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16. Abstract

The objective of this research project is to investigate the corrosion and bond performance of different coatings and nontraditional metals in salt-contaminated concrete. An accelerated macrocell corrosion test is being carried out to determine the behavior of galvanized, stainless steel-clad, epoxy-coated, PVC-coated, nylon-coated, and 304 stainless steel reinforcing bars cyclically exposed to a chloride solution. To date, there has been no change in the readings to indicate that corrosion of the reinforcement has initiated. Pullout testing was conducted to compare the bond behavior of bars with different polymer coatings. There were not any significant differences observed in the bond behavior of the epoxy, PVC, and nylon coatings. Each coating type was able to achieve a similar maximum applied pullout force and exhibited similar load–slip behavior during testing.

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Feasibility of Various Coatings for the Protection of Reinforcing Steel—Corrosion and Bond Testing

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Research Project 7-4904
"Feasibility of Hot Dipped (Zinc) Galvanizing and Other Coatings
for the Protection of Reinforcing Steel"

Conducted for the
Texas Department of Transportation
in cooperation with the
U.S. Department of Transportation
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by the
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1. Overview

1.1 Introduction

Corrosion of steel reinforcement is by far the greatest threat to the integrity of concrete structures and has often been compared to cancer in the human body. This is a very fitting comparison because each can potentially kill the body or structure by attacking one or more of its vital components, whether those components are its organs, bones, blood, or reinforcing steel in concrete.

Articles on concrete reinforcement corrosion were first published in the early 1900s. Research carried out by the U.S Bureau of Standards in 1913 concluded that the addition of a small amount of salt into the concrete greatly increased the occurrence of reinforcement corrosion in concrete (Husock 1982). The magnitude of the problem has been fully realized in the past four decades. Most states instituted a bare pavement policy in freezing weather by the late 1960s. After this policy was enacted, the use of deicing salts increased from slightly more than 2 million tons in 1960 to over 9 million tons in 1970. The resulting infrastructure problem has grown from one of relatively isolated incidents of damage to one of extensive and widespread damage, necessitating repairs that are estimated to cost hundreds of billions of dollars. In a 1993 Federal Highway Administration (FHWA) report, it was estimated that the cost of immediately eliminating all of the highway deficiencies would be $212 billion, with the cost of annual maintenance being $67 billion through 2011 (Husock 1982).

The cancer analogy for reinforcement corrosion is also appropriate from another perspective. The best method for controlling both cancer and corrosion is prevention. It would help to reduce the amount of destructive deicing salts applied to roadways, but other methods of keeping roadways clear of snow and ice are not as efficient and economical as conventional salts. Therefore, other methods of preventing or limiting corrosion are needed. Often, careful design detailing and proper specifications are sufficient to keep corrosion problems under control. However, many concrete structures are built in severe environments where traditional methods of controlling corrosion are not sufficient.

Over the last 30 years, there has been an extensive amount of research devoted to the development of technologies that will prevent or delay corrosion and extend the service life of concrete structures placed into severe environments. One of the most widely used technologies is epoxy-coated reinforcing bars. Epoxy coatings were first placed into service in Pennsylvania in 1973. Laboratory results since 1973 have indicated that epoxy coatings increase the corrosion resistance of reinforcing steel.

Early in the development of epoxy-coated reinforcement, engineers realized that the coating might have an effect on concrete-steel bond. The transfer of forces from the steel to the concrete is imperative for desirable performance of concrete structures. The stress transfer, or bond, between the steel and concrete can be developed in several ways: (1) adhesion between the two materials, (2) friction along the surface as the bar slips, relative to the concrete, and (3) bearing against the lugs. Coatings are most likely to affect the adhesion and friction components of bond. Laboratory studies have indicated that epoxy coatings decrease bond along the bar and that the amount of bond decrease is dependent on the confinement provided by the structure. There is a greater reduction of bond when there is less concrete cover or transverse steel to provide confinement. Inadequate bond capacity is potentially dangerous because loss of anchorage capacity can occur with little or no warning.

New coatings and other types of steel that potentially offer more corrosion resistance are being introduced into the market at an increasing rate. It is important to develop a methodology to evaluate new and nontraditional materials. This evaluation methodology must address the corrosion resistance provided by these new materials and any possible effects these materials might have on the bond between the concrete and reinforcement.

1.2 Research Objectives

The objective of this research project is to investigate the performance of different nontraditional metallic materials for concrete reinforcement in corrosive environments and their effects on the concrete-reinforcement bond. The purpose of this study was to identify types of new materials that would be suitable in Texas Department of Transportation projects for reducing the effects of reinforcement corrosion in concrete. This research project was divided into the following tasks:

- Determine long-term corrosion performance of coated, nontraditional, and traditional metals using macrocell specimens. These materials would be tested using macrocell specimens with configurations similar to those in Project 1265 (Kahhaleh et al. 1994).
- Develop a polarization resistance and immersion test method to evaluate the corrosion performance of new materials. The results of these tests would be compared with the macrocell test results to determine if there is a correlation between the observed short- and long-term corrosion performances.
- Develop a test method to evaluate the bond performance of bars with different organic coatings. The test results would be compared with test results reported in previous studies of epoxy coatings to determine whether the various coatings have similar reductions in bond strength.

The results of this study should be of benefit in the selection of more corrosion resistant coatings and metals for concrete reinforcement. This research should also help develop a more efficient method to evaluate the corrosion and bond performance of new materials.

This report describes the variables, test program, and results of the long-term macrocell corrosion experiments and of the bond experiments for various organic reinforcement coatings. The variables, test program, and results of the polarization resistance and immersion experiments are described in more detail in Research Report 4904-2.

2. Background and Literature Survey

2.1 Concrete-Reinforcing Steel Bars

Steel bars for concrete reinforcement are governed by standards that specify their metallurgical and mechanical properties and are typically classified according to the method of production and strength. Testing of the metallurgical and mechanical properties is typically conducted at the mill. Bars must also be inspected carefully at the construction site to ensure compliance with the established standards and design documents.

Several mechanical properties of reinforcing bars are important for purposes of design, including strength, ductility, and bond. The yield strength and tensile strength of the reinforcing steel are determined from uniaxial tension tests of reinforcing bar specimens. Acceptable limits are specified in the standards concerning the minimum number of specimens to be tested, minimum yield stress, minimum tensile strength, and minimum elongation. The reinforcing steel must have sufficient ductility to enable fabrication and to ensure that structures can deform plastically at the ultimate limit state. The maximum plastic deformation of structures is a function of the maximum plastic strain, which is measured between the yield point and tensile strength. Also, the reinforcing steel bars must be capable of developing sufficient bond with the concrete for efficient, economical anchorages and lap splices. Good bond is also required to ensure the proper distribution of cracks under service conditions.

2.2 Corrosion Mechanism in Concrete

Corrosion is the destructive result of chemical reactions between a metal or metal alloy and its environment (Jones 1996). Metals in nature are not found in their desired state and must be extracted to form useful materials. Corrosion is the process by which an extracted metal returns to chemical compounds that are similar or equal to those found in nature.

The alkaline environment in concrete provides excellent corrosion protection for the reinforcing steel under normal conditions. Hydroxides, which have very high pH values, are created during the hydration of portland cement. Typical pH values for concrete range from 12.5 to 14 (Locke 1982). At such high pH values and in the presence of oxygen, a microscopically thin layer of iron oxide is formed on the steel surface. This oxide film passivates the steel from corrosion.

Changes must occur within the concrete to break down the oxide film in order for the passivation to lose effectiveness. There are two general processes which can occur within concrete that cause the passivating effect to be destroyed:

1. Carbonation that reduces the alkalinity by neutralizing alkaline compounds through reactions with carbon dioxide or other acidic materials.
2. Electrochemical reactions involving chloride ions in the presence of oxygen.

2.2.1 Carbonation

Carbonation occurs when carbon dioxide from the ambient air reacts with the hydroxides in the pore solutions to form carbonates plus water (Jones 1996). These reactions cause the alkalinity to drop from pH values of 12.5 or 14 to 8 or 9. The reduced pH values of the concrete allow the oxide film to become unstable and the reinforcing bars change from a passive corrosion state to an active state. The rate of carbonation penetration into hardened concrete is slow and the effects of carbonation can be minimized easily through proper design and detailing of the structure.

2.2.2 Electrochemical Corrosion

By far the most common corrosion mechanism in concrete is electrochemical. As stated earlier, the primary cause of the electrochemical process in concrete is the presence of free chloride ions in solution. It is speculated that chloride ions penetrate through pores or defects and break down the oxide film more easily than do other ions (ACI 222 1996). There are many potential sources for chlorides, including proximity to salt water environments, industrial brines, deicing salts, and even chlorides that are cast in during construction. Small chloride levels in concrete are not sufficient to initiate corrosion. Test results to determine a more exact concentration level threshold have had significant variations and are subject to debate. An FHWA report stated that corrosion is not likely when chloride levels are at or below 0.15%, based on weight of cement, and that corrosion is likely when chloride levels are above 0.30%, based on weight of cement (Locke 1982).

In addition to the breakdown of the oxide film, an electrochemical or galvanic cell must be established. When electrochemical processes take place in concrete, the concrete structure can be thought of as an inefficient battery. Just as in alkaline batteries, corrosion in concrete creates an electric current by developing a galvanic cell. There are four requirements for a galvanic cell (ACI 222 1996):

1. Anode
2. Cathode
3. Electrolyte
4. Electrical circuit

Anodes are sites where oxidation reactions occur and cathodes are sites where reduction reactions occur. These sites develop because of differences or nonuniformities in the steel reinforcement. Differences in the reinforcement can be caused by placing different types of steel or welds in contact or by variations in the chemical and/or physical environment of the surrounding concrete. Chlorides are very effective in developing anodic and cathodic sites because their concentration varies throughout the structure, which causes variations in the passivating oxide film. Following are the two electrochemical reactions that occur during the corrosion of steel (Jones 1996):

1. Anodic reaction

   $Fe \rightarrow Fe^{2+} + 2e^-$

2. Cathodic reaction

   $2H_2O + O_2 + 4e^- \rightarrow 4OH^-$

$Fe(OH)_2$ is a weak base formed during the reaction and is unstable. In the presence of oxygen, another reduction reaction occurs and $Fe(OH)_2$ is converted into $Fe(OH)_3$, or rust, which precipitates out of solution.

An electrolyte is an aqueous medium through which electric current flows. In this instance, the electrolyte is the concrete itself. Chlorides, permeating into hardened concrete, act as a double-edged sword. Not only do chlorides break down the protective oxide film of the reinforcement, but chlorides also increase the conductivity of the concrete, allowing more current to flow.

The requirement of an electrical circuit is always satisfied in a concrete structure. Columns and beams are reinforced with steel cages, and slabs are reinforced with one or two mats of reinforcement. Metal ties, mechanical connectors, and chairs, which are used to facilitate construction, create electrical connections among virtually all of the reinforcing bars in a reinforced concrete member.

Deterioration of concrete due to corrosion is a progressive process. Corrosion byproducts occupy a much larger volume than does the original reinforcing steel. This increase in volume creates high radial pressures and tensile forces in the concrete surrounding the steel and quickly causes cracking. There may be only a few early clues to indicate that corrosion is occurring beneath the surface, such as cracking, staining, or delaminating concrete. As corrosion continues, the concrete cover begins to spall. Structural distress may eventually result owing to the loss of cross-sectional areas of the reinforcement or the loss of bond from continued spalling.

