PROTECTING PRESTRESSING STRAND IN TRANSPORTATION STRUCTURES AND IMPROVING STRAND-CONCRETE BONDING

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ABSTRACT

Corrosion of steel strands in prestressed concrete may significantly reduce the structural capacity of prestressed elements and lead to costly maintenance and repairs. Epoxy coating of strands is not an effective measure for corrosion protection and inflicts a loss in bond between the steel and concrete. A novel inorganic nanoporous coating has been developed as an alternative for protecting prestressing strands. Methods of applying the coating and levels of corrosion resistance have been analyzed via electrochemical tests, comparing corrosion pitting potentials of coated and uncoated samples. Tests conducted include small scale pull-out tests to analyze the effect on bond strength and electrochemical tests to show that the inorganic coating offers good corrosion protection to steel wires in strand. The corrosion tests showed improved resistance of the coated wires as compared to uncoated. The pull-out tests revealed an increase in maximum load for coated wires when compared to uncoated wires. This suggests an increased ability for the steel to maintain chemical adhesion to concrete as a result of the novel coating. Performance results for corrosion and pullout are provided for the nano-coated strand and uncoated strand.

Keywords: Strand, Corrosion, Bond, Prestressing, Bridges, Coating

INTRODUCTION

The objective of the work described here was to prove the viability of thin nanoporous inorganic coatings in protecting steel prestressing strands from corrosion. Corrosion of steel in pre-stressed concrete, particularly in highway bridges where coatings are not used, can be a severe problem that leads to loss in structural capacity due to both the reduction of cross-sectional area of the steel and the loss in bond between the damaged steel tendon and the concrete which surrounds it. The nano coating is intended to improve corrosion resistance and simultaneously increase the bond capacity between concrete and strand.

The useful life of prestressed concrete members in transportation structures can be seriously affected by deterioration due to corrosion of the steel strand. This is more severe in bridge structures close to marine environments where seawater is present and in cold regions where de-icing salts are used during the winter period since pre-tensioned members use uncoated strands or bars[1] .

The loss of even one or a few strands has an impact on prestressed members since their ability to sustain load relies on the tensile strength of the tendons. Weakening of the steel and resultant concrete cracking can cause loss of prestress transfer and failure of the member. For example the girder in Figure 1 shows clear signs of concrete spalling caused by the corrosion products of rusting strand in the US-45 Bridge in Milwaukee.

Figure 1. Strand and rebar deterioration in US 45 bridge in Milwaukee.

In addition to safety concerns for highway bridges and other prestressed structures, the cost of corrosion is a major problem. The annual direct cost of corrosion in highway bridges in the United States is estimated at $8.3 billion including replacement and maintenance[2]. The deteriorating effects and high costs of corrosion on pre-stressed concrete members have led to the development of a number of corrosion protection methods. However, these methods are not without flaws and their use is limited. The most common approaches are: concrete sealers and barriers, chemical stabilization, electrochemical protection, and epoxy coatings on steel. An ultimate alternative is to replace the steel with materials such as stainless steel or fiber-reinforced plastic.

Epoxy-coated reinforcement (ECR) is used extensively in construction to protect steel from corrosion. Epoxy coating works by preventing chloride and moisture from reaching the surface of the steel. Some studies have shown favorable results, while other research has documented poor performance. A study by Clear found that ECR typically outperformed uncoated reinforcement, but the increased performance was not long term[3]. Clear determined that the increase in life of ECR in northern U.S. and Canadian environments would be in the range of only 3 to 6 years in most instances, rather than the more than 40 years previously estimated. This was attributed to the progressive loss of coating adhesion to the steel and under-film corrosion.

The ability of a prestressed member to sustain service loads and control cracking also depends on the attained transfer lengths. The latter term refers to the length of strand over which the prestress is effectively transferred into the concrete. This length is in turn partially dependant on the bond strength of the steel tendon to the concrete. The nature of bond strength is complex and varies throughout the length of the member. Because of the complexity and importance of the steel-concrete bond, many researchers and agencies have developed several methods for predicting bond. The North American Strand Producers (NASP) Bond Test is one of the most studied methods and has been compared to other methods such as the Moustafa Method and found to be more repeatable.

