Textured Epoxy Coated and Galvanized Reinforcement to Reduce Cracking in Concrete Bridge Decks and Components

Brandon Ross, PhD, PE
Amir Poursaee, PhD, PEng
Sachin Sreedhara, EIT
Matt Mueller, PE

Glenn Department of Civil Engineering,
Clemson University
Clemson, South Carolina

WisDOT ID no. 0092-19-01

August 2021

RESEARCH & LIBRARY UNIT

WHRP

WISCONSIN HIGHWAY RESEARCH PROGRAM

WISCONSIN DOT
PUTTING RESEARCH TO WORK

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No. WisDOT ID no. 0092-19-01	**2. Government Accession No.**	**3. Recipient's Catalog No.**
4. Title and Subtitle Textured epoxy-coated and Galvanized Reinforcement to Reduce Cracking in Concrete Bridge Decks and Components		**5. Report Date** October 2021 **6. Performing Organization Code**
7. Author(s) Brandon Ross Amir Poursaee Sachin Sreedhara Matt Mueller		**8. Performing Organization Report No.**
9. Performing Organization Name and Address Glenn Department of Civil Engineering Lowry Hall, Clemson University, Clemson, SC, 29634		**10. Work Unit No.** **11. Contract or Grant No.** 0092-19-01
12. Sponsoring Agency Name and Address Wisconsin Department of Transportation Research & Library Unit 4802 Sheboygan Ave. Rm 104, Madison, WI 53707		**13. Type of Report and Period Covered** Final Report, 2019-2021 **14. Sponsoring Agency Code**
15. Supplementary Notes NA		

16. Abstract

The objective of this project was to evaluate the influence of different reinforcing bar surface coatings on crack control performance. Five different reinforcing bar coatings were used: black (uncoated), conventional (smooth) epoxy, textured-epoxy, hot-dipped galvanized, and continuously galvanized coatings. Five different series of laboratory tests were conducted to evaluate the impact of coatings on bar-concrete bond, shrinkage cracking, static flexural cracking, and cyclic flexural cracking. Similar trends were observed throughout all tests, with textured epoxy-coated bars providing superior bond and crack control performance. Performance (percentages relative to the average performance of all the bar types) are summarized as: black (uncoated) bars performed 10% better in load tests and 2% worse in shrinkage tests, smooth epoxy coated bars performed 27% worse in load tests, and 8% worse in shrinkage tests, textured epoxy-coated bars performed 15% better in load tests and 15% better in shrinkage tests, hot-dipped galvanized bars performed 5% better in shrinkage tests (and were not evaluated in load tests) and continuously galvanized bars performed 3% worse in load tests and 8% worse in shrinkage tests. Two field studies were also conducted on the same bridge construction project. The bridge deck did not crack during the research period and comparisons in bar performance could not be made based on the deck. Girders with textured-epoxy bars as bottom flange confinement tended to have smaller flange cracks and larger web cracks than girders with smooth epoxy and hot-dipped galvanized bars. While this observation was consistent with theory, the mixed results do not lead to definitive conclusions regarding the best bar coating for girder confinement reinforcement.

17. Key Words Epoxy Coated Rebar; Bond; Cracking; Deck; Roughness; Galvanized Rebar	**18. Distribution Statement** No restrictions. This document is available through the National Technical Information Service. 5285 Port Royal Road Springfield, VA 22161

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

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

DISCLAIMER

This research was funded through the Wisconsin Highway Research Program by the Wisconsin Department of Transportation and the Federal Highway Administration under Project 0092-19-01. The contents of this report reflect the views of the authors who are responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official views of the Wisconsin Department of Transportation or the Federal Highway Administration at the time of publication.

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. This report does not constitute a standard, specification, or regulation.

The United States Government does not endorse products or manufacturers. Trade and manufacturers' names appear in this report only because they are considered essential to the object of the document.

EXECUTIVE SUMMARY

Cracking in concrete bridge elements can negatively impact durability, functionality, and strength. While some degree of cracking is generally expected and accepted, it is desirable to "control" the cracks by keeping their widths and lengths within tolerable limits. One well-established approach to controlling cracks is to place steel reinforcing bars in areas of likely cracking. This project evaluated the influence of different reinforcing bar surface coatings on crack control performance. Five different reinforcing bar coatings were used: black (uncoated), conventional (smooth) epoxy, textured-epoxy, hot-dipped galvanized, and continuously galvanized coatings. Laboratory and field studies were conducted to address this question: Do alternative coatings provide improved crack control relative to the smooth epoxy-coatings currently used by the Wisconsin Department of Transportation?

Five different series of laboratory tests were conducted to evaluate the impact of coatings on bar-concrete bond, static flexural cracking, cyclic flexural cracking, and shrinkage cracking. While none of the results were statistically significant, consistent trends were observed throughout all test programs. For example, textured epoxy-coated bars demonstrated better than average bond and crack control performance in 75% of the test series. Overall performances of the different coatings are summarized in Table 1:

Table 1 – Summary of crack control performance of bar types. Percentages are relative to the average performance of all bar types in comparable tests.

Bar Type	Performance in Load Cracking Tests	Performance in Shrinkage Cracking Tests
Black (uncoated)	10% better	2% worse
Textured epoxy-coated	15% better	15% better
Smooth epoxy-coated	27% worse	8% worse
Hot-dipped galvanized	Not tested	5% better
Continuously galvanized	3% worse	8% worse

Two field studies were conducted. The same bridge construction project was used for both studies, with the first study focusing on the cast-in-place concrete bridge deck and the second focusing on the precast-pretensioned concrete girders. Half of the concrete deck was reinforced with textured epoxy-coated bars and the other half was reinforced with hot-dipped galvanized bars. The bridge deck did not crack during the research period and comparisons in bar performance could not be made based on the deck. Nevertheless, details and documentation of the bridge deck case study are provided in this report to aid in future comparisons.

In the second field study, smooth epoxy, textured-epoxy, and hot-dipped galvanized bars were alternately used as confinement reinforcement in the girders' bottom flanges. End region cracks were compared in the days following prestress transfer. Girders with textured-epoxy bars tended to have smaller flange cracks and larger web cracks than girders with smooth epoxy and hot-dipped galvanized bars. While this overall trend was consistent with theory, the mixed results do not lead to definitive conclusions regarding the best bar coating for girder confinement reinforcement.

Based on the results of the project, the research team makes the following recommendations:

- Textured-epoxy and hot-dipped galvanized bars provided superior crack control performance in laboratory tests relative to the smooth epoxy bars. Textured-epoxy and hot-dipped galvanized bars are recommended as alternatives for reinforcement in concrete bridge decks.
- Continuously galvanized bars performance in lab tests was the same as or better than the smooth epoxy bars. Continuously galvanized should receive consideration as an alternative reinforcement for concrete bridge decks.

- Laboratory and field tests should be conducted to compare alternative bar coatings' corrosion mitigation effects and life-cycle costs. These topics are beyond the scope of the current project; however, they are essential criteria for selecting reinforcement coatings.
- The use of textured epoxy-coated and hot-dipped galvanized bars as confinement reinforcement in precast concrete girders is neither encouraged nor discouraged. These alternative bars did not provide consistent advantages or disadvantages in the field study.
- Future visits should be made to the case study bridge to evaluate the long-term performance of the textured-epoxy and hot-dipped galvanized reinforcement. Such visits should evaluate crack control and the extent of and rebar corrosion.

Table of Content

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Overall Objectives

The project had two overall objectives:

Objective 1: Measure the relative crack-control performance of black (uncoated), smooth epoxy, textured-epoxy, and galvanized-bars. Comparisons will be made based on literature review, laboratory tests, and field studies.

Objective 2: If improved crack-control performance is observed, then create specifications and guidelines to facilitate implementation.

1.2 Motivation

The research presented in this report was motivated by the proposition of controlling cracks in concrete and thereby improving the longevity of concrete bridge elements. *In this report, "crack control" is synonymous with limiting the width and length of cracks*. Cracking of concrete elements can negatively impact their durability, functionality, and strength. While some degree of cracking is generally expected and accepted, it is desirable to minimize the extent of cracking. One well-established approach to controlling cracks is to place steel reinforcing bars in areas of likely cracking. These bars do not prevent cracking; however, they can control cracks by limiting their widths and lengths to tolerable limits. The effectiveness of the bars in controlling cracks is governed by many factors, including surface coatings placed on bars. The research presented in this report evaluated the impact of different bar coatings, used to mitigate corrosion of the underlying steel rebar, on crack control. The logic is that smaller cracks will lead to longer-lasting concrete bridge elements, which will lead to longer-lasting bridges, which will lead to a better transportation system for the citizens of Wisconsin.

1.3 Scope and Variables

The research was strictly focused on concrete crack control. The driving question was: Do alternative coatings provide improved crack control relative to the smooth epoxy-coatings currently used by the Wisconsin Department of Transportation? Related issues, including the impact of coating on corrosion mitigation, were not addressed in the project.

Four different types of rebar coatings and uncoated rebar were considered: black (uncoated), textured epoxy-coated, smooth epoxy coated, hot-dipped galvanized, and continuously galvanized (Figure 1). Lab tests were limited to one concrete mix and one size of bar. Bars used in the lab tests were provided by bar suppliers and represent products available in the construction marketplace at the time of the research project.

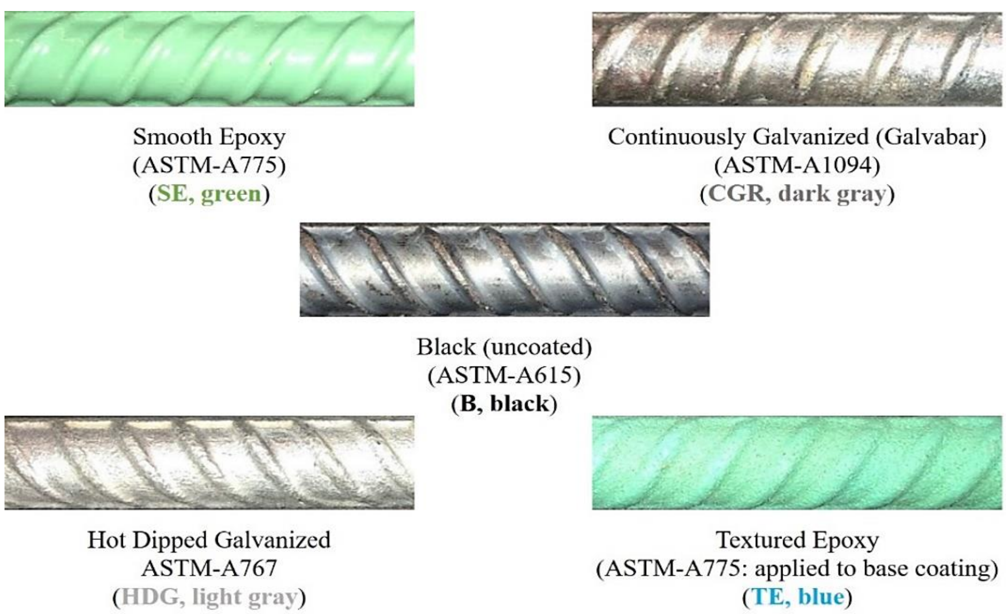


Figure 1 - Types of reinforcement coatings considered in this project. Color code and abbreviations associated with each bar coating type are shown in parentheses.

CHAPTER 2: BACKGROUND AND LITERATURE REVIEW

2.1 Cracking and Reinforcement Corrosion in Concrete

"There are two types of concrete. Concrete that has already cracked and concrete that will crack." – (Overheard during an American Concrete Institute Convention). Cracking is ubiquitous in concrete structures due to the material's relatively low tensile strength. Cracks can form at different stages in a concrete structure's service life and are initiated or exacerbated by many different phenomena. For example, cracking can occur due to early age shrinkage or due to in-service thermal or structural loadings. Cracks influence the durability, serviceability, and strength of concrete structures. Because concrete cracking is ubiquitous, consequential, and multifaceted, it has been the focus of myriad research studies. For example, a search on Google Scholar for the keywords "concrete cracking" identified 1720 results for just the year 2020. A comprehensive discussion of cracking in concrete bridges can be found in Synthesis Report No. 500 from the National Co-operative Highway Research Program (2017) [1]. The following subsections focus on concrete cracking in bridge decks and precast concrete girders.

2.1.1 Bridge Decks

While cracks occur in all bridge structures, they are particularly problematic in bridge decks (Figure 2). Decks are exposed to precipitation, are directly loaded by traffic, and are in contact with deicing chemicals. Cracks in bridge decks provide access points for corrosion agents, including those in deicing chemicals, to initiate and exacerbate corrosion of steel reinforcement [1]. Indeed, corrosion of steel reinforcement can be a primary limitation on the service life of concrete bridge decks [3], and controlling cracks can be an effective strategy in mitigating the effects of corrosion [4].

Figure 2 - Examples of under deck bridge cracking. Photos are from a previous WHRP report [5].

Previous research has identified many factors that can affect the occurrence and extent of cracking in concrete bridge decks ([1] and [6-11]):

- Environmental conditions during concrete placement and curing,
- Concrete mix design and material properties,
- Construction practices during placement and curing,
- Reinforcement details,
- Bridge layout (i.e., skew and span),
- Structural stiffness,
- Bearing conditions and restraints,
- Corrosion and chloride content,
- Thermal loads and freeze-thaw cycles, and
- Structural loads.

The impact of cracking on bridge deck durability and corrosion also has been extensively addressed in the research literature. The following approaches for mitigating corrosion in bridge decks have been evaluated in recent studies [12-18]:

- Installing sealants and overlays on the deck surface,
- Repairing cracks using epoxy injection or other crack-sealing products,
- Using reinforcement with protective coatings (i.e., epoxy or galvanized), and
- Using reinforcement with corrosion-resistant alloys.

Clearly, there is a wealth of information on mitigation cracking in concrete decks and on mitigation of corrosion in bridge deck reinforcement. The topic of this report – controlling cracks using alternative reinforcements – is only one of many factors related to the service life of concrete bridge decks.

2.1.2 Girders

End region cracking of precast-pretensioned concrete girders is a common challenge in Wisconsin (Figure 3) and in general. The primary cause of end region cracks is tensile stresses that occur from concentrated prestressing forces and are distributed from their point of application in the bottom flange to other parts of the girder cross-section (Figure 4).

End region cracks have been studied for decades, and there is a large body of literature discussing causes and mitigation strategies. The topic has recently been the focus of projects from the Wisconsin DOT [19], Florida DOT [20], Alabama DOT [21], and National Cooperative Highway Research Program [22]. Factors associated with end region cracking include:

- Cross-section geometry,
- Magnitude and location of pretension forces,
- Detailing of end region reinforcement, and
- Concrete tensile strength at the time of prestress transfer.

Partial debonding of select strands has been shown to reduce end region tensile stresses and the resulting cracks ([19], [20], and [23]). More aggressive approaches for preventing or reducing end region cracks include using ultra-high-performance concrete regions [24] and vertical post-tensioning [25] in the end region. The effect (if any) of alternative reinforcement coatings on end region cracks has not previously been considered.

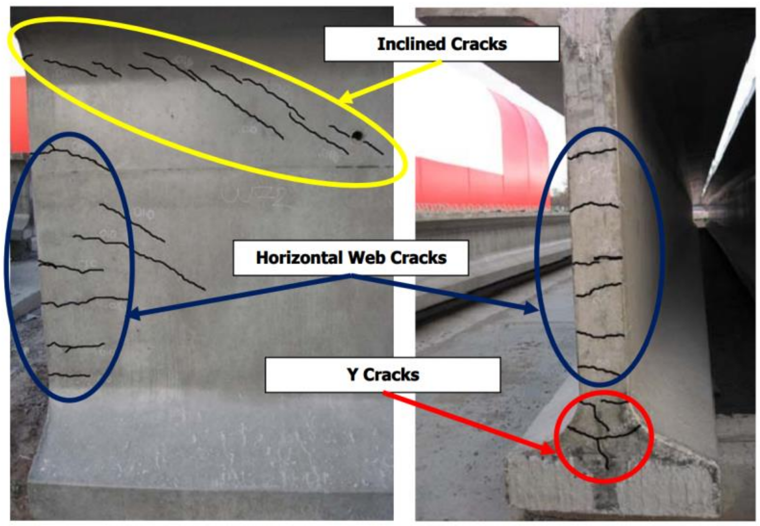


Figure 3 - Type of end region cracks [19].

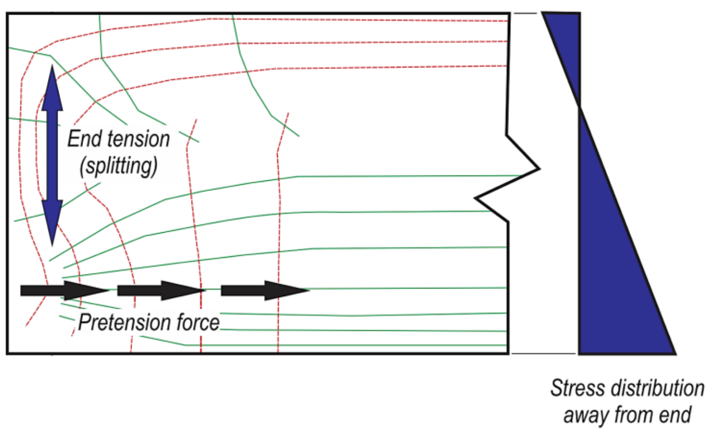


Figure 4 - End region cracks form due to tensile stresses (green trajectory lines), which form as the pretension force is distributed from the bottom flange to the rest of the cross-section. Figure based on Willis [23].

2.2 Reinforcing Bars and Coatings

The first specification for steel reinforcing bars was issued in 1910 [26]. Since that time, there have been numerous advances in reinforcement technology, including coatings to mitigate corrosion. The following sections briefly introduce the bars and coatings that were used in the laboratory and field studies of this project.

2.2.1 Black (uncoated) bar

All bars in the project complied with ASTM-A615 [27]. Different coatings were considered in the project; however, all bar specimens – regardless of coating – started with an ASTM-A615 compliant bar.

2.2.2 Smooth epoxy-coated bar

Typical epoxy-coated bars are labeled as “smooth” in this report to differentiate them from the novel textured epoxy-coated bars that were also used in the project. Smooth epoxy-coated bars complied with ASTM-A775 [28]. The epoxy coating is applied over an ASTM-A615 black bar. The purpose of the epoxy coating is to mitigate corrosion, the epoxy coating acting as a barrier between the bar and corrosive materials. The first bridge deck with epoxy-coated bars in the United States was built in Philadelphia, PA in 1973 [29]. Since that time, epoxy-coated bars have become ubiquitous in bridges throughout the United States.

The coating process begins with abrasive cleaning to remove rust and mill scale from the bar surface. The bar is then heated in an oven or through induction heating, whereafter a charged epoxy powder is applied using an electrostatic spray nozzle. The heat and the charge adhere the powder to the surface resulting in the epoxy coating. The coated bar is water quenched and cooled.

After cooling, the bar is checked for “holidays,” which are small cracks or pinholes that are often too small for visual observation. Holidays are identified by passing a current through the bar and noting any electrical continuity through the coating. The process from cleaning to holiday checking can be automated and can take only a few minutes. ASTM-A775 specifies the permissible level of coating damage and repair methods. Per ASTM-A775, the epoxy coating thickness is between 7 and 12 mils for bar sizes Nos. 3 to 5.

2.2.3 Textured epoxy-coated bar

Textured epoxy is a novel coating designed to mitigate corrosion while also having a rough surface that is suitable for the concrete bond. The fabrication process is like that described in the previous section for the Smooth epoxy-coated bar. The only difference is the powder spray that produces the smooth coating is immediately followed by a second powder spray that creates the texture. Currently, there is not an ASTM standard for Textured epoxy-coated bars; however, the initial coating used in the textured bars complies with ASTM-A775. Because of the two-coating process, the total thickness of epoxy on the textured bars in the project was approximately 6.4 % thicker than the smooth epoxy coating. While the conventional epoxy bar has a smooth and shiny surface, the textured-epoxy bar has a rough and gritty surface (Figure 1). Although the measure is subjective, members of the research team reported the surface feeling similar to 180-grit sandpaper. Handling, bending, and installation procedures for smooth epoxy-coated bars are also used for textured epoxy-coated bars.

2.2.4 Hot-dipped galvanized bar

Galvanizing is a zinc coating that is chemically bonded to the steel surface to mitigate corrosion. Hot dipping is the most common method to apply galvanizing. Hot-dipped galvanizing, often called 'batch galvanizing,' involves immersing clean and pre-fluxed steel in a kettle of molten zinc at about 450^{o}C. During the immersion time, while the steel is heated to the temperature of the molten zinc, a metallurgical reaction occurs between the steel and the zinc [30]. Hot-dipped galvanized bars in the project complied with ASTM-A767 [31].

The reaction between steel and molten zinc produces a coating on the steel made up of a series of iron zinc alloy layers that grow from the steel/zinc interface, with a layer of essentially pure zinc at the outer surface. What distinguishes galvanizing from other types of coatings is that the galvanized layer is metallurgically bonded to the steel due to inter-alloying between the steel and the molten zinc. A key feature of hot-dip coatings is that the outer layer that remains on the surface of the product as it is withdrawn from the kettle and is generally about 1.6-2 mil thick. It is the presence of this "eta layer" that controls much of the behavior of zinc when in contact with wet cement [30].

2.2.5 Continuously galvanized bar

Continuously galvanized rebar was developed in China in 2011 and introduced to the American market in 2018 under the trade name GalvaBar [32]. The continuous coating is an in-line (thus not batch dipping) process similar to the coating of sheet and pipe products, where a blast cleaned and preheated bar is fed through a molten zinc bath for not more than 1-2 s [33], and the total time at temperature including the preheating stage is not more than 4-5 s. By adding a small amount of aluminum (0.2%) to the zinc bath, a coating typically 2-2.4 mil thick is produced that is almost entirely pure zinc, with only a very thin layer (approximately 0.004 mils) of a ternary ($Fe_2Al_{5-x}Zn_x$) alloy at the zinc/steel interface. Apart from the economy and speed of production with the continuous galvanizing method, a key feature of this type of coating is the improved formability of the coated product [30].

2.3 Surface Roughness

Previous research has shown that the lack of surface roughness of epoxy-coated reinforcement impacts bond strength with concrete [34-36]. Smooth bar surfaces are associated with a relatively poor bond, whereas rough bar surfaces contribute to a stronger bond. This is the very phenomenon that motivated this project to consider textured-epoxy bars. Because textured-epoxy bars can be produced with different levels of surface roughness, it is necessary to measure and document the roughness. Measurement parameters include *Sa*, the arithmetical mean height of a surface, and *Ra*, the arithmetical mean height along a line. At the scale of rebar surface roughness, *Ra* and *Sa* are typically reported in micrometers. In everyday language, *Ra* and *Sa* can be described as the average height of the peaks relative to the base of the valleys.