2.3 Corrosion Prevention Strategies

Careful attention must be given to the detailing of a structure during design and good construction practices must be followed for the likelihood of corrosion to be minimized. Several details and specifications that enhance corrosion resistance include

- Increased concrete cover
- Use of low permeability concrete
- Efficient drainage systems
- Minimum slope of exposed surfaces
- Limited chloride content of concrete mix ingredients

Of these details and specifications, depth of cover of the reinforcement and permeability of the concrete primarily control the likelihood and extent of corrosion. Increasing cover provides indirect corrosion protection by forcing chloride ions to penetrate concrete further before reinforcement is encountered. The rate of penetration through the cover is a function of the permeability of the concrete. Factors that influence the permeability of hardened concrete include amount of cement, water to cement ratio, consolidation of the concrete, and microcracking of the concrete surface. Limiting chloride penetration helps to keep the passivating film intact.

Traditional design and standard specifications may not be sufficient to prevent corrosion if the structure is constructed in an extremely harsh environment. Several new technologies have been developed to increase the service life of concrete structures in aggressive environments. These technologies include:

- Coated reinforcing bars
- Polymer- or latex-modified concrete
- Corrosion inhibitors
- Cathodic protection
- Waterproof membranes

A technology that has become widely used in North America is fusion-bonded, epoxy-coated reinforcement. Very fine epoxy powder is sprayed onto thoroughly cleaned bars and cured at high temperature. Epoxy coatings theoretically serve as an impermeable barrier to water, oxygen, and chlorides. It is impossible to manufacture and maintain a perfect epoxy coating. Holidays and handling damage are always present on epoxy-coated bars and can lead to corrosion. Therefore, manufacturing and job site handling are extremely important because the epoxy layer is brittle and can easily scratch or chip from abrasion between bars and construction equipment.

Several studies, including previous research performed at the University of Texas at Austin (Vaca-Cortes 1998), have indicated that epoxy-coated bars are more corrosion resistant than are uncoated bars, even when the coating is damaged. Epoxy-coated bars generally experienced uniform corrosion with shallow pitting, whereas uncoated bars experienced extensive corrosion with moderate to severe pitting.

2.4 Concrete–Steel Bond

Concrete is an excellent material when subjected to compressive forces, but the tensile strength of concrete is typically only about 8%–15% of its compressive strength (MacGregor 1992). Therefore, the tensile strength of concrete is neglected in design and reinforcing bars are needed to equilibrate the internal forces and moments. Tensile and compressive forces are transferred to bars through bond action. A common assumption in the analysis of structural concrete is that the strain in the steel is equal to the strain in the surrounding concrete, which implies there is no slip between the concrete and the steel. Another assumption in limit state design is that the steel stress can reach the specified minimum yield strength. Bond action must provide adequate anchorage for the steel to reach yield and allow for inelastic strain to be developed. The ductile behavior of concrete structures depends on the ability of the reinforcing steel to reach yield strength and deform inelastically.

2.4.1 Bond Mechanics

The bond mechanism between steel and concrete can be broken into three components:

3. Adhesion
4. Friction
5. Bearing

The effects of concrete–steel adhesion and friction are related to the mechanics of bond action. Adhesion is the chemical bond that forms between the reinforcing bar and the concrete surface during hydration. Friction forces increase the efficiency of the force transfer because the force acts opposite to the direction of slip, but the amount of friction decreases as the tensile force increases because of Poisson effects on the bar. Adhesion increases the amount of friction because small concrete particles adhere to the steel surface, which causes the roughness of the reinforcing surface to increase (Cairns 1994).

The bond mechanism between steel and concrete can be seen in Figure 2.1. Bearing is the principal force transfer mechanism. Bearing forces are transferred perpendicular to the surface of the reinforcing bar deformations, which are at an angle to the axis of the reinforcing bar. The resulting equal and opposite forces in the concrete can be broken into two components: (1) longitudinal and (2) radial. The longitudinal component is responsible for developing tension in the reinforcing bars and the radial component creates circumferential tension in the concrete around the bar.

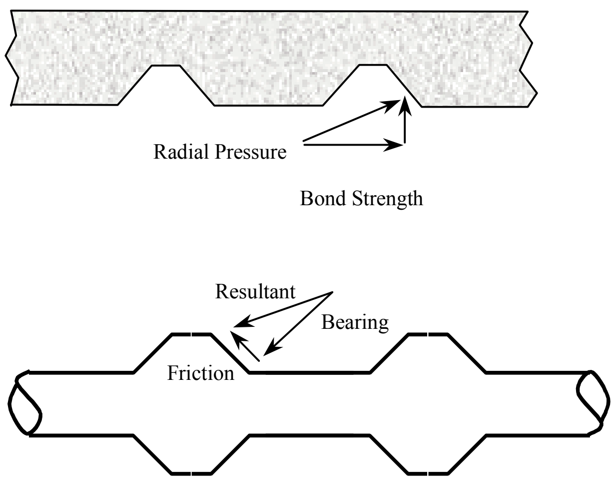

Figure 2.1: Force Transfer Mechanism

There are two general types of failure mechanisms associated with concrete–steel bond: splitting and pullout. Typical splitting failures can be seen in Figures 2.2–2.4 (Orangun 1977) and a pullout failure can be seen in Figure 2.5 (Cairns 1992).

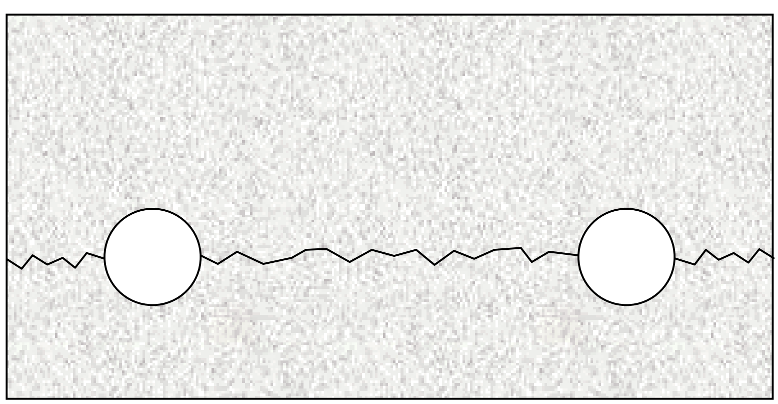

Figure 2.2: Side Split Failure

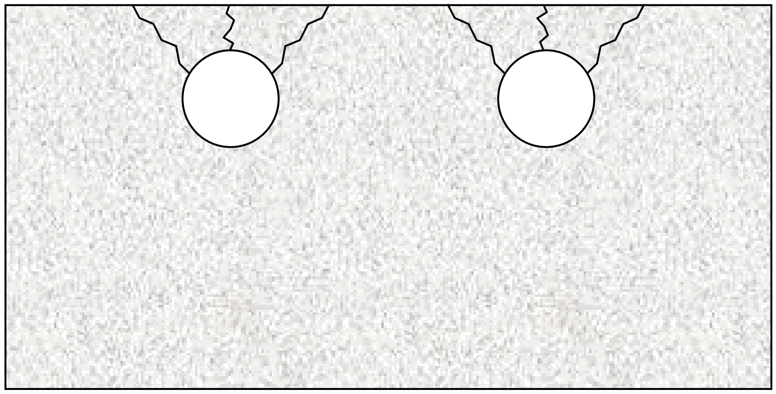

Figure 2.3: V-Notch Failure

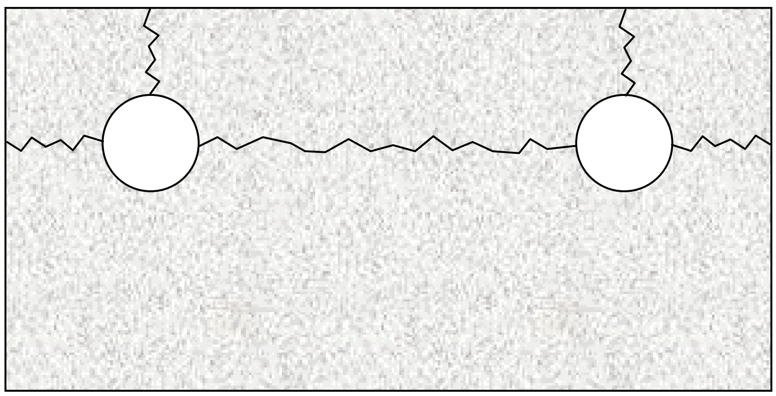

Figure 2.4: Face-and-Side Split Failure

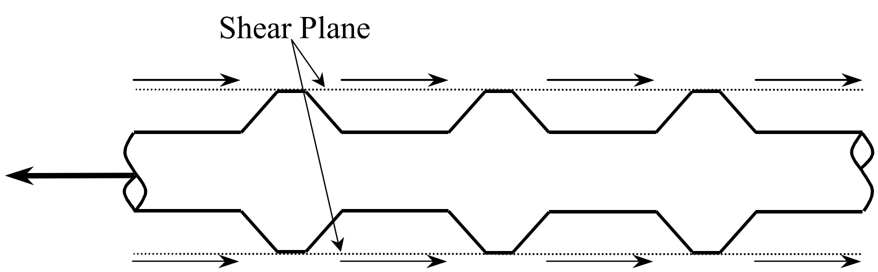

Figure 2.5: Pullout Failure

2.4.2 Splitting Failure

A splitting failure occurs when the reinforcing bars are not well confined and the radial force exceeds the capacity of the surrounding concrete. The type of splitting failure that occurs depends on the relative differences among bar spacing, bottom or top cover, and side cover. A side-split failure occurs if the side cover is less than the top cover or half of the bar spacing, and a V-notch failure occurs if half of the bar spacing and the side cover are both greater than the top cover. An intermediate type of failure, a face-and-side-split failure, occurs if the top and side covers are approximately equal. Splitting failures have also been found to depend on the bar size, bar spacing, concrete strength, use of lightweight concrete, and the casting position of the bar.

2.4.3 Pullout Failure

A pullout failure occurs when reinforcing bars are well confined and the embedment or splice lengths are insufficient to develop yield and strain hardening of the steel. These failures are characterized by a series of cracks developing along a shear plane connecting the peaks of the reinforcement deformations. The failure pattern indicates that resistance to pullout is controlled by the capacity of concrete in shear, and the friction and adhesion components are of much less importance than with a splitting failure.

2.5 ACI Provisions for Development of Reinforcement

The current ACI Building Code provisions related to steel–concrete bond are based largely on work published by Orangun, Jirsa, and Breen in 1977 (ACI 318 1999). This study developed a nonlinear regression equation on the basis of test results for beams with lap splices. This regression equation takes into account the effects of concrete cover, bar spacing, bar diameter, concrete strength, and transverse reinforcement on the length required to develop yield stress in bars anchored in a tension zone. A modified form of this equation was finally incorporated into the ACI Building Code Requirements for Structural Concrete in 1989 and was further revised in 1995. Following is the current ACI Building Code equation for the development of deformed bars in tension (ACI 318 1999):

$$\frac{l_d}{d_b} := \frac{3 \cdot f_y \cdot \alpha \cdot \beta \cdot \gamma \cdot \lambda}{40 \cdot \sqrt{f'_c} \cdot \left(\frac{c + K_{tr}}{d_b}\right)}$$

Notation:

l_d = development length (in)

d_b = nominal diameter of bar (in)

f_y = specified yield strength of reinforcement (psi)

f'_c = specified compressive strength of concrete (psi)

c = spacing or cover dimension (in)

K_{tr} = transverse reinforcement index

α = reinforcement location factor

β = epoxy coating factor

γ = reinforcement size factor

λ = lightweight concrete factor

The values for the α, β, γ, and λ multipliers were obtained from relevant research results. The specification states that the factor β for epoxy-coated bars with cover less than $3d_b$ or bar spacing less than $6d_b$ is equal to 1.5. The factor β is equal to 1.2 for all other conditions. Also, the product of the top reinforcement factor, $\alpha = 1.3$, and β is limited to 1.7. The term $(c + K_{tr})/d_b$ takes into account the amount of cover, bar spacing, and presence of transverse confining reinforcement. The maximum value for $(c + K_{tr})/d_b$ is limited to 2.5 to safeguard against pullout failure.