The novel strand coating used in this project to provide corrosion protection and improved concrete bond is a sol-gel, a liquid containing very small, suspended particles. The sol is zirconium-based (ZrO_2). Zirconium was chosen as a possible candidate for strand applications due to its corrosion-resistant properties[4]. The sol-gel process (using a substance that is in both liquid and solid phases) involves the formation of an oxide network and the gelation of sol in a liquid medium[5].

The application of sol-gels to steel has shown the ability to increase steel's resistance to corrosion. Dip-coating was chosen as the method of application for the sol-gel here, with each layer of applied sol having a thickness of 0.4 – 0.6 nanometers. After deposition on the steel substrate, the nano-particles form an integrated protective network through a heat sintering process.

Lengths of Grade 270 low relaxation 0.6 inch diameter strand were donated by three manufacturers for corrosion and bond testing. They will be referred to as strand manufacturers A, B, and C. For simplicity all testing was done on single wires removed from the (0.6" and 0.5" diameter) strand.

CORROSION TESTING

Setup:

Electrochemical techniques are often used to provide preliminary evaluation of corrosion resistance and involve accelerated tests that are analogous to long-term corrosion development in the field. The results are useful in comparing relative corrosion pitting potentials of metals in a corrosive environment. The corrosion resistance of the coated wires was compared to that of the uncoated. Specifically, the potentiodynamic anodic polarization technique was used here and includes a three-electrode system to determine the required voltage to cause a rapid and sudden increase in current that signals the start of pitting corrosion.

A three electrode test cell consists of the working electrode (the strand wire) and a counter electrode. A third electrode (a reference) is included to reduce the effect of additional polarizations in the cell[6]. In this case the potential of the working electrode is measured with respect to the reference electrode. The counter electrode in this cell completes the circuit and transmits current to or from the working electrode. The electrolyte solution used during the tests was 0.23M NaCl in a Ca(OH)2 saturated solution. This solution has a pH of 12.4, and is meant to simulate an environment similar to concrete. Figure 2 shows an electrochemical cell used for the tests, the electrode arrangement and electrolyte container. The electrodes were connected to a multichannel potentiostat which applies the voltage sweep and measures the current produced in the cell.

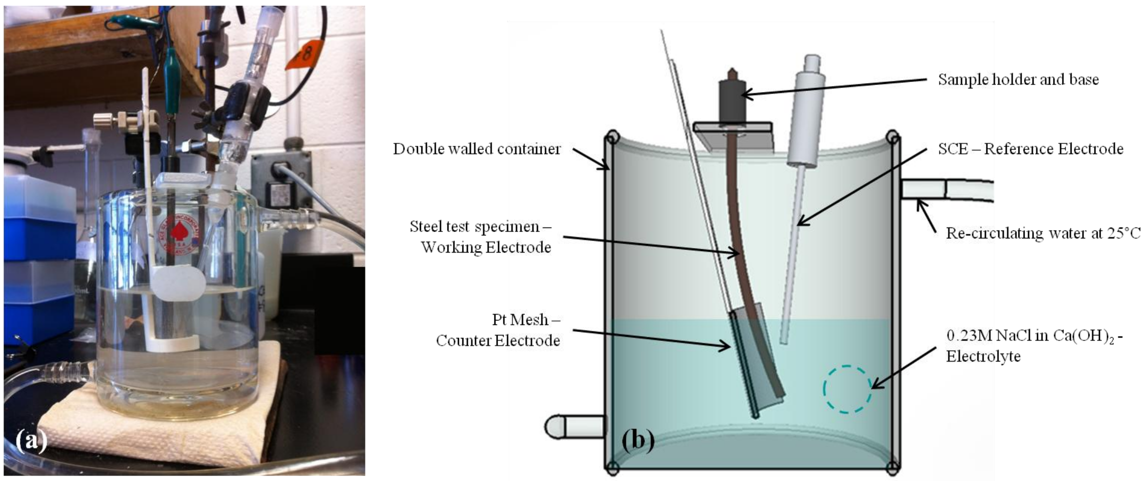


Figure 2. Three-Electrode Cell used for the polarization Experiments

Figures 3, 4 & 5. (clockwise from top right): In-situ electrochemical test setup, strain gauge bonded to steel wire, and three-electrode potentiodynamic anodic polarization test surrounding tensioned wire.