2.4 Reinforcement-Concrete Bond

2.4.1 Theory and previous studies

Transfer of forces between concrete and embedded steel bars, i.e., reinforcement-concrete bond, can occur through cohesion, adhesion, and mechanical interlocking between the bar deformations and concrete. The contributions of these mechanisms are conditional upon the level of force transfer, surface coating of the rebar, and geometry of bar deformations. Adhesion and cohesion (if present) are primary at small load levels, and mechanical interlocking is primary at ultimate load levels. The interlocking mechanism is shown in Figure 5. Equal and opposite bearing forces act normal to the bar deformations. The longitudinal component transfers the force between the bar and concrete, while the radial component leads to tensile stresses in the surrounding concrete. The tensile stresses can lead to splitting cracks depending on the confinement, cover, and spacing of the bars. Darwin and Graham [37] observed that initial (low load) slip resistance and ultimate bond strength increase as the relative rib (deformation) area increases. Relative rib area is the ratio of rib area normal to the bar axis to the product of nominal bar perimeter and rib spacing.

The effect of epoxy coating thickness on deformed bars and bar parameters on bond strength in concrete was studied by Chul Choi et al. [34]. It was concluded that epoxy coating in deformed bars has a greater effect in reducing the bond strength as the bar size increases. Also, the higher the bearing area due to the rib deformation pattern in bars, the lower the effect of epoxy coating on the reduction of bond strength in concrete.

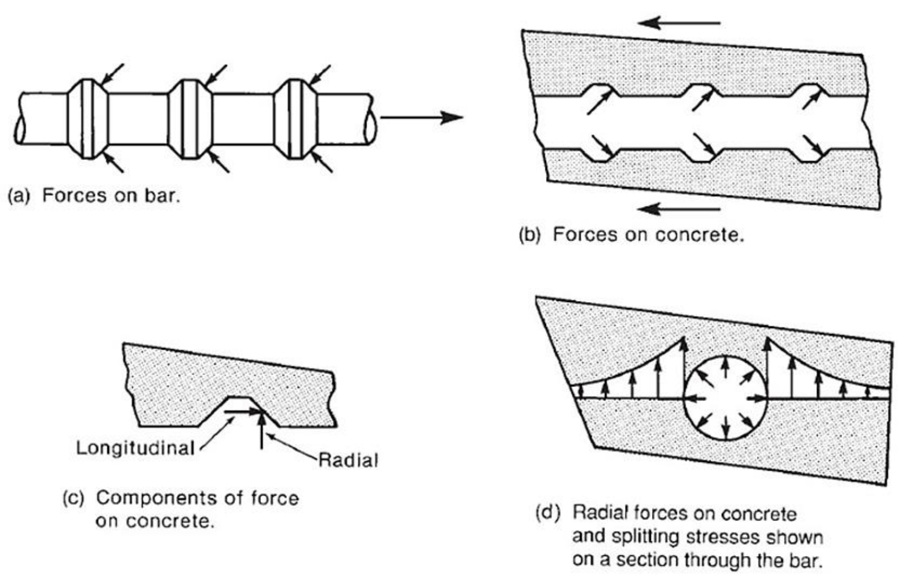


Figure 5- Bond transfer mechanism (Figure from [38]).

The bond strength of hot-dipped galvanized, epoxy-coated, and uncoated bars was studied by Kayali and Yeomans [38]. They reported that there is no statistically significant difference in bond strength between uncoated and hot-dipped galvanized bars in 28-day cured concrete. A reduction in bond strength of 25% to 42% was observed in the epoxy-coated bars.

Kim and Andrawes [40, 41] experimentally tested the bond behavior of textured epoxy-coated, smooth epoxy-coated, and uncoated bars. It was observed that textured-epoxy and uncoated bars had higher slip resistance relative to smooth epoxy-coated bars. Additionally, the textured-epoxy-coated bars had greater crack control performance than both the uncoated and epoxy-coated bars. In a recent paper, the same research group presented an approach for simulating the textured-epoxy coating using the finite element method [35]. The current report adds to Kim and Andrawes by evaluating textured-epoxy bars using different test methods, including shrinkage crack testing. Consideration of hot-dipped and continuously galvanized bars is another distinction of the report.

The Illinois DOT also conducted a small study comparing the concrete pull-out strength of textured epoxy-coated bars and uncoated bars. The textured epoxy-coated bars were provided by multiple epoxy suppliers and demonstrated 9% higher pullout strength on average than the uncoated bars [42].

2.4.2 AASHTO LRFD

AASHTO LRFD [43] recognizes the impact of reinforcement surface coating on bond performance. Section 5.11.2.1.2 requires that the development length of epoxy-coated bars be increased by up to 50% depending on bar cover and spacing distances. The required development length for hooked bars is also increased for epoxy-coated bars (Section 5.11.2.4.2). It is understood that “epoxy-coated bars” in AASHTO LRFD are “smooth epoxy-coated” bars as described in this report. Textured epoxy-coated bars are a relatively new product and are not addressed implicitly or explicitly in AASHTO LRFD. Also, galvanized coatings are not explicitly mentioned in the sections dealing with development length; they are considered the same as an uncoated bar when calculating development lengths.

2.5 Crack Control

2.5.1 Theory

In addition to improving structural capacity, steel reinforcing bars are also used to control the width of cracks that form in concrete. When a concrete crack intersects a bar, the crack is restrained and any widening of the crack results in increased tensile stress in the bar. Thus, reinforcement is detailed in a manner to control cracking, i.e., to prevent cracks from growing beyond a tolerable width. Reinforcing bars can be used to control cracks caused by shrinkage, temperature effects, flexural loads, and other load effects. The effectiveness of reinforcement for crack control is inversely related to bar spacing, cover distance, and level of bar stress [44].

2.5.2 AASHTO LRFD

Crack control is considered at the service limit state in AASHTO LRFD [43]. As such, the bar stresses associated with crack control are much lower than the specified yield stress. For example, Section 5.10.10.1 specifies that splitting reinforcement at the ends of pretensioned concrete girders should be designed for bar stress not greater than 20 ksi. The commentary associated with this section states that “The primary purpose of the choice of the 20-ksi steel stress limit for this provision is crack control.”

Section 5.7.3.4 contains requirements for detailing distributed reinforcement for crack control. Equations are provided for calculating the minimum bar spacing to control flexural cracks, considering cover depth, the thickness of member, service-limit bar stress, and exposure conditions. The requirements of 5.7.3.4 make no distinction between bars with different coatings.

Reinforcement requirements for bridge decks are provided in section 9.7.2.5 for the "Empirical Design" approach. The section commentary states that "[the reinforcement amount of] 0.3 percent of the gross area…is specified for better crack control in the positive moment area." Again, no distinction is made in AASHTO LRFD between bars with different coatings. However, other areas of design do consider distinctions between different coatings. For example, AASHTO Guide Specs for Service Life Design for Highway Bridges (2020) [45] has different classes of reinforcement based on coating.

CHAPTER 3: LABORATORY STUDIES

3.1 Overview

Five different programs of laboratory tests were conducted in the project, with reinforcement coating being the only variable in the tests. Each test program included between one and eight series (Table 2). A “series” is a set of specimens that were cast at the same time from the same batch of concrete (or mortar) and included one specimen with each of the considered coating types. The concrete or mortar mix design was consistent for all specimens within a given test program. Material properties, including concrete compressive strength, steel modulus of elasticity, and coating surface roughness, were also measured. Details and results of the material tests are presented in the report Appendix.

The original test plan included “galvanized” bars and did not differentiate between hot-dipped and continuously galvanized bars. After the initial test programs were conducted with continuously galvanized bars, the decision was made to add hot-dipped galvanized bars to the remaining programs.

Table 2 - Laboratory test programs and associated bar coatings (‘X’ denotes that coating type was considered in the test program)

Bar Coating	**Test Program**				
	Shrinkage Cracking	**Bond**	**Cyclic load**	**Static load cracking**	**“Short” beams**
Black	X	X		X	X
Smooth epoxy	X	X	X	X	X
Texture epoxy	X	X	X	X	X
Hot-dipped galvanized	X		X		
Continuously galvanized	X	X		X	X
Number of series	**8**	**4**	**1**	**3**	**3**

Deliberate steps were taken to enable fair and meaningful comparisons between the different bar coatings. Each of the coatings was equally represented in each series; thus, unavoidable variations between batches of concrete (or mortar) similarly impacted specimens with each coating type. Other more subtle steps were also taken to facilitate fair comparisons. Examples include rotating formwork between specimens with different bar coatings, rotating the testing order, conducting all tests in a series within as small a time window as practically possible, and ensuring that the grade mark portion of the bars was outside of the critical locations that influenced crack control.

3.2 Comparison Index (Data Normalization)

Recognizing that concrete variations were unavoidably between the different series of specimens, a means of normalizing the data was required to facilitate meaningful comparisons. A "comparison index" was calculated to normalize the results within each series. The comparison index equals the measurement value for a given specimen divided by the average measurement for all specimens in the same series. A value larger than 1.0 indicates poorer than average performance, whereas a value less than 1.0 indicates performance superior to the average. Example comparison index values are shown in Table 3. In the example, the specimen with the smooth epoxy bar had a comparison index of 1.20, meaning that the specimen's crack width was 20% larger than the average of all other cracks in the series. An added benefit of the comparison index is that it allows results to be compared between different test programs, test series, and coating types.

Table 3 - Example of Comparison Index (Data are demonstrative and not from a specific series).

Bar Coating	Crack Width (in.)	Comparison Index (Specimen crack width / Series average)
Black	0.018	0.94
Smooth epoxy	0.023	1.20
Texture epoxy	0.016	0.83
Hot-dipped galvanized	0.019	0.99
Continuously galvanized	0.020	1.04
Series average	0.019	--

3.3 Image Analysis of Cracks

Crack sizes were measured using ImageJ software [46]. This software analyzes digital images to determine widths, lengths, and areas. The process is shown from left to right in Figure 6. An item of known length was captured within a digital image and is used to establish a scale of pixels/mm within the software. After the scale was established, the format of the image was converted to 8-bit. The threshold tool in ImageJ was then used to tune and highlight the portion of the image containing the crack. Any “noise” around the crack was edited in MS Paint to eliminate the small spots which would add to the highlighted portion of the crack. The highlighted cracked portion was identified as a set of discrete particles close to each other in ImageJ and was converted to an area measurement using the scale. The average width was then determined outside the program by dividing the area by the manually measured crack length.

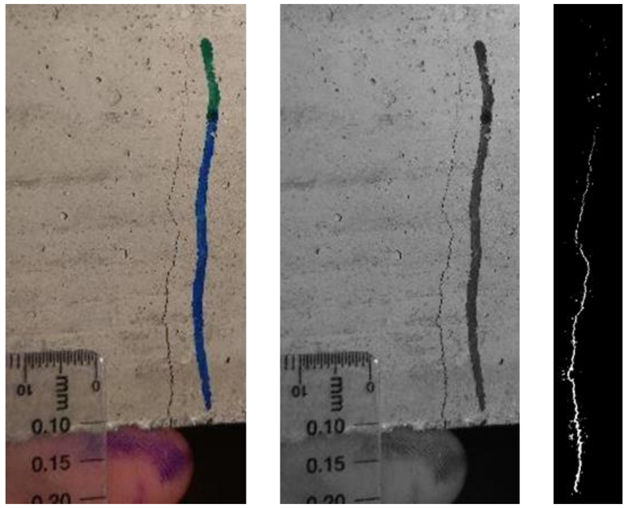


Figure 6 - Original photo (left), conversion to 8-bit (center), crack highlight (right).

3.4 Surface Roughness

A VHX-7000 Keyence optical microscope was used to measure the surface roughness from samples of each coating type. The VHX-7000 has a depth of field that is 20 times greater than conventional optical microscopes. It can deliver 2D and 3D measurements, roughness, contamination, grain size, and other analyses with one tool. Additionally, observation can be carried out automatically at magnifications from 20× to 6000× without changing the lens. Example microscope images for textured-epoxy and smooth epoxy-coated bars are shown in Figure 7. The roughness measurement was particularly relevant for documenting the textured-epoxy bars because they are a new product and do not have a standardized level of roughness. The measured values are shown in Figure 8. Values in the figure for a given coating type are the average of two measurements taken on three bar samples. The figures' values were corrected to account for the round surface of the bars, which impacted the microscope roughness measurements. The correction was automated in the software used to run the microscope.

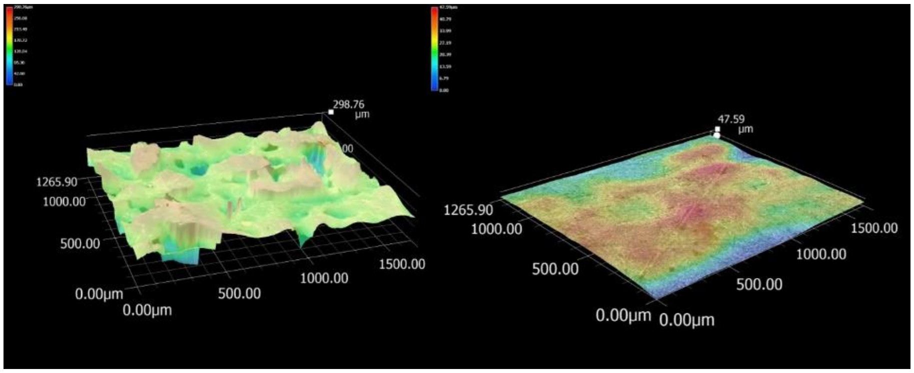


Figure 7 - Microscope images for textured-epoxy surface (left) and smooth-epoxy surface (right). Colors in the image denote the surface topography.

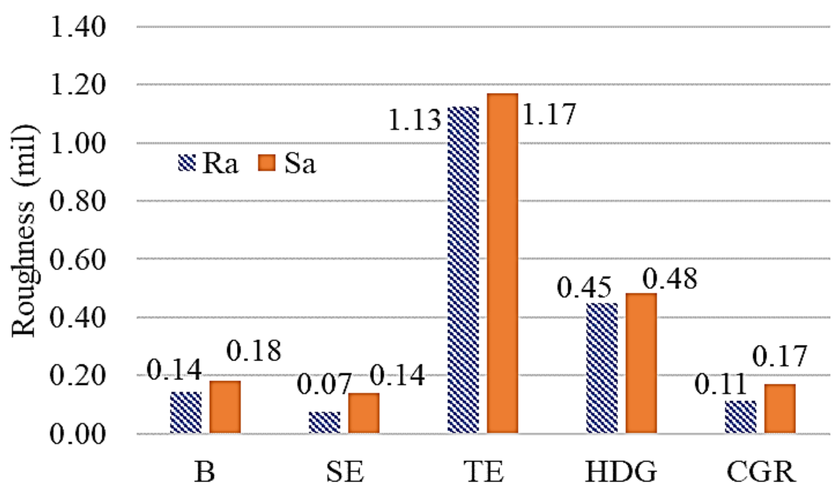


Figure 8 - Roughness measurements for samples of each bar coating type.

The microscope-measured roughness for the textured-epoxy bars was 1.13 mil and 1.17 mil for Ra and Sa, respectively. The coefficient of variation of roughness for the textured bars was 0.27 for Ra and 0.24 for Sa. Using tactile comparisons, members of the research team reported that the textured epoxy-coated bar roughness "felt" between 220 and 180 grit sandpaper. This result is subjective and will vary from person to person. An efficient method of measuring roughness is needed to support specifying and procuring textured epoxy-coated bars. One promising method is “replica tape.” This tape is burnished against a surface to make a negative that can then be used to measure the surface thickness. Replica tape is commercially available; however, development work is required to determine how this method can be applied to measure roughness on a curved rebar surface. Another possible method would be to use digital images and the ImageJ software to measure the roughness profile. This approach would also require further development.

3.5 Shrinkage

3.5.1 Test Setup and Procedure

The impact of the reinforcement coatings on the control of shrinkage cracks was tested using the approach shown in Figure 9. Mortar was cast around a solid steel block and a rebar sample. The steel block in the bottom of the specimen restrained shrinkage of the fresh mortar, resulting in a crack on the top surface (Figure 10) at the location of a crack initiator. The rebar crossed through the crack initiator and controlled the crack width. This setup was adapted from Raoufi et al. [47].

The mortar was prepared using a pan mixer and was placed in the formwork in two layers. After each layer, the specimen was placed on a vibrating table to conciliate the mortar. The formwork was removed approximately 3-hours after casting. A table fan was placed in front of the specimens after the formwork removal to accelerate evaporation and enhance shrinkage cracking. Mortar mixture proportions, flow table results, and compressive strengths are reported in the Appendix.

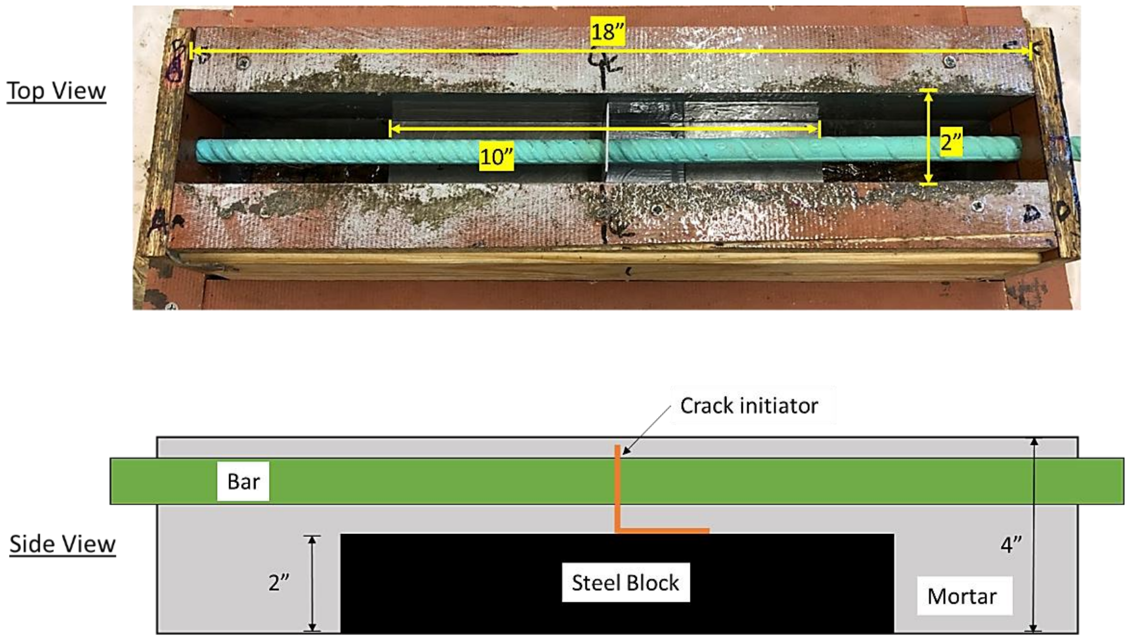


Figure 9 - Shrinkage cracking test set-up.

Cracks were observed in all specimens, and crack data were collected 24 hours after casting the mortar. Digital images of the cracks were collected, and crack width was also measured at three locations using a handheld microscope. An example crack is shown in Figure 10. Eight series of shrinkage tests were conducted, and one specimen of each coating type was included in each series.

Figure 10 - Shrinkage cracking in an example test specimen.

3.5.2 Test Results

The eight series provided sufficient data to conduct statistical comparisons of the shrinkage cracking results. The analysis of variance (ANOVA) approach was used to compare crack widths between series and between coating types. ANOVA and the Tukey-Kramer methods were also used to compare results between specimens with different bar coatings. Statistical comparisons in this report are for the ImageJ average crack width data. Similar results and trends were observed in analyses of data collected using the microscope.

The ANOVA identified statistical differences at the 95% confidence level between crack widths in different series. Because the same mix design and procedures were used for each series, the inherent variability between batches is culpable in the ANOVA results. The statistically significant differences observed between batches support the use of the comparison index to normalize test results between different series.

Statistically significant differences in crack widths for different bar coatings were not observed at the 95%, or 90%, confidence levels. The data in Table 4 can be used to see how closely the observed differences were to be statistically significant. Data in the table are the ANOVA/Tukey-Kramer comparisons between the different coatings. The Table 4 values are the "absolute difference" divided by the "critical value" and can be interpreted as how close the difference was to be statistically significant at the 90% level. The highest value in the table is 0.85, which indicates that the measured differences between textured-epoxy (TE) bars and the smooth-epoxy (SE) bars were 85% of the difference needed for statistical significance. This result suggests that textured-epoxy bars have superior crack control to the smooth epoxy bars, although not to a statistically significant level. This result is consistent with the trends observed throughout the test program.

Table 4 - Tukey-Kramer comparisons between coating types. Higher values indicate a greater likelihood of difference between bars.

	B	SE	TE	HDG	CGR
SE	0.21	--	--	--	--
TE	0.64	0.85	--	--	--
HDG	0.42	0.63	0.22	--	--
CGR	0.09	0.12	0.73	0.51	--

Comparison Index results are shown in Figure 11 to provide a graphical means of evaluating and interpreting the shrinkage crack data. The "box" portion of the data indicates the upper and lower quartiles of the data. The "whisker" portion shows the range of the data points, excluding any outliers. Data in the figure come from ImageJ and microscope measurements, and only three outliers were recorded in the dataset out of 128 comparison index values. The "x" in the figure indicates the mean value, and the horizontal line in the box indicates the median value.

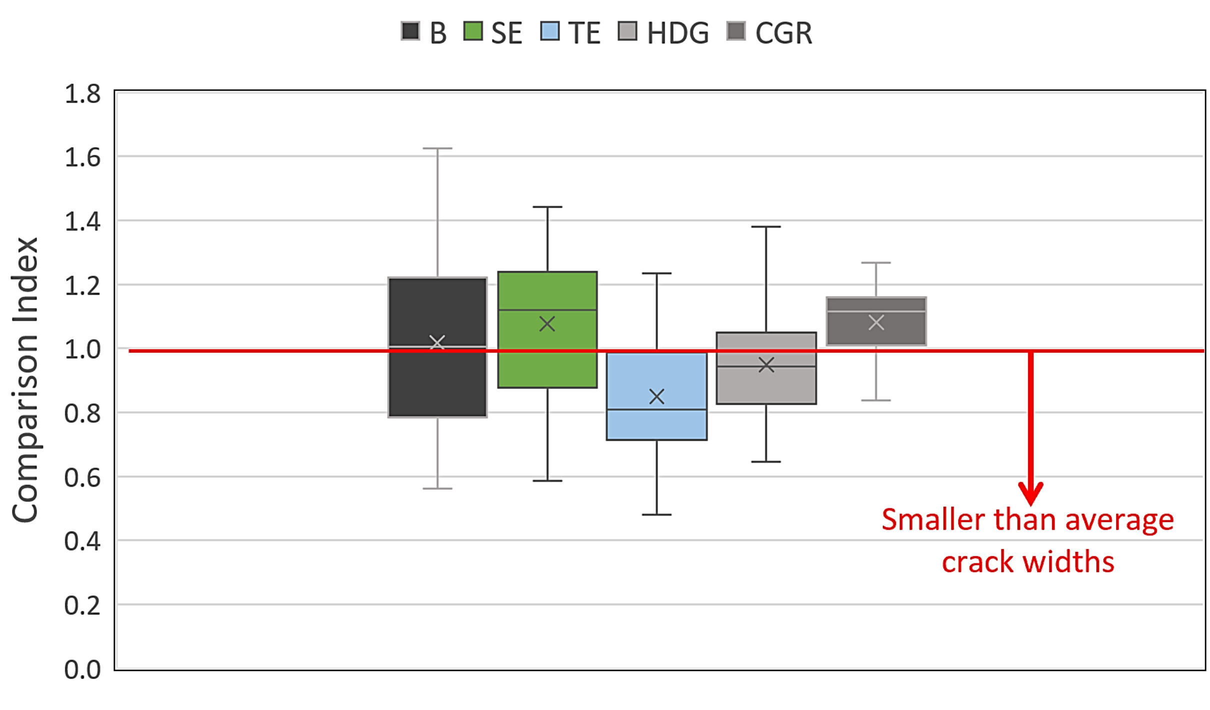


Figure 11 - Comparison index of the average crack width, prepared using the data from image analysis.

