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BEHAVIOR OF EPOXY-COATED TEXTURED REINFORCEMENT BARS

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16. Abstract

Cracking in bridge decks is a common but difficult problem to control. Both research and experience show that the use of epoxy-coated reinforcement, which is mandated by most state departments of transportation (DOT's) for bridge decks, increases cracking. Although the epoxy coating protects the steel from corrosion, bond strength is compromised and the increased cracking exacerbates durability issues in concrete. As a means to improve bond and reduce the formation of cracks, the Illinois Department of Transportation (IDOT) proposed texturizing the surface of epoxy-coated bars. IDOT developed a prototype textured epoxy coating and this report details a preliminary study on the bond strength of reinforcing bars with the new coating. Direct pull-out tests were performed on uncoated, standard epoxy-coated, and textured epoxy-coated No. 5 and No. 8 reinforcing bars to compare the bond characteristics. Standard epoxy-coated bars clearly demonstrated an increased tendency to slip and split the concrete. Initially, bars with the textured epoxy coating showed good force-slip behavior similar to black steel, but a rapid degradation of slip resistance was observed. On average, the peak nominal bond stress developed in the textured epoxy-coated No. 5 bars was approximately 17% lower than the uncoated bars. Pull-out specimens with No. 8 bars were confined using steel and shape memory alloy (SMA) wires to prevent concrete splitting. The confined No.8 bar specimens demonstrated behavior similar to the No. 5 bar specimens. In addition to the direct pull-out tests, three beam specimens were fabricated using No. 5 bars as a preliminary means to compare the bond behavior of the bars flexure. Overall, in both the direct pull-out and flexural testing—the added frictional resistance of the textured epoxy-coating showed promise as an effective way to improve slip resistance and reduce concrete cracking. However, further research is needed to optimize the coating and characterize its behavior.

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Members of the Technical Review panel were the following:

- Jayme Schiff, TRP Chair, IDOT
- Dan Brydl, IDOT
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- Scott Hughes, IDOT
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EXECUTIVE SUMMARY

For the past 25 years, the state of Illinois has been using epoxy-coated reinforcement in bridge decks in order to reduce problems arising from corrosion, such as spalling and potholing. Over this period of time, a significant increase in deck cracking has been noted. While many environmental and design factors may have contributed to this increase, the problem may have been considerably exacerbated by the ineffective bond between epoxy-coated reinforcement and concrete. Research studies have shown that the lack of friction in epoxy-coated reinforcement leads to increased cracking and wider cracks in concrete. To address this issue, the Illinois Department of Transportation (IDOT) developed a new textured epoxy coating that not only protects the steel but also provides a rough interface to facilitate better stress transfer between the concrete and reinforcement.

This report details a preliminary investigation of the bond behavior of the new textured epoxy-coated reinforcing bars developed by IDOT. In the first phase of this study, direct pull-out tests were performed on No. 5 and No. 8 bars to comparatively establish the bond strength of textured epoxy-coated bars against uncoated and standard epoxy-coated bars. In the second phase of the study, beam specimens reinforced with single bars were used to test the bond performance in flexure.

The test results showed that the improved frictional properties in the new textured epoxy coating can provide increased slip resistance comparable to uncoated reinforcement—and can reduce cracking under flexure. However, the textured epoxy-coated bars were not able to attain the same magnitude of bond strength as uncoated bars. Overall, the idea is promising, but further research is needed to optimize the coating and more accurately characterize its behavior.

CONTENTS

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The annual Infrastructure Report Card published by the American Society of Civil Engineers (ASCE), estimates that more than 9% of all bridges in the US were structurally deficient in 2016. With the average age of bridges exceeding 40 years, the number of bridges requiring major rehabilitation is likely to grow rapidly (ASCE 2017). Of all the major components in a bridge structure, the maintenance of bridge decks is often a major area of expenditure for many agencies. This is particularly true in regions with harsh winters—where the combination of freeze-thaw cycles and the heavy use of de-icing salts can lead to severe spalling, reinforcement corrosion, and damage the substructure incurring costly repair expenses. Moreover, severe corrosion resulting in section loss in reinforcing steel can have detrimental consequences on the structural capacity (Rodriguez et al. 1997; Vu & Stewart 2000; Coronelli & Gambarova 2004). Many of these problems identified above initiate from concrete cracking. While cracks can form due to vehicular loads, most cracks in bridge decks form in the transverse direction. This is due to the restraint of deformation under shrinkage and thermal stresses by the supporting girders (Krauss & Rogalla 1996; Issa 1999). Cracks allow the penetration of water, air, and de-icing salts—which accelerates the degradation of the bridge deck. To minimize problems arising from reinforcement corrosion, most departments of transportation (DOTs) require the use of epoxy-coated reinforcing bars in bridge decks and parapet walls. The reduced bond strength of epoxy-coated reinforcing bars relative to conventional uncoated steel is well understood and reflected in design guidelines including ACI 318 (ACI 2014), and AASHTO LRFD Bridge Design Specifications (AASHTO 2012). Due to poor bond, the effectiveness of stress transfer between the concrete and reinforcing steel is reduced. Studies have also noted increased transverse cracking and crack widths in bridge decks constructed with epoxy-coated reinforcing steel (Krauss & Rogalla 1996). Although epoxy coating effectively protects the steel reinforcement from corrosion, it is a compromising solution since it exacerbates other problems arising from deck cracking.

Other mitigation measures that have been proposed include the use of fiber reinforced polymer (FRP) composites (Alagusundaramoorthy et al. 2006; Berg et al. 2006; among others)—and various changes to the reinforcement layout, concrete mix design, and curing techniques (Ramey et al. 1997; Schmitt & Darwin 1999). Despite being corrosion free and providing high strength, FRP composites have not gained popularity primarily due to uncertainties surrounding their long-term performance and their cost. Typical FRP composites also behave in a brittle manner, which may deprive the bridge deck of its ductility. Changing the reinforcement layout or the mix design may undermine the strength and durability. At the same time, advanced curing techniques may be time consuming and simply not feasible under field conditions.