2.6 Coating Effects on Concrete–Steel Bond

Epoxy-coated bars have been commercially available for over 20 years; however, PVC- and nylon-coated bars are not yet commercially available. Consequently, there have been numerous research projects regarding the bond behavior of epoxy-coated reinforcing bars but relatively few projects have included bond testing of other organic coatings. Therefore, the following discussion regarding coating effects on concrete–steel bond will focus entirely on the test results of epoxy-coated bars.

The greatest concern regarding the use of epoxy coating for reinforcement in structural concrete has been its effect on bond between the concrete and the reinforcement. The ability of steel to transfer forces to the concrete through bond action is critical to the short- and long-term performance of concrete structures. Following are several factors that may affect the bond behavior of epoxy-coated reinforcement (Cairns 1992):

- Adhesion is prevented because the layer of epoxy acts as a bond breaker between the steel and the hydrating cement.
- Friction is reduced because the epoxy coating reduces the microscopic irregularities caused by mill scale.
- Mechanical properties of the coating are different than those of concrete and steel and may change the state of stress in the concrete surrounding the bar.
- Thicker coatings tend to be uneven, which typically decreases the effective height of the bar deformations.

2.6.1 Differences in Bar Deformation Geometry

Pullout tests have been used to determine the effects of differences in rib geometry on the bond strength of epoxy-coated bars. A series of tests was performed that evaluated the influence of bar rib face angle, rib spacing, rib height, and concrete strength (Hamad 1995). In this study, specially machined coated reinforcing bars were tested in an eccentric pullout specimen. The results of these tests were compared with tests of similarly machined uncoated bars. These tests indicated that coated bars slipped more than did uncoated bars, regardless of the test variable. With all other test variables held constant, the relative bond strength of the coated bars increased as the rib face angle increased, rib spacing decreased, and rib height increased. These trends appeared to be independent of differences in concrete strength.

Even though variations in bar geometry and concrete strength can produce significant differences in bond strength results, these variables appear to have no effect in the evaluation of coatings for comparison purposes only. A series of pullout tests, using different bar sizes, various bar deformation patterns, and different concrete strengths, was performed to determine differences in stress transfer between coated and uncoated bars (Hamad 1990). In these tests, it was found that the bond strength of epoxy-coated bars was lower than that of uncoated bars by approximately 10%–25%. This decrease in the pullout resistance of epoxy-coated bars did not appear to be influenced by any of the parameters considered. Therefore, direct comparisons of relative bond behavior can be made between coated and uncoated bars, provided that there are no differences in rib geometry, concrete strength, and transverse reinforcement among specimens.

2.6.2 Loss of Adhesion

The lack of adhesion between epoxy-coated reinforcement and concrete has been well documented. Autopsies were performed of several failed spliced beam specimens with epoxy-coated and uncoated reinforcement (Treece 1989). These autopsies showed no indication that concrete adheres to epoxy-coated reinforcement. The concrete in direct contact with the epoxy-coated bars had a smooth, glassy surface and the coated bars appeared clean, with no concrete residue left on the deformations. The autopsies of similar specimens with uncoated reinforcement indicated that adhesion had occurred. The concrete surface in direct contact with uncoated bars was dull and rough and the uncoated bars that were removed had concrete particles firmly attached to the shaft, with large deposits on the sides of the deformations.

2.6.3 Decreased Friction

A series of tests was performed that compared the frictional characteristics of a mill-scale steel-concrete interface with that of a fusion- bonded, epoxy-coated steel-concrete interface (Cairns 1994). Specimens were rectangular concrete prisms, each of which were cast between two steel plates. Half of the steel plates were coated with epoxy and half were left uncoated. The specimens were compressed during testing to impose a normal stress on the steel–concrete interface. A horizontal force was applied to create shear stress along the interface. This force was steadily increased until the maximum load was achieved. These sandwich specimens failed by shear along the concrete-steel plate interface. The results of these tests indicate that there are two components to friction: a frictional component and an adhesion component. The observed frictional components are similar for coated and uncoated bars; however, there is no adhesion for coated bars. At low values of normal stress, the maximum applied shear for the coated steel decreased by approximately 40%, as compared with the uncoated steel. The difference between coated and uncoated bars decreased as the applied normal stress increased.

2.6.4 Comparison of Coated and Uncoated Reinforcement Bond Forces

With the loss of adhesion and friction, bearing on the bar deformations is the only component that contributes to the development of coated bars. A comparison of the resulting bond forces for uncoated and epoxy-coated bars is shown in Figures 2.6 and 2.7.

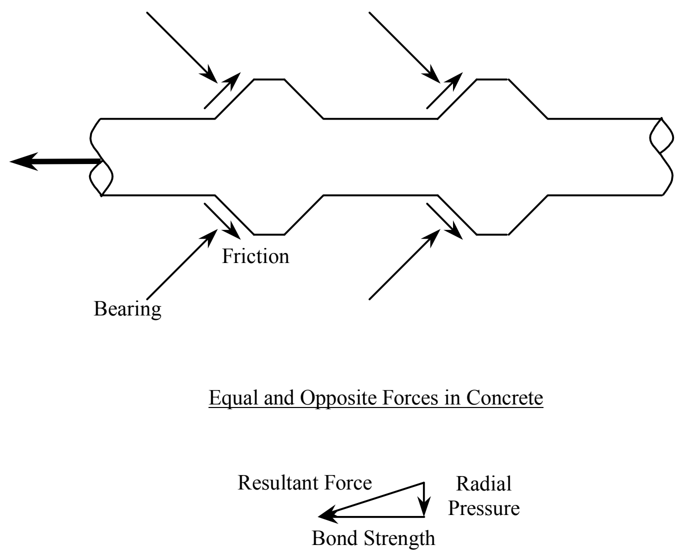

Figure 2.6: Uncoated Reinforcement Bond Forces

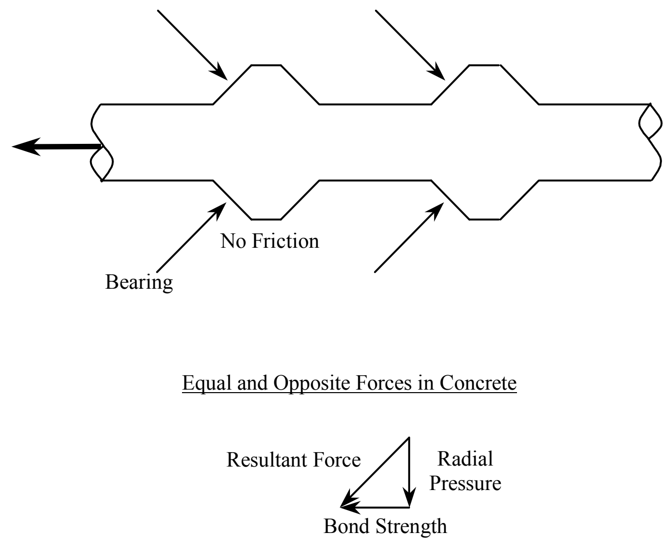

Figure 2.7: Coated Reinforcement Bond Forces

The friction and bearing force vectors can be added to determine the resultant force. As can be seen in Figures 2.6 and 2.7, friction is beneficial to bond because it decreases the angle of the resultant force, which results in a smaller radial splitting force. The use of epoxy-coated bars increases the angle of the resultant bond force and causes higher radial splitting force. This indicates that epoxy-coated bars will have less bond capacity because they are more likely to experience a premature splitting failure than are uncoated bars.

2.6.5 Pullout Resistance

Pullout-type specimens have been used extensively in an attempt to quantify the difference in bond capacity between epoxy-coated and uncoated reinforcement. Several independent research programs have used various pullout specimens to evaluate the decrease in bond strength of epoxy-coated reinforcement (Cairns 1994, Choi 1991, Clifton 1983, Hamad 1990, Kayyali 1995). The results of these studies vary; however, the average pullout strength of epoxy-coated reinforcement was less than was the average pullout strength of uncoated reinforcement. In general, the pullout strength for epoxy-coated reinforcement was reduced to about 80%–95% of the pullout strength for uncoated reinforcement. This decrease in bond was also demonstrated in a series of pullout tests in which coated and uncoated bars were instrumented with strain gauges (Cusens 1993). The strain gradient along the length of the bar was measured and found to be less for coated bars than for uncoated bars. The decrease in strain gradient indicates that forces are not transferred into coated reinforcing as efficiently as they are into uncoated reinforcement.

2.6.6 Lapped Splice Strength

It is essential to determine building code provisions by using test specimens that are representative of practical situations. The state of stress and the high splitting resistance found in typical pullout tests are not representative of normal conditions found in concrete members. For example, present ACI Code provisions for the development length multiplier, α, for epoxy-coated reinforcement were based on studies of the strength of lapped joints in beams.

The ACI provisions are based on a study of 21 beams with lap splices in a constant moment region. These beams were tested in nine groups and the bond strength of epoxy-coated bars was compared with that of uncoated bars (Treece 1989). In each of the nine series, a different combination of variables was examined but the only variable within a series was the coating thickness. The variables tested included bar size, concrete strength, casting position, and coating thickness. For each of these tests, the mode of failure was a splitting failure at the splice region and the bond strength could be determined from the stress developed in the steel. The results of these tests showed an average decrease in bond strength of 35% for coated reinforcement. The results of these tests did not appear to be influenced by any of the variables tested other than that of the bars being coated or uncoated. This reported bond reduction is much higher than was reported in previous pullout testing. Therefore, it was concluded that a greater development length is required with small cover or closely spaced bars, which causes splitting to be the more likely mode of failure.

2.6.7 Deflection, Crack Spacing, and Crack Width

Beam tests have also been used to determine the effect of epoxy-coated reinforcement on the amount of deflection and the spacing and widths of cracks. Deflections, crack spacing, and crack widths were also measured in the previously mentioned study of 21 beams with lap splices. Little difference was found between the measured deflections of beams with epoxy-coated and uncoated bars. This indicates that the use of epoxy-coated reinforcement does not significantly influence the stiffness of concrete members. Specimens with epoxy-coated bars have fewer cracks but the width of the cracks is greater in these specimens than in uncoated bar specimens. Because there was no difference between the deflections of coated and uncoated bar specimens, the total width of all cracks must be equal.

2.6.8 Flexural Strength

It is clear that the use of epoxy-coated reinforcement creates problems for detailing concrete reinforcement. However, the use of epoxy-coated reinforcement does not affect the ultimate strength of concrete members, provided that the concrete member is properly detailed in order to develop the reinforcing steel. A series of tests was performed to determine the effect of epoxy coating on the flexural strength of reinforced concrete beams. Slip of the reinforcement was also monitored during these tests. These beams were simply supported and tested in four-point loading, with a constant moment region near the center. Reinforcement was developed near the supports for a simply supported beam, away from the region of maximum moment. Beams with epoxy-coated reinforcement failed in flexure at an average load that was 2% less than for beams with uncoated reinforcement. However, loads at which epoxy-coated reinforcement experienced significant slip were 23% less than for the uncoated reinforcement. Therefore, the increased amount of slip for epoxy-coated reinforcement in the anchorage zone did not significantly affect the ultimate flexural strength of the member.