A novel test setup was required to perform corrosion tests on wires that were under stress levels typical for strand in prestressed members. This test setup included a steel frame to support the tensioned wire as shown in Figures 3-5. The wires were stressed to 216 ksi in the frame. The tension was held at a relatively constant 216 ksi level until the completion of each corrosion test and was monitored by a strain gage on each wire.

Three wires from manufacturer C were first tested in an uncoated condition and coated condition, but in an unstressed state. Then three coated and uncoated C-type wires were tested for corrosion resistance while under high tension stress.

Results:

During the corrosion tests, an increasing voltage is applied to the cell until a spike in the current flow is detected. This spike occurs when pitting corrosion initiates. A high applied positive voltage at the pitting corrosion potential (i.e. the spike in current) indicates a more corrosion-resistant coating. The test method involves applying a potential to the reference electrode and measuring the current at the counter electrode in the presence of a steel wire, which acts as the working electrode[7].

Unstressed wires: The graphs of Figure 6 show the “pitting corrosion potential”, or the maximum mV applied to each of the unstressed wire specimens before pitting corrosion started. A higher positive value of voltage indicates higher resistance to corrosion. Clearly the coated wires withstand a higher average positive voltage before the pitting corrosion initiates. The pitting corrosion potentials are listed in Table 1.