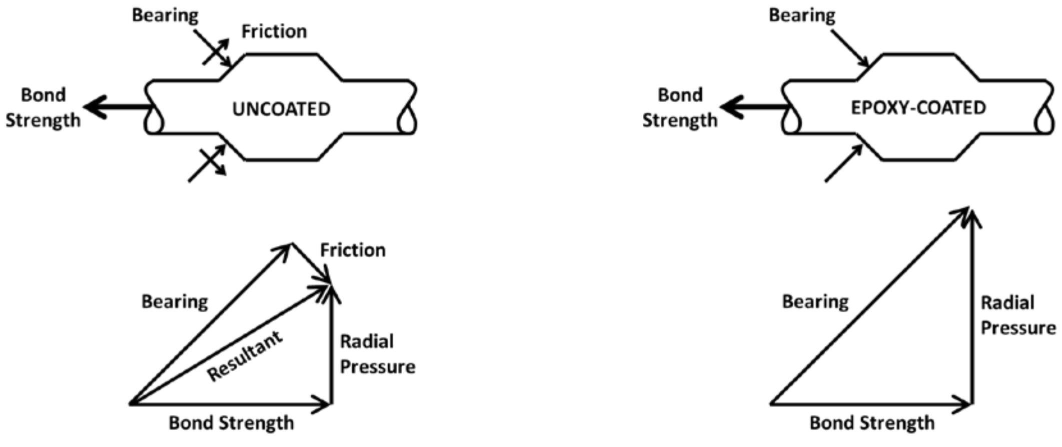
The Illinois Department of Transportation (IDOT) has proposed a different approach to reducing both the occurrence and width of cracks in bridge decks with epoxy-coated steel reinforcement. Their goal is to improve the bond strength between the concrete and reinforcement by increasing the surface roughness of the epoxy coating to levels similar to that of uncoated black steel. This report describes the results of preliminary tests conducted on epoxy-coated steel reinforcing bars with a special textured surface recently developed by IDOT. A series of direct pull-out tests were performed on No.

5 and No. 8 bars and the textured epoxy-coated reinforcement is compared to uncoated bars and standard epoxy-coated bars.

1.2 PROBLEM DESCRIPTION

When cracks develop early in the service life of a bridge deck, they generally become larger over time. This is particularly true of transverse cracks. Most cracks in concrete bridge decks form as a result of restraining shrinkage and stresses developed due to thermal loading. While composite design results in more efficient girder designs, the restraint provided by the composite action greatly increases cracking. The report by Krauss & Rogalla (1996) provides extensive details on the factors that affect bridge deck cracking at early stages. Although the use of epoxy-coated reinforcement is identified as only a minor contributor, it is an area that can be more easily and economically controlled than other factors—such as modifying the concrete mix design or changing the girder design. Examining how bond strength is developed between concrete and reinforcing steel, sheds light on why epoxy-coated reinforcing bars potentially lead to increased cracking.

It is widely understood that the bond between reinforcement and concrete is comprised of three main components: chemical adhesion, friction, and bearing. In typical deformed reinforcing bars, the contribution of chemical adhesion is negligible and stress is transferred predominantly through bearing. While the magnitude of the friction force is not significant in comparison to the bearing, it plays an important role. Experiments conducted by Cairns & Abdullah (1994) showed that epoxy coating reduces the friction generated at the steel-concrete interface by up to 50%. Treece & Jirsa (1989) attributes this loss of friction as the main cause for the difference in bond strength of uncoated and epoxy-coated steel as well as increased crack widths in concrete reinforced with epoxy-coated bars. The mechanics behind the increased cracking is easy to understand through a free-body diagram. Figure 1-1 shows the force components acting on a single rib on a reinforcing bar.



(a) (b)

Figure 1-1. Components of bond acting on a reinforcing bar (a) Uncoated bar, and (b) Epoxy-coated bar.

Surface roughness, rib profile, normal pressure, and the amount of slip, all contribute to the friction force (Tastani & Pantazopoulou 2009). As illustrated, the absence of friction at the rib face changes the interaction between the reinforcing bar and surrounding concrete. To develop equivalent bond strength in an epoxy-coated bar, a higher bearing force is required, which leads the bar to apply higher radial pressure on the concrete. This radial pressure reduces the splitting resistance of the surrounding concrete, increasing both the propensity for the concrete to crack and the width of the crack (Lutz & Gergely 1967; Treece & Jirsa 1989; Cleary & Ramirez 1991). Therefore, it was postulated that cracking in bridge decks—reinforced with epoxy-coated steel—could be better controlled if the epoxy surface could be texturized to facilitate a frictional bond component. Friction becomes negligible if the localized crushing of concrete becomes excessive at high slip levels. However, friction may be an effective solution when there are relatively low strain levels typical of shrinkage (Tastani & Pantazopoulou 2009). Although accurately quantifying the friction at the reinforcement-concrete interface was outside the scope of this study, it may be an important consideration in more detailed studies. It is worth noting that a potential added benefit of improving the bond strength of epoxy-coated reinforcement is that it may reduce the required development length leading to cost savings in construction.

1.3 TEXTURED EPOXY-COATED REINFORCING BARS

The textured epoxy-coated reinforcing bars, introduced by IDOT, were produced by an IDOT approved manufacturer that supplies conventional epoxy-coated steel bars. One of the main requirements of the creative process from both the manufacturer and IDOT was the ability to produce the new reinforcing bar using existing technology and equipment to minimize cost. The specific materials and process used to generate the textured epoxy-coating are proprietary. However, creating the texturized epoxy coating is a two-step process in which a coat of conventional epoxy is applied first to the black steel followed by a textured powder. The No. 5 and No.8 textured epoxy-coated reinforcing bars used in this study had an average maximum surface roughness, R_{max}, of 5.0 mils as tested in accordance with ASTM D7127 (ASTM 2017a). Considering ASTM A775 requires that black steel be blast cleaned to provide R_{max} between 1.5 mils and 40 mils prior to epoxy coating, the roughness of the textured epoxy-coating is quite significant compared to conventional uncoated steel reinforcement (ASTM 2017b). IDOT specifies the total thickness of the textured epoxy coating to be less than 16 mils but does not subject the coating to flexibility requirements. Figure 1-2 shows a side-by-side comparison of uncoated, standard epoxy-coated, and textured epoxy coated reinforcing bars used in this study.


(a) (b) (c)

Figure 1-2. No. 5 reinforcing bars used in this study; (a) Uncoated, (b) Standard epoxy-coated, and (c) Textured epoxy-coated.

The difference in surface condition in the three bars can be clearly distinguished in Figure 1-2. The standard epoxy coating is glossy and smooth while the textured epoxy coating is matte and gritty to the touch. The color of the textured epoxy coating was intentionally altered by the manufacturer to prevent confusion between the standard and textured epoxy bars.