The entire "box" for the textured-epoxy specimens falls below 1.0. This means that ¾ of the crack size measurements for textured-epoxy specimens were lower than the average of all bar coating types specimens in comparable tests. The average comparison index for textured-epoxy bars was 0.85, indicating 15% better crack control than the average of all bars. Hot-dipped galvanized specimens had the next best crack control with an average comparison index of 0.95. The black, continuously galvanized, and smooth epoxy-coated bars had average comparison index values of 1.02, 1.08, and 1.08, respectively.

3.6 Reinforcement-Concrete Bond

3.6.1 Test Setup and Procedure

Bond tests were conducted according to the specifications of ASTM A944 [48]. These tests involve pulling a bar that is cast in a concrete block and measuring the level of slip between the bar and concrete. A schematic of the test setup is shown in Figure 12, and a photo is shown in Figure 13. Bar coatings in the test program included uncoated, textured-epoxy, smooth-epoxy, and continuously galvanized. Four series of tests were conducted. The bonded length (see Figure 13) was 6 in. for series one and two and 4 in. for series three and four. The decision to switch to 4 in. bonded length was based on the desire to conduct tests as close to the experimental development length as possible. It was reasoned that the shorter bonded length would result in more slip, which was the primary measure used to compare between the bar types. The concrete used for the blocks was a typical mix used by the South Carolina DOT. The mix design is reported in the Appendix. Concrete cylinders were collected from each batch and used to test compressive strength. Formworks were removed from the specimens approximately one week after casting. As per

ASTM 944, tests were conducted after the concrete reached a minimum of 4500 psi compressive strength.

Load data were collected using a load cell placed between the hydraulic jack and the strand chuck and was checked by a pressure gauge placed in the hydraulic line supplying the jack. Two linear potentiometers were placed at the back of the specimen to measure slip, and two were placed at the front to measure displacement (Figure 13). The average measurement of each potentiometer pair was used to analyze the tests. The linear potentiometers, load cell, and pressure gauge were calibrated immediately prior to testing. Data were continuously monitored and recorded using a computer data acquisition system.

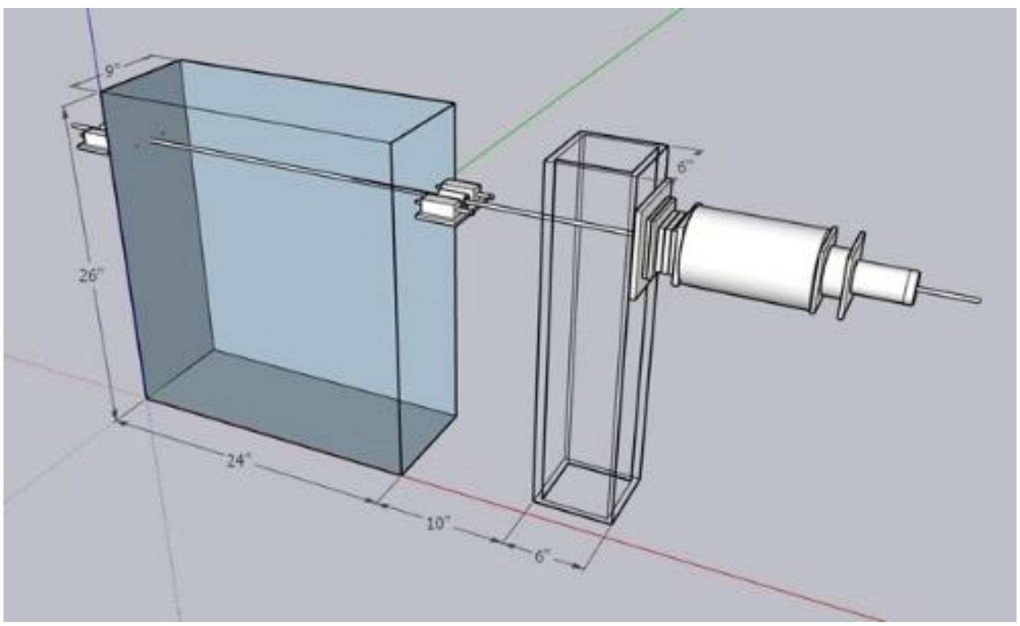


Figure 12 - Bond test schematic set-up.

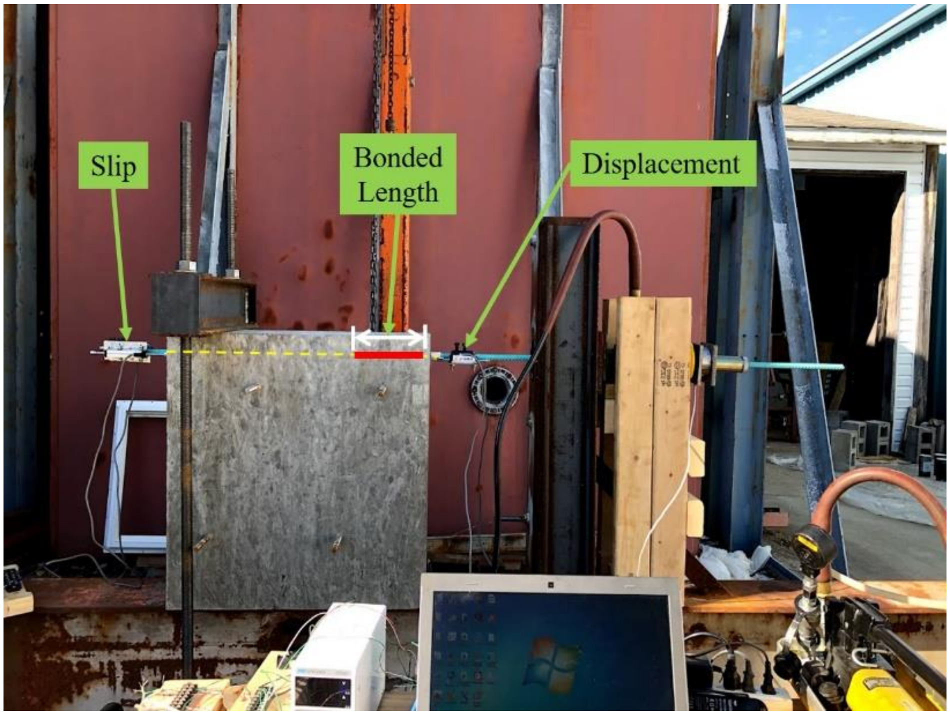


Figure 13 - Bond test set-up.

3.6.2 Test Results

Testing was stopped when a splitting failure occurred in the concrete adjacent to the bonded length (Figure 14) or when it was evident that the reinforcement was well past yielding. Representative load vs. displacement and load vs. slip plots are shown in Figure 15 and Figure 16, respectively. Data in the figures are from series 2. Similar plots for the other series and specimens can be found in the Appendix. From Figure 15, it can be observed that the displacement was approximately linear elastic until the bars yielded.

Series 1 and 2 had a bonded length of 6 in., which was sufficient for all specimens to reach full development. In other words, all bar types were able to support the minimum specified yield stress. The minimum specified yield stress for all bars was 60 ksi, which corresponds to a load of

12 kip. Series 3 and 4 had a bonded length of 4 in. In series 4, the uncoated and smooth-epoxy specimens only reached 11.2 kip and 10.5 kip, respectively.

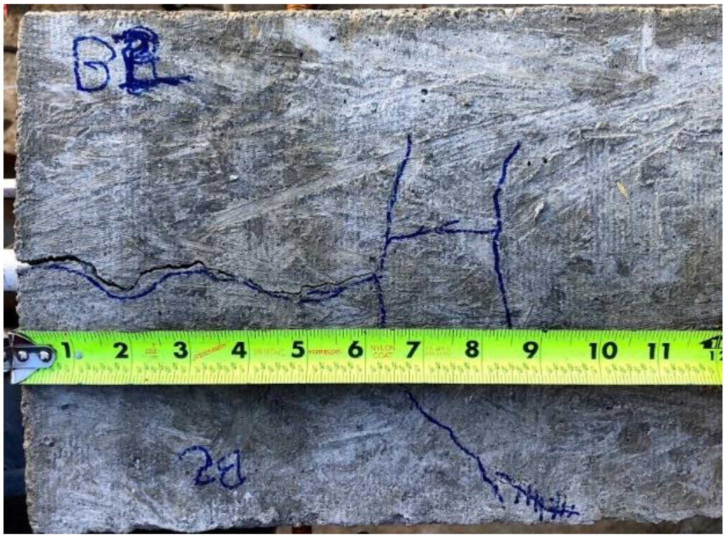


Figure 14 - Splitting failure in the black bar specimen from series 2, which had a bonded length of 6 in.

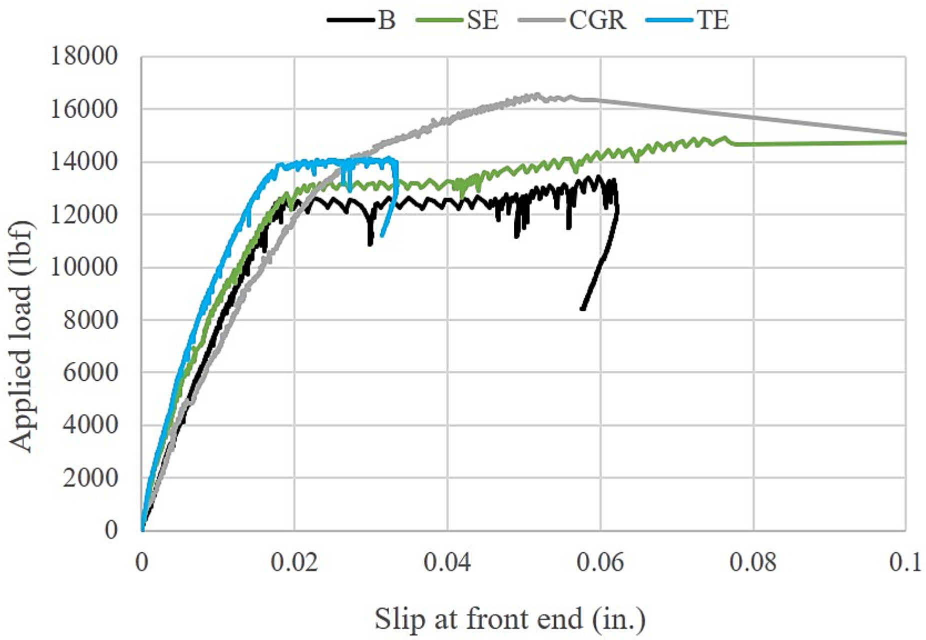


Figure 15 - Load vs. displacement for bond series 1.

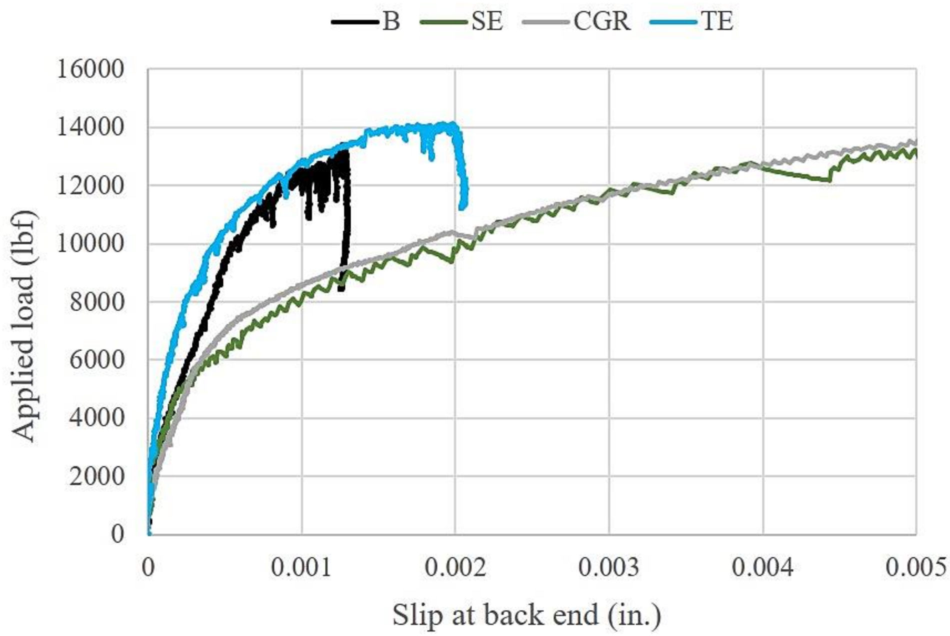


Figure 16 - Load vs. slip for bond series 1.

At a given load level, the displacement measured at the front of the specimen was always greater than the slip measured at the back. This is because the displacement measurement included elongation of the bar. Referring to Figure 16, the amount of slip was small when the load was initially applied. The slip increased significantly as the load approached the specified yield strength of the bar.

Two benchmark stress levels were selected for comparing the slip between specimens with different bar coating types. The first benchmark was 33% of the yield stress, which corresponds to service-level stresses. The second benchmark was 80% of the yield stress, approaching but less than ultimate strength. Comparison index values were calculated for all specimens and are reported in Figure 18. Two trends are noted from the comparison index values. First, textured-epoxy bars had the lowest slip in seven of the eight comparisons. The only exception was the 33% load level in series 4. Second, the smooth-epoxy bars had the most slip in five of eight comparisons. These trends indicate that the textured-epoxy bars have superior bond capacity than the smooth epoxy-coated bars. Furthermore, textured-epoxy bars should not be treated the same as smooth epoxy-coated bars when calculating development length. Additional testing is recommended to confirm this observation and determine the range of roughness properties and concrete strengths for which it is valid.

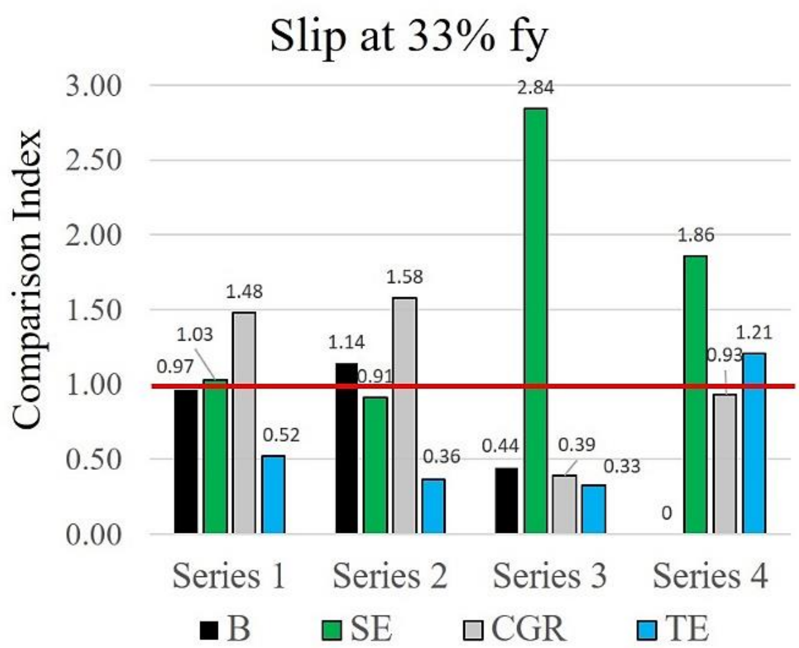


Figure 17 - Comparison index of bar slip at 33% of yield stress

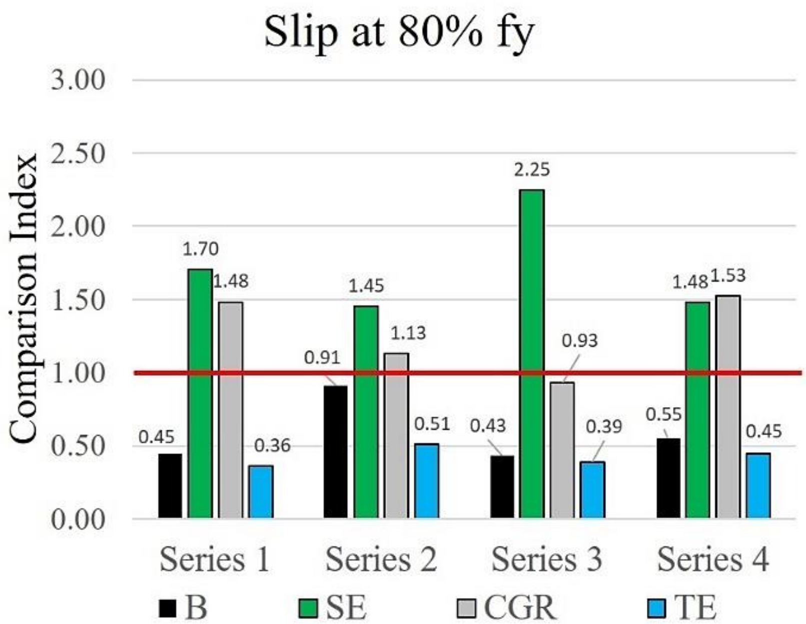


Figure 18 - Comparison index of bar slip at 80% of yield stress

3.7 Static-Load Beams

3.7.1 Test Setup and Procedure

The static load test setup was based on the Peterman Beam Test [49]. The basic concept of the test is a simple-span beam with a load suspended at two points (Figure 19). The specimen cross-section, span length, and load were designed so that the beam would crack extensively but would not reach flexural failure. This setup allowed investigation and documentation of the cracks. Three series of specimens were tested, with each series having one specimen with black, textured-epoxy, smooth-epoxy, and continuously galvanized coated bars. Concrete and steel material properties are reported in the Appendix.

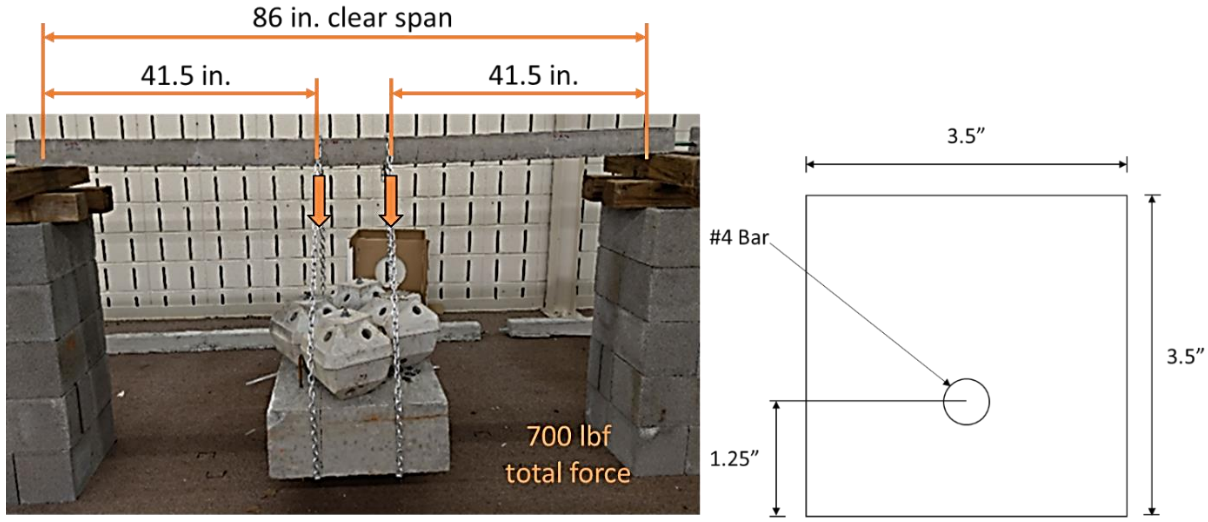


Figure 19 - Static-load test set-up (left) and specimen cross-section (right).

Data collection included measuring beam deflection and documentation of cracks. Digital images of cracks were collected (Figure 20), and the crack quantities, locations, spacings, and lengths were measured. The digital images were analyzed using ImageJ to determine crack length, width, and area. A handheld microscope was used to check a few of the crack width results from ImageJ and were found to be in good agreement. Data were collected immediately, 24-hours, and 7-days after load was applied.

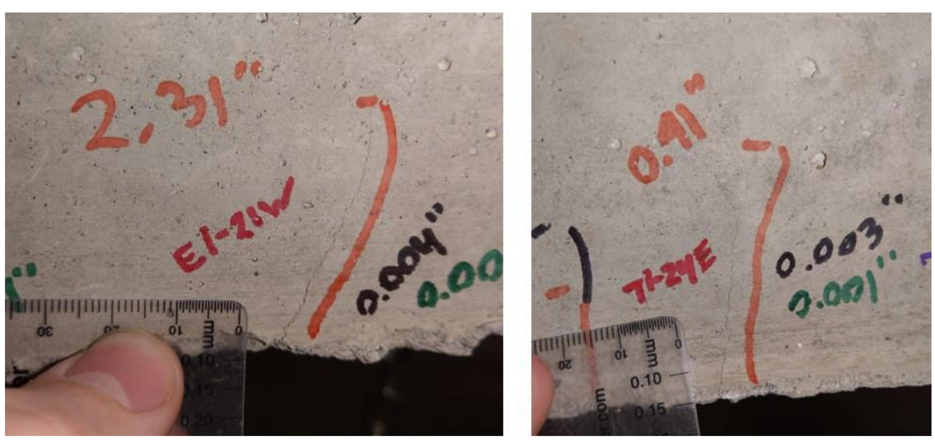


Figure 20 - Sample images of cracks from a smooth epoxy-coated specimen in the first series.

3.7.2 Test Results

No significant changes were observed between the data collected immediately after and in the days following load placement. This is likely due to the maturity of the concrete at the time of testing, as the beams were loaded no sooner than two months after casting. Loading at earlier ages is recommended as future research to evaluate how the different bar coatings interact with the creep and shrinkage of concrete.