3. Macrocell Test Program

3.1 Introduction

There have been numerous research projects to study the corrosion resistance of an individual coating or metal for concrete reinforcement protection but relatively few projects have tested numerous materials of different types to make comparisons and determine which ones offer better corrosion performance. This long-term corrosion study involves the testing of 176 macrocell specimens to compare the corrosion resistance of different metallic coatings, organic coatings, and corrosion resistant steels.

3.2 Scope

The objective of the macrocell test program is to compare the resistance to corrosion of different coatings and metals when embedded in concrete. The purpose is to identify which materials provide better protection for concrete-reinforcing steel.

Care was taken in the design and construction of the macrocell specimens so that each specimen was as nearly identical as possible. The only test variable was the type of corrosion resistant bar. The macrocell specimens were grouped according to the type of corrosion resistant bar. Sixteen macrocells were constructed for each type of corrosion resistant bar. Within each of these groups of macrocells were different bar coupling configurations. The control group consisted of uncoated bars with normal mill scale. Eight macrocells were constructed for each of the control groups. A detailed description of the Macrocell Experimental Program is given in Research Report 4904-2. A summary of the macrocell configurations is shown in Table 3.1. A schematic representation of a macrocell specimen is shown in Figure 3.1 and an actual macrocell specimen is shown in Figure 3.2

Table 3.1: Schedule of Macrocell Test Specimens

Bar Type	Bar Size	Top: Resistant Steel Bottom: Black Steel	Top: Resistant Steel Bottom: Resistant Steel	Top: Resistant Steel Bottom: No Steel	Top: No Steel Bottom: Black Steel
Control A (Black Steel)	4	4*	0	2**	2
Galvanized A	4	8	4	4	0
Galvanized B	4	8	4	4	0
Epoxy A	4	8	4	4	0
Epoxy B	4	8	4	4	0
Nonbendable Epoxy	4	8	4	4	0
Nylon	4	8	4	4	0
PVC	4	8	4	4	0
304 Stainless Steel	4	8	4	4	0
Control B (Black Steel)	6	4*	0	2**	2
Epoxy A	6	8	4	4	0
304 Stainless Steel-Clad	6	8	4	4	0

* Black steel on top and bottom.
** Black steel on top.

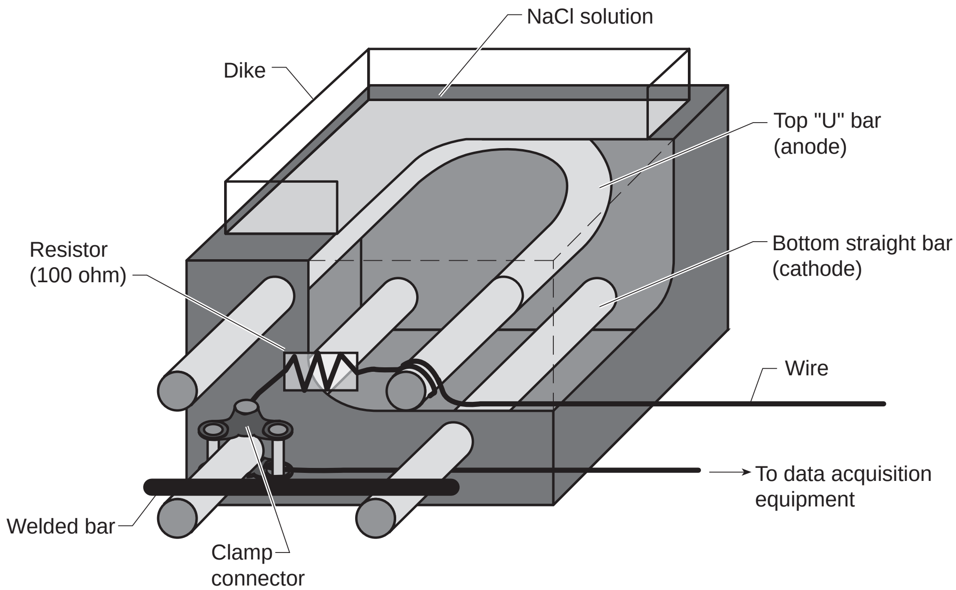

Figure 3.1: Typical Project 1265 Macrocell Specimen

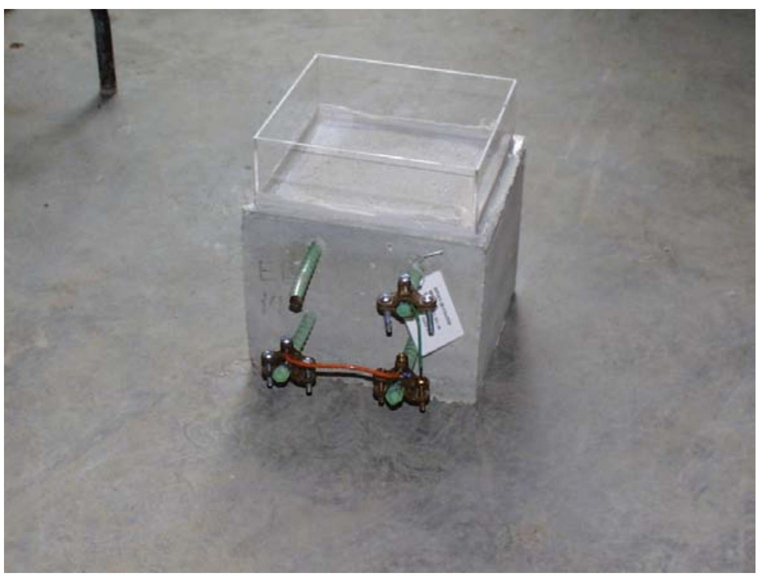

Figure 3.2: Completed Macrocell Specimen

4. Pullout Test Program

4.1 Introduction

Epoxy-coated bars have been commercially available for over 20 years; however, no other types of organic coatings for reinforcing bars are currently on the market. Consequently, there have been numerous research projects to test the bond behavior of epoxy-coated reinforcing bars but relatively few projects have included bond testing of other organic coatings, such as PVC or nylon. This study involves the testing of 18 pullout specimens to compare the bond strengths of bars coated with PVC, nylon, and epoxy.

4.2 Scope

The objective of the bond testing is to develop a method to evaluate the bond performances of bars with different organic coatings. The purpose is to determine the decrease in bond strength for reinforcing bars coated with different organic materials. This research program is not intended to develop building code provisions.

Care was taken in the design and construction of the pullout specimens so that each specimen was as nearly identical as possible. The only test variable was the type of organic coating. For each type of test material, three pullout specimens were cast with coated bars and three pullout specimens were cast with uncoated bars. The coated and the uncoated bars from a particular group were from the same heat (batch), with the same chemical composition and bar deformation pattern. Then the pullout results were compared to determine whether the bond behaviors of different coatings were similar.

4.2.1 Organic Coatings

PVC, nylon, and epoxy coatings were included in the pullout test program. An adequate amount of material was received from each of the manufacturers for the construction of the macrocell and the pullout specimens. However, the manufacturer of the epoxy-coated bars submitted additional uncoated and epoxy-coated bars because the original epoxy-coated bars were not the required length for the pullout specimens.

4.2.2 Bar Size

Bond strength is a function of bar size. For direct comparisons to be made between the different coating materials, the test bars must be the same size. Because the macrocell and the pullout materials were the same, #4 bars were used for the pullout specimens.

4.3 Selection of Bond Test Program

There have been numerous types of tests used to determine the bond strength of steel-reinforcing bars in concrete. Specimens used for these tests can be generally divided into three groups: pullout specimens, beam-end specimens, and beams with lap splices.

Pullout testing was the method selected to evaluate the bond performances of different organic coatings. A traditional pullout specimen is shown in Figure 4.1. Pullout specimens are simple to construct and to test and have been used for decades to test bond in concrete. This simplicity makes pullout testing the preferred method for screening new coating materials that are introduced on the market. Pullout test results can be used to determine the bond strength of bars in conditions in which premature splitting of the surrounding concrete is not critical.

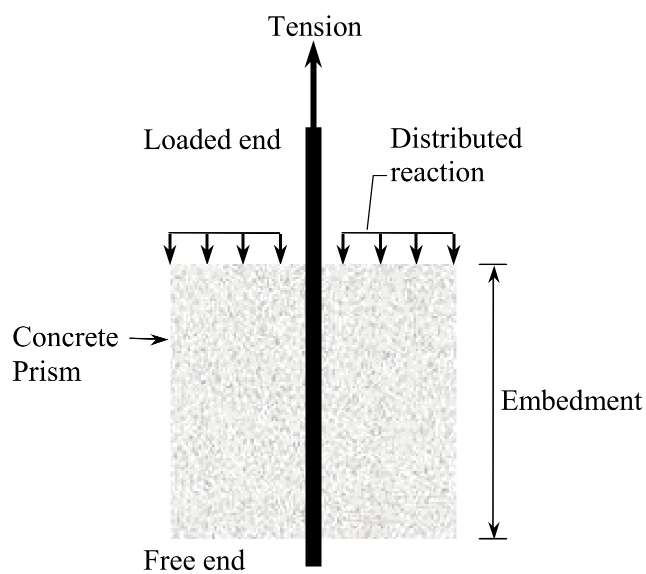

Figure 4.1: Typical Pullout Specimen

The disadvantage of pullout testing is that it does not accurately represent the structural behavior of real concrete structures. Concrete and reinforcing bars are rarely in opposing states of stress. A pullout test creates an artificial state of stress, with the test bar pulled in tension and the concrete prism placed into compression. Developing a bar in tension within a compression zone increases the pullout strength, because compression in concrete increases bearing on the bar deformations. Also, pullout failures are much less likely in typical concrete structures than are splitting failures. Pullout specimens are designed with a large amount of concrete cover and transverse reinforcement confinement to prevent a splitting failure mode.

Beam-end specimens and beams with lap splices are better representations of actual structural behavior. A typical beam-end bond specimen is illustrated in Figure 4.2, and a beam specimen with lap splices in a constant moment region is illustrated in Figure 4.3. Beam-end specimens mimic classic flexural behavior and can be used to test different variables and failure modes rather easily. Also, there is an ASTM standard test method for comparing bond strength with the use of beam-end specimens (ASTM A944 1995). Beams with lap splices represent the limiting case for bond in concrete and the current ACI Building Code Provisions are based, in part, on this type of test (Treece 1989). These specimens are designed to produce splitting failures. A short lap splice length was selected that would fail before the steel yielded. Also, transverse reinforcement was not provided in the constant moment region to control splitting cracks. Owing to the short splice length, the efficiency of stress transfer between adjacent bars becomes critical and the stress transfer efficiency is directly related to the resultant of the adhesion, friction, and bearing forces in bond.