1.4 REPORT OUTLINE

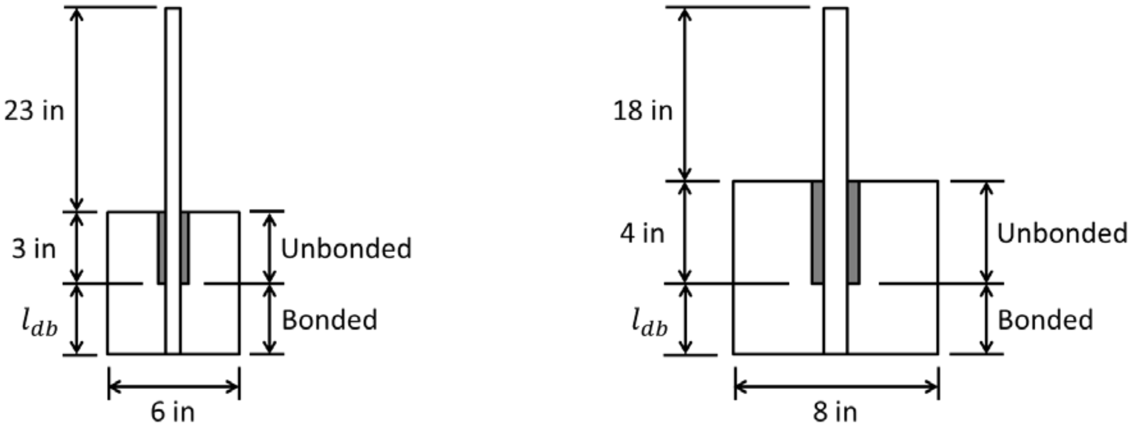
This report is composed of four main chapters:

- Chapter 1 explains the motivation and reasoning behind the development of the new textured epoxy-coated reinforcing bars, and describes the characteristics of the coating.
- Chapter 2 presents the results of direct pull-out tests performed on No. 5 and No. 8 bars. The bond-slip behavior of textured epoxy-coated bars is compared to uncoated and standard epoxy-coated steel reinforcement. In the case of the No. 8 bars, external confinement was needed to prevent failure due to concrete splitting.
- Chapter 3 presents supplementary tests performed using beam specimens. Three beams reinforced with single uncoated, epoxy-coated, and textured epoxy-coated bars were fabricated and tested to compare bond characteristics in flexure.
- Chapter 4 summarizes the observations and findings from this study.

CHAPTER 2: DIRECT PULL-OUT TESTING

2.1 SPECIMENS

All reinforcing bars used in this study were Grade 60 steel (yield strength, f_y = 60 ksi) and produced by the same manufacturer. The nominal diameter of the No. 5 and No. 8 bars used were 0.625 in and 1 in., respectively. To comparatively establish the bond strength of textured epoxy-coated reinforcing bars against uncoated and standard epoxy-coated bars, direct pull-out tests were carried out using specimens described in Figure 2-1. The specimen dimensions were based on RILEM pull-out test specifications (RILEM 1994).



(a) (b)

Figure 2-1. Pull-out test specimens; (a) No. 5 bars, and (b) No. 8 Bars.

The specimens were cast using round commercially available concrete form tubes. PVC sleeves were used to create the unbonded regions in the specimens to prevent cone-type failure of the concrete at the loaded end. The ends of the PVC sleeve were sealed with a silicone based caulking to keep out the concrete. Bonded lengths of 2 in. and 3 in. were considered for the No. 5 specimens and 5 in. for the No. 8 specimens. The typical IDOT bridge superstructure mix design was used for the concrete. Details of the mix design are summarized in Table 2-1.

Table 2-1. Concrete Mix Used in the Pull-out Specimens

Material	Quantity (/yd^3)
Washed Sand	1,167 lbs
Crushed 19 mm Aggregate	1,362 lbs
Crushed 9.5 mm Aggregate	453 lbs
Cement	455 lbs
Fly Ash	155 lbs
Water	29.9 gal

For concrete used in bridge superstructure, IDOT specifies a target air content of 6.5%, a maximum water content of 0.42, and a minimum compressive strength of 4.0 ksi at 14 days. All three criteria were met and the concrete achieved an average compressive strength of 5.1 ksi at 28 days.

A special reaction frame was fabricated to pull the reinforcing bars from the top using a 600 kip MTS servo-controlled uniaxial loading frame. Bar slip was measured at the free end of the specimens using a linear variable differential transformer (LVDT). The test setup is shown in Figure 2-2.

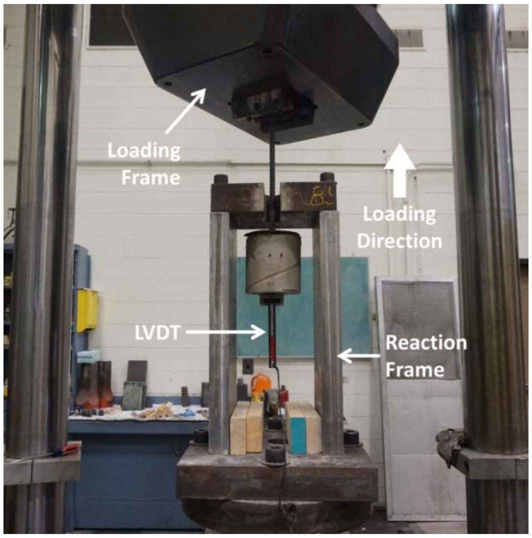


Figure 2-2. Pull-out test setup.

The bars were pulled at rates equal to one-thousandths of the bar diameter per second until significant slip was observed. After the testing, several bars were pulled out completely to examine the bar surfaces.

It is important to note that pull-out type tests generally yield higher bond strengths than in development length or splice tests. This is due to the fact that the loading in pull-out tests creates internal compression struts in the concrete which provide additional resistance to the bar pull-out. The study by Kayyali & Yeomans (1995) also notes that increasing the unbonded length further increases the bond strength. Another problem with the direct pull-out specimens used in this study is the potential for bursting, which can happen if the concrete does not provide adequate resistance in the transverse direction. This failure mode is discussed in detail below. Despite these issues, direct pull-out tests were adopted for this preliminary study because it is a low cost, simple alternative for obtaining a general comparison of the bond-slip characteristics.

