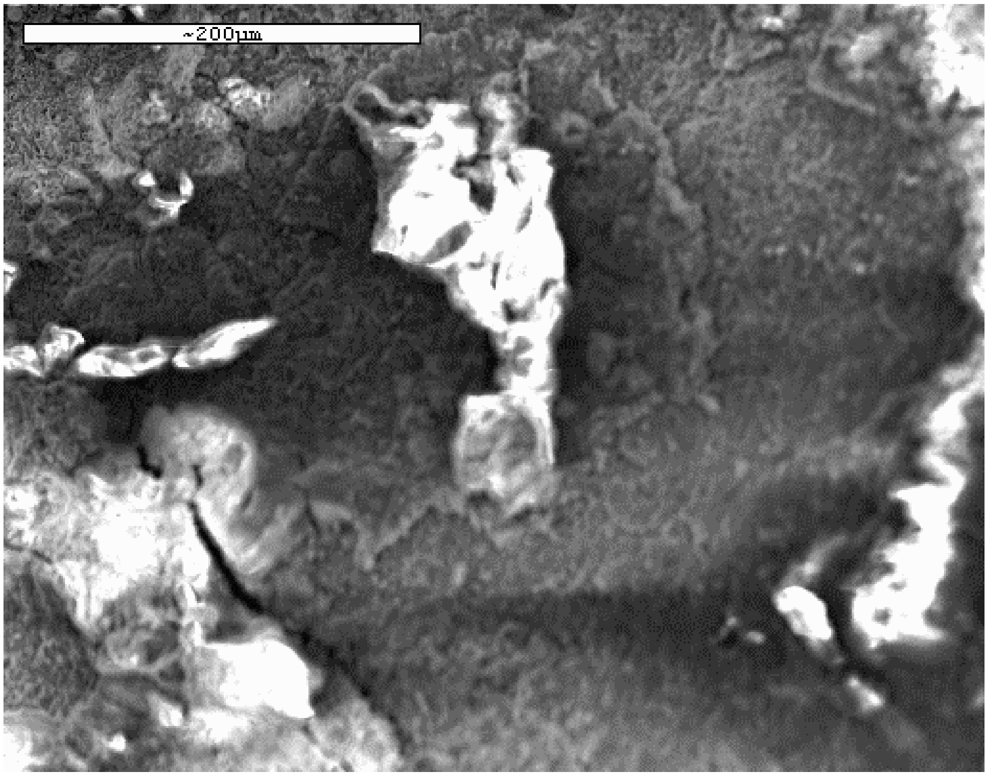

Figure 24: SEM of Oxidized Core Region of Impacted #6 Sample (same as Figure 20)