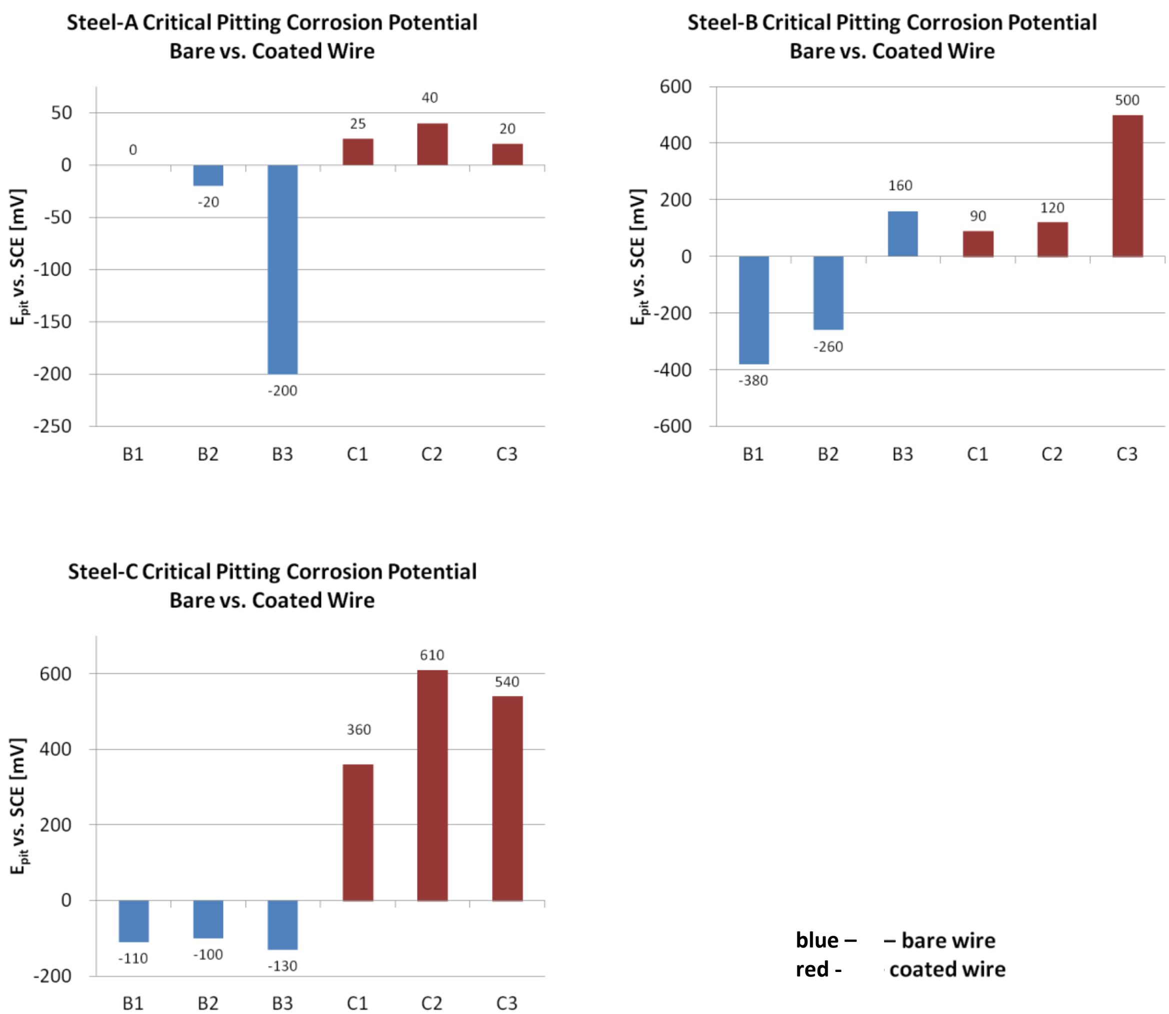


Figure 6. Test results showing pitting corrosion potential for test specimens.

Table 1. Critical pitting corrosion potential values – unstressed wires[8].

TEST	Critical Pitting Corrosion Potential (mV)
Type A Uncoated (2 test average))	-110
Type A Coated (3 test average)	28
Type B Uncoated (3 test average)	-160
Type B Coated (3 test average)	236
Type C Uncoated (3 test average)	-113
Type C Coated (3 test average)	503

Table 2: Critical pitting corrosion potential values for Type C wires under stress.

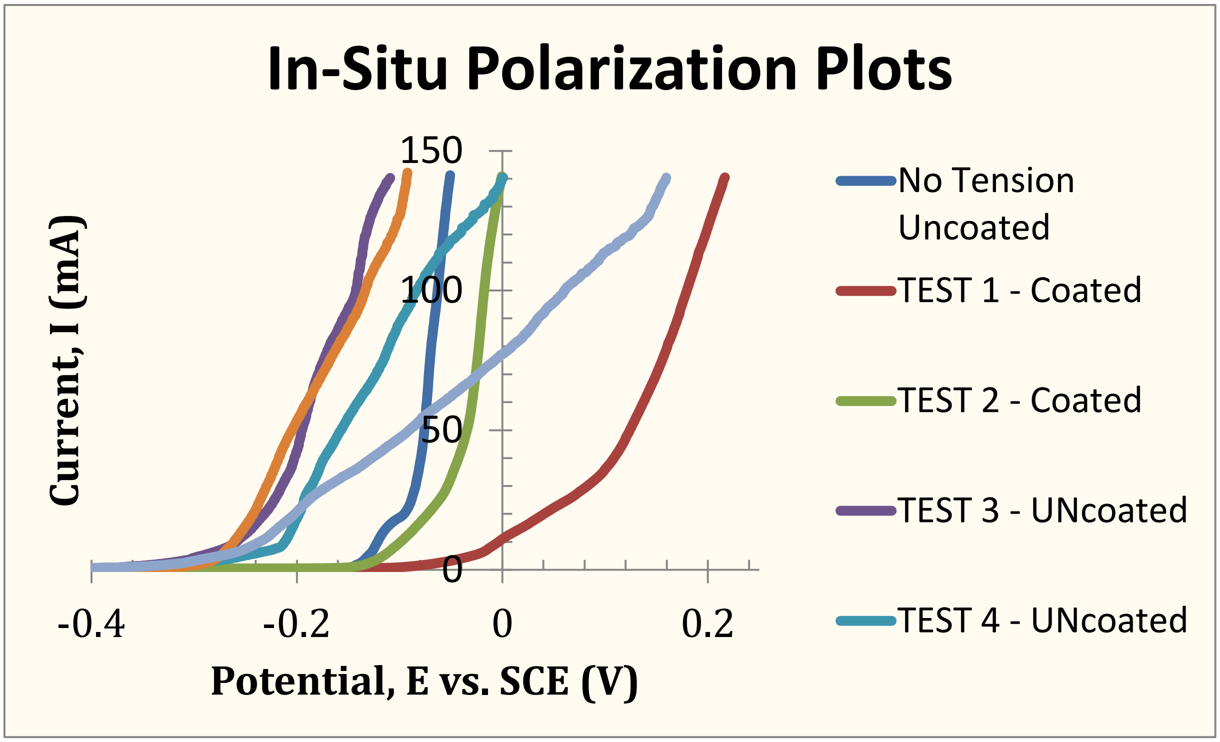
TEST	Critical Pitting Corrosion Potential (mV)
No Tension - Uncoated	-106
1 - Coated	52
2 - Coated	-57
5 - Coated	-281
3 - Uncoated	-227
4 - Uncoated	-237
6 - Uncoated	-278