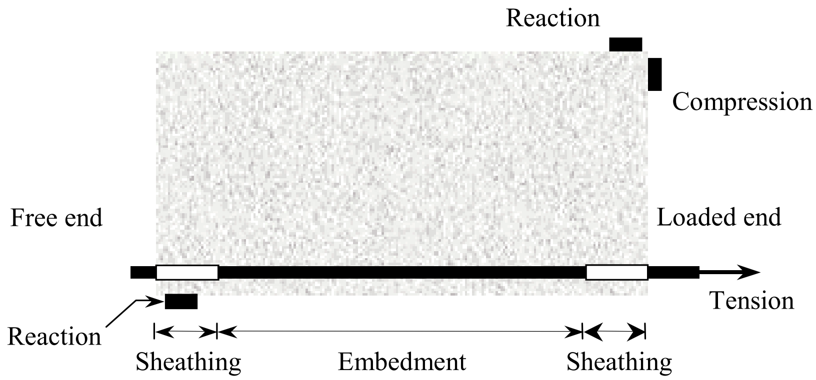

Figure 4.2: Typical Beam-End Specimen

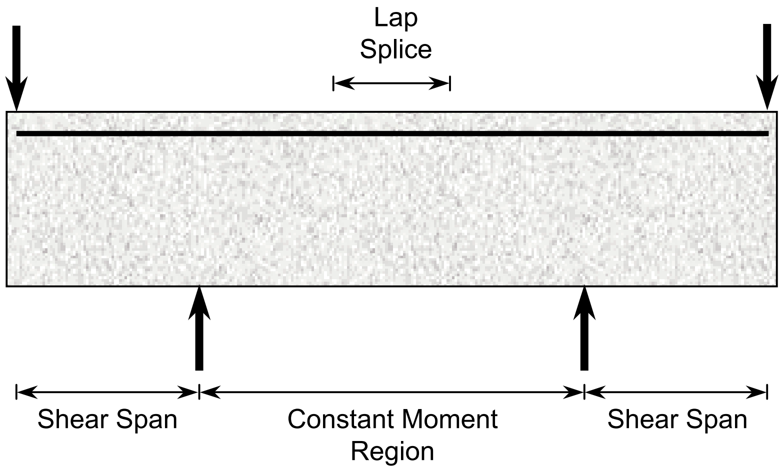

Figure 4.3: Typical Beam Specimen with Lap Splices

The biggest disadvantage of testing beam-end specimens and beams with lap splices is that these programs require significant time and expense to complete. The specimens are bulky and the test equipment is complicated. Owing to the high costs of building the specimens and the test configuration, these tests are not preferred for purposes of screening new materials.

4.4 Design of Pullout Specimens

The pullout specimen design was based on calculations for the embedment length of the test bar. The ACI Building Code equation for the development length of reinforcement in tension was used for this calculation, which is given in Section 2.5. The values of steel stress, the α, β, γ, and λ multipliers, and the transverse reinforcement index were chosen because the ACI Code equation is conservative in order to prevent pullout type failures and to ensure the ductile behavior of concrete structures. The assumed stress to be developed in the steel was 20,000 psi, which is half of yield for an idealized Grade 40 bar, and the compressive strength of the concrete was assumed to be 6,000 psi. The α, β, γ, and λ multipliers were assumed to be 1.0. Also, the value used for the transverse reinforcement index was 2.5, which is the maximum allowed in the ACI Building Code. The calculated embedment length was 3.75 in. Following is an example of the calculation for the embedment length of these pullout specimens:

d_b = 0.5 in.

f_y = 20,000 psi

f'_c = 6,000 psi

α = $\beta = \gamma = \lambda = 1.0$

$$l_d = d_b \cdot \left[\frac{3 \cdot f_y \cdot \alpha \cdot \beta \cdot \gamma \cdot \lambda}{40 \cdot \sqrt{f'_c} \cdot (2.5)} \right]$$

l_d = 3.873 in.

Use 3.75- in. embedment

As was stated above, the pullout strength can be increased artificially because compression increases the confining forces on the bar at the loaded end. To minimize this effect, the bars were debonded for a distance of 3.75 in. from the compression reaction surface, as is shown in Figure 4.4. This debonded length is equal to the embedment length and also approximately equal to the diameter of the center hole ram used during testing. The bars were also debonded near the free end for 2.5 in. Spiral #3 deformed bars surrounded the test bar for additional transverse confinement and crack control. The embedment length was completely enclosed within the spiral confinement because the bar was debonded at both ends of the specimen.

The overall dimensions of the pullout specimen were 10 in. long by 10 in. wide by 10 in. high. The 10-in. length was required in order to accommodate the two debonded bar sections and the embedment length. A

10-in. by 10-in. cross-sectional area provided adequate space for the spiral confining reinforcement. A schematic diagram of the pullout specimen can be seen in Figure 4.4.

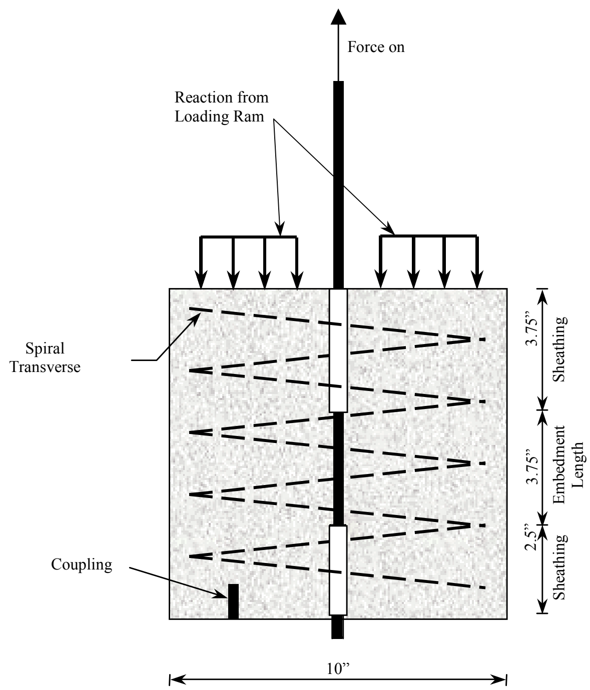

Figure 4.4: Schematic Diagram of Pullout Specimen

4.5 Construction of Pullout Specimens

4.5.1 Bar Preparation

All of the bars submitted by the PVC manufacturer were coated. A hook, which was used to dip the bars to apply the coating, was removed from each bar (see Figure 4.5). The coatings were removed from three bars for use in the control specimens. It is important in the bond testing of coated bars that the control specimens have uncoated bars from the same heat treatment in order to minimize differences in the chemical composition and bar deformation pattern. The PVC coating was removed by submerging the bars in methylene chloride. The methylene chloride softened the PVC coating and the softened coating was removed with a wire brush. A bar with the PVC coating removed can be seen in Figure 4.6.

The length of the nylon bars was not sufficient for this particular pullout specimen and test setup. Numerous attempts were made to acquire additional #4 uncoated and nylon-coated bars; however, the nylon -manufacturer was unable to submit these materials. To obtain the length of bar required for the pullout test, two nylon bars were welded together, end-to-end. A picture of the welded bars can be seen in Figure 4.7. The nylon coatings were removed from three bars for use in the control specimens. The nylon was chemically resistant to methylene chloride, so the nylon was burned off with a propane torch instead. The burned section of nylon coating can be seen in Figure 4.8.

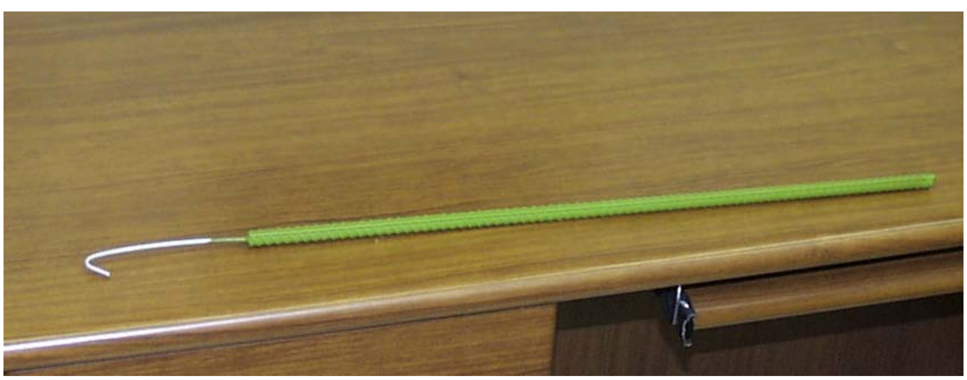

Figure 4.5: Typical PVC-Coated Bar

Figure 4.6: Typical Bar After Removal of PVC Coating

Figure 4.7: Typical Nylon-Coated Bar Weld

Figure 4.8: Nylon Coating Removed for Control Specimens

The additional uncoated and coated bars that were submitted by the epoxy-coated bar manufacturer were from the same heat (batch) and did not require any additional preparation.

4.5.2 Formwork and Bar Placement

A separate form was used to cast each pullout specimen. Six sets of forms were constructed so that all of the pullout specimens for a particular coating type could be cast simultaneously. Three batches of concrete were required to cast the specimens for each type of coating and the forms were reused for each pour. Screws were used to assemble the forms. The forms consisted of four separate panels that could be assembled and disassembled easily with four screws. A typical form that is ready for concrete casting can be seen in Figure 4.9.

No chairs or other types of supports were used for the placement of the test bar. The pullout specimens were side cast instead, and the ends of the test bars rested directly on the formwork. Both ends of the bar protruded through holes centered in the sides of the formwork. Beam bolsters were used to support the spiral reinforcement in the proper position. The reinforcing steel and test bar set-up can be seen in Figure 4.10.

A coupling for a 3/8-inch-diameter threaded rod was cast into the pullout specimen near the free end of the protruding test bar. The purpose of the cast-in coupling was to provide an accurate reference point for measuring slip during the pullout test.

Figure 4.9: Typical Form for Pullout Specimens

Figure 4.10: Typical Reinforcing Steel and Test Bar Setup

4.5.3 Concrete Casting

As was stated earlier, six sets of forms were constructed so that all of the pullout specimens for a particular coating could be cast simultaneously. The concrete placement operator is shown in Figure 4.11. The concrete was mixed outside and brought inside with the use of wheelbarrows. The pullout specimens were cast indoors. Scoops were used to place the concrete in the formwork. Then the forms were placed on a vibrating table to consolidate the concrete, as can be seen in Figure 4.12.

The top surfaces were trowel finished. After the initial set of the concrete, the formwork was covered with wetted curing blankets to create a moist curing environment and to prevent shrinkage cracks. A picture of the initial curing of macrocell specimens is shown in Figure 4.13.

Figure 4.11: Concrete Placement for Pullout Specimens

Figure 4.12: Concrete Consolidation

Figure 4.13: Curing of Pullout Specimens

4.6 Material Properties

4.6.1 Bar Properties

The American Society for Testing and Materials (ASTM) publishes A615 "Standard Specification for Deformed and Plain Billet-Steel Bars for Concrete Reinforcement" and A775 "Standard Specification for Epoxy-Coated Reinforcing Steel Bars." A summary of the deformation and coating properties required for #4 and #6 bars by these specifications can be found in Table 4.1.

Table 4.1: ASTM A615 and A775 Requirements

		Deformation Requirements (inches)			Epoxy Coating Requirements
Bar Size	Nominal Diameter (in)	Minimum Average Spacing	Minimum Average Height	Maximum Gap	Thickness (0.001 in)
4	0.5	0.350	0.020	0.191	7-12
6	0.75	0.525	0.038	0.286	7-12

Measurements of the bar deformation and coating properties were taken from a random sampling of bars when received from the manufacturer. The bar deformation properties were recorded using Mitutoyo Digimatic digital calipers, and the coating thickness was measured using a Mikrotest Thickness Gage (Figure 4.14). The measurements are listed in Table 4.2 and include the average deformation spacing, average deformation height, average gap between deformations, and average coating thickness.