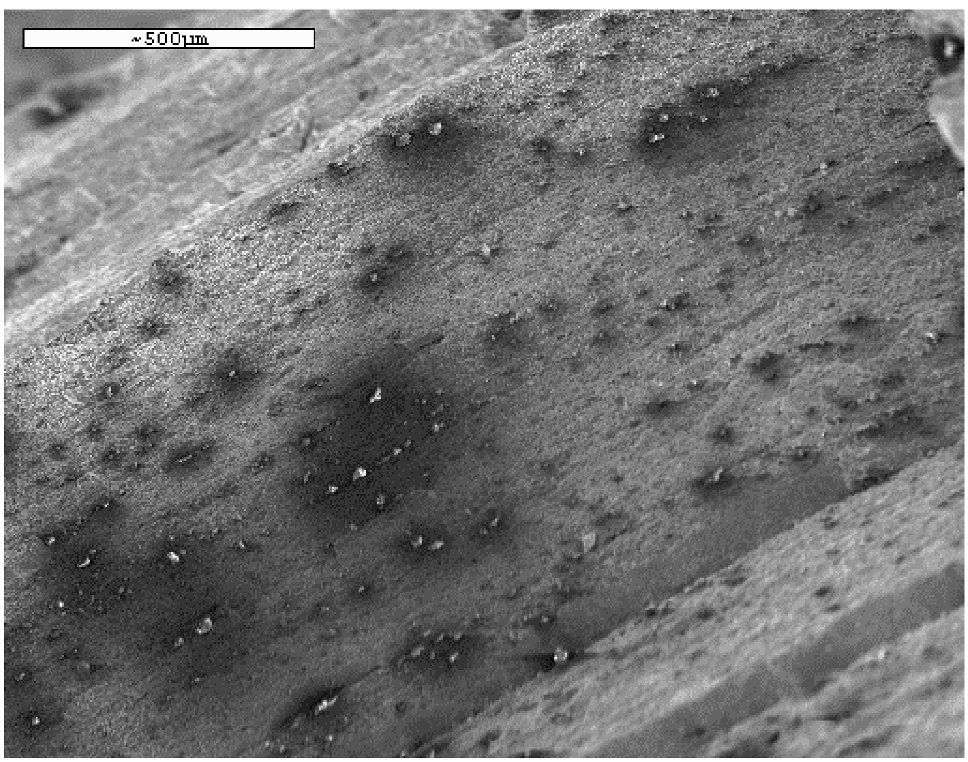

Figure 25: SEM Micrograph of Unoxidized Core Region of #6 Sample with Interior Corrosion