Stressed wires: All of the corrosion tests with prestress applied were conducted on wires from manufacturer C. Three repetitions of corrosion tests on uncoated samples were performed, and three repetitions on coated samples were performed. One test was run on an unstressed and uncoated wire for comparison. The actual voltage versus current plots are shown in Figure 7. The pitting potential is taken as the voltage measured from the x-intercept of the curve tangent line, after the curve lifts off the x-axis. Visually it is approximately where the curves lift off the x-axis. The actual corrosion potential values, measured from the tangent intersect, are listed in Table 2.

Discussion:

The electrochemical tests show that the nanoporous zirconium coating provides an increase in the ability of steel wires comprising pre-stressing strand to resist corrosion. For both the unstressed and stressed tests the potential of the coated wires was higher compared to uncoated.

Figure 7. Corrosion tests: applied voltage (x-axis) and resulting current (y-axis), for Type



C wires while under stress; Tests #1-#6 are all on tensioned wires.

The first two tests of tensioned coated samples provided more positive pitting potential values than those for uncoated samples. However, the increase in potential between coated and uncoated wires is not as large as that seen for non-tensioned samples. Clearly the tensioned condition is increasing the susceptibility to corrosion of both the coated and uncoated wires, but the coated wires perform better.

Test 5 of a stressed coated sample, performed just as poorly as the uncoated samples. This occurred because the steel wire accidentally reached its yield point during tensioning prior to Test 5. This test was the only test of the six in-situ tests during which the strain gauge did not perform properly, either due to an electrical issue or a loss in bond between the gauge and the wire. Excessive load was accidentally applied and the steel had yielded prior to the realization that the strain gauge and the steel wire total stretch were not compatible. The occurrence of yielding was verified by the approximate maximum pressure in the hydraulic jack and by the permanent elongation in the wire. Although Test 5 does not contribute another data point to show the viability of the coating on normal wires, this test incidentally shows that the nanoporous coating is not good beyond the yield point - the wire behaves as if it were uncoated. This means that the coating film is less ductile than the steel and fails at a certain point prior to the breaking point of the wire.

BOND TESTING

While the coatings should be effective as a corrosion protection method they should also not be detrimental to the bond between strand and concrete which serves to transfer prestress to the concrete member. The steel-concrete bond was evaluated using pull-out tests.

Setup:

Wire pullout tests, from concrete, were loosely based on the NASP Bond Test described in the NCHRP 603 Report. That test consisted of "pulling" complete steel strand from a concrete mortar cylinder and measuring the force required to achieve sufficient slip of the strand relative to the mortar.