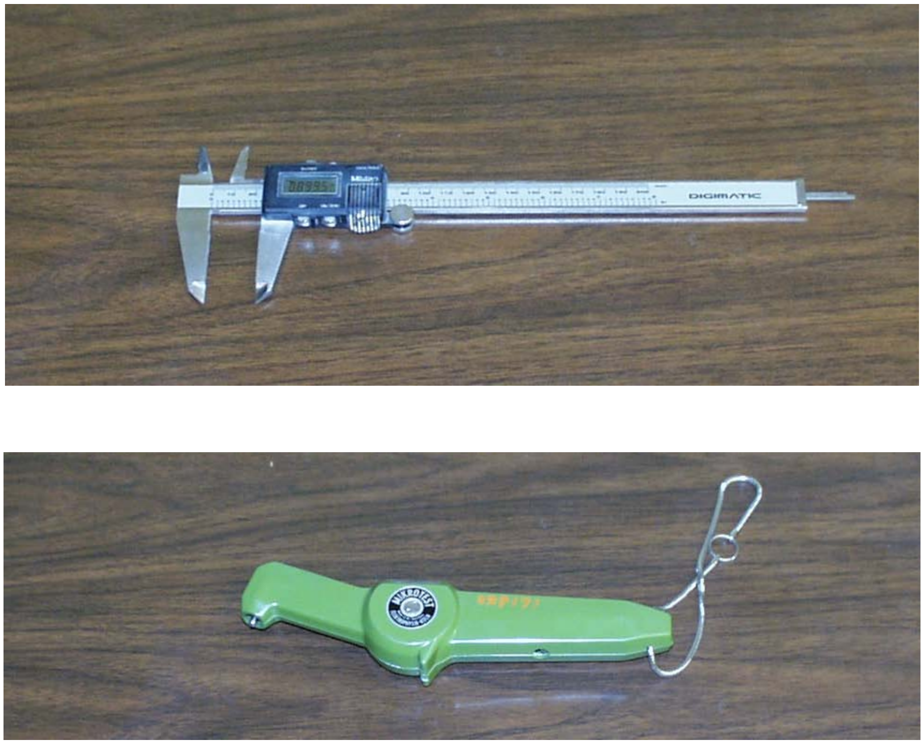

Figure 4.14: Digital Calipers and Coating Thickness Gage

Table 4.2: Measured Bar Deformation and Coating Properties

			Deformation Measurements (in.)			Coating Measurements (0.001 in.)		
Bar Type	Bar Size	Deformation Pattern	Average Spacing	Average Height	Average Gap	Average Thickness	High	Low
Control A (Black Steel)	4	Parallel & Diagonal	0.310	0.073	0.127	N/A	N/A	N/A
Galvanized A	4	Parallel	0.333	0.047	0.164	7.5	10	6
Galvanized B	4	Diagonal	0.339	0.054	0.186	9.4	13	7
Epoxy A	4	Parallel	0.324	0.059	0.154	13.1	15	11
Epoxy B	4	Parallel	0.313	0.049	0.177	11.7	13	10
Nonbendable Epoxy	4	Diagonal	0.347	0.066	0.167	13.0	17	10
Nylon	4	Diagonal	0.267	0.058	0.122	17.2	21	12
PVC	4	Diagonal	0.309	0.035	0.172	10.2	15	6
304 Stainless Steel	4	Diagonal	0.331	0.062	0.164	N/A	N/A	N/A
Control B (Black Steel)	6	Parallel	0.497	0.079	0.245	N/A	N/A	N/A
Epoxy A	6	Parallel	0.505	0.082	0.259	12.3	14	10
304 Stainless Steel-Clad	6	Diagonal	0.462	0.109	0.147	33.7	39	28

The deformation properties of the PVC- and nylon-coated bars used in the pullout tests are the same as those listed in Table 4.2. However, additional epoxy-coated bars were received for use in the pullout specimens, and the deformation properties for these additional bars are listed in Table 4.3. All of the deformation properties are within ASTM-specified limits, which are listed in Table 4.1. Coating thickness measurements were taken for each bar used in the pullout tests with the Mikrotest Thickness Gauge. Thirty measurements were taken from the bar, 15 from each side. Care was taken during measurement to avoid the ends of the bar, where the thickness tends to be greater. The bar-coating thicknesses are listed in Table 4.4 The thickness measurement distributions varied significantly for each coating type and are shown in Figures 4.15–4.17. ASTM A 775-97, "Standard Specification for Epoxy-Coated Reinforcing Steel Bars," has stated:

> *For acceptance purposes, at least 90% of all recorded thickness measurements of the coating after curing shall be 7 to 12 mils.*

On the basis of this criterion, the bar-coating thickness of PVC 1, PVC 3, and each of the epoxy specimens is within the ASTM-specified limits. However, the coating thickness of PVC 2 and each of the nylon specimens is not within these limits, with the majority of measurements exceeding the upper limit of 12 mils.

Table 4.3: Deformation Properties of Additional Epoxy-Coated Bars

			Deformation Measurements (in.)		
Bar Type	Bar Size	Deformation Pattern	Average Spacing	Average Height	Average Gap
Epoxy	4	Parallel	0.333	0.022	0.159

Table 4.4: Summary of Bar-Coating Thicknesses

Test Bar	Average Thickness (0.001 in.)	Standard Deviation (0.001 in.)
PVC 1	9.4	1.6
PVC 2	13.8	2.0
PVC 3	7.4	1.6
Epoxy 1	11.4	1.0
Epoxy 2	11.6	1.3
Epoxy 3	11.1	1.2
Nylon 1	16.3	2.3
Nylon 2	19.0	2.1
Nylon 3	16.4	2.9

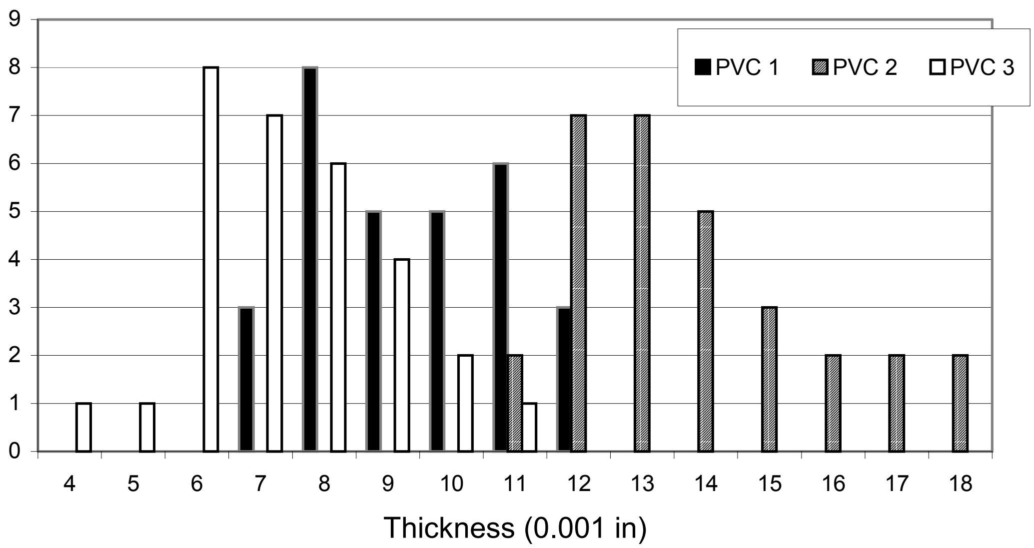

Figure 4.15: Distribution of PVC Thickness Measurements

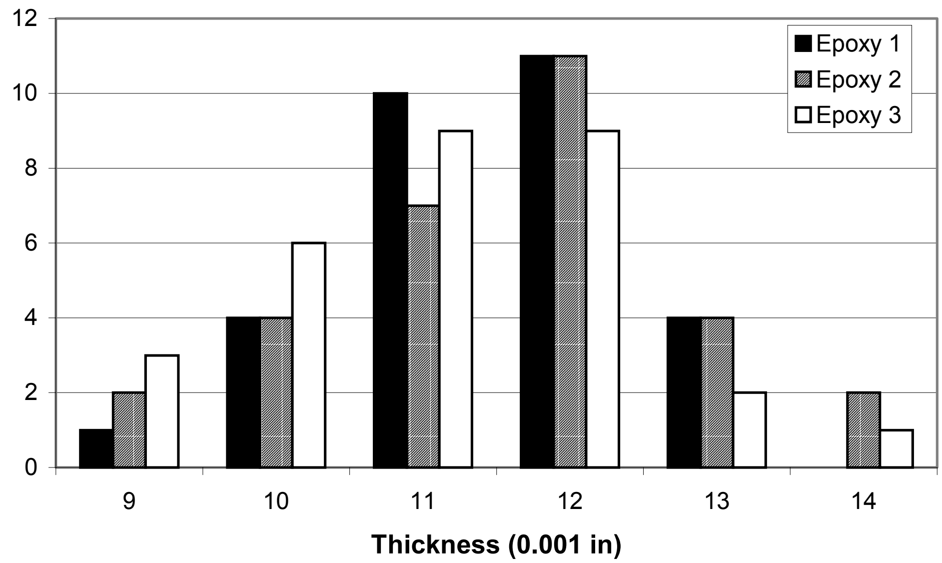

Figure 4.16: Distribution of Epoxy Thickness Measurements

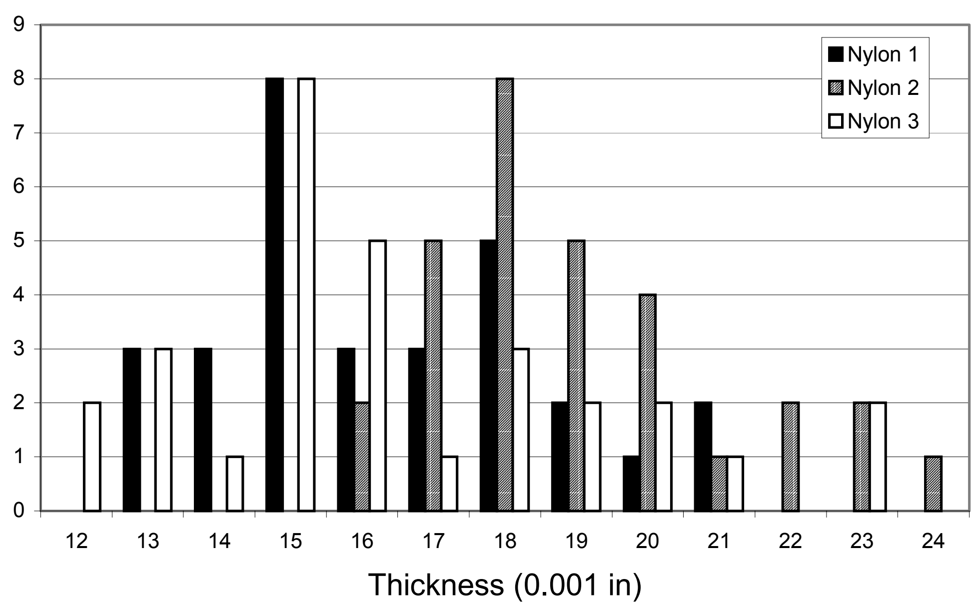

Figure 4.17: Distribution of Nylon Thickness Measurements

4.6.2 Concrete Properties

Premixed bags of concrete materials were used for the pullout specimens for convenience. The PVC specimens were cast on December 9, 1999, the epoxy specimens were cast on February 22, 2000, and the nylon specimens were cast on March 20, 2000. The concrete compressive strength tests for these specimens were performed on the same day as the pullout tests. The average concrete compressive strength for each coating group is listed in Table 4.5.