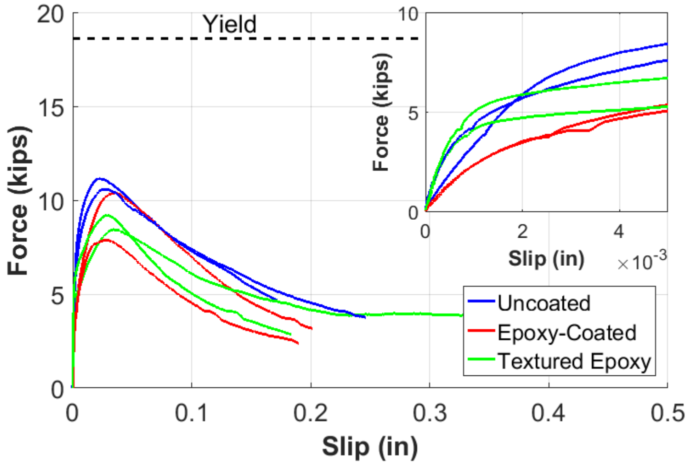
2.2 TEST RESULTS

2.2.1 No. 5 Bars

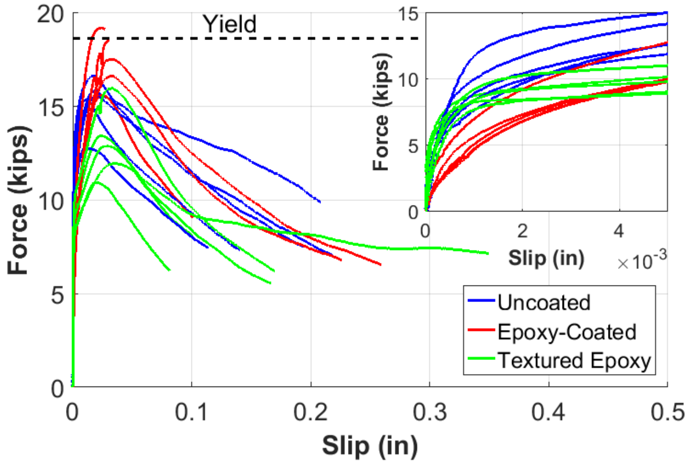
In total, six No. 5 specimens were tested with a bonded length of 2 in., and 15 specimens were tested with a bonded length of 3 in. The resulting force-slip curves are shown in Figure 2-3. A close-up of the initial force-slip behavior at very low slip is shown on the inset axes.

On average, the 3 in. bonded length yielded higher average pull-out forces by 40%, 96%, and 48% for the uncoated, epoxy-coated, and textured epoxy-coated bars respectively, compared to l_{db} = 2 in. Between the two bonded lengths, the average peak bond stress developed by the uncoated and standard epoxy-coated bars was approximately 2.68 ksi. For the textured epoxy-coated bars, the average was 2.23 ksi. The bond stress was calculated using the nominal surface area of the bonded region.

It is clear from the slope of the force-slip curves that epoxy-coated specimens displayed notably reduced resistance to slip compared to uncoated bars. However, the epoxy-coated bar specimens surprisingly achieved peak pull-out strengths comparable to uncoated bars. This observation demonstrates that despite the lack of frictional resistance, the epoxy-coated bars were able to develop sufficient pull-out strength on bearing force alone. As illustrated in Figure 2-1 and noted by Cleary & Ramirez (1991), the added bearing force in epoxy-coated reinforcing bars leads to higher radial pressure on the surrounding concrete. The radial pressure pushes the concrete apart making the relative movement of the bar easier. The effect of increased radial pressure was further demonstrated in the epoxy-coated specimens with l_{db} = 3 in. as two specimens failed due to concrete splitting. The two curves that terminate near the line indicating the theoretical yield force show these failures. No other No. 5 specimen failed by splitting. As expected of tensile failure modes in concrete, the failure was sudden and brittle. Failure due to concrete splitting is further discussed below and in Section 2.2.2 with the No. 8 bar test results.



(a)



(b)

Figure 2-3. No. 5 bar pull-out test results; (a) l_{db} = 2 in, and (b) l_{db} = 3 in.

Contrary to expectations, results from the pull-out testing did not show that the textured epoxy coating could provide improved bond strength over standard epoxy-coated reinforcing bars. At l_{db} = 2 in the average peak pull-out force of the textured epoxy-coated bars was 19% lower than that of the uncoated bars. At l_{db} = 3 in the difference was 14%. Although the textured epoxy-coated bar specimens did not develop the same levels of force as the uncoated specimens, it can be seen in the inset axes that at low levels of slip, the textured epoxy coating provided high initial slip resistance comparable to uncoated bars. However, the slope of the force-slip curves changes sharply signifying the rapid loss of bond. It is also clear that the textured epoxy-coating does not provide any additional slip resistance compared to the standard epoxy-coated bars in the post-peak regime.

For any bar to slip, adhesion and friction between the bar surface and surrounding concrete must be overcome. Once this component of the bond is broken, slip occurs predominantly due to concrete crushing at the rib (Lutz & Gergely 1967). In both the uncoated and textured epoxy-coated bars, the high initial slip resistance shown in the bond-slip curves in Figure 2-3 is likely attributable to friction. The standard epoxy coating, which provides almost no friction, does not demonstrate this behavior. The key difference in the behavior of the uncoated and textured epoxy-coated bars is in how major slip occurs, after friction is overcome. It is clear that slip resistance diminishes for both bar types at approximately 0.002 in. of slip but the reduction is much more significant in the textured epoxy-coated bars. The textured coating provides even less slip resistance in the post-friction range than the standard epoxy coating. This suggests the bearing force component at the rib is much lower in the textured epoxy-coated bars compared to the other two bar types.

To establish further insight on this phenomenon, several bars were completely pulled out of the concrete to examine them. Figure 2-4 shows the typical condition of No. 5 bar specimens along the embedded region after they were pulled out.

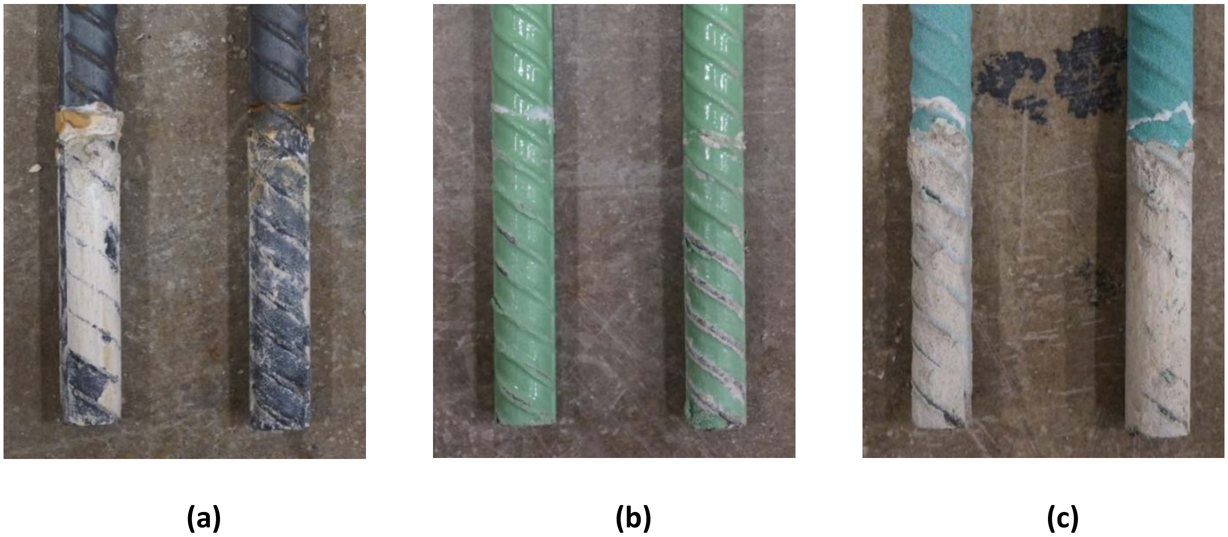


Figure 2-4. Typical condition of the embedded region after complete pull-out; (a) Uncoated, (b) Epoxy-coated, and (c) Textured epoxy-coated.