Table 5 and Figure 21 presents the comparison index values for each of the specimens and metrics of the static-load test program. The comparison index values were calculated as described in section 3.2 for all metrics except "# Cracks," wherein the comparison index was calculated as the average crack quantity from the series divided by the specimen quantity. This adjustment was made because a greater quantity of cracking – perhaps counterintuitively – indicates a better bond between the bars and concrete. Good bond "spreads" the flexural-tensile strain over the length of the beam so that it is "taken up" by many narrow cracks. Conversely, poor bond results in fewer and wider cracks. An extreme example would be a concrete beam with unbonded reinforcement. A single large crack typically opens in such beams because the unbonded reinforcement can't spread the strain throughout the beam length.

The textured-epoxy bars have the best overall performance, with an average comparison index of 0.90. This means that textured-epoxy coating performed 10% better than the average of all coatings in the test program. The worst performing was smooth epoxy-coated bars which performed 13% worse than the average. Uncoated and continuously galvanized bars were 3% worse and 4% better than average performance, respectively.

Table 5 - Summary of comparison index values for static load test program. Outlier data points are marked with an asterisk*.

Specimen	# Cracks	Avg. Width	Avg. Length	Avg. Spacing	Max Width	Average Comparison Index – Specimen	Average Comparison Index – Coating Type
B1	0.98	1.04	0.98	1.04	1.09	1.03	1.03
B2	1.07	0.89	0.97	0.99	1.08	1.00	
B3	1.48*	0.91	1.07	1.10	0.79*	1.07	
SE1	1.10	1.24	1.11	0.98	1.23	1.13	1.13
SE2	1.18	1.13	1.13	1.26	1.06	1.15	
SE3	0.97	1.20	1.07	1.06	1.20	1.10	
CGR1	1.10	0.87	0.82	1.23	0.94	0.99	0.96
CGR2	1.02	0.95	0.92	0.96	0.84	0.94	
CGR3	0.93	1.03	0.86	0.90	1.01	0.95	
TE1	0.86	0.84	1.10	0.75	0.74	0.86	0.90
TE2	0.80	1.03	0.98	0.80	1.02	0.93	
TE3	0.82	0.86	1.00	0.94	1.00	0.92	

When the reinforcement-concrete bond is weak, fewer cracks appear, but these cracks tend to be wider and longer. The average crack width, average crack length, and maximum average crack width are indicators of cracking severity. The smooth epoxy-coated beams had the highest or nearly the highest comparison index for each of these metrics, indicating the most severe cracking in the test program. Comparisons of crack severity between the black, textured-epoxy, and continuously galvanized bars show mixed results depending on the metric and series.

The textured epoxy-coated specimens had the greatest number of cracks in each series. In contrast, the smooth epoxy-coated bars had the fewest cracks in two of the three series. This result is attributed to superior bond for textured-epoxy bars and relatively poor bond for smooth-epoxy bars. The crack spacing is related to the number of cracks in a beam. If there are fewer cracks, then the spacing between the cracks is larger. The specimens with textured-epoxy bars had the lowest, or near lowest, crack spacing in all series.

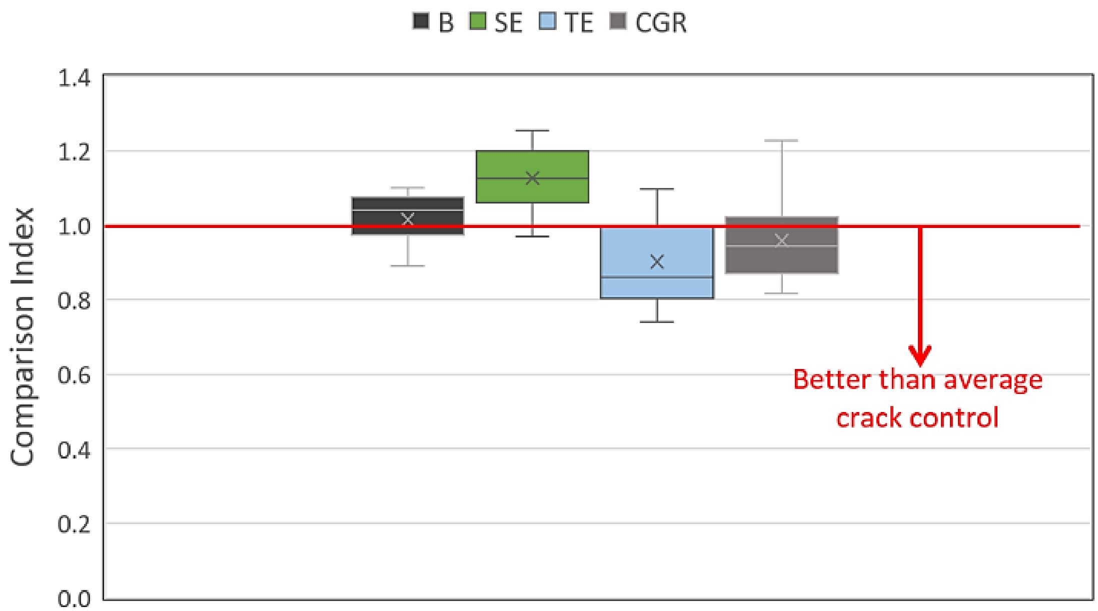


Figure 21 - Comparison index values for static-load cracking tests.

The black bar specimen in series 3 had relatively few cracks resulting in a comparison index of 1.48. This corresponds to large crack spacings and an 0.79 comparison index for maximum width. These are the only outliers in the data from the static load beam tests and are attributed to the randomness of concrete cracking. The outlier data points are not shown in Figure 20. Because of the randomness, caution is warranted when making conclusions from any one data point. An analysis of the data across all metrics and specimens provides a better picture of how the different coatings impacted bond and cracking. Additional details and discussion of the static-load test program can be found in the conference paper and thesis by Murphy [50, 51].

3.8 Short Beams

3.8.1 Test Setup and Procedure

"Short" beam specimens were 36-in. long and used the same cross-section as the static-load specimens (Figure 22). A "crack initiator" was placed between the bottom of the beam and the bar at midspan to intentionally weaken the beam and force a crack to occur at a known location. In this manner, a sensor could be positioned at the crack location to measure the growth of the crack as the load was applied. The crack initiator also served as a support for the bar to ensure it was at the designed depth.

Three series of short beams were cast. Each series had one specimen with black, smooth epoxy-coated, textured epoxy-coated, and continuously galvanized bars. The short beams were cast at the same time, and from the same concrete batches as the bond and static-load specimens. Details of the mix design and concrete strength are in the report Appendix.

The beams were tested in a universal testing machine where the applied load and crack growth were simultaneously monitored.

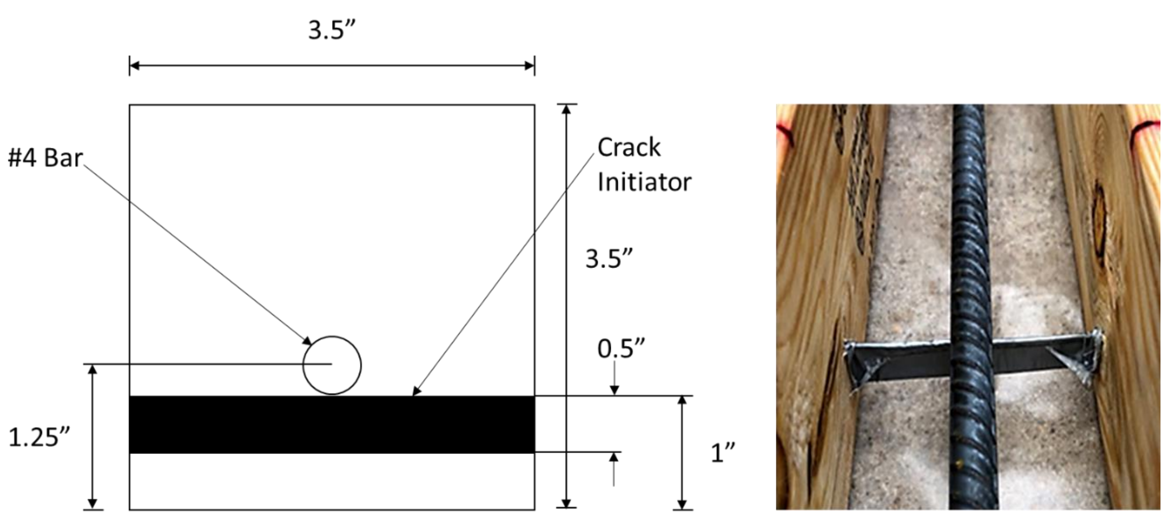


Figure 22 – Section and details of short beam specimens.

Figure 23 shows the free-body diagram of the test setup. Linear potentiometers (LP) were used at the center of the beam to measure crack displacement. The woodblocks used to mount the LP had consistent dimensions for each test specimen. This ensured comparable crack opening data across tests. The overall setup for the test is shown in Figure 24. The setup of the linear potentiometers is shown in Figure 25.

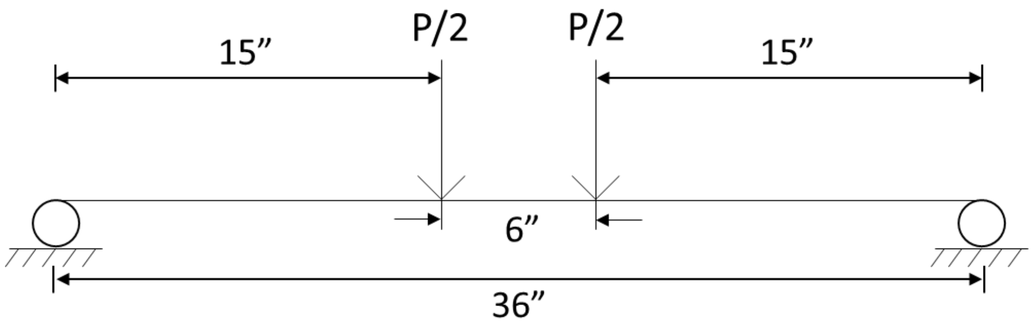


Figure 23 - Free Body Diagram of the test set-up.

Figure 24 - Short beam test set-up.

Figure 25 - Linear potentiometer set-up using woodblocks.

3.8.2 Test Results

Load vs. crack opening responses are shown in Figure 26 for the beams in series 2. Similar plots for the other series can be found in the Appendix. The figure shows the beam behavior under small loads, which are of particular interest because they reflect service level conditions. For reference, an applied load of 1000 lbf results in calculated bar stress of 20 ksi.

The average comparison index was calculated for each specimen and series using crack opening measurements at 500 lbf, 750 lbf and 1000 lbf (Table 6.) The values have been adjusted to account for subtle differences in the modulus of elasticity of the bars. Tested MOE values of the bars are reported in the Appendix. Uncoated bar specimens showed the best performance having crack widths 19% less than the average of the other specimens. Textured-epoxy and Smooth-epoxy specimens showed the worst performance having crack width 6% and 14% more than the average, respectively. Continuously galvanized bars performed at approximately the test program average.

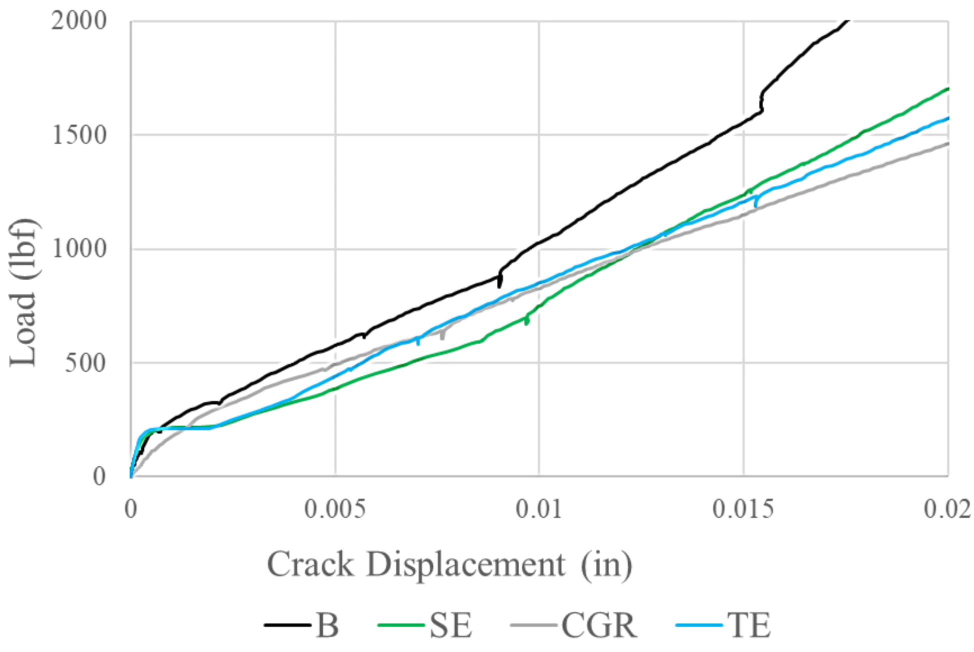


Figure 26 - Load vs displacement from series 2.

Table 6 - Summary of comparison index values for short beam test program.

Specimen	Crack Displacement at 500 lb.	Crack Displacement at 750 lb.	Crack Displacement at 1000 lb.	Average Comparison Index - Specimen	Average Comparison Index - Bar Type
B1	0.75	0.83	0.84	0.81	0.81
B2	0.91	0.97	1.06	0.98	
B3	0.59	0.65	0.71	0.65	
SE1	1.25	1.14	1.04	1.15	1.13
SE2	1.11	1.07	0.98	1.06	
SE3	1.18	1.22	1.18	1.20	
CGR1	0.97	1.04	1.09	1.03	1.01
CGR2	1.14	1.09	1.08	1.10	
CGR3	0.91	0.91	0.85	0.89	
TE1	1.04	0.99	1.03	1.02	1.04
TE2	0.85	0.88	0.88	0.87	
TE3	1.31	1.20	1.23	1.25	

3.9 Cyclic Load

3.9.1 Test Setup and Procedure

Three specimens were loaded to 1,000,000 cycles to evaluate the response of beams with alternative rebar coatings to cyclic loading. The specimens had either smooth-epoxy, textured-epoxy, or hot-dipped galvanized coatings. The specimen cross-section (Figure 27) and loading scheme were intended to approximate a segment of the concrete bridge deck. All specimens were cast from the same concrete batch, which had a 28-day average concrete strength is 5140 psi. The mix design was the same as that used in the other test programs. Specimen geometry and boundary conditions are shown in Figure 27.

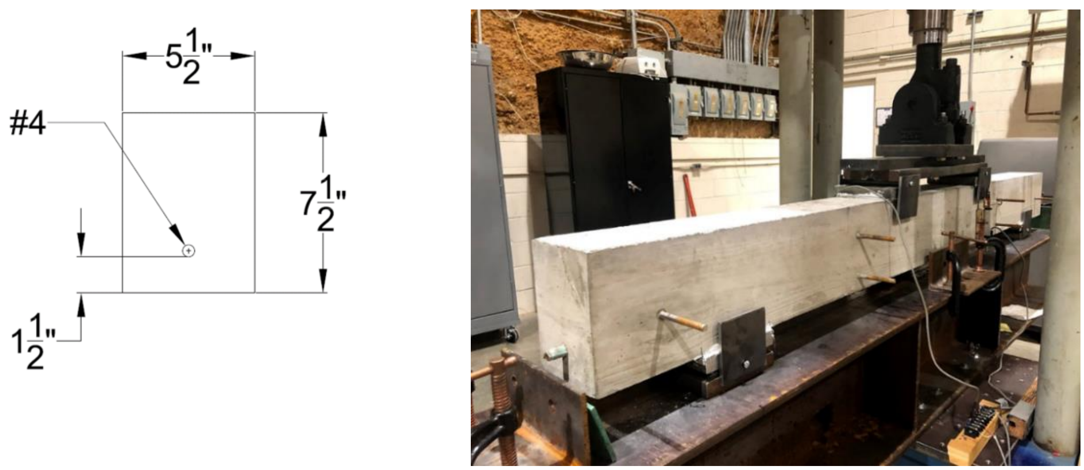


Figure 27 - Cyclic load test specimen cross-section (left) test setup (right).

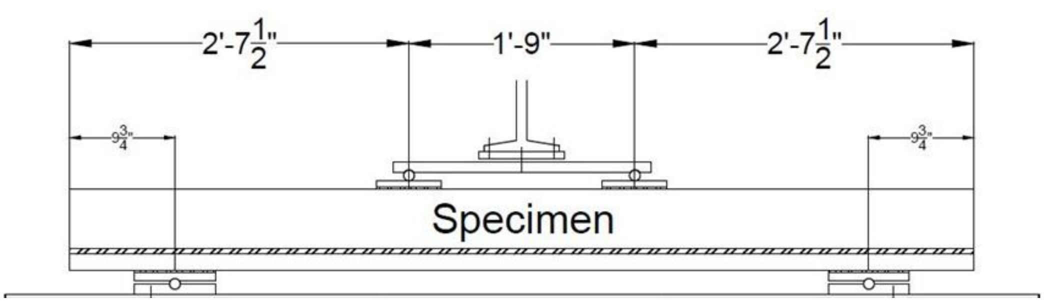


Figure 28 - Cyclic load test geometry.

Testing was conducted using an actuator regulated by a servo valve and hydraulic pump. Testing commenced with a monotonic test to 4.5 kips to produce flexural cracking. With the specimens cracked, the remainder of the testing was completed using load-controlled cycles as shown in Figure 28. Each cycle ranged from 1 kip to 3 kip at a frequency of 2 Hz. This load range corresponds to calculated bar stresses of 11 to 33 ksi.

Load and displacement data were collected during "measurement cycles" after each order of magnitude (1, 10, 100, …) of load cycles. Data were also collected after 500,000 cycles. The measurement cycles consisted of ten cycles from 1 kip to 3.0 kips at a frequency of 0.2 Hz. The unloaded displacement was measured and recorded at the end of each measurement cycle.

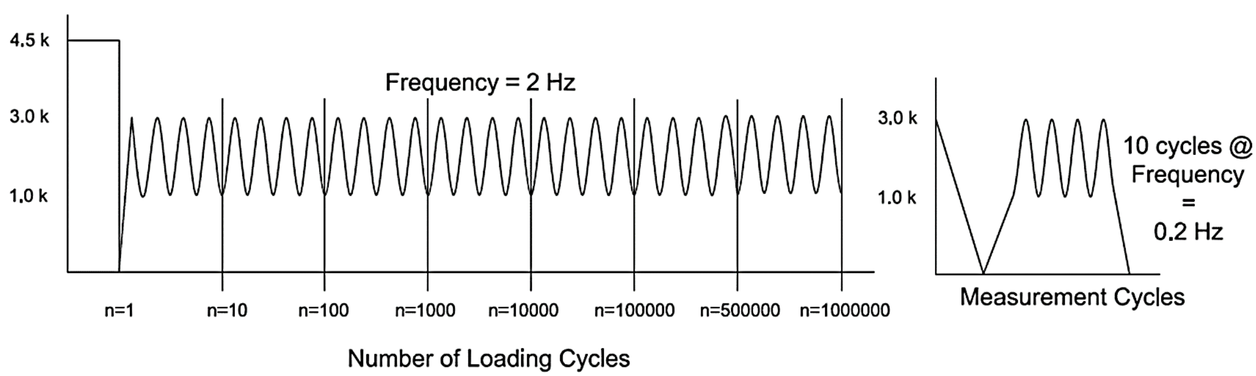


Figure 29 - Cyclic-loading protocol (left) and measure cycle protocol (right).

3.9.5 Test Results

A reduction in the stiffness over one million cycles was observed in each specimen as shown in Figure 30. Data in the figure are normalized by the initial pre-cracked stiffness. The drop in stiffness between the first and tenth cycles reflects the change in stiffness after cracking. The stiffness of the textured-epoxy and smooth epoxy-coated specimens showed a slight increase between cycles 10 and 1000. This result is perplexing, and no satisfying explanation can be given. The trend was not observed in the specimen with the hot-dipped galvanized bar. It is possible that the result is due to errors in the instrumentation or test set-up; however, calibration of instruments before and after testing lends confidence to the overall trend of stiffness reduction at higher numbers of load cycles.

Stiffness of all specimens decreased between 10,000 and 1,000,000 cycles. The textured-epoxy specimen maintained a stiffness closest to its pre-cracked condition, while the smooth-epoxy specimen indicated stiffness loss.

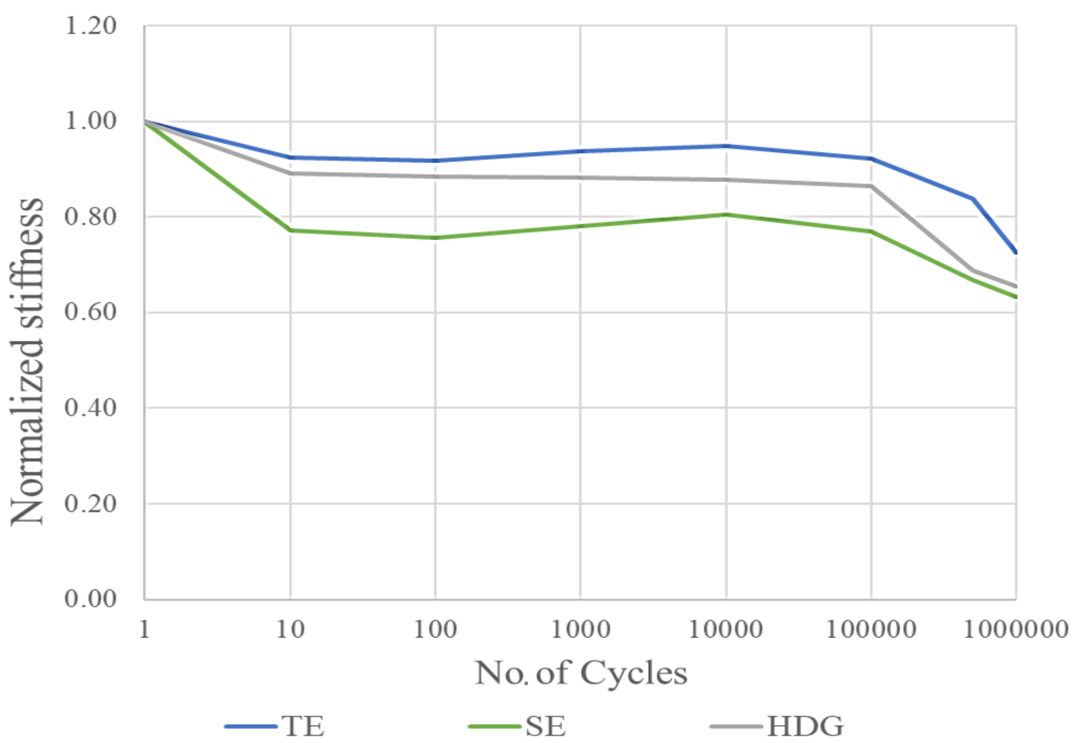


Figure 30 - Stiffness variation as a function of load cycles.