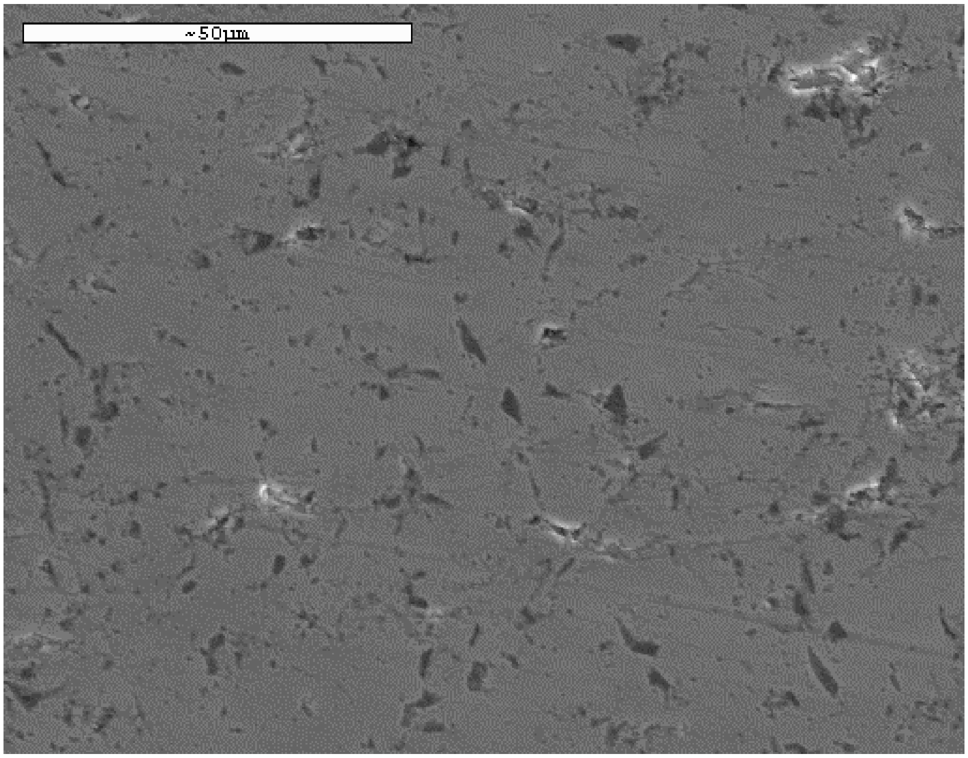

Figure 26: SEM Micrograph of Cladding of #10 Sample

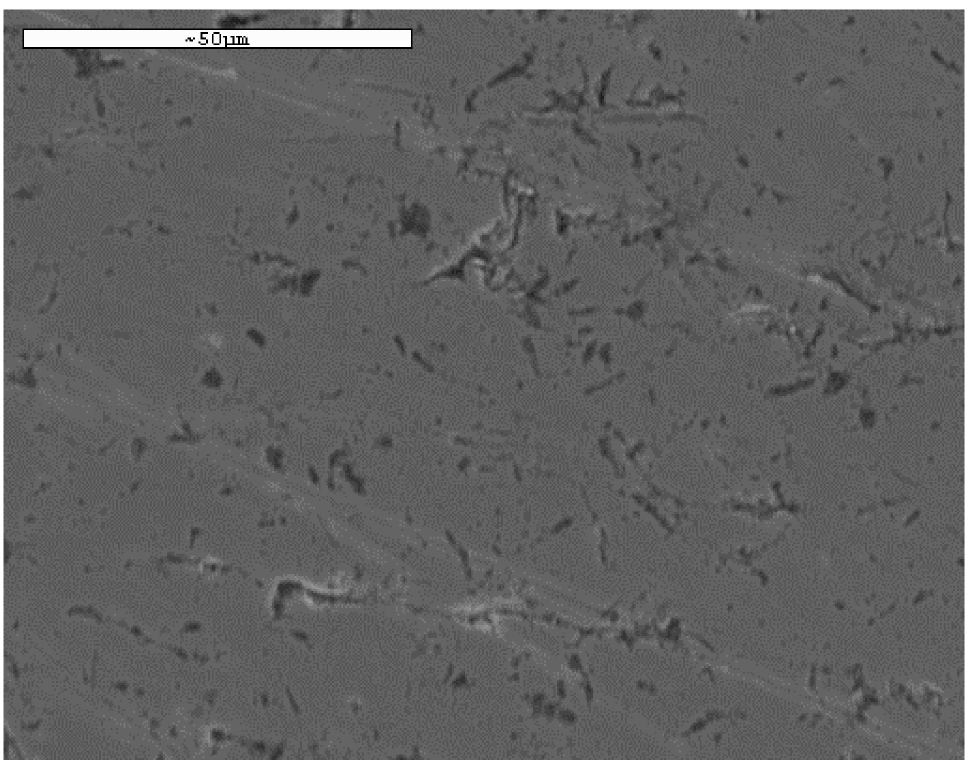

Figure 27: SEM Micrograph of Core of #10 Sample

Figure 26 and Figure 27 show the core and cladding of the #10 sample. The dark shapes may be carbide inclusions or they may be voids with polishing particles in the void. They did show a large carbon presence, but differentiation was not made prior to the end of the research.

CONCLUSIONS

The material exhibited several problems that may have serious consequences in both the short- and long-term:

- *Lack of metallurgical bond between core and cladding*—This problem can lead to voids at the core-cladding interface. The full effect of these voids is hard to predict, but they could lead to premature cracking of the cladding and significantly reduce the resistance of the material to corrosion. All samples examined displayed a continuous gap at the core-cladding interface. These gaps were 30 to 150 µm (about 1-5 mils) in thickness. As the samples were cut prior to examination, the interfacial gap may be due to the cutting process. A sample was processed by cutting the cladding in one position and then pulling the cladding off with a pliers. The cladding was removed easily and the now exposed core-cladding interface indicated only 2-3 areas of core-cladding contact, making up 10-20% of the total possible contact area.

- *Failure to supply proper size samples and any size sample in a timely fashion*—At the outset of this project, the supplier promised to deliver 40 feet of #6 material in early April 2000, as a shipment of #6 stainless steel clad rebar was being made for the Florida DOT. Although Florida received material, SDDOT did not. The supplier then promised 40 feet of #8 size material in May. This material also was not shipped. Finally, 40 feet of #10 stainless steel clad rebar was received on June 9, 2000, far too late for much of the original planned testing to be finished by the June 23, 2000 deadline. Virginia DOT reported a similar problem that forced them to get samples from a finished bridge project in Ontario, Canada.