Table 4.5: Pullout Specimen Concrete Compressive Strength

Coating Group	Compressive Strength (psi)	Standard Deviation (psi)
PVC	8,270	170
Epoxy	4,990	75
Nylon	6,510	140

4.7 Experimental Program

The loading equipment for the pullout tests is pictured in Figure 4.18. Tensile load was applied by using a 20-ton center-hole hydraulic ram, and half-inch prestressed strand grips were used to transfer the load from the ram to the bar. The applied load was measured with an electronic load cell and checked with a pressure gauge. The output from the load cell was powered by a constant voltage supply and was monitored using the Fluke 8060A True RMS Multimeter, as is shown in Figure 4.19.

The set-up to measure slip can be seen in Figure 4.20. The slip was measured by using a linear displacement gauge in contact with the free end of the test bar. The gauge was attached to a threaded rod, and the threaded rod was anchored into the coupling that was cast into the pullout specimen.

Figure 4.18: Hydraulic Ram, Load Cell, and Grips

Figure 4.19: Hand Pump and Load Cell Output

Figure 4.20: Slip Measured by Linear Displacement Gauge

The complete pullout test loading set-up can be seen in Figure 4.21.

Figure 4.21: Complete Pullout Test Loading Setup

Each bar was tested monotonically in tension until failure. Failure is defined as the inability to increase applied load, and the pullout strength is the maximum applied load. Load was applied to the bar in stages and slowly in order to prevent any dynamic effects. The number of load stages for each bar depended on the expected capacity of the bar and the load increment was decreased at increasing loads to better observe the nonlinearity of the load–slip relationship. At each load stage, measurements of load and slip were recorded manually. Photographs were taken to record the failure. For some tests, additional loading after failure was required in order to remove the grips from the test bar.

5. Pullout Test Results

5.1 Introduction

In this chapter, the results of 16 pullout tests are summarized and analyzed. The general behavior of the specimens is discussed in terms of its load–slip response and coated and uncoated bar specimens are compared. On the basis of the results of the tests, the performance of coated bars is compared with that of uncoated bars.

5.2 General Behavior During Testing

The load-slip response of the PVC, epoxy, and nylon specimens can be seen in Figures 5.1, 5.2, and 5.3, respectively. The specimen name describes the series of coated and uncoated bars. Specimens numbered 1, 2, and 3 for a particular series indicate coated bars, and specimens numbered 4, 5, and 6 indicate uncoated control bars.

PVC 5 had a different deformation pattern than did the other PVC specimens and its results were not included in the analysis of the data. The results for Epoxy 6 were significantly different than were the other epoxy specimens and its results were considered to be unreliable.

The PVC and epoxy specimens failed in pullout; however, the nylon specimens failed prior to pullout when the weld fractured.

In general, the slip increased as the load increased. The relationship between load and slip is approximately linear at lower loads. As the load approached the capacity of the embedment, the slope of the load-slip curve began to decrease, characterized by large increases in deflection with little increase in load. This general shape for the load-slip curve was observed for all tests, although the ultimate capacities and slips differed. This general shape was also observed for the nylon specimens, despite the premature weld fracture. The pullout failures of the PVC and epoxy specimens were sudden, and the minimal amount of load-carrying capacity that remained after pullout was attributed to sliding friction along the cylinder of concrete between the bar deformations. No splitting cracks were observed before failure.