Unloaded displacement is compared for the specimens Figure 31. Data for each specimen are normalized to the unloaded displacement after the cracking stage and before the first ten cycles. Hence, the normalization is relative to the displacement of the beams after they had cracked. The post-cracking displacements used for normalization were 0.012 in. for textured-epoxy, 0.028 in. for smooth-epoxy, and 0.012 in. for hot-dipped galvanized.

The unloaded displacement grew 60% to 80% over the cycles indicating damage due to the loading. Similar to the trends observed in stiffness, the changes in displacement were also most notable after 10,000 cycles. At the end of all cycles, the absolute unloaded displacement was 0.021 in. for textured-epoxy, 0.046 in. for smooth-epoxy, and 0.022 in. for hot-dipped galvanized. The beams with textured-epoxy and hot-dipped galvanized coated bars had higher percent change but lower total displacement than the beam with the smooth epoxy-coated bar.

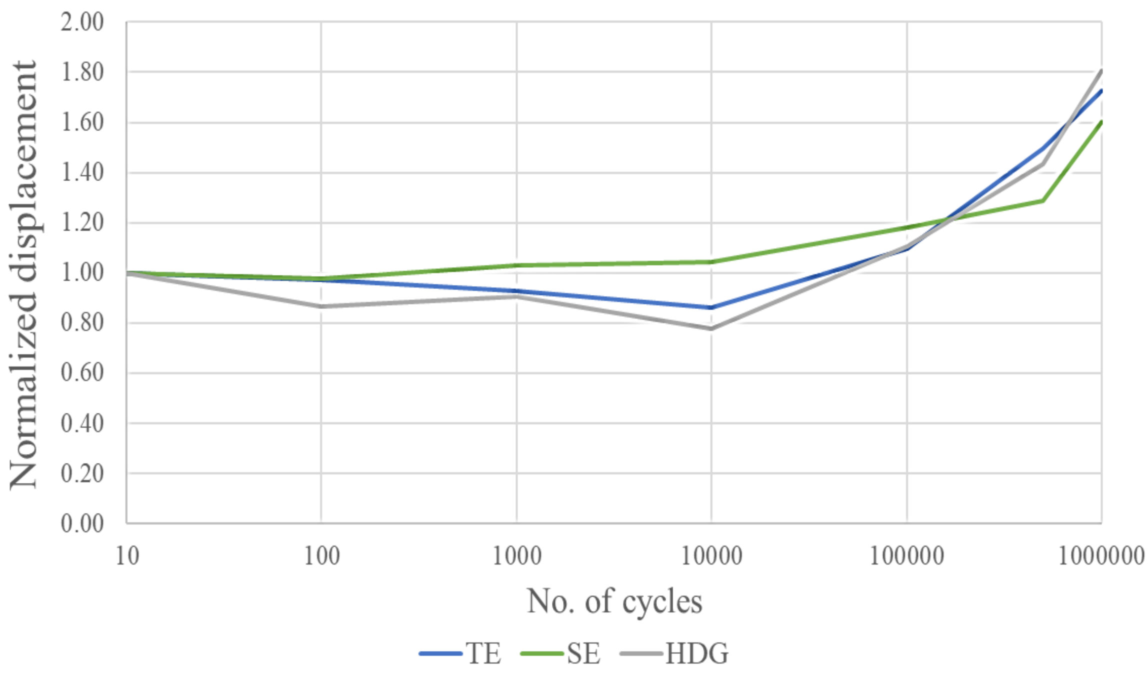


Figure 31 - Initial displacement values (normalized) at the data collection stages.

Firm conclusions cannot be reached based on only three specimens. All the specimens exhibited similar trends in their loss of stiffness and unloaded displacements. Changes were most significant after 10,000 load cycles. Additional testing is needed to determine if the similarities remain consistent and to compare the magnitudes of the changes observed between beams with different bar types. Because of the inherent variability in concrete cracking and bond and the subtlety of the measurements, follow-up testing should include replicate specimens with each bar type. Consistency (or lack thereof) among the replicates would lend greater confidence to comparisons between specimens with different bar types.

3.10 Synthesis of Results

Figure 32 synthesizes results from the reinforcement-concrete bond, static-load, and short beam programs. These programs represent ten series, 40 specimens, and 128 measurements. The figure is based on the comparison index values from all 128 measurements; it provides an overall view of how each coating type maintained concrete bond and controlled load-induced cracks.

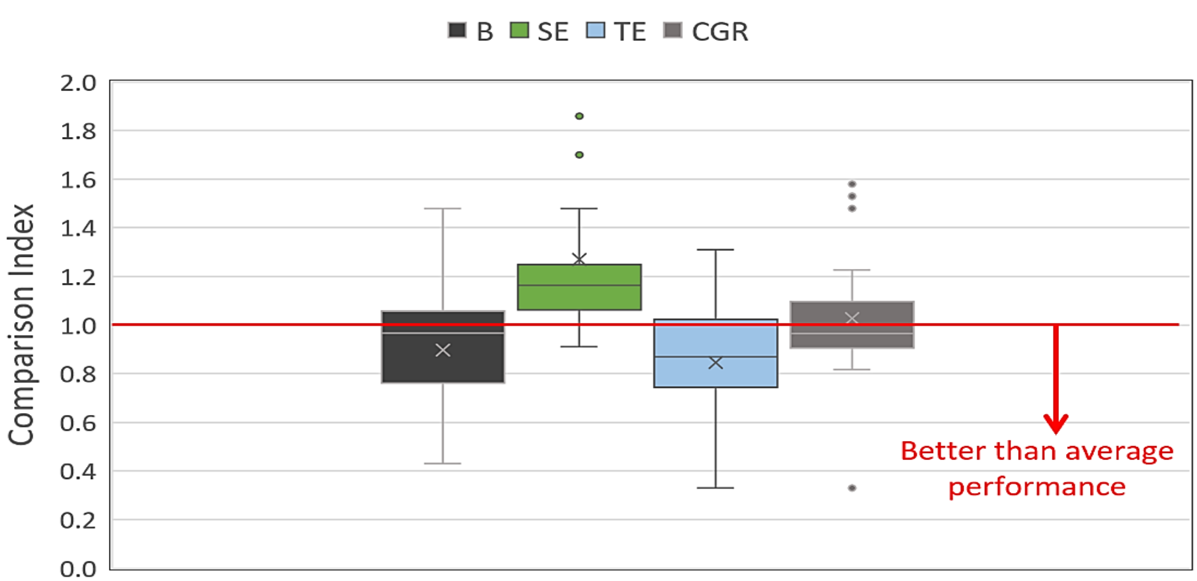


Figure 32 - Synthesis of results for bond, static load, and small beam test programs.

It is clear from Figure 32, that the uncoated and textured epoxy-coated bars performed better than the smooth epoxy-coated bars. The inner-quartile ranges (box in the figure) do not intersect with the textured epoxy-coated range. The continuously galvanized reinforcement also performed better than the smooth epoxy-coated bars, however, the trend is not as strong. The average comparison index for each coating type (‘X’ in the figure) was 0.90, 1.27, 0.85, and 1.03 for uncoated, smooth-epoxy, textured-epoxy, and continuously galvanized bars, respectively.

Data from the shrinkage cracking test program were previously synthesized and discussed in section 3.5.2 and Figure 11. A few comments are made relative to the synthesized results presented in Figure 11 and Figure 31. First, the textured-epoxy bars had the lowest comparison index in the load tests (0.85) and shrinkage tests (0.85). Smooth-epoxy bars had the worst performance of all the coating types in the load tests (1.27) and shrinkage cracking tests (1.08). Notably, the continuously galvanized bars performed at the same level or better than smooth-epoxy bars.

CHAPTER 4: FIELD STUDIES

The alternative reinforcement coatings were implemented in a newly constructed bridge on I-39 near Madison, Wisconsin. The bridge identification number is B-13-729. The bridge is a 143-ft single-span supported by eight precast-pretensioned concrete girders. Both the girders and deck were used in the field studies. A cross-section is shown in Figure 33.

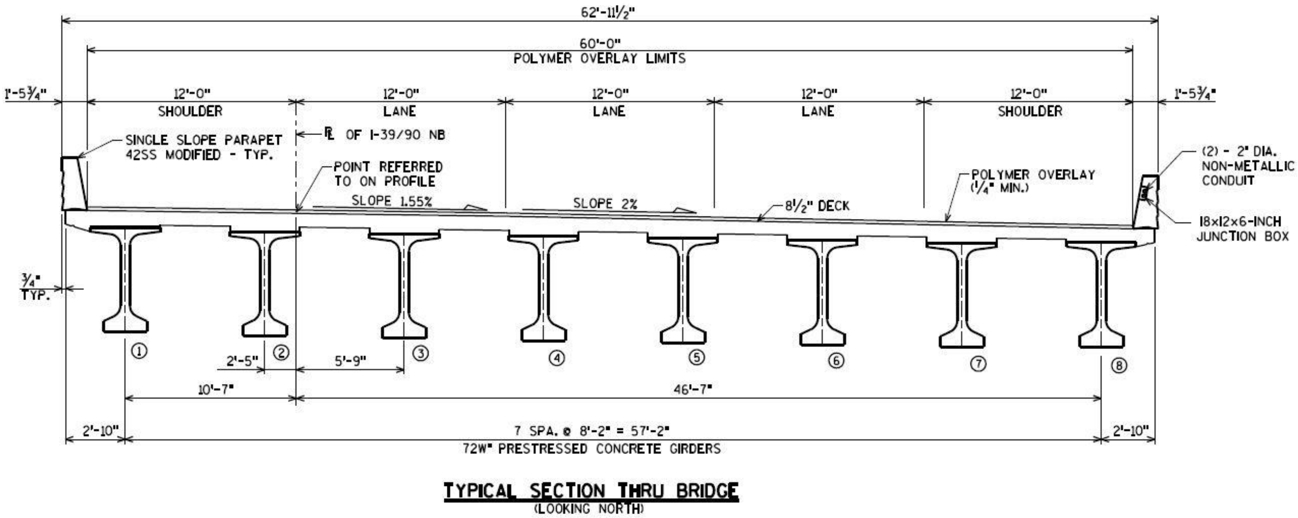


Figure 33 - Cross-section of the bridge showing the girders and deck.

4.1 Bridge Deck

4.1.2 Deck Design and Construction

The concrete deck was 8.5 in. thick (not including haunches) and was cast on October 7th, 2020. It was reinforced with top and bottom mats with #5 bars transverse at 8.5 in. spacing and with #4 bars longitudinal at 4.5 in spacing. The deck was covered and cured for 26 days. Details of the mix design and weather conditions during casting are given in the Appendix.

Typical deck reinforcement in Wisconsin consists of smooth epoxy-coated bars. The southern half of the field study bridge deck was reinforced with textured epoxy-coated bars and the northern half with hot-dipped galvanized bars (Figure 34). The alternative bars were used in both directions in the top and bottom mats (Figure 35).

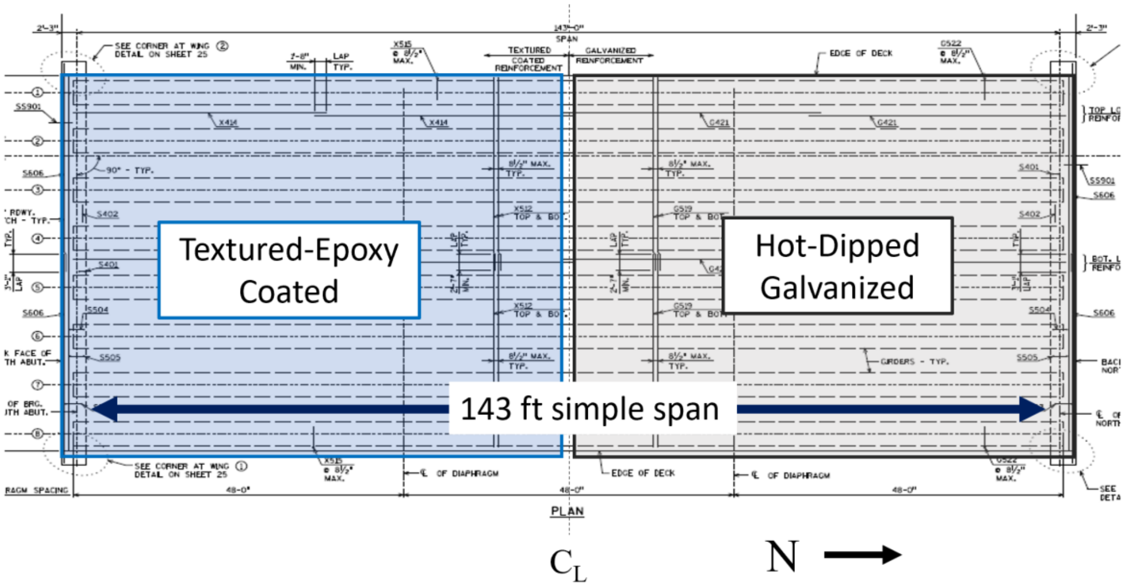


Figure 34 - Placement of textured epoxy-coated and hot-dipped galvanized bars in the deck.

Figure 35 - Photo of the deck before casting concrete (looking east).

4.1.3 Site visits

Two site visits were made to the bridge deck to assess the deck condition and look for cracks. The first visit was made on November 2, 2020, the day the curing cover was removed. The second visit was made on March 7, 2021. This date was chosen because the bridge was free of snow and dirt and because the polymer overlay had not yet been placed. The original intent of the research was to compare the cracking between the portions having textured-epoxy and hot-dipped galvanized bars, however, no cracks were observed in the deck. The top of the deck was visually assessed by walking the deck area and the underside of the deck was visually assessed from the ground level below the bridge at the abutments.

An informal evaluation was also made by the bridge contractor in June 2021, nine months after the deck was cast. No cracking was observed. The absence of cracks in the deck is attributed to high-quality concrete material and effective curing practices. This result is desirable for the long-term durability of the deck but does not provide a means of comparing the crack-control performance of the alternative bars. Follow-up visits to the bridge are recommended to compare the long-term performance of the deck portions with textured-epoxy and hot-dipped galvanized bars. Future visits should include assessment of concrete cracking, and perhaps more importantly, the presence and extent of bar corrosion.

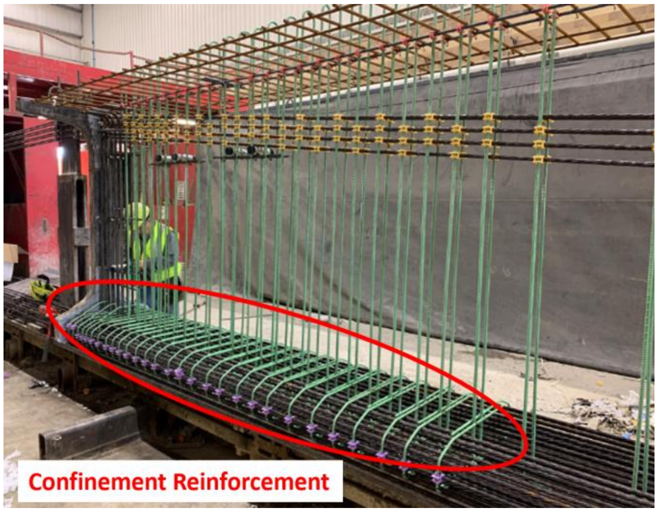
4.2 Girder End Regions

4.2.1 Girder Construction and Data Collection

The eight girders for the field study were prefabricated at the County Materials facility in Janesville, WI. Girders had the 72W cross-section. Detailed drawings of the prestressing and reinforcement are provided in the Appendix. Details of the concrete mix design are also in the Appendix. All the girders were constructed in July 2020.

The primary goal of the girder end region field study was to compare cracking between girders having different bar coatings on the confinement reinforcement (Figure 36). Smooth epoxy-coated bars are currently used for confinement reinforcement in Wisconsin. Each end of the study girder had either smooth epoxy-coated, textured epoxy-coated or hot-dipped galvanized bars confinement reinforcement (Figure 36). As girders were cast two at a time on the stressing bed, a secondary goal was to determine if bed location impact cracking. End of bed and interior of bed positions were considered.

Close-up digital images were taken of each crack for processing in ImageJ. For the cracks to form and stabilize, photos were collected immediately after form removal, a few hours after form removal, and one week after prestressing was released into the girders. A few representative crack photos are included in the Appendix. All photos and measurements are for the cracks on the girder ends.



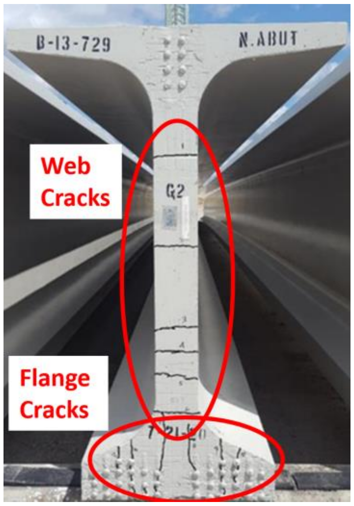


Figure 36 - Girder reinforcement prior to casting concrete (left) and representative end cracking (right).

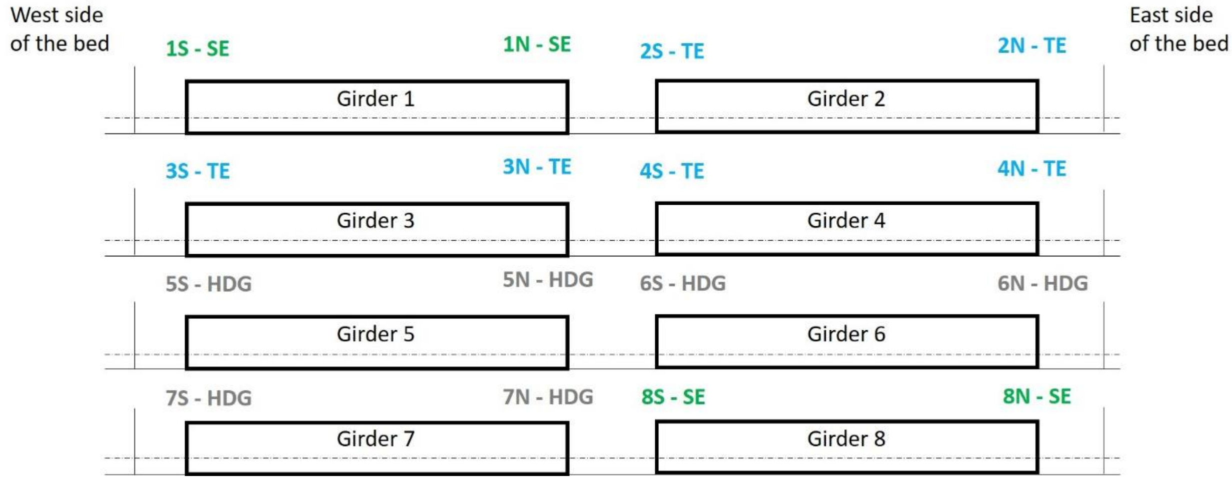


Figure 37 - Location of girders and bar coating types on stressing bed.

4.2.3 Evaluation of end cracks

Figure 38 compares end cracks in the web and flange according to the different bar coatings for the confinement reinforcement. The figure shows the comparison index values; absolute crack sizes are reported in the Appendix. Girder ends with textured epoxy-coated bars tended to have smaller than average crack widths in the bottom flange and larger than average crack widths in the web. One possible explanation is that improved crack control from the textured-epoxy confinement bars allowed the prestressing force to transfer over a shorter length, which in turn led to higher splitting stresses and crack widths in the web. Additional work is required to determine the validity of this explanation. It is also possible that using textured-epoxy bars as splitting reinforcement at girder ends would be effective at controlling end cracks in the web.

Figure 39 compares the cracks based on the location of the girder end in the stressing bed. No discernable difference can be observed in the crack widths based on stressing bed location.

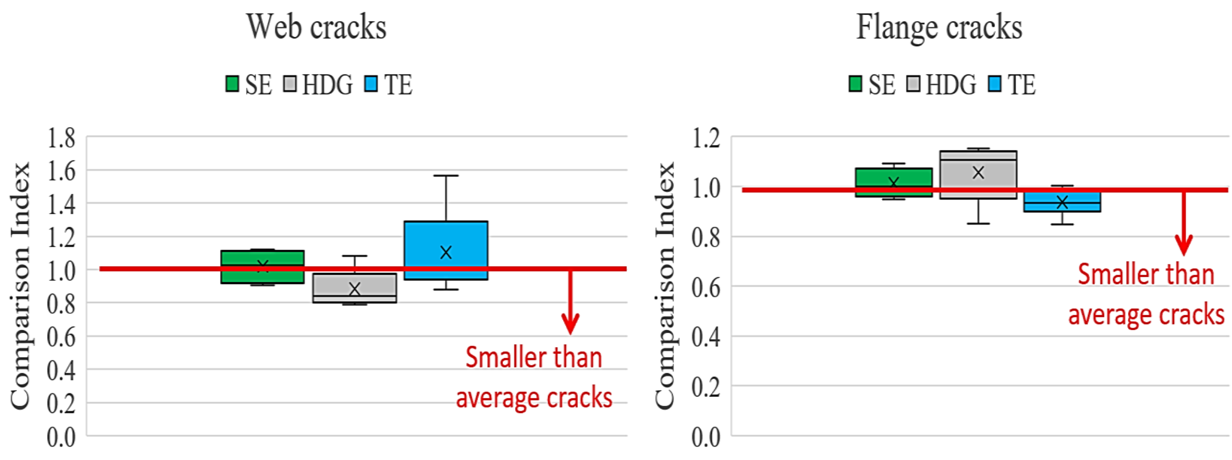


Figure 38 - Crack widths at girder ends with different confinement bar coatings.

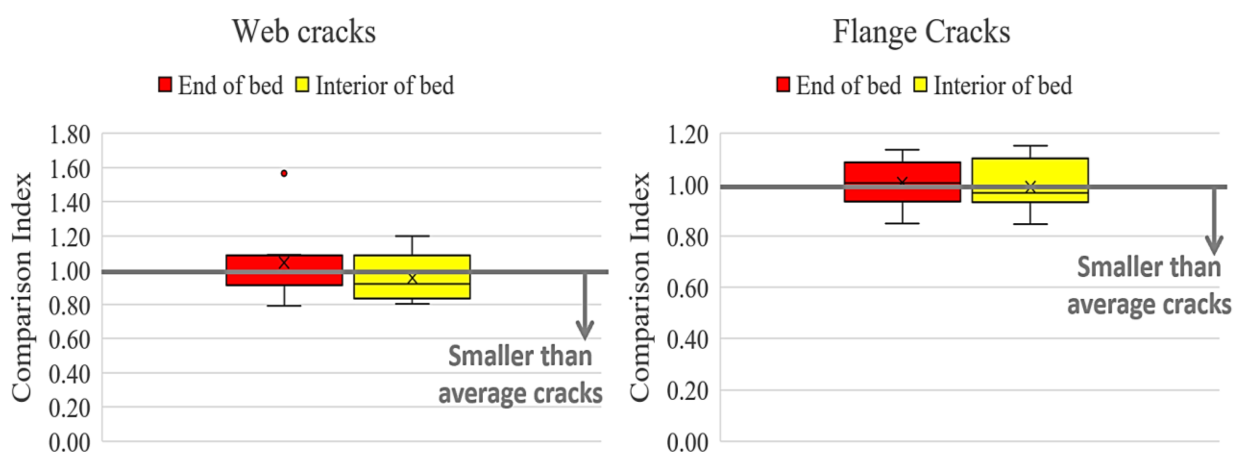


Figure 39 - Crack widths at girder ends based on stressing bed position.