The bars shown in Figure 2-4 were embedded 76 mm deep. The limits of the embedded region are clearly distinguishable in the uncoated and textured epoxy-coated specimens. As shown in Figure 2-4 (b), the surface of the standard epoxy-coated bars was clean. Although some loose crushed concrete powder was observed, there was no cement paste adhered to the bars. In contrast, considerable amounts of concrete residue accompanied the uncoated and textured epoxy-coated bars, but there were noticeable differences in the residue itself. In the case of uncoated bars, the residue was densely compacted but could be easily removed and broken apart with a fingernail. In the textured epoxy-coated bars, the residue was more difficult to remove and it was observed that there was a layer of uncrushed porous concrete paste adhered to the surface of the bar in addition to some crushed concrete. This adhered layer of paste would have effectively reduced the height and angle of the rib face, thereby reducing the ability for the bar to bear on the concrete.

In contrast to the uncoated or textured epoxy-coated bars, the standard epoxy-coated bar specimens did not show any significant signs of concrete crushing or shearing between the ribs. This may be attributable to the fact that the increased radial pressure arising from higher bearing forces, makes it easier for the bar to slip out without concrete crushing by pushing and splitting the concrete outward. The concrete surface at the bar interface was closely examined in epoxy-coated bar specimens that failed due to splitting. However, there were no visible signs of concrete crushing which supports this claim. It was also clear that both the standard epoxy and textured epoxy coatings could be easily damaged if sufficient slip occurs. Abrasion by the concrete clearly scraped the coating off the ribs in the coated bars shown in Figure 2-4 (b) and (c), exposing the black steel underneath.

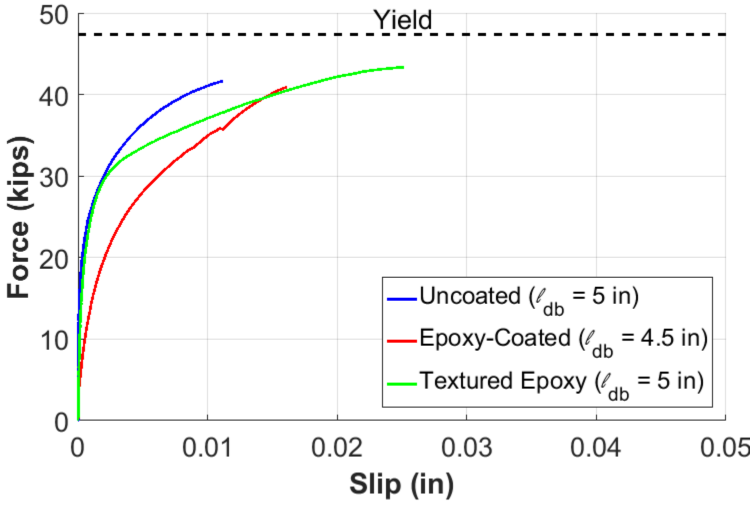
From these observations, it may be possible to develop a textured coating that can improve the slip resistance of conventional epoxy-coated reinforcement, while also retaining its bearing force component. This can be done by optimizing the adhesion and roughness characteristics of the coating.

2.2.2 No. 8 Bars

No. 8 bar specimens were tested with an embedded length of 5 in. The testing of No.8 bars did not go as expected—as specimens failed prematurely due to concrete splitting, regardless of the bar type. Since splitting failures are not very meaningful to this study, the embedded length of an epoxy-coated specimen was reduced to determine if failure due to slippage could be induced. This was done by sawing 0.5 in. off the end of the specimen. An epoxy-coated bar was chosen because it is the most liable to slip. However, the shortened specimen also failed due to splitting. Results from these tests are shown in Figure 2-5.

The bond stress developed at failure was approximately 2.65 ksi, 2.90 ksi, and 2.75 ksi for the uncoated, epoxy-coated, and textured epoxy-coated bars respectively. These values are marginally higher than the average peak bond stresses obtained by the No. 5 bars, which attained peak pull-out force at slip ranging between approximately 0.02 in. and 0.04 in. The bond stress and bending of the bond-slip curve both suggest that the bars were close to peak strength and pulling out. The failure occurred at almost identical levels of pull-out force in all three specimens, which suggests that the diameter of the concrete simply was not sufficient enough to provide adequate splitting resistance. Since the failure occurred with relatively minimal bar slip, there were no signs of distress in the concrete at the reinforcing bar interface. In Figure 2-5 (b), imprints of the ribs are clearly visible in the concrete but no crushing or cracking is evident between the ribs.

Despite the premature failure, the initial force-slip behavior of the No. 8 bars was similar to that of the No. 5 bars. The initial force-slip behavior of the textured epoxy-coated bar was very similar to that of the uncoated bar, but diverged as the force increased. The slip resistance of the epoxy-coated bar was considerably lower than the uncoated or textured epoxy-coated bar. Since little to no damage is done to the concrete at relatively low levels of slip, it is likely that slip occurring prior to the peak pull-out force can be elastically restored. This is also true for the No. 5 bars.



(a)

(b)

Figure 2-5. Pull-out testing of No. 8 bars that resulted in splitting failure; (a) Force-slip results, and (b) Failed concrete.

2.2.3 Confinement of No. 8 Specimens

Since the main purpose of this study was to compare the force-slip characteristics of the three different types of reinforcement, it was necessary to prevent the splitting mode of failure and induce bar slip. Therefore, to provide additional resistance against splitting, confinement methods were considered. Confinement of concrete is a well-studied area with numerous models available in the literature (Mander et al. 1988; Mirmiran & Shahawy 1997; among others). Some researchers have also investigated the effect of confinement on the pull-out strength of deformed reinforcing bars. Harajli et al. (2004) conducted pull-out tests on specimens with steel transverse reinforcement and specimens confined with fiber reinforced (FRP) composites. Torre-Casanova et al. (2013) used a unique loading frame to apply confining pressure to rectangular pull-out specimens. In both studies, marginal improvements were noted in the peak pull-out strength. Despite the consideration in this study, it should be noted that neither transverse reinforcement nor external confinement is used in typical bridge deck construction.