The setup described in the NASP Bond Test specifications and the small-scale tests used on the individual wires differed in four aspects: (1) test specimen, (2) size of the concrete mortar cylinder, (3) casting of the mortar and (4) the testing frame.

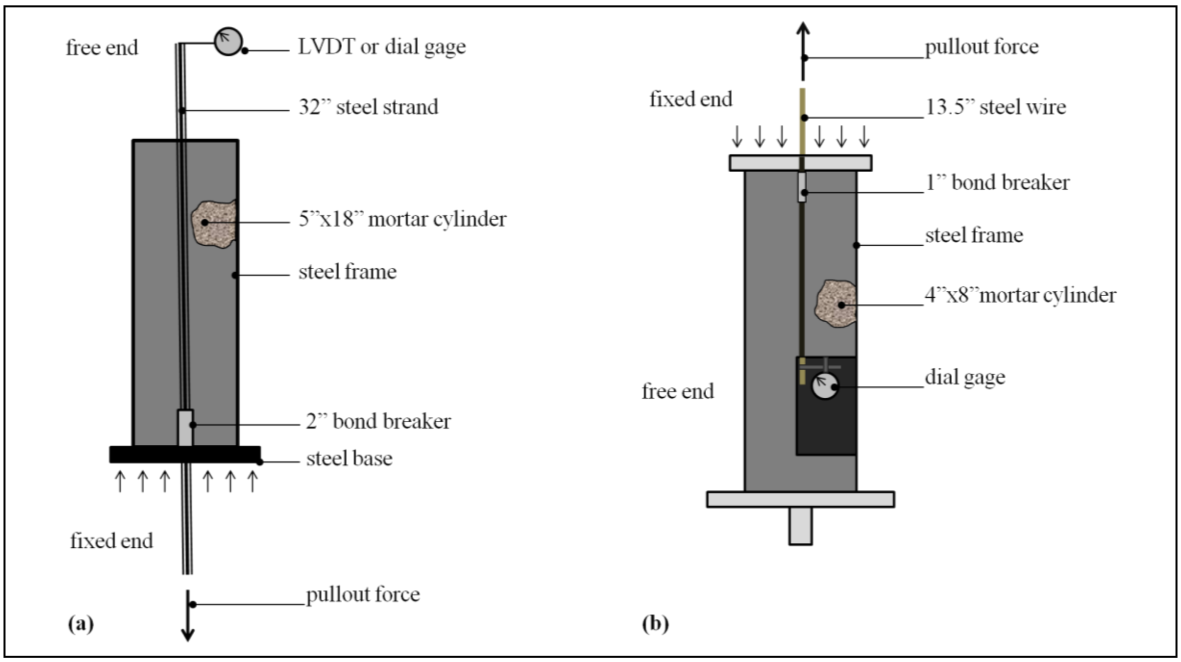


Figure 8. (a) NASP Bond Test setup and (b) Small-Scale Bond Test setup

A comparison of the two test setups is shown in Figure 8. The NASP Bond Test requires the test specimen to be a 32 inch long 7-wire strand with an embedment length of 16 inches. The small-scale counterpart used a single 13.5inch long center wire obtained from the 7-wire strand. The embedment length was 8 inches with a de-bonded section of 1inch at the end.

The wire was secured to the top grip on the moving crosshead of the Sintech hydraulic test machine and the steel frame enclosing the test cylinder was anchored at bottom grip. A dial gage was attached to the wire with a holder so that the plunger is in contact with the bottom of the mortar cylinder to measure wire pullout. The rate of applied displacement on the top wire was set at 0.1in/min.

Results:

Three results are reported from the bond tests: pull-out force at 0.1 in of slip, maximum pull-out force, and mortar strength. Table 3 summarizes the preliminary bond test results for all the wires.