CHAPTER 6: CONCLUSIONS AND KEY OBSERVATIONS

Lab Tests

- Textured epoxy-coated bars demonstrated the best performance of any coating type in the lab tests. Their overall performance was 15% better than the average of all coating types.
- Smooth epoxy-coated bars had the worst performance in the lab tests. Overall, they were 27% and 8% worse than the average of all coating types in load tests and shrinkage tests, respectively.
- The performance of the continuously galvanized bars was similar to the smooth-epoxy bars in shrinkage tests and better in load tests. Overall, continuously galvanized bars were 3% and 8% worse than the average of all coating types in load tests and shrinkage tests, respectively.
- Relative to the average performance of all coating types, uncoated bar performance was 10% better and 2% worse in load tests and shrinkage tests, respectively.
- Hot-dipped galvanized bars were only used in the cyclic-load and shrinkage test programs. They performed 5% better than the average of all coating types in the shrinkage tests.
- The hot-dipped galvanized, textured-epoxy, and smooth-epoxy bars showed similar behavior in cyclic-load tests. Damage in all specimens was observed after 10,000 cycles and continued until the tests stopped at 1,000,000 cycles. Additional tests are needed to evaluate the performance differences between bar coating types under cyclic loading.

Field Tests

- The cast-in-place concrete deck did not crack during the research project. This is a desirable outcome for WisDOT; however, it does not allow a comparison of crack control between the deck portions with textured-epoxy and hot-dipped galvanized bars.
- In the precast-pretensioned girder field study, no relationship was observed between end cracking and placement on the stressing bed. The type of coating on the confinement reinforcement appeared to impact the width of end cracks in the flange and web. Most notable were the girders with textured epoxy-coated confinement reinforcement; flange cracks were narrower, and web cracks were wider in these specimens.

CHAPTER 6: RECOMMENDATIONS

- Textured-epoxy and hot-dipped galvanized bars provided superior performance in laboratory tests relative to the smooth-epoxy bars. Textured epoxy-coated and hot-dipped galvanized bars are recommended as alternatives for reinforcement in concrete bridge decks.
- Continuously galvanized bars' performance in lab tests was the same as or better than the smooth-epoxy bars. Continuously galvanized should receive consideration as an alternative reinforcement for concrete bridge decks.
- Laboratory and field tests should be conducted to compare alternative bar coatings' corrosion mitigation effects and life-cycle costs. These topics are beyond the scope of the current project; however, they are essential criteria for selecting reinforcement coatings.
- The use of textured epoxy-coated and galvanized hot-dipped galvanized bars as confinement reinforcement in precast concrete girders is neither encouraged nor discouraged. These alternative bars did not provide consistent advantages or disadvantages in the field of concrete cracking study.
- Future visits should be made to the case study bridge to evaluate the long-term performance of the textured-epoxy and hot-dipped galvanized deck reinforcement. Such visits should evaluate crack control and the extent of and rebar corrosion.

ACKNOWLEDGMENTS

The research team grateful acknowledged the contributions made to research by numerous individuals and organizations. Clemson students Aaron Murphy, Khalil Goodman, Pushkar Rathod, Sam Dodd, Grace Crocker, Brianna Crabtree, Delaney McFarland, Rumi Shresta, Pawan Acharya Lancelot Reres, and Bibek Bharadwaj assisted with either building formwork, casting concrete, or testing specimens. Aaron Murphy also took the lead on static-load and short beam test programs. Test fixtures were fabricated with the assistance of technicians Scott Black and Danny Metz. Materials for the test specimens were donated by Sherwin-Williams and AZZ. Roughness measurements were made at the National Brick Research Center with the help of Nathaniel Huygen and John Sanders.

Precast concrete girders for the field study were fabricated at the County Materials facility in Janesville, WI. County Materials welcomed members of the research team to their facility and provided timely information to enable the research. Dr. Todd Davis of the Milwaukee School of Engineering assisted with data collection for the girder field study. Dr. Taylor Sorensen, formerly with Clemson University and now with Brigham Young University, assisted with ImageJ processing of the girder data.

The bridge deck field study benefited from an amazing team of engineering and construction personnel. Jim Grender of CGC inc, Dustin Hunt of HNTB, Joe Jirsa of KL Engineering, Mary Gehrke of CGC inc, and Michelle Howe of AECOM provided construction, welcomed the research team to the bridge site, and were quick to return emails. They fully supported the research team and never made us feel that we were in their way. The crack-free bridge deck in the field is a testament to their professionalism and attention to detail.

Personnel at the Wisconsin Highway Research Program and Wisconsin Department of Transportation were well organized, kept the research informed of deadlines, and smoothly handled project logistics. The efforts of Dr. Dante Fratta, Jamie Valentine, Sabrina Bradshaw, Ethan Severson, and Heidi Noble are noted and appreciated.

Finally, the project received guidance from the Technical Oversight Committee and Project Oversight Committee. Dave Kiekbusch chaired both committees. We wish Dave enjoyment in his rapidly approaching retirement. Other members of these committees included: Dr. Michael Oliva, James Luebke, James Parry, and William Oliva.

REFERENCES

1. Transportation, Research Board and National Academies of Sciences, Engineering, and Medicine. 2017. *Control of Concrete Cracking in Bridges*, edited by Henry G. Russell. Washington, DC: The National Academies Press. doi:10.17226/24689.
2. Udaipurwala, A., Poursaee, A., and Schiff, S.D., 2015. "Corrosion Activity in Precast Concrete Elements and Cementitious Closure Pours." *Journal of Bridge Engineering* 20 (12): 04015013. doi:10.1061/(ASCE)BE.1943-5592.0000757.
3. Williamson, G., Weyers, R.E., Brown, M.C., and Sprinkel, M.M., 2007. *Bridge Deck Service Life Prediction and Costs*, edited by Virginia Transportation Research Council, Virginia. Dept. of Transportation.
4. Aboalarab, L., "The Effect of Crack Opening Size and Repair Methods on Corrosion of Steel Reinforcement in Concrete" (2019). *Clemson University Dissertations*. 2397.
5. Foley, C.M., Wan, B., and Komp, J., 2010. *Concrete Cracking in New Bridge Decks and Overlays*: Wisconsin Highway Research Program.
6. Issa, M.A., 1999. "Investigation of Cracking in Concrete Bridge Decks at Early Ages." *Journal of Bridge Engineering* 4 (2): 116-124. doi:10.1061/(ASCE)1084-0702(1999)4:2(116).
7. Schmitt, T.R., and Darwin, D., "Cracking in Concrete Bridge Decks," SM Report No. 39, University of Kansas Center for Research, Inc., Lawrence, KS, April 1995, 164 pp.
8. Krauss, P.D., and Rogalla, E.A., 1996. *Transverse cracking in newly constructed bridge decks.* NCHRP Rep. No. 380. Washington, DC: Transportation Research Board, National Research Council.

9. Lindquist, W.D., Darwin, D., Browning, J.P., and Miller, G.G., "Effect of Cracking on Chloride Content in Concrete Bridge Decks," ACI Materials Journal, Vol. 103, No. 6, November-December 2006, pp. 467-473.

10. Darwin, D., Khajehdehi, R., Alhmood, A., Feng, M., Lafikes, J., Ibrahim, E.K., and O'Reilly, M., "Construction of Crack-Free Bridge Decks: Final Report, " SM Report No. 121, The University of Kansas Center for Research, Inc., Lawrence, KS, December 2016, 160 pp.

11. Hadidi, R., and Saadeghvaziri, M.A., 2005. "Transverse Cracking of Concrete Bridge Decks: State-of-the-Art." *Journal of Bridge Engineering* 10 (5): 503-510. doi:10.1061/(ASCE)1084-0702(2005)10:5(503).

12. Bektaş, B., Albughdadi, A., Freeseman, K., and Bazargani, B., 2020. *Protocols for Concrete Bridge Deck Protections and Treatments*: Wisconsin Department of Transportation.

13. Aboalarab, L., Ross, B.E., and Poursaee, A., 2020. "The Impact of Repair Method on the Chloride-Induced Corrosion of Steel Embedded in Cracked Concrete." *Advances in Civil Engineering Materials; Advances in Civil Engineering Materials* 9 (1): 143-151. doi:10.1520/ACEM20190200.

14. Corrosion Protection Performance of. 2008. *2008-47* Minnesota Department of Transportation. http://digital.library.wisc.edu/1793/54130

15. Frosch, R. J., Gutierrez, S., and Hoffman, J.S., *Control and Repair of Bridge Deck Cracking*. Publication FHWA/IN/JTRP-2010/04. Joint Transportation Research Program, Indiana Department of Transportation and Purdue University, West Lafayette, Indiana, 2010. https://doi.org/10.5703/1288284314267

16. Bales, E.R., Chitrapu, V., and Flint, M.M., 2018. *Bridge Service Life Design*, edited by Virginia Polytechnic Institute and State University. Charles E. Via, Jr. Dept. of Civil and Environmental Engineering. https://rosap.ntl.bts.gov/view/dot/37141.

17. Darwin, D., Browning, J., O'Reilly, M., and Xing, L., "Critical Chloride Corrosion Threshold for Galvanized Reinforcing Bars", SL Report 07-2, University of Kansas Center for Research, Inc., Lawrence, Kansas, December 2007, 36 pgs.

18. Lawler, J.S., Krauss, P.D., Kurth, J., and McDonald, D., 2011. "Condition Survey of Older West Virginia Bridge Decks Constructed with Epoxy-Coated Reinforcing Bars." *Transportation Research Record* 2220 (1): 57-65. doi:10.3141/2220-07. https://doi.org/10.3141/2220-07.

19. Oliva, M.G., and Okumus, P., 2011. *Finite Element Analysis of Deep Wide-Flanged Pre-Stressed Girders to Understand and Control End Cracking*: Wisconsin Department of Transportation.

20. Ross, B.E., Consolazio, G.R., and Hamilton, H.R., 2013. *End Region Detailing of Pretensioned Concrete Bridge Girders*, edited by University of Florida. Dept. of Civil and Coastal Engineering. https://rosap.ntl.bts.gov/view/dot/25872.

21. Ronanki, V.S., Burkhalter, D.I., Aaleti, S., Song, W., and Richardson, J.A., 2017. "Experimental and Analytical Investigation of End Zone Cracking in BT-78 Girders." *Engineering Structures* 151: 503-517. doi: https://doi.org/10.1016/j.engstruct.2017.08.014.

22. National Academies of Sciences, Engineering, and Medicine. 2010. *Evaluation and Repair Procedures for Precast/Prestressed Concrete Girders with Longitudinal Cracking in the Web*. Washington, DC: The National Academies Press. https://doi.org/10.17226/14380

23. Willis, M.D., "POST-TENSIONING TO PREVENT END-REGION CRACKS IN PRETENSIONED CONCRETE GIRDERS" (2014). MS Thesis, *Clemson University*, https://tigerprints.clemson.edu/all_theses/1963

24. Hamilton, H.R., and Consolazio, G.R., 2020. *Hybrid Prestressed Concrete Bridge Girders using Ultra-High Performance Concrete*: Florida Department of Transportation.

25. Ross, B.E., Willis, M.D., Hamilton, H.R., and Consolazio, G.R., 2014. "Comparison of Details for Controlling End-Region Cracks in Precast, Pretensioned Concrete I-Girders." PCI Journal 59 (2): 96–108.

26. "CRSI: History of Reinforcing Steel." https://crsi.org/index.cfm/basics/history-of-reinforcing-steel.

27. ASTM International. *A615/A615M-20 Standard Specification for Deformed and Plain Carbon-Steel Bars for Concrete Reinforcement*. West Conshohocken, PA; ASTM International, 2020. doi: https://doi.org/10.1520/A0615_A0615M-20

28. ASTM International. *A775/A775M-19 Standard Specification for Epoxy-Coated Steel Reinforcing Bars*. West Conshohocken, PA; ASTM International, 2019. doi: https://doi.org/10.1520/A0775_A0775M-19

29. Andrade, C., Barrett, T., Isgor, O.B., ElBatanouny, M., Hansson, C.M., Holland, R.B., Kahn, L.F., et al. 2016. "List of Contributors." In *Corrosion of Steel in Concrete Structures*, edited by Amir Poursaee, xi. Oxford: Woodhead Publishing. doi:https://doi.org/10.1016/B978-1-78242-381-2.01002-6.

30. Yeomans, S.R., Galvanized steel reinforcement, in Corrosion of Steel in Concrete Structures, Poursaee, A., Editor 2016, Woodhead Publishing. p. 294.

31. ASTM International. *A767/A767M-19 Standard Specification for Zinc-Coated (Galvanized) Steel Bars for Concrete Reinforcement*. West Conshohocken, PA; ASTM International, 2019. doi: https://doi.org/10.1520/A0767_A0767M-19

32. "Hdg Vs. Cgr." 100 Year Strong: Galvanized Rebar Alliance., accessed Jun 8, 2021, https://www.100yearstrong.com/hdg-vs-cgr.

33. Sharma, R., Goodwin, F.E., and Dallin, G.W., 2014. *Continuous Galvanized Rebar for Corrosion Control in RCC Structures*.

34. Choi, O.C., Hadje-Ghaffari, H., Darwin, D., and McCabe, S.L., "Bond of Epoxy-Coated Reinforcement: Bar Parameters," ACI Materials Journal Vol. 88, No. 26, March-April 1991, pp. 207-217.

35. Zhang, Z., Jung, D., and Andrawes, B., 2020. "Evaluation of Surface Roughness and Bond-Slip Behavior of New Textured epoxy-coated Reinforcing Bars." *Construction and Building Materials* 262: 120762. doi:https://doi.org/10.1016/j.conbuildmat.2020.120762.

36. Chang, J.J., Yeih, W., and Tsai, C.L., 2002. "Enhancement of Bond Strength for Epoxy-Coated Rebar using River Sand." *Construction and Building Materials* 16 (8): 465-472. doi:https://doi.org/10.1016/S0950-0618(02)00101-0.

37. Darwin, D., and Graham, E.K., "Effect of Deformation Height and Spacing on Bond Strength of Reinforcing Bars," Project 56, SL Report 93-1, The Reinforced Concrete Research Council, January 1993, 71 pp.

38. Wight, J.K., and MacGregor, J.G., 2011. *Reinforced Concrete : Mechanics and Design.* Harlow: Pearson Education.

39. Kayali, O., and Yeomans, S.R., "Bond of Ribbed Galvanized Reinforcing Steel in Concrete." *Cement and Concrete Composites* 22.6 (2000): 459-67. Web.

40. Kim, K.E., and Andrawes, B., 2018. *Behavior of Epoxy-Coated Textured Reinforcing Bars*: University of Illinois, Urbana-Champaign.

41. Kim, K.E., and Andrawes, B., "Exploratory Study on Bond Behavior of Textured epoxy-coated Reinforcing Bars." *Journal of Materials in Civil Engineering* 31.8 (2019): 04019151. Web.

42. Mueller, M., and Hughes, E., "Textured, Epoxy Coated Reinforcement Bar Investigation" Final Report, Illinois Department of Transportation Bureau of Materials & Physical Research, 2015.

43. American Association of State Highway and Transportation Officials. *AASHTO LRFD Bridge Design Specifications, Customary U.S. Units*. Washington, DC: American Association of State Highway and Transportation Officials, 2020.

44. Frosch, R.J., 1999. "Another Look at Cracking and Crack Control in Reinforced Concrete." *ACI Structural Journal* 96 (3). doi:10.14359/679.

45. American Association of State Highway and Transportation Officials, (AASHTO), ed. 2020. *Guide Specification for Service Life Design of Highway Bridges*: AASHTO.

46. *ImageJ*: National Institutes of Health, http://rsbweb.nih.gov/ij/.

47. Raoufi, K., Pour-Ghaz, M., Poursaee, A., and Weiss, J., *Restrained shrinkage cracking in concrete elements: role of substrate bond on crack development.* ASCE Journal of Materials in Civil Engineering, 2011. **June**: p. 895-902.

48. ASTM International. *A944-10(2015) Standard Test Method for Comparing Bond Strength of Steel Reinforcing Bars to Concrete Using Beam-End Specimens*. West Conshohocken, PA; ASTM International, 2015. doi: https://doi.org/10.1520/A0944-10R15

49. Peterman, R.J., A simple quality assurance test for strand bond. PCI Journal, 2009. **54**(2): p. 143-161.

50. Murphy, A., Sreedhara, S., Poursaee, A., Ross, B.E., "Comparison of Flexural Cracking in Reinforced Concrete Beams with Different Rebar Coatings," PCI National Conference, Precast/Prestressed Concrete Institute, New Orleans, LA (and Virtual), 2021.

51. Murphy, A., "Comparison of Flexural Cracking in Reinforced Concrete Beams with Different Bar Coatings" MS Thesis, Clemson University, 2021.

APPENDICES

APPENDIX A – MATERIAL TESTING

A1: Modulus of elasticity (MOE) and apparent yield strength

Type of bar	Average MOE (ksi)
Black	27250
Smooth Epoxy	27000
Textured Epoxy	26800
Hot Dipped Galvanized	28960
Continuously Galvanized	27630

Type of bar	Apparent yield strength (ksi)
Black	63
Smooth Epoxy	63
Textured Epoxy	67
Hot Dipped Galvanized	Not tested
Continuously Galvanized	67
*Based on displacement data from ASTM A944 Bond tests	

A2: Concrete Mix Design (Lab Tests)

Concrete mix design	
Material	Design Quantity
Cement (Type I/II)	500 lb
Fly Ash	125 lb
Coarse Aggregate	1825 lb
Fine Aggregate	883 lb
Plasticizer	-
Water	35 gal
Air Entrainer	-
Air Content	-
Water/Cement	0.467
Slump	3 in

The above mix design was used in building the test specimens for Bond tests, static-load long beam tests, short beam tests and Cyclic load tests. The strength data of each mix accordingly with the series and the testing time have been presented in the respective test data sheets.

APPENDIX B – SHRINKAGE CRACK TEST

<table>
<tr><th colspan="6">Shrinkage Test Summary of specimen series 1</th></tr>
<tr><td colspan="3">Bar Size: #4
Bar Type: HDG, SE, CGR, TE, B</td><td colspan="3">Cast Date: 04-27-2020
Data collected on: 04-28-2020</td></tr>
<tr><th colspan="6">7 Day Mortar Compressive Strength</th></tr>
<tr><td colspan="2">Test Age(days)</td><td colspan="2">No. of Cubes</td><td colspan="2">Avg. compressive strength (psi)</td></tr>
<tr><td colspan="2">7</td><td colspan="2">6</td><td colspan="2">5200</td></tr>
<tr><th colspan="6">Mix Design</th></tr>
<tr><td colspan="3">Cement:Sand</td><td colspan="3">1:2.25</td></tr>
<tr><td colspan="3">w/c ratio</td><td colspan="3">0.42</td></tr>
<tr><td colspan="3">Super Plasticizer</td><td colspan="3">2.5g/1000g of cement</td></tr>
<tr><td colspan="3">Sand Moisture content</td><td colspan="3">0.14%</td></tr>
<tr><td colspan="3">Flow Table Diameter</td><td colspan="3">9.5 in</td></tr>
<tr><th colspan="6">Crack Width Data on 4-28-2020</th></tr>
<tr><th>Specimen Type</th><th>Crack width I (in)</th><th>Crack width II (in)</th><th>Crack width III (in)</th><th>Avg. Crack width (in)</th><th>Comparison Index</th></tr>
<tr><td>Black</td><td>0.026</td><td>0.025</td><td>0.028</td><td>0.0263</td><td>1.28</td></tr>
<tr><td>Hot-dip Galvanized</td><td>0.018</td><td>0.021</td><td>0.018</td><td>0.0190</td><td>0.92</td></tr>
<tr><td>Smooth Epoxy</td><td>0.018</td><td>0.020</td><td>0.017</td><td>0.0183</td><td>0.89</td></tr>
<tr><td>Continuously Galvanized</td><td>0.022</td><td>0.023</td><td>0.024</td><td>0.0230</td><td>1.12</td></tr>
<tr><td>Textured Epoxy</td><td>0.015</td><td>0.0225</td><td>0.011</td><td>0.0162</td><td>0.79</td></tr>
<tr><th colspan="6">Crack Data from ImageJ</th></tr>
<tr><th>Specimen Type</th><th>Ave. Crack width (mm)</th><th>Comparison Index</th><th colspan="2">Cracked Area (mm^2)</th><th>Comparison Index</th></tr>
<tr><td>Black</td><td>0.196</td><td>0.94</td><td colspan="2">26.93</td><td>1.35</td></tr>
<tr><td>Hot-dip Galvanized</td><td>0.200</td><td>0.96</td><td colspan="2">18.57</td><td>0.93</td></tr>
<tr><td>Smooth Epoxy</td><td>0.181</td><td>0.87</td><td colspan="2">17.41</td><td>0.88</td></tr>
<tr><td>Continuously Galvanized</td><td>0.265</td><td>1.27</td><td colspan="2">19.72</td><td>0.99</td></tr>
<tr><td>Textured Epoxy</td><td>0.202</td><td>0.97</td><td colspan="2">16.80</td><td>0.84</td></tr>
<tr><td colspan="6">Comments:
• Casted at 4.30 pm
• Detached formwork at 8 pm
• Black and textured specimens have got an initial crack while detaching the formwork</td></tr>
</table>

Shrinkage Test Summary of specimen series 2	
Bar Size: #4 Bar Type: B, HDG, SE, CGR, TE	Cast Date: 05-13-2020 Data collected on: 05-15-2020

7 Day Mortar Compressive Strength		
Test Age(days)	No. of Cubes	Avg. compressive strength (psi)
7	6	4342

Mix Design	
Cement:Sand	1:2.25
w/c ratio	0.42
Super Plasticizer	2.5g/1000g of cement
Sand Moisture content	0.14%
Flow Table Diameter	8.5 in

Crack Width Data on 5-15-2020					
Specimen Type	Crack width I (in)	Crack width II (in)	Crack width III (in)	Avg. Crack width (in)	Comparison Index
Black	0.022	0.021	0.019	0.0207	1.40
Hot-dip Galvanized	0.015	0.017	0.015	0.0157	1.06
Smooth Epoxy	0.014	0.015	0.010	0.0130	0.88
Continuously Galvanized	0.014	0.011	0.012	0.0123	0.84
Textured Epoxy	0.012	0.011	0.013	0.0120	0.81

Crack Data from ImageJ				
Specimen Type	Ave. Crack width (mm)	Comparison Index	Cracked Area (mm^2)	Comparison Index
Black	0.235	1.62	16.85	1.10
Hot-dip Galvanized	0.190	1.31	14.63	0.95
Smooth Epoxy	0.107	0.74	16.23	1.06
Continuously Galvanized	0.090	0.62	17.26	1.13
Textured Epoxy	0.102	0.70	11.68	0.76