The remaining No. 8 bar specimens, all with embedment lengths of 5 in., were confined using passive and active methods. In active confinement, lateral pressure is externally applied by the confining element. Passive confinement, which is the more common and traditional method of concrete confinement, depends on the dilation of the concrete. In this study, 0.08 in. diameter steel and NiTiNb shape memory alloy (SMA) wires were used for passive and active confinement respectively. Each confining method was applied to one specimen of each bar type, for a total of six confined specimens. Examples of confined No. 8 bar pull-out specimens are shown in Figure 2-6. Detailed descriptions of the NiTiNb alloy and active confinement of concrete using SMAs are available in Andrawes et al. (2009) and Shin & Andrawes (2010).

(a) **(b)**

Figure 2-6. Confined No.8 bar pull-out specimens; (a) Steel wire, and (b) SMA.

The yield stress of the steel wire was 36 ksi and the recovery stress of the NiTiNb SMA was 80 ksi. Both the steel and SMA wires were wrapped along the embedded length of the reinforcing bar in a continuous spiral with mechanical connectors providing fixity at the ends. The target confining pressure was relatively low at 0.1 ksi, which was achieved with a spacing of 0.45 in. within the steel spiral and 1.0 in. in the SMA. The SMA confined specimens were placed in the loading frame before the SMA was activated by heating the wire beyond the austenite finish temperature of approximately 167ºF with a torch. The specimens were loaded using the same setup and protocol as the No. 5 bar specimens and unconfined No. 8 bar specimens. The test results are shown in Figure 2-7 together with the results of the unconfined No. 8 bar specimens.

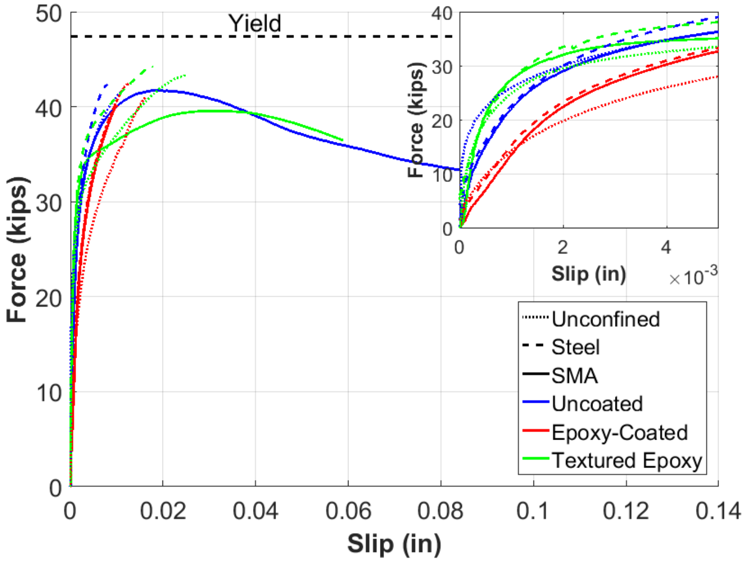
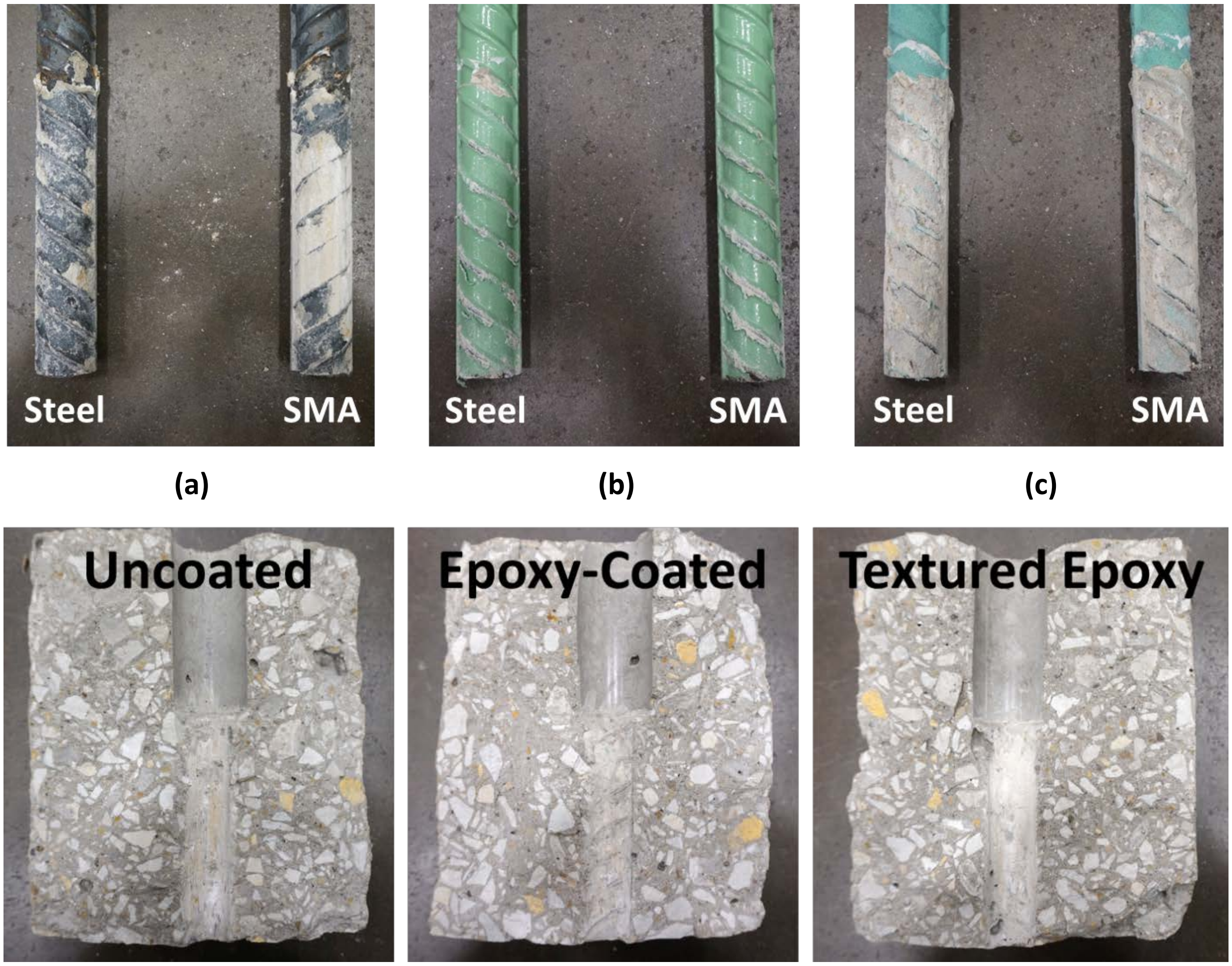


Figure 2-7. Confined and unconfined No. 8 bar pull-out results.