Table 3. Bond test results for wires (4 tests each)

Test	**Pull-out Force at 0.1" (lb)**	**Max Load (lb)**	**fc' (psi)**
Bare wire "A"	150 (avg) std dev = 74	512 (avg) std dev = 177	4580
Coated wire "A"	245 (avg) std dev = 129	1227 (avg) std dev = 311	4580
Bare wire "B"	443 (avg) std dev = 104	474 (avg) std dev = 73	5155
Coated wire "B"	197 (avg) std dev = 43	868 (avg) std dev = 138	5155
Bare wire "C"	256 (avg) std dev = 48	445 (avg) std dev = 41	5060
Coated wire "C"	178 (avg) std dev = 70	799 (avg) std dev = 192	5060

The type A coated wires showed an increase of 63% in pull-out force at 0.1 inches of slip with respect to bare wire. The max pull-out load had a 140% increase. The coated type B wire actually had a lower pullout force at 0.1 inch, 44% of the uncoated value. The maximum load, however, showed an 83% increase. The coated type C wire also had a reduced pullout force at 0.1 inch slip, 70% of the uncoated wire's force, but had the maximum load increased by 80% compared to the uncoated.

While the force at 0.1 inch of slip is a standard reference value used in measuring strand bond, it is an arbitrary reference value and does not seem to be an appropriate measure for wire bond. The 0.1 inch reference value was employed by NASP because of low variability in results at that level. The pull-out tests here were not meant to prove appropriate pull-out strength for in-service conditions, but rather to make relative comparisons of overall strength due to surface bonding of the materials. For in-service conditions, the use of full seven-wire strand provides additional bond strength due to mechanical interlock and increased friction.

The load versus slip plots for the wires show a linear behavior, past the 0.1 inch limit, up to the maximum capacity as visible in Figure 9 for the coated wire "C". The maximum resisting load developed by the wires that were coated increased by 80 to 140% when compared to the uncoated wire capacities. A comparison of the maximum bond loads is shown in Figure 10.

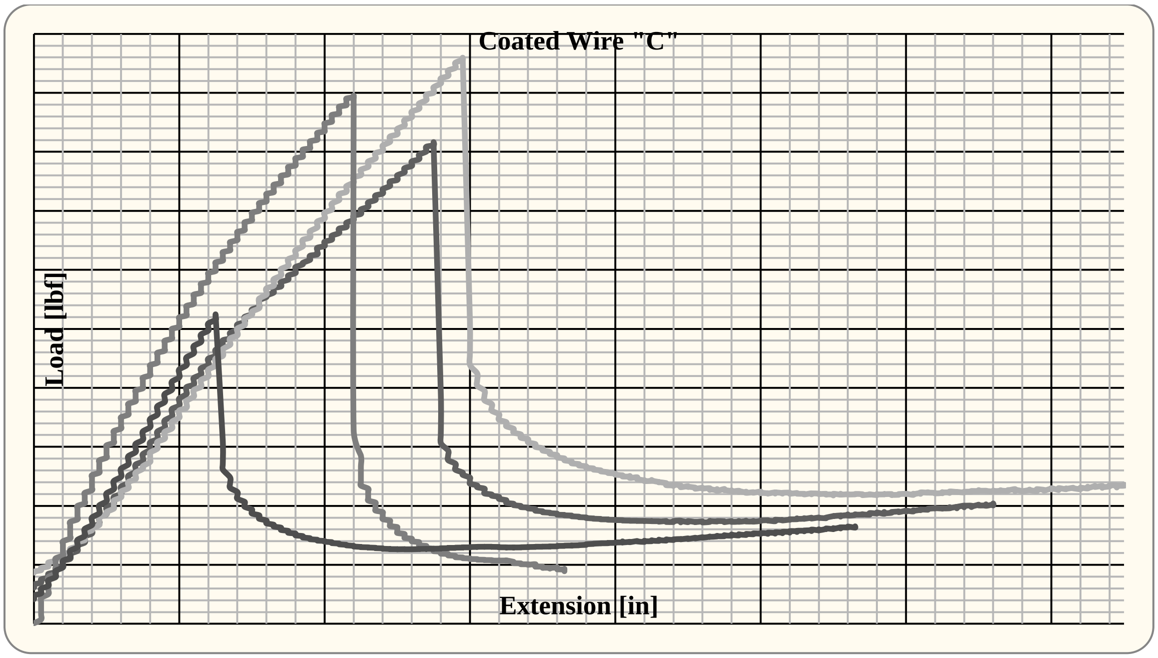


Figure 9. Load and slip or extension plot for coated wire C in pullout test.