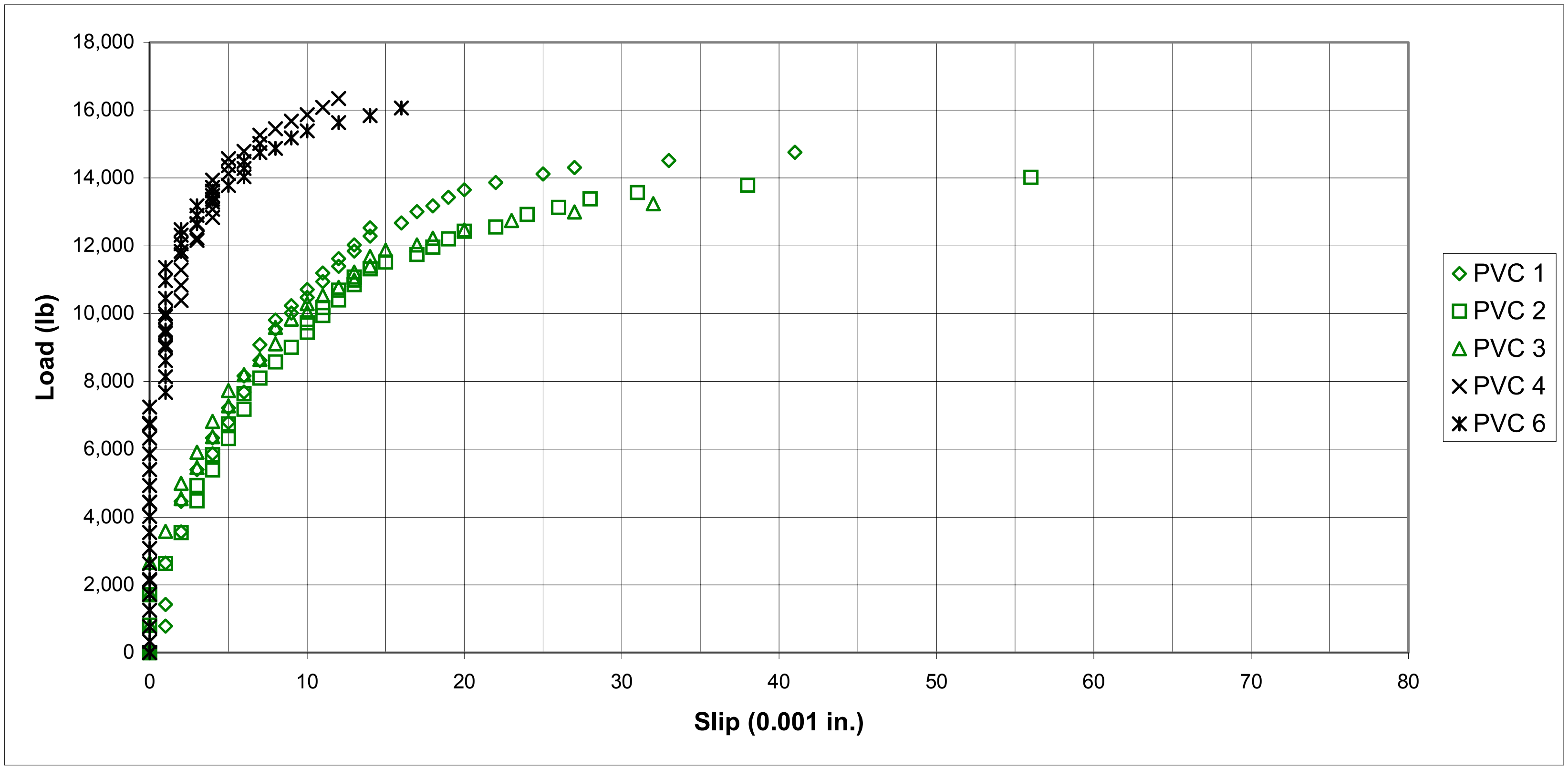

Figure 5.1: Load-Slip Response of PVC Specimens

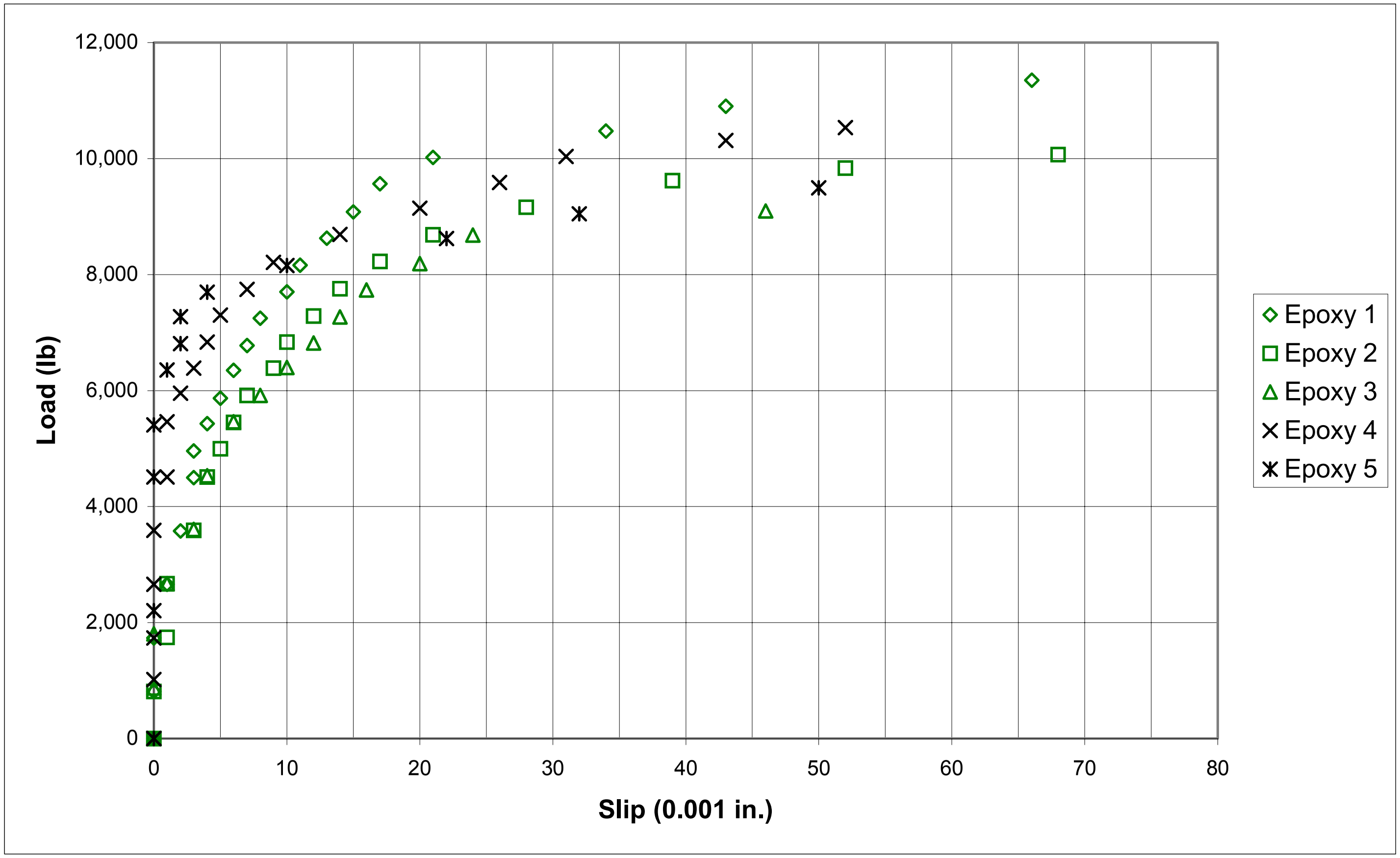

Figure 5.2: Load-Slip Response of Epoxy Specimens

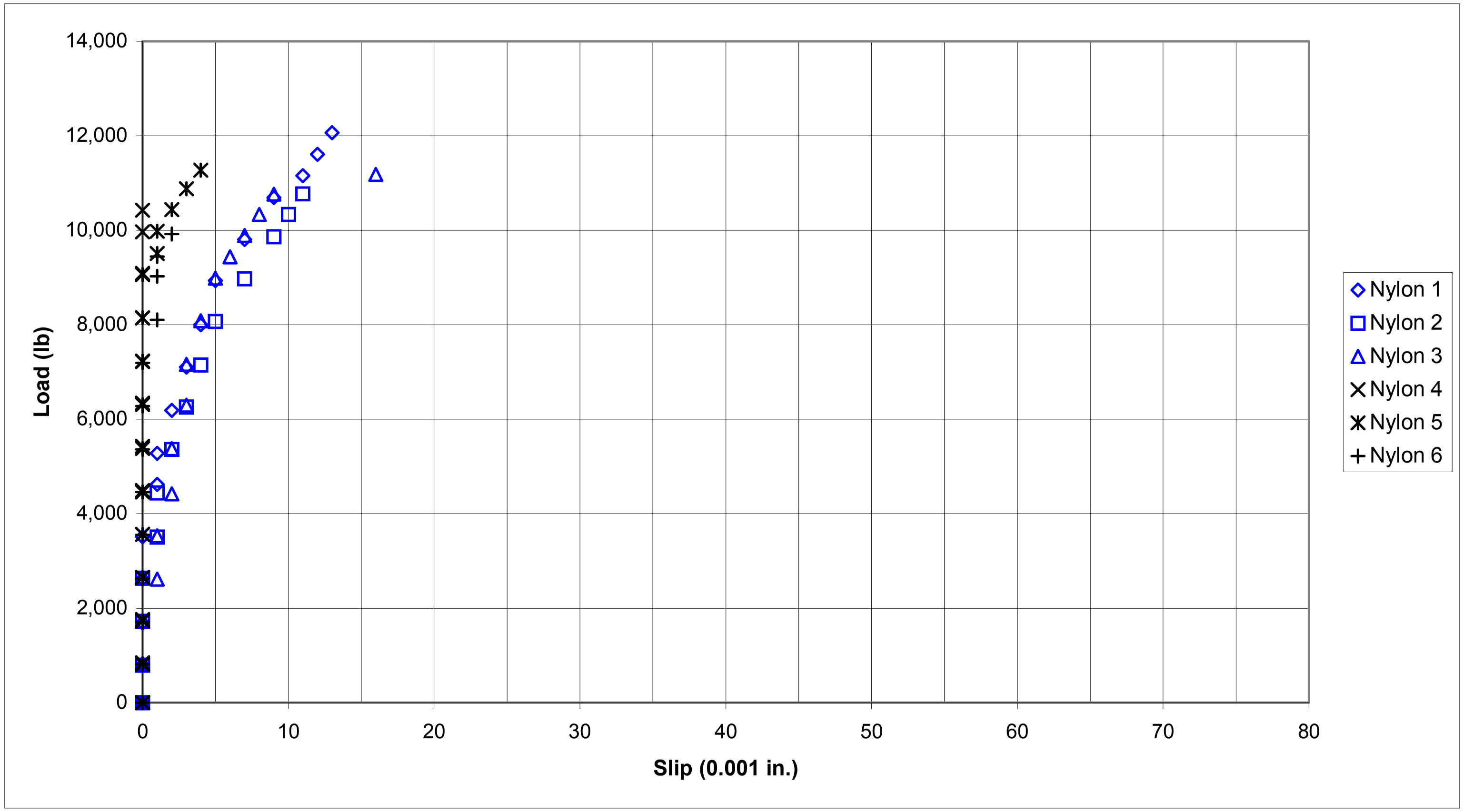

Figure 5.3: Load-Slip Response of Nylon Specimens

The uncoated specimens in the PVC group reached yield and strain hardened. The average measured yield stress for the uncoated PVC bars was 62,200 psi. Yielding and strain hardening would not have affected the slip measurements, because the plastic deformations occur along the loaded portion of the bar and the slip was monitored at the free end.

PVC and epoxy specimens that have failed in pullout can be seen in Figures 5.4 and 5.5, respectively. The relative slip between the bar and the concrete prism is indicated. In several cases, additional force was applied after pullout to remove the grips from the bar. A typical weld fracture for the nylon specimens can be seen in Figure 5.6.

Figure 5.4: Typical PVC Pullout Failure

Figure 5.5: Typical Epoxy Pullout Failure

Figure 5.6: Typical Nylon Weld Fracture

As was previously stated, the failure mode for the PVC and epoxy specimens was pullout. Therefore, the embedment length reached its capacity and the bond strength of the uncoated and coated bars can be compared. The bond ratio was calculated for the PVC and epoxy specimens and is defined as the bond strength of the coated bars divided by the bond strength of the uncoated bars. The average bond ratios and 95% confidence limits are included in Table 5.1 for the PVC and epoxy specimens. Owing to the premature weld fracture of the nylon specimens, the results of these tests could not be included in this comparison.

Table 5.1: Bond Ratio Comparison

Coating Type	Average Bond Ratio	95 % Confidence Limits
PVC	0.86	0.82 to 0.91
Epoxy	1.02	0.91 to 1.13

There is a significant database of information related to pullout testing of epoxy-coated reinforcement. As was stated in Section 2.6.5, the average bond ratio for pullout specimens of epoxy-coated bars typically range from 0.80 to 0.95. The pullout test results for the PVC and the epoxy specimens in this research project are consistent with previous testing. The 95% confidence limits for both the PVC and the epoxy coatings are within the range of results previously reported for epoxy- coated bars. There was significantly more scatter in the observed load–slip response for the epoxy specimens than for the PVC specimens. Whereas the average bond ratio for the epoxy specimens was 1.02, the minimum observed bond ratio was 0.86, which is more typical of previous tests.

There were differences in the concrete compressive strengths of the PVC, epoxy, and nylon specimens at the time of testing that significantly affect the observed pullout capacity. For comparison purposes, the pullout capacities were normalized by using the square root of the concrete strength; these are listed in Table 5.2. The square root of the strength was chosen because the pullout capacity is related to the shear strength of the concrete, and the shear strength of concrete is a function of the square root of its compressive strength. The average concrete compressive strength, f'_c, was measured on the day of pullout testing.

Table 5.2: Normalized Capacity of Coated Bar Specimens

Specimen	Average f'c (psi)	Maximum Applied Load (lb)	Normalized Load (lb/√f'c)
PVC 1	8,270	14,760	162.3
PVC 2	8,270	14,030	154.3
PVC 3	8,270	13,240	145.6
Epoxy 1	4,990	11,350	160.7
Epoxy 2	4,990	10,070	142.6
Epoxy 3	4,990	9,100	128.8
Nylon 1	6,510	12,060	149.5
Nylon 2	6,510	10,770	133.5
Nylon 3	6,510	11,180	138.6

Little difference was also observed between the normalized pullout capacities of the PVC and the epoxy-coated specimens. Pullout failure for the coated PVC and epoxy specimens typically occurred within a range of 140 (lb/√f'c) to 160 (lb/√f'c). Maximum applied loads for the nylon specimens were also very similar. The minimum normalized load capacity of the nylon-coated specimens was 133 (load/√f'c) before weld fracture.

Average secant moduli corresponding to a slip of 0.002 in. were calculated from the load–slip response of each coating type; these are listed in Table 5.3. The slip stiffness ratio was calculated by dividing the average secant modulus for coated specimens by the average secant modulus for uncoated specimens.

Table 5.3: Comparison of Coated and Uncoated Slip Stiffness

Specimen	Secant Modulus at Slip of 0.002 in.
PVC-Coated	21,350
PVC-Control	61,080
Stiffness Ratio	0.350
Epoxy-Coated	23,260
Epoxy-Control	45,180
Stiffness Ratio	0.515
Nylon-Coated	32,980
Nylon-Control	63,560
Stiffness Ratio	0.519

The slip stiffness ratios of the PVC, epoxy, and nylon specimens were also very similar. Higher secant modulus, or slip stiffness, indicates that a bar is relatively more resistant to slip. The stiffness ratios of the epoxy and nylon specimens were nearly identical, despite the greater thickness of the nylon coating. The stiffness ratios of the PVC specimens were less than those of the epoxy specimens; however, the smaller stiffness ratio does not appear to significantly affect the pullout capacity or the bond ratio of the PVC specimens.

The scatter observed for the epoxy specimens may be attributed to slight differences in the bar deformation geometry between specimens. As was stated in Section 2.6.1, changes in the bar deformation geometry affect the results of bond testing. There are always variations in the deformations created during the manufacture of the bars. The effects of these differences tend to average out when the embedment length is long, as compared with the diameter of the bar. However, the embedment length was very short in this series of pullout tests, and slight differences in the height or angle of the ribs could significantly change the measured pullout resistance.

5.3 Failure Hypothesis

Treece and Jirsa proposed that the primary reason for the reduction in bond strength between epoxy-coated and uncoated bars is the loss of adhesion between the epoxy-coated bars and the surrounding concrete (Treece 1989). The loss of adhesion also causes the loss of most or all of the friction capacity. This hypothesis has been supported by the results of research performed in the last decade.

Similar behavior would be expected for PVC and nylon coatings, because the same bond mechanics apply to all types of organic coatings and not only to epoxy coatings. In each case, the reinforcing bar is coated with a polymer that prevents adhesion and decreases or prevents friction. Bearing on the bar deformations is the only significant development force present for coated reinforcement. The loss of adhesion is easily observed because the coated bars begin to slip immediately, whereas the uncoated bars are able to resist slip until the applied load is about half of the pullout capacity.

The pullout test results in this research project for PVC and nylon coatings were consistent with this hypothesis. There were not any significant differences observed in the load–slip behavior of the PVC and epoxy specimens. No definite conclusions could be drawn from the testing of the nylon coating series because these specimens did not fail in pullout. However, the nylon-coated specimens were able to resist applied loads similar to the pullout capacities of the PVC and epoxy specimens and exhibited similar slip stiffness characteristics, as compared with PVC and epoxy.

5.4 Further Research

Pullout tests will have to be repeated for the nylon-coated bar series because these bars did not fail in pullout. The bond ratios for the nylon-coated bars must be compared with the pullout test results of this study and to the database of previous pullout testing to confirm that these bars exhibit similar behavior.

The present study was intended only to compare the general behavior of PVC- and nylon-coated bars with that of epoxy-coated bars. It can be concluded from this study that there are not any significant differences in the pullout behavior of bars coated with different types of plastics. However, current ACI Building Code provisions specifically mention only the use of epoxy-coated reinforcement. Additional testing must be performed before PVC- and nylon-coated reinforcement can be used in practice. It is essential to determine building code provisions for these materials from tests that simulate the behavior of actual concrete structures. Pullout tests are very poor representations of actual concrete behavior and should not be used for this purpose. Testing of beams with lap splices must be performed before these materials can be accepted because this type of test addresses the more common splitting failures that typically result from the more severe bond strength reduction for coated bars.

6. Summary and Conclusions

6.1 Corrosion Testing

An accelerated macrocell corrosion test is still underway to determine the behavior of galvanized, stainless steel-clad, epoxy-coated, PVC-coated, nylon-coated, and 304 stainless steel reinforcing bars cyclically exposed to a chloride solution. The corrosion readings are included in a companion study. To date, there have been modest changes only in the current flow for the test materials (see Research Report 4904-2).

Polarization resistance and immersion tests were also performed as part of the corrosion test program. The results of these tests are included in Research Report 4904-2. After the conclusion of the macrocell testing, the results of the polarization resistance and immersion tests will be compared with the results of the macrocell tests to determine if there is a correlation between these two different test methods.

6.2 Bond Testing

Pullout tests were conducted to compare the bond behavior of bars with different polymer coatings. There were not any significant differences observed in the bond strength for the PVC and epoxy coatings. The nylon-coated specimens experienced weld fracture prior to pullout. Despite the different concrete strengths and failure modes, each coating type achieved a similar maximum applied pullout force and exhibited similar slip stiffness during testing. In each case, the reinforcing bar was coated with a polymer that prevents adhesion and decreases or prevents friction, which leaves bearing on the bar deformations as the primary development force.

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