Comments:

- Casted at 5.00 pm
- Detached formwork at 7.30 pm
- Black, Conventional Galvanized and Epoxy specimens have got an initial crack while detaching the formwork

Shrinkage Test Summary of specimen series 3					
Bar Size: #4 Bar Type: TE, B, HDG, SE, CGR			Cast Date: 05-27-2020 Data collected on: 05-28-2020		
7 Day Mortar Compressive Strength					
Test Age(days)	No. of Cubes		Avg. compressive strength (psi)		
7	6		5174		
Mix Design					
Cement:Sand			1:2.25		
w/c ratio			0.42		
Super Plasticizer			2.5g/1000g of cement		
Sand Moisture content			0.14%		
Flow Table Diameter			9.25 in		
Crack Width Data on 5-28-2020					
Specimen Type	Crack width I (in)	Crack width II (in)	Crack width III (in)	Avg. Crack width (in)	Comparison Index
Black	0.010	0.015	0.010	0.0117	0.69
Hot-dip Galvanized	0.018	0.020	0.015	0.0177	1.05
Smooth Epoxy	0.020	0.023	0.020	0.0210	1.25
Continuously Galvanized	0.018	0.0225	0.022	0.0208	1.24
Textured Epoxy	0.008	0.016	0.015	0.0130	0.77
Crack Data from ImageJ					
Specimen Type	Ave. Crack width (mm)	Comparison Index	Cracked Area (mm^2)	Comparison Index	
Black	0.085	0.62	10.00	0.70	
Hot-dip Galvanized	0.208	1.51	14.75	1.03	
Smooth Epoxy	0.174	1.27	20.33	1.42	
Continuously Galvanized	0.154	1.12	16.51	1.16	
Textured Epoxy	0.066	0.48	9.79	0.69	
Comments: • Casted between 4.45 pm to 5.30 pm • Detached formwork between 7.50 pm to 8.30 pm • Textured, Galvanized, Conventional Galvanized and Epoxy specimens have got an initial crack while detaching the formwork					

Shrinkage Test Summary of specimen series 4					
Bar Size: #4 Bar Type: CGR, TE, B, HDG, SE			Cast Date: 06-04-2020 Data collected on: 06-05-2020		
7 Day Mortar Compressive Strength					
Test Age(days)		No. of Cubes		Avg. compressive strength (psi)	
7		6		5185	
Mix Design					
Cement:Sand			1:2.25		
w/c ratio			0.42		
Super Plasticizer			2.5g/1000g of cement		
Sand Moisture content			0.14%		
Flow Table Diameter			8.75 in		
Crack Width Data on 6-5-2020					
Specimen Type	Crack width I (in)	Crack width II (in)	Crack width III (in)	Avg. Crack width (in)	Comparison Index
Black	0.024	0.023	0.024	0.0237	1.01
Hot-dip Galvanized	0.022	0.023	0.02	0.0217	0.93
Smooth Epoxy	0.02	0.02	0.02	0.0200	0.85
Continuously Galvanized	0.028	0.03	0.027	0.0283	1.21
Textured Epoxy	0.024	0.022	0.024	0.0233	1.00
Crack Data from ImageJ					
Specimen Type	Ave. Crack width (mm)	Comparison Index	Cracked Area (mm^2)	Comparison Index	
Black	0.162	0.84	22.14	1.10	
Hot-dip Galvanized	0.196	1.02	17.12	0.85	
Smooth Epoxy	0.113	0.59	16.81	0.84	
Continuously Galvanized	0.339	1.76	22.18	1.10	
Textured Epoxy	0.153	0.79	22.12	1.10	

Comments:

- Casted between 4.15 pm to 4.45 pm
- Detached formwork between 7.15 pm to 7.45 pm
- All the specimens have got an initial crack while detaching the formwork

Shrinkage Test Summary of specimen series 5	
Bar Size: #4 Bar Type: SE, CGR, TE, B, HDG	Cast Date: 06-11-2020 Data collected on: 06-12-2020

7 Day Mortar Compressive Strength		
Test Age(days)	No. of Cubes	Avg. compressive strength (psi)
7	6	4683

Mix Design	
Cement:Sand	1:2.25
w/c ratio	0.42
Super Plasticizer	2.5g/1000g of cement
Sand Moisture content	0.14%
Flow Table Diameter	8.5 in

Crack Width Data on 6-12-2020					
Specimen Type	Crack width I (in)	Crack width II (in)	Crack width III (in)	Avg. Crack width (in)	Comparison Index
Black	0.011	0.009	0.011	0.0103	0.76
Hot-dip Galvanized	0.011	0.009	0.010	0.0100	0.74
Smooth Epoxy	0.013	0.015	0.019	0.0157	1.15
Continuously Galvanized	0.014	0.016	0.016	0.0153	1.13
Textured Epoxy	0.016	0.018	0.016	0.0167	1.23

Crack Data from ImageJ				
Specimen Type	Ave. Crack width (mm)	Comparison Index	Cracked Area (mm^2)	Comparison Index
Black	0.068	0.56	9.70	0.86
Hot-dip Galvanized	0.078	0.65	10.39	0.92
Smooth Epoxy	0.173	1.44	14.06	1.24
Continuously Galvanized	0.134	1.12	9.88	0.87
Textured Epoxy	0.148	1.23	12.68	1.12

Comments:

- Casted between 4.00 pm to 4.45 pm
- Detached formwork between 7.00 pm to 7.30 pm
- All the specimens except galvanized have got an initial crack while detaching the formwork

Shrinkage Test Summary of specimen series 6					
Bar Size: #4 Bar Type: HDG, SE, CGR, TE, B			Cast Date: 06-20-2020 Data collected on: 06-21-2020		
7 Day Mortar Compressive Strength					
Test Age(days)	No. of Cubes		Avg. compressive strength (psi)		
7	6		5114		
Mix Design					
Cement:Sand			1:2.25		
w/c ratio			0.42		
Super Plasticizer			2.5g/1000g of cement		
Sand Moisture content			0.14%		
Flow Table Diameter			8.5 in		
Crack Width Data on 6-21-2020					
Specimen Type	Crack width I (in)	Crack width II (in)	Crack width III (in)	Avg. Crack width (in)	Comparison Index
Black	0.02	0.01	0.007	0.0123	0.80
Hot-dip Galvanized	0.012	0.017	0.025	0.0180	1.17
Smooth Epoxy	0.011	0.01	0.01	0.0103	0.67
Continuously Galvanized	0.017	0.018	0.015	0.0167	1.09
Textured Epoxy	0.017	0.016	0.025	0.0193	1.26
Crack Data from ImageJ					
Specimen Type	Ave. Crack width (mm)	Comparison Index	Cracked Area (mm^2)	Comparison Index	
Black	0.066	0.69	10.12	0.91	
Hot-dip Galvanized	0.132	1.38	12.18	1.10	
Smooth Epoxy	0.104	1.08	13.28	1.20	
Continuously Galvanized	0.100	1.04	12.35	1.12	
Textured Epoxy	0.077	0.80	7.39	0.67	

Comments:

- Casted between 1.00 pm to 1.45 pm
- Detached formwork between 4.00 pm to 4.45 pm
- All the specimens except galvanized have got an initial crack while detaching the formwork

Shrinkage Test Summary of specimen series 7					
Bar Size: #4 Bar Type: HDG, SE, CGR, TE, B			Cast Date: 07-17-2020 Data collected on: 07-18-2020		
7 Day Mortar Compressive Strength					
Test Age(days)	No. of Cubes		Avg. compressive strength (psi)		
14	6		5159		
Mix Design					
Cement:Sand			1:2.25		
w/c ratio			0.42		
Super Plasticizer			2.5g/1000g of cement		
Sand Moisture content			0.14%		
Flow Table Diameter			8.25 in		
Crack Width Data on 7-18-2020					
Specimen Type	Crack width I (in)	Crack width II (in)	Crack width III (in)	Avg. Crack width (in)	Comparison Index
Black	0.01	0.013	0.012	0.0117	1.20
Hot-dip Galvanized	0.011	0.012	0.013	0.0120	1.23
Smooth Epoxy	0.006	0.007	0.007	0.0067	0.68
Continuously Galvanized	0.01	0.01	0.01	0.0100	1.03
Textured Epoxy	0.01	0.01	0.005	0.0083	0.86
Crack Data from ImageJ					
Specimen Type	Ave. Crack width (mm)	Comparison Index	Cracked Area (mm^2)	Comparison Index	
Black	0.066	0.69	7.08	0.93	
Hot-dip Galvanized	0.132	1.38	6.20	0.81	
Smooth Epoxy	0.104	1.08	10.56	1.39	
Continuously Galvanized	0.100	1.04	7.73	1.01	
Textured Epoxy	0.077	0.80	6.51	0.85	
Comments: • Casted between 4.30 pm to 5.00 pm • Detached formwork between 7.00 pm to 8.00 pm • Black and Epoxy specimens have got an initial thin crack while detaching the formwork					

Shrinkage Test Summary of specimen series 8	
Bar Size: #4 Bar Type: HDG, SE, CGR, TE, B	Cast Date: 07-21-2020 Data collected on: 07-22-2020

7 Day Mortar Compressive Strength

Test Age(days)	No. of Cubes	Avg. compressive strength (psi)
7	6	5179

Mix Design

Cement:Sand	1:2.25
w/c ratio	0.42
Super Plasticizer	2.5g/1000g of cement
Sand Moisture content	0.14%
Flow Table Diameter	8.75 in

Crack Width Data on 7-22-2020

Specimen Type	Crack width I (in)	Crack width II (in)	Crack width III (in)	Avg. Crack width (in)	Comparison Index
Black	0.015	0.011	0.01	0.0120	1.22
Hot-dip Galvanized	0.01	0.01	0.012	0.0107	1.09
Smooth Epoxy	0.008	0.009	0.005	0.0073	0.75
Continuously Galvanized	0.006	0.009	0.008	0.0077	0.78
Textured Epoxy	0.012	0.012	0.01	0.0113	1.16

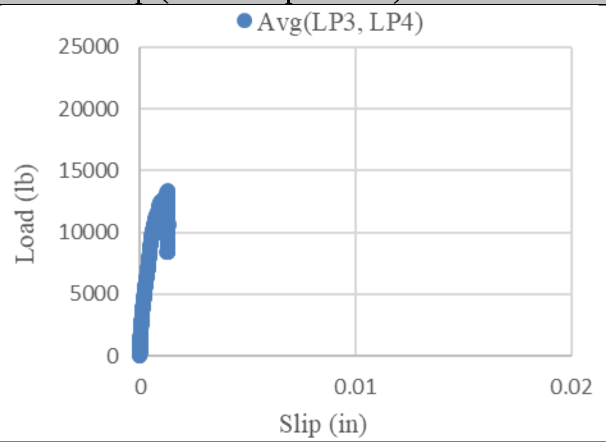
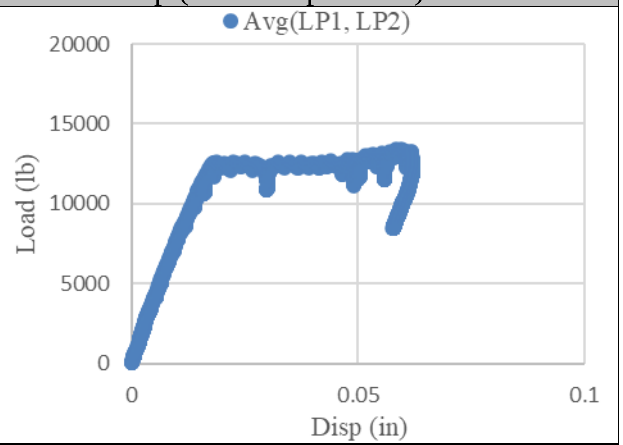
Crack Data from ImageJ

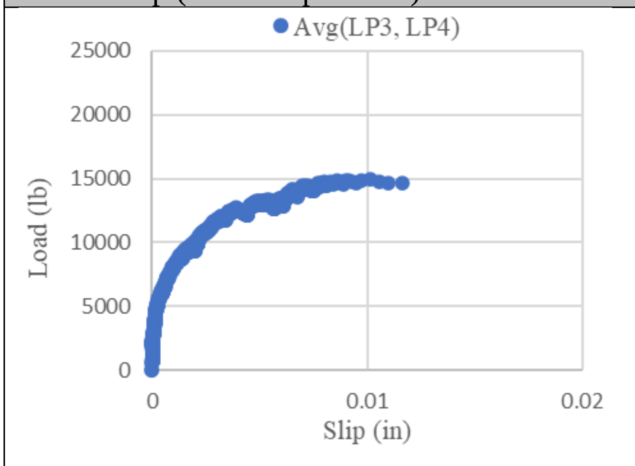
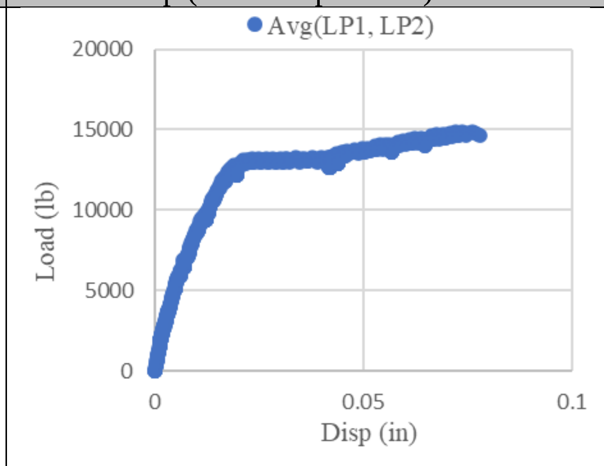
Specimen Type	Ave. Crack width (mm)	Comparison Index	Cracked Area (mm^2)	Comparison Index
Black	0.066	0.69	7.40	1.17
Hot-dip Galvanized	0.132	1.38	4.55	0.72
Smooth Epoxy	0.104	1.08	7.33	1.16
Continuously Galvanized	0.100	1.04	7.12	1.12
Textured Epoxy	0.077	0.80	5.31	0.84

Comments:

- Casted between 4.40 pm to 5.40 pm
- Detached formwork between 8.00 pm to 8.40 pm
- All the specimens except textured epoxy have got an initial thin crack while detaching the formwork

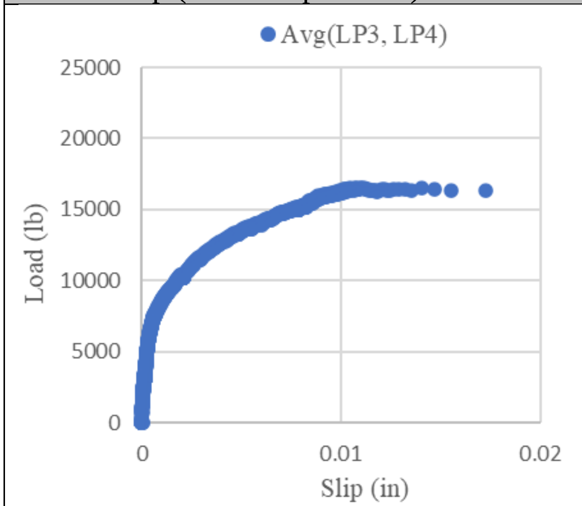
APPENDIX C – BOND TEST

<table>
<tr><td colspan="4">Bond Test Summary of specimen B1</td></tr>
<tr><td colspan="2">Bar Size: #4
Bar Type: Black Bonded Length: 6 in</td><td colspan="2">Cast Date: 10-07-2019
Test Date: 11-04-2019</td></tr>
<tr><td colspan="4">Concrete Compressive Strength</td></tr>
<tr><td>Test Age(days)</td><td colspan="2">No. of Cylinders</td><td>Avg. compressive strength (psi)</td></tr>
<tr><td>2</td><td colspan="2">1</td><td>2510</td></tr>
<tr><td>9</td><td colspan="2">2</td><td>3900</td></tr>
<tr><td>14</td><td colspan="2">1</td><td>4080</td></tr>
<tr><td>21</td><td colspan="2">2</td><td>4620</td></tr>
<tr><td>28 (Age at testing of B1)</td><td colspan="2">3</td><td>5070</td></tr>
<tr><td>30 (E1 & G1)</td><td colspan="2">1</td><td>5150</td></tr>
<tr><td>35 (T1)</td><td colspan="2">1</td><td>5360</td></tr>
<tr><td colspan="2">Load – Slip (back of specimen)</td><td colspan="2">Load – Disp (front of specimen)</td></tr>
<tr><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td colspan="2">Slip at 4 kip = 0.0001225 in</td><td>Max Load = 13416 lb</td><td>Max Stress = 68328 psi</td></tr>
<tr><td colspan="2">Slip at 10 kip = 0.0005375</td><td colspan="2">Apparent Yield Stress ~ 65 ksi</td></tr>
<tr><td colspan="2">Description of the test</td><td colspan="2">Picture after test</td></tr>
<tr><td colspan="2">The rebar was not loaded upto its bond failure. Instead, test had to be stopped as the jack reached the maximum stroke length. From the load –disp plot the bar has yielded.</td><td colspan="2">The specimen did not crack. Hence, no photos were taken.</td></tr>
</table>

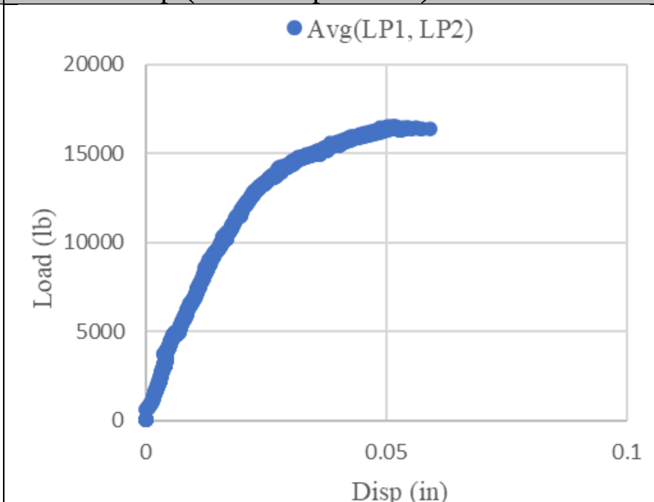
<table>
<tr><th colspan="3">Bond Test Summary of specimen E1</th></tr>
<tr><td colspan="2">Bar Size: #4
Bar Type: Smooth Epoxy
Bonded Length: 6 in</td><td>Cast Date: 10-07-2019
Test Date: 11-06-2019</td></tr>
<tr><th colspan="3">Concrete Strength</th></tr>
<tr><td>Test Age(days)</td><td>No. of Cylinders</td><td>Avg. compressive strength (psi)</td></tr>
<tr><td>2</td><td>1</td><td>2510</td></tr>
<tr><td>9</td><td>2</td><td>3900</td></tr>
<tr><td>14</td><td>1</td><td>4080</td></tr>
<tr><td>21</td><td>2</td><td>4620</td></tr>
<tr><td>28 (B1)</td><td>3</td><td>5070</td></tr>
<tr><td>30 (E1 & G1)</td><td>1</td><td>5150</td></tr>
<tr><td>35 (T1)</td><td>1</td><td>5360</td></tr>
<tr><th colspan="2">Load – Slip (back of specimen)</th><th>Load – Disp (front of specimen)</th></tr>
<tr><td colspan="2">
</td><td>
</td></tr>
<tr><td colspan="2">Slip at 4 kip = 0.000131 in</td><td>Max Load = 14902 lb | Max Stress = 75896 psi</td></tr>
<tr><td colspan="2">Slip at 10 kip = 0.0020445 in</td><td>Apparent yield strength = 68 ksi</td></tr>
<tr><th colspan="2">Description of the test</th><th>Picture after test</th></tr>
<tr><td colspan="2">The rebar was loaded beyond its yielding point and there was a bond failure with splitting of concrete.</td><td></td></tr>
</table>

Bond Test Summary of specimen G1		
Bar Size: #4 Bar Type: Continuously Galvanized Bonded Length: 6 in		Cast Date: 10-07-2019 Test Date: 11-06-2019
Concrete Strength		
Test Age(days)	No. of Cylinders	Avg. compressive strength (psi)
2	1	2510
9	2	3900
14	1	4080
21	2	4620
28 (B1)	3	5070
30 (E1 & G1)	1	5150
35 (T1)	1	5360

Load – Slip (back of specimen)



Load – Disp (front of specimen)

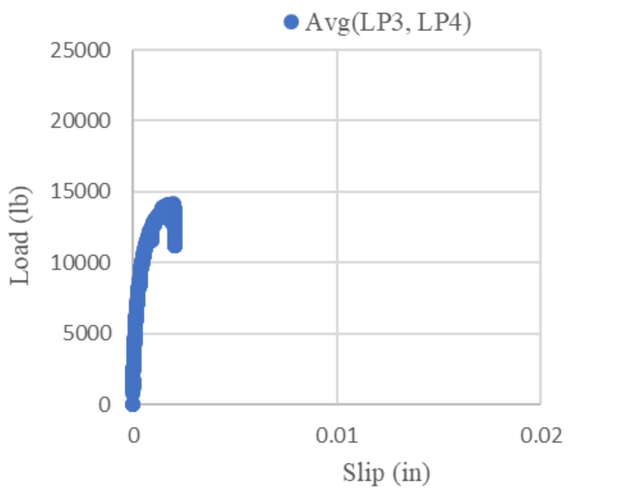
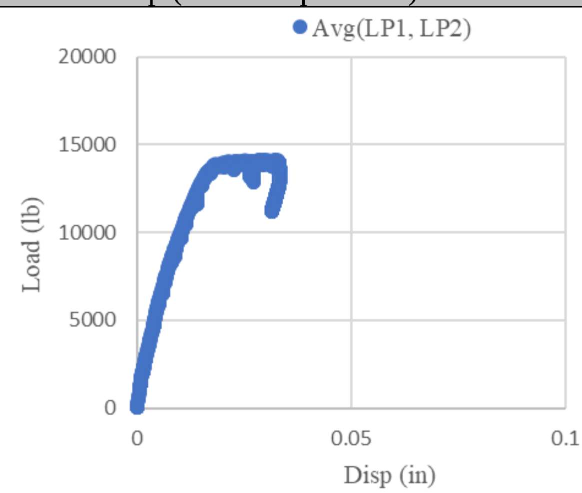


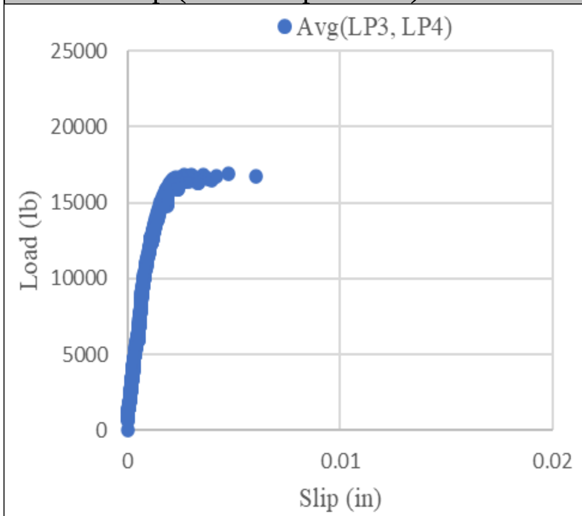
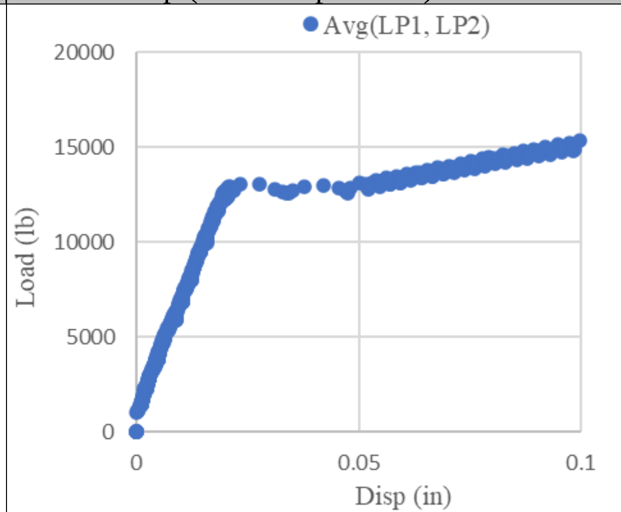
Slip at 4 kip = 0.0001875	Max Load = 16528 lb	Max Stress = 84177 psi
Slip at 10 kip = 0.001778	Apparent Yield Stress ~ 65 ksi	

Description of the test

Rebar was loaded beyond its yield point and the specimen failed with splitting of concrete.