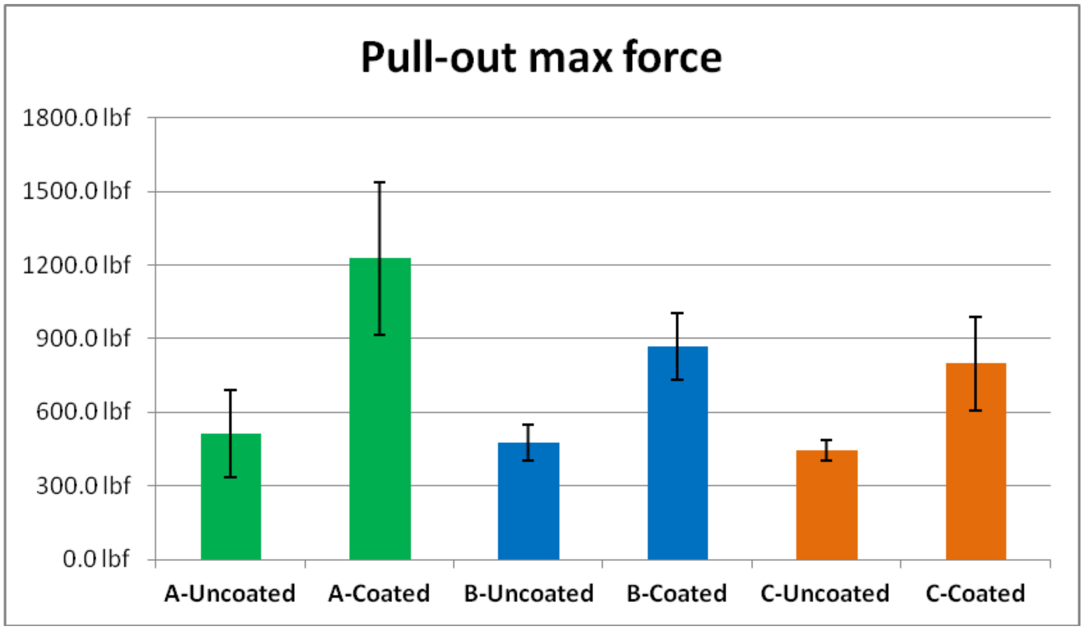


Figure 10. Comparison of wire pullout forces.

CONCLUSIONS AND RECOMMENDATIONS

The results in this report on preliminary testing are encouraging and intriguing. The wires with nanoporous coatings show an improvement in corrosion resistance and also an increase in the steel-concrete bond strength, ensuring satisfactory transfer of prestress. Further efforts are needed to completely prove the qualities of the coatings and a specific focus is required to make the coating process practical for industry.

The coatings provide a substantial increase in corrosion resistance for the Grade 270 pretressing wire, as measured by accelerated tests, when under the long term tension stress levels expected in prestressed concrete members as compared to the uncoated strand that are now commonly used in prestressed concrete bridge girders.

Unlike other coatings, such as epoxy, the nanoporous coating does not reduce the strength of the steel-concrete bond but was shown to actually improve bond by 80 to 140%. This extra bond could improve transfer lengths in girders and may impact the shear strength at the ends of girders.

A natural concern might be related to the toughness of the thin nano coatings and whether they can experience handling conditions without damage. Although testing has not yet been conducted, the nanoporous coating is expected to be tougher......since it is a ceramic material with a greater hardness than steel.

The next step in this research should focus on how to best pre-treat the steel wires prior to coating and on how to devise an industrial process applying the coatings. Then future research should also determine how resistant the coating is to physical abrasion and the bond characteristics of the full 7 wire strand rather than individual wires.

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