As noted above, the unconfined epoxy-coated specimen had an embedment length of 4.5 in. Overall, there was no significant difference in the force-slip behavior between the passively and actively confined specimens. However, all specimens other than the SMA confined uncoated and textured epoxy-coated specimens failed prematurely due to concrete splitting. The overall behavior of the two specimens that failed in the pull-out mode is very similar to what was observed in the No. 5 bars. While the textured epoxy coating provided good initial bond comparable to that of the uncoated bar, the slip resistance degraded extremely rapidly before the concrete split, shortly after the peak pull-out force was recorded.

In comparison to the No. 5 bars, where the average peak pull-out force of the textured epoxy-coated bars was up to 19% lower compared to the uncoated bars—the No. 8 textured epoxy-coated bar with SMA confinement attained 95% of the peak pull-out force of the corresponding uncoated bar. The maximum bond stress developed by the SMA confined uncoated and textured epoxy-coated bars were 2.65 ksi and 2.52 ksi respectively. Although the magnitude of slip observed in the confined specimens that failed by splitting was relatively low, there was significant evidence of concrete crushing at the bar interface, unlike the unconfined specimens. Figure 2-8 shows the reinforcing bars removed at the end of testing and the concrete surface in split specimens. In Figures 2-8 (a), (b), and (c), the bar on the left was removed from steel confined specimens while the bar on the right was removed from SMA confined specimens. The split concrete surfaces in Figures 2-8 (d) were all from steel confined specimens.



(a) **(b)** **(c)**

(d)

Figure 2-8. Confined No. 8 pull-out specimens after testing.

Visually, there was no significant difference between the steel and SMA confined specimens. Although all three passively confined specimens failed due to splitting, concrete crushing and grinding in the embedded region can be clearly seen in Figure 2-8 (d). In the uncoated and textured epoxy-coated bar specimens, the concrete in the embedded region was left smooth with crushed powder left behind. Similar to the No. 5 bars, while the residue generated by the uncoated bars was densely compacted powder—the residue on the textured epoxy-coated bars showed a combination of shearing and crushing of the porous concrete. The epoxy-coated bar induced noticeably less crushing, as imprints of the ribs were still clearly visible. This again is an indication of the increased radial pressure at the bar ribs and an increased tendency to slip.

CHAPTER 3: FLEXURAL TESTING

3.1 BEAM SPECIMENS

To supplement the pull-out test results and gain comparative insight on the bond performance of the textured epoxy-coated reinforcement under more representative loading conditions—simple beam specimens were fabricated and tested in flexure. The beam design and test setup are illustrated in Figure 3-1.

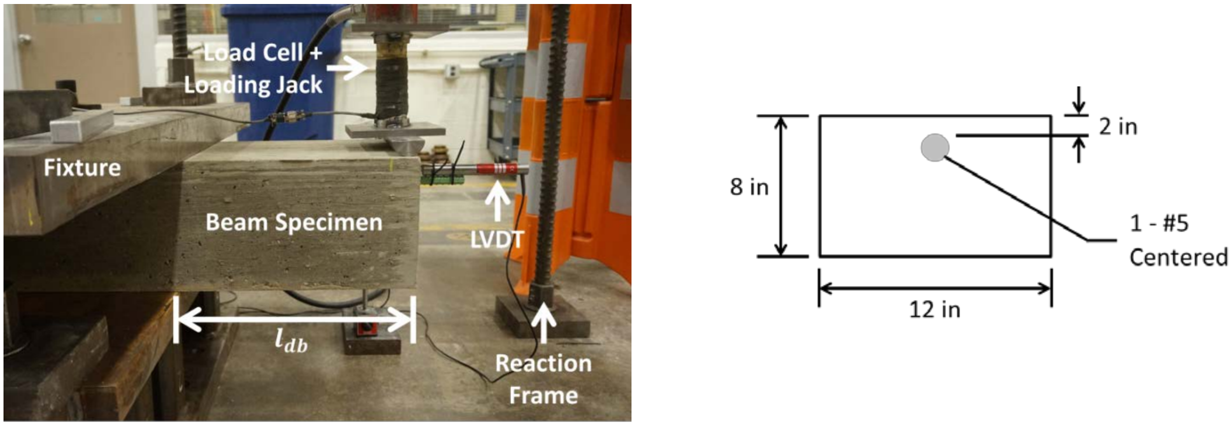


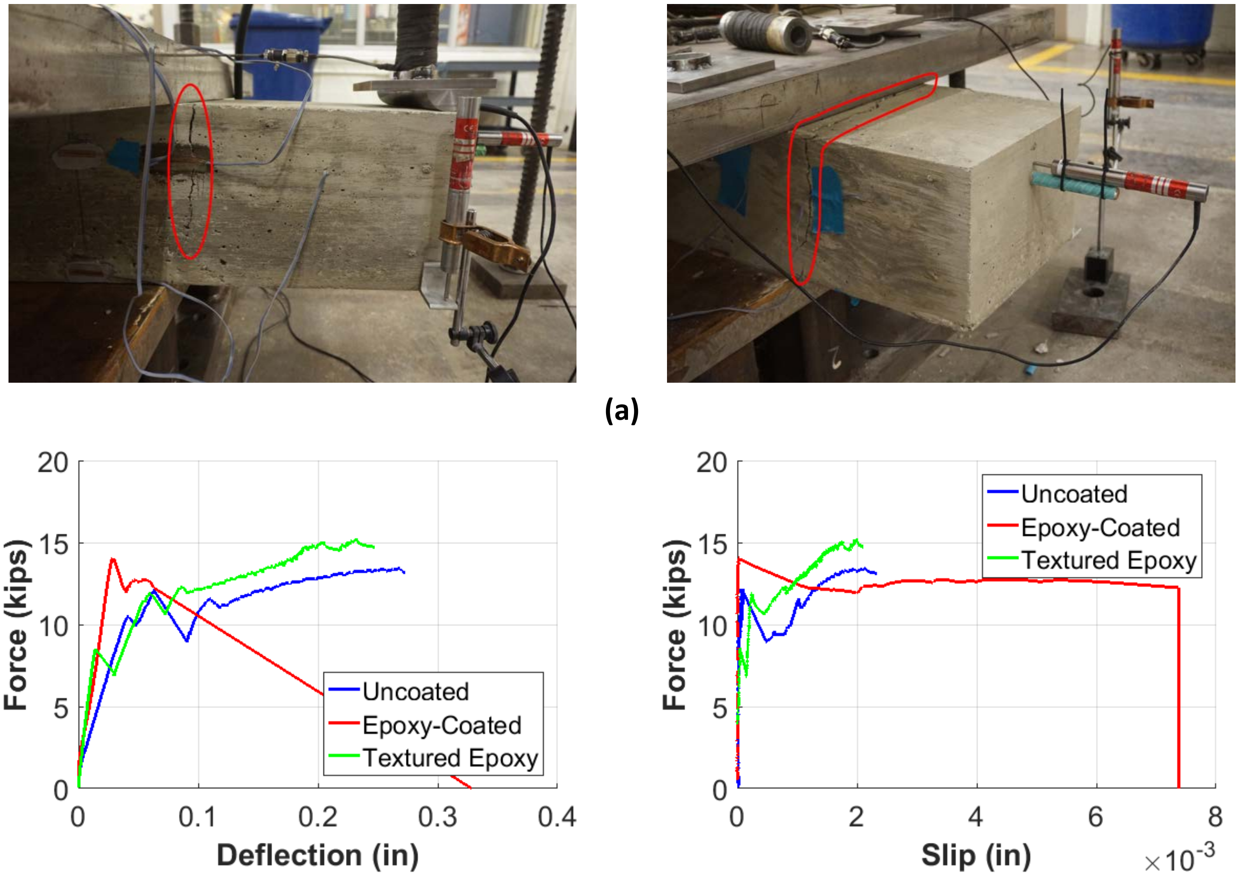
Figure 3-1. Beam specimen design and test setup.