- *Quality control of material*—In particular, the cladding thickness varied by 30-50% (as measured by coefficient of variation). One area was found to be out of specification (less than 0.5 mm), although this may have been due to cutting the material. Furthermore, neither the #10 bar sent in June nor the demonstration piece of #6 material met the nominal size specification. The bars sent averaged about 10% greater in size than the ASTM specifications for #6 and #10 size bars. Also, conversations with the Ontario MOT indicated that it had received a mixture of 304 clad and 316L clad rebar when only the 316L clad material had been ordered. The 316L clad material is superior to the 304 in corrosion resistance but is more expensive. These concerns may be alleviated by the presence of an inspector during material production.

- *Possibility of internal corrosion*—During testing, one sample of the #6 demonstration bar was found to have a large area of internal corrosion within the black steel core. This internal corrosion did not appear to be linked to corrosion at the core-cladding interface. The internal corrosion created a weak spot that broke under an impact load of approximately 250 psi. Examination of other tested #6 samples indicated a few areas of minor internal corrosion. Internal corrosion was not observed on cut faces of the #10 material. The cause of the internal corrosion is not known at the present time. If the internal corrosion were present due to poor manufacturing, the presence of an inspector might help alleviate this problem. Also, we are currently trying to define a method by which any internal corrosion can be identified in the bar prior to placement in the bridge deck.

From a corrosion standpoint, the stainless steel clad rebar from Nuovinox/Stelax will last the required 75 years given adequate bridge maintenance and with end-capping. However, the mechanical behavior of the material over 75 years is less clear-cut. Most of the problems encountered appear to be solvable by having an inspector present during manufacturing. The one difficulty not able to be dealt with is the lack of metallurgical bond between the core and the cladding, which may lead to an interfacial gap. This gap may have severe consequences for the material's ability to last 75 years, as it may lead to cracking of the cladding and subsequent increased corrosion, causing severe cracking of the concrete and a decrease in the life of the bridge deck. Alternatively, the gap may have little if any effect on the life of the structure. Currently, the data do not exist to distinguish between these two alternatives.

IMPLEMENTATION RECOMMENDATIONS

1. Based upon this research, the use of the stainless steel clad rebar is **not** recommended. While the stainless steel clad material from Stelax, Ltd. appears to give sufficient corrosion resistance to achieve a 50-75 year life span if the ends are epoxy-coated or welded with a corrosion resistant material, the lack of metallurgical bonding between the cladding and core complicates the analysis to such an extent that the long term effects are difficult to predict. As the stability of the cladding over the life of the bridge deck can not be guaranteed, the stainless steel clad rebar should not be used. In addition, several problems with quality control of the SSC rebar again make the use of this material problematic.

2. If this material is used despite the above recommendation, an inspector should go to the manufacturing site and oversee the production of the stainless steel clad rebar for use in South Dakota bridge decks. Florida DOT did this and Virginia DOT is planning on doing this. An inspector might help alleviate some of the quality control issues mentioned previously.

3. It is recommended that alternative materials be tested for their corrosion resistance and other properties similar to the SSC rebar tested in this work. During the course of this work, several other corrosion resistant rebar materials were found and will soon be produced. In particular, a Texas company, SMI-CMC, is beginning to produce stainless steel clad rebar by the Osprey process. The Osprey process material has the advantage of creating a metallurgical bond between the stainless steel cladding and the black steel core. Also, the stainless steel can be clad at any thickness from approximately 1 mil to about 2 inches with very little variation in the film thickness. The anticipated cost for this material is about 2-5 times that of typical rebar. In addition to the Osprey process material, a California company, MMFX, is beginning production of two new types of corrosion resistant rebar material. These two materials are a microcomposite steel with approximately 13% chromium, and a dual-phase ferritic steel.