As indicated in Figure 3-1, the beam consisted of a single No. 5 reinforcing bar. The depth and clear cover were chosen to be consistent with typical bridge deck thickness and cover used by IDOT. As an exploratory experiment, only one specimen was cast for each bar type using the same mix design shown in Table 1 except the w/c ratio was slightly lower at 0.39. The concrete used in the beam specimens reached a compressive strength of 7.1 ksi at 28 days. It should be noted that at the time of testing, the beams had been curing under ambient conditions for up to 10 weeks.

The development length, l_{db} for epoxy-coated bars in tension calculated as per guidelines in the AASHTO LRFD Bridge Design Specifications (AASHTO 2012), was approximately 10.6 in. In order to induce failure due to slip, the standard epoxy-coated bar was tested at l_{db} = 10 in. The specimens with uncoated and textured epoxy-coated bars were tested at the same length in order to directly compare the results. The beams were tested as cantilevers by clamping them between two rigid steel plates with an overhang equal to l_{db}. The load was applied at the free end using a hand-operated hydraulic jack with the deflection and bar slip relative to the concrete being recorded with LVDT's.

3.2 TEST RESULTS

Despite the relatively deep aspect ratio ($a/d < 2.5$) created by the short embedment length, the behavior of all three beams was predominantly dominated by flexure as evidenced by the cracking patterns. The force-deflection and force-slip curves for each specimen are shown in Figure 3-2, along with examples of flexural cracking observed in the beams.



(a)

(b)

(c)

Figure 3-2. Bond strength testing of reinforcing bars in tension; (a) Flexural cracking observed in beam specimens, (b) Force-deflection behavior, and (c) Force-slip behavior.

The sudden drops in force shown in the force-deflection and force-slip curves correspond to crack initiation and propagation. In the case of the standard epoxy-coated bar, there was almost no slip resistance after cracking. It was observed that as the flexural crack propagated through the beam cross-section, the concrete began slipping relative to the bar and eventually slid off completely. This behavior is clearly demonstrated in the force-slip curve in Figure 3-2 (c). It shows that once slippage is initiated in a standard epoxy-coated bar, there is very little slip resistance between the bar and concrete. In contrast, both the uncoated and textured epoxy-coated bars behaved in a ductile manner without significant slip. Despite minor declines in the applied force at cracking, both beams were able to continue carrying load. Although there is a sudden jump in the slip at cracking, it is quickly arrested as the concrete engages the bar again. Based on the force-slip behavior of the three bars, it is likely that friction at the bar-concrete interface plays a crucial role in the post-cracking bond-slip behavior. When comparing the uncoated and textured epoxy-coated bars, it is clear that the slip that occurs at cracking is considerably higher in the uncoated bar than the textured epoxy-coated bar. Furthermore, after the first major crack, the uncoated bar showed a slight plateau in the force-slip curve. In comparison, the drop in applied force and the slip are both much less significant in the textured epoxy-coated bar—which suggests the increased friction in the textured epoxy-coated bar could reduce both the width and propagation of cracks. Given the limited scope and sample size in this part of the study, however, further investigation is needed to validate these observations.

CHAPTER 4: SUMMARY AND CONCLUSIONS

As a means to reduce cracking in bridge decks reinforced with epoxy-coated steel, IDOT developed a novel textured epoxy coating to enhance bond and facilitate better stress transfer between the reinforcement and the concrete. This exploratory study compared the bond strength of textured epoxy-coated bars, against uncoated and standard epoxy-coated reinforcing bars, using direct pull-out and flexure tests. The main findings are summarized below:

- The added friction in the textured epoxy-coated bars provided high initial slip resistance comparable to black steel. However, the slip resistance in the textured epoxy-coated bars degraded very rapidly after the friction resistance was overcome.
- Closer examination of the bar surfaces after testing, revealed that a layer of concrete paste was firmly adhered to the bonded length of the textured epoxy-coated bars—which would have reduced the bearing force component at the rib face—considerably reducing the bond strength.
- The average peak bond strength in the No.5 textured epoxy-coated bars was up to 19% lower than that observed in the uncoated bars. The textured coating did not provide any improvements in the post-peak bond-slip behavior.
- Passive and active confinement methods were used to prevent the concrete in No. 8 bar pull-out specimens from splitting. The confinement did not affect the bond-slip behavior of the bars. The behavior was similar to the No. 5 pull-out specimens, which were all unconfined.
- The confined No. 8 textured epoxy-coated bars also displayed high initial slip resistance, but the textured epoxy-coated bars performed poorly once the frictional bond component was lost.
- It was noticed that both the standard and textured epoxy coating could be easily damaged through slip, forming localized areas of exposed steel.
- Under flexure, the beam reinforced with standard epoxy-coated reinforcement showed almost no resistance to slip upon cracking. The textured epoxy-coated reinforcement and uncoated reinforcement demonstrated significantly higher slip resistance with the textured epoxy-coated bar demonstrating superior resistance to crack widening. However, further research is needed to examine the behavior of these bars in flexure.

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