Picture after test

<table>
<tr><th colspan="4">Bond Test Summary of specimen T1</th></tr>
<tr><td colspan="2">Bar Size: #4
Bar Type: Textured Epoxy
Bonded Length: 6 in</td><td colspan="2">Cast Date: 10-07-2019
Test Date: 11-11-2019</td></tr>
<tr><th colspan="4">Concrete Strength</th></tr>
<tr><th>Test Age(days)</th><th>No. of Cylinders</th><th colspan="2">Avg. compressive strength (psi)</th></tr>
<tr><td>2</td><td>1</td><td colspan="2">2510</td></tr>
<tr><td>9</td><td>2</td><td colspan="2">3900</td></tr>
<tr><td>14</td><td>1</td><td colspan="2">4080</td></tr>
<tr><td>21</td><td>2</td><td colspan="2">4620</td></tr>
<tr><td>28 (B1)</td><td>3</td><td colspan="2">5070</td></tr>
<tr><td>30 (E1 & G1)</td><td>1</td><td colspan="2">5150</td></tr>
<tr><td>35 (T1)</td><td>1</td><td colspan="2">5360</td></tr>
<tr><th colspan="2">Load – Slip (back of specimen)</th><th colspan="2">Load – Disp (front of specimen)</th></tr>
<tr><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td colspan="2">Slip at 4 kip = 6.6E-05</td><td>Max Load = 14130 lb</td><td>Max Stress = 71963 psi</td></tr>
<tr><td colspan="2">Slip at 10 kip = 0.0004365</td><td colspan="2">Apparent Yield Stress ~ 70 ksi</td></tr>
<tr><th colspan="2">Description of the test</th><th colspan="2">Picture after test</th></tr>
<tr><td colspan="2">The rebar was loaded well beyond its yield point. No bond failure happened. The test was stopped as the jack reached its maximum stroke length.</td><td colspan="2"></td></tr>
</table>

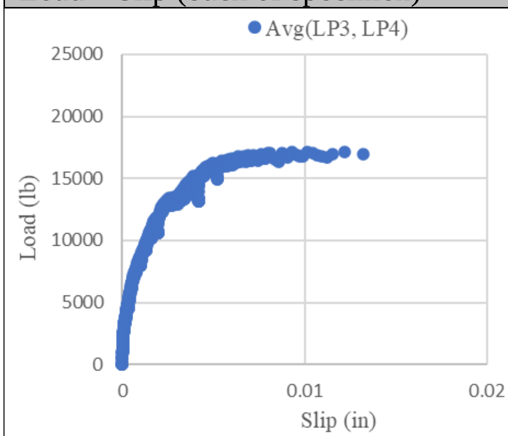
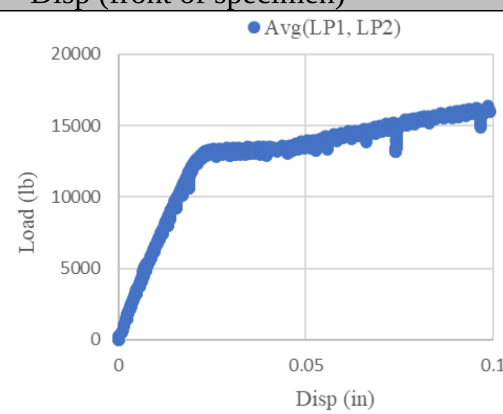
<table>
<tr><th colspan="4">Bond Test Summary of specimen B2</th></tr>
<tr><td colspan="2">Bar Size: #4
Bar Type: Black Bonded Length: 6 in</td><td colspan="2">Cast Date: 10-28-2019
Test Date: 12-18-2019</td></tr>
<tr><td colspan="4">Concrete Strength</td></tr>
<tr><td>Test Age(days)</td><td>No. of Cylinders</td><td colspan="2">Avg. compressive strength (psi)</td></tr>
<tr><td>7</td><td>2</td><td colspan="2">4960</td></tr>
<tr><td>8</td><td>1</td><td colspan="2">4940</td></tr>
<tr><td>14</td><td>1</td><td colspan="2">5590</td></tr>
<tr><td>21</td><td>1</td><td colspan="2">5690</td></tr>
<tr><td>28</td><td>3</td><td colspan="2">5940</td></tr>
<tr><td>45 (E2 & G2)</td><td>1</td><td colspan="2">6960</td></tr>
<tr><td>51 (B2 & T2)</td><td>2</td><td colspan="2">6860</td></tr>
<tr><td colspan="2">Load – Slip (back of specimen)</td><td colspan="2">Load – Disp (front of specimen)</td></tr>
<tr><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td colspan="2">Slip at 4 kip = 0.0002425</td><td>Max Load = 16871 lb</td><td>Max Stress = 85923 psi</td></tr>
<tr><td colspan="2">Slip at 10 kip = 0.0008695</td><td colspan="2">Apparent Yield Strength ~ 69 ksi</td></tr>
<tr><td colspan="2">Description of the test</td><td colspan="2">Picture after test</td></tr>
</table>

The rebar was loaded beyond its yield point. Bond failure happened with splitting of concrete.	

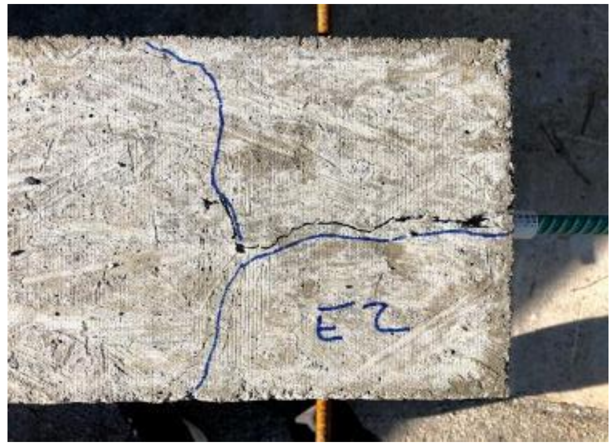
Bond Test Summary of specimen E2	
Bar Size: #4 Bar Type: Smooth Epoxy Bonded Length: 6 in	Cast Date: 10-28-2019 Test Date: 12-12-2019

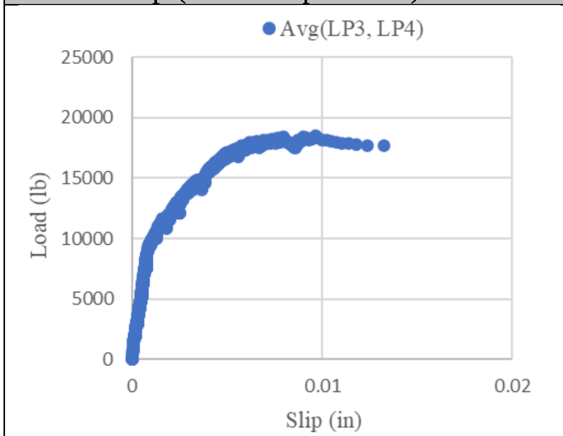
Concrete Strength

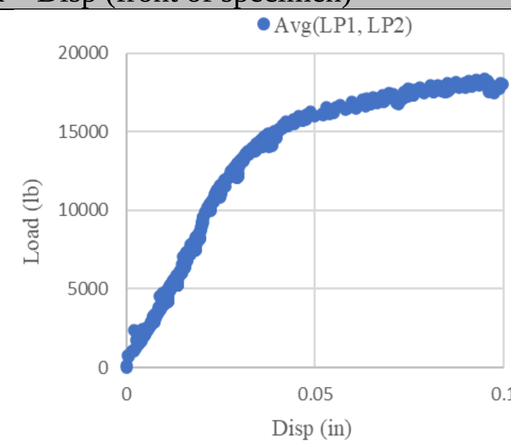
Test Age(days)	No. of Cylinders	Avg. compressive strength (psi)
7	2	4960
8	1	4940
14	1	5590
21	1	5690
28	3	5940
45 (E2 & G2)	1	6960
51 (B2 & T2)	2	6860

Load – Slip (back of specimen)	Load – Disp (front of specimen)
	

Slip at 4 kip = 0.000194	Max Load = 17166 lb	Max Stress = 87425 psi
Slip at 10 kip = 0.0013865	Apparent Yield Stress ~ 71 ksi	
Description of the test	Picture after test	

The rebar was loaded beyond its yield point. Bond failure happened with splitting of concrete.	

<table>
<tr><th colspan="3">Bond Test Summary of specimen G2</th></tr>
<tr><td colspan="2">Bar Size: #4
Bar Type: Continuously Galvanized
Bonded Length: 6 in</td><td>Cast Date: 10-28-2019
Test Date: 12-12-2019</td></tr>
<tr><th colspan="3">Concrete Strength</th></tr>
<tr><th>Test Age(days)</th><th>No. of Cylinders</th><th>Avg. compressive strength (psi)</th></tr>
<tr><td>7</td><td>2</td><td>4960</td></tr>
<tr><td>8</td><td>1</td><td>4940</td></tr>
<tr><td>14</td><td>1</td><td>5590</td></tr>
<tr><td>21</td><td>1</td><td>5690</td></tr>
<tr><td>28</td><td>3</td><td>5940</td></tr>
<tr><td>45 (E2 & G2)</td><td>1</td><td>6960</td></tr>
<tr><td>51 (B2 & T2)</td><td>2</td><td>6860</td></tr>
<tr><th colspan="2">Load – Slip (back of specimen)</th><th>Load – Disp (front of specimen)</th></tr>
<tr><td colspan="2">


</td><td>


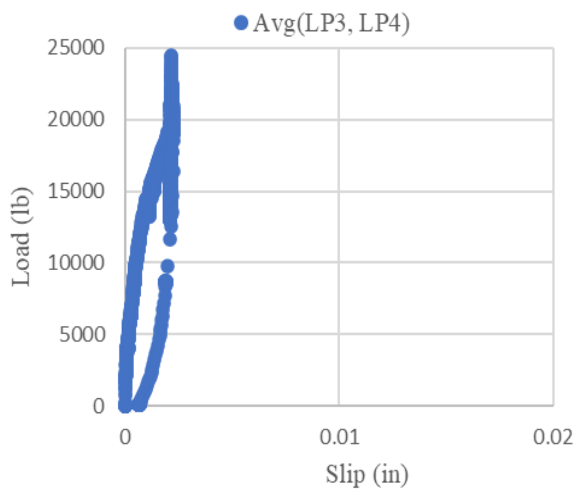
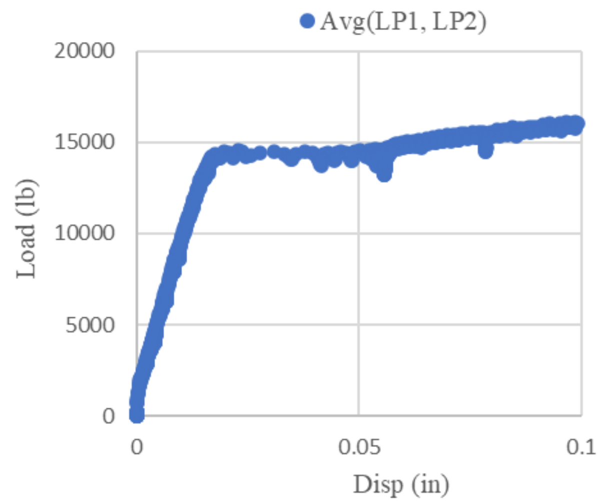
</td></tr>
<tr><td colspan="2">Slip at 4 kip = 0.000335</td><td>Max Load = 18490 lb
Max Stress = 94167 psi</td></tr>
<tr><td colspan="2">Slip at 10 kip = 0.0010775</td><td>Apparent Yield Stress ~ 67 ksi</td></tr>
<tr><th colspan="2">Description of the test</th><th>Picture after test</th></tr>
<tr><td colspan="2">The rebar was loaded beyond its yield point. Bond failure happened with splitting of concrete.</td><td>

</td></tr>
</table>

Bond Test Summary of specimen T2	
Bar Size: #4 Bar Type: Textured Epoxy Bonded Length: 6 in	Cast Date: 10-28-2019 Test Date: 12-18-2019

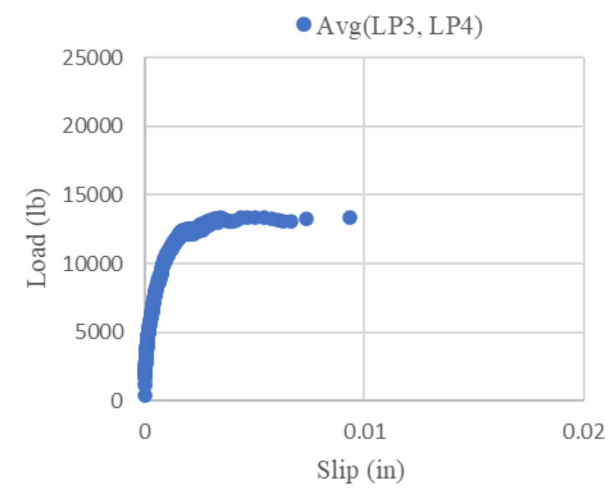
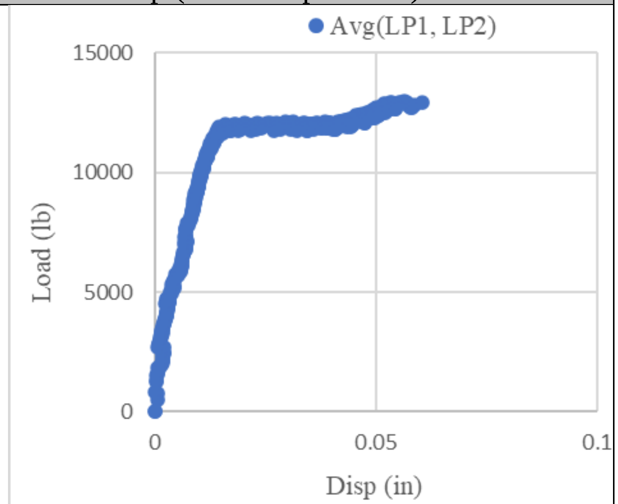
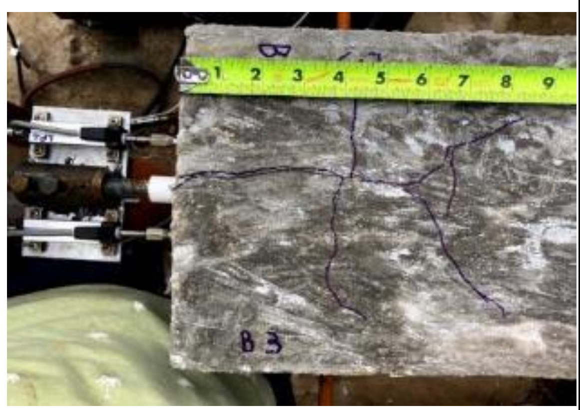
Concrete Strength

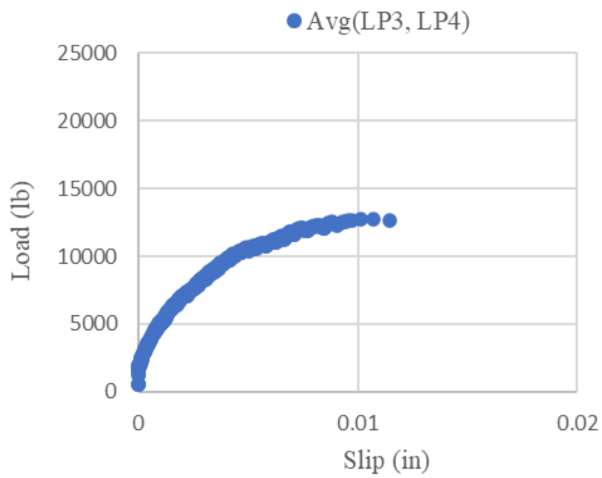
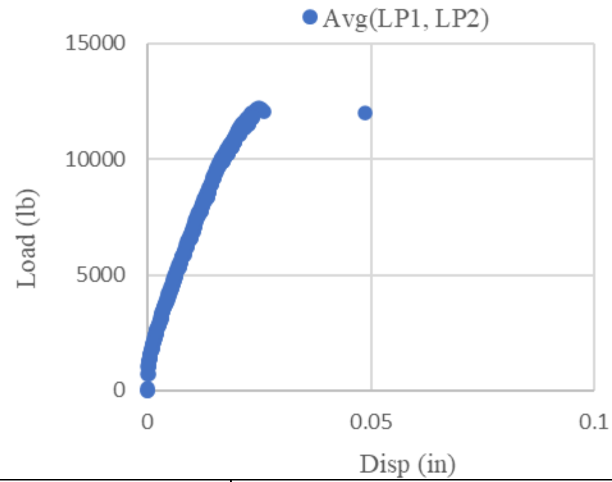
Test Age(days)	No. of Cylinders	Avg. compressive strength (psi)
7	2	4960
8	1	4940
14	1	5590
21	1	5690
28	3	5940
45 (E2 & G2)	1	6960
51 (B2 & T2)	2	6860

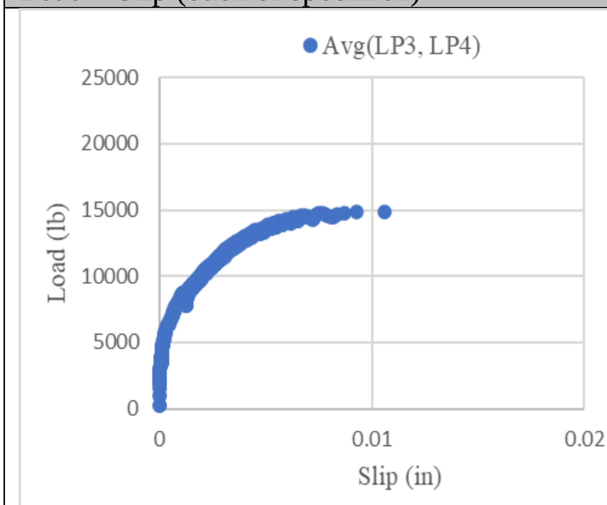
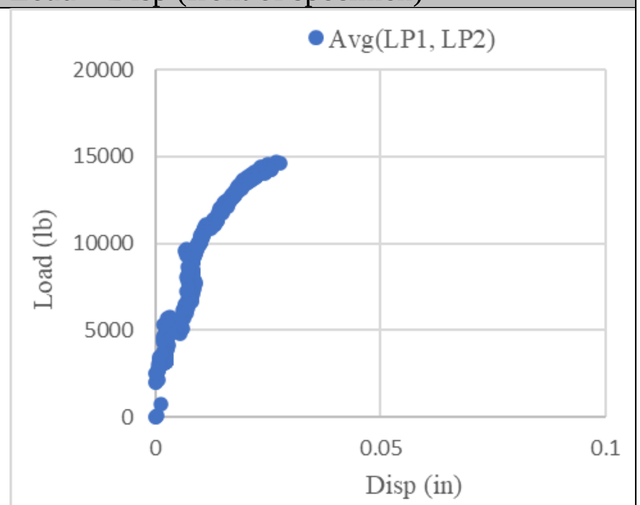
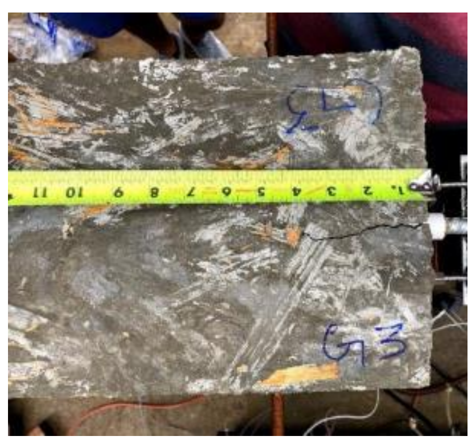
Load – Slip (back of specimen)	Load – Disp (front of specimen)
	

Slip at 4 kip = 7.7E-05	Max Load = 24445 lb	Max Stress = 124496 psi
Slip at 10 kip = 0.000486	Apparent Yield Stress ~ 72 ksi	

Description of the test	Picture after test
The rebar was loaded well beyond its yield point. No bond failure happened. The test was stopped as the jack reached its maximum stroke length.	

<table>
<tr><th colspan="4">Bond Test Summary of specimen B3</th></tr>
<tr><td colspan="2">Bar Size: #4
Bar Type: Black Bonded Length: 4 in</td><td colspan="2">Cast Date: 12-11-2019
Test Date: 02-12-2020</td></tr>
<tr><td colspan="4">Concrete Compressive Strength</td></tr>
<tr><td>Test Age(days)</td><td>No. of Cylinders</td><td colspan="2">Avg. compressive strength (psi)</td></tr>
<tr><td>7</td><td>2</td><td colspan="2">3345</td></tr>
<tr><td>14</td><td>2</td><td colspan="2">4389</td></tr>
<tr><td>21</td><td>2</td><td colspan="2">4985</td></tr>
<tr><td>28</td><td>3</td><td colspan="2">5017</td></tr>
<tr><td>56 (G3 & T3)</td><td>1</td><td colspan="2">7429</td></tr>
<tr><td>63 (B3 & E3)</td><td>2</td><td colspan="2">6940</td></tr>
<tr><td colspan="2">Load – Slip (back of specimen)</td><td colspan="2">Load – Disp (front of specimen)</td></tr>
<tr><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td colspan="2">Slip at 4 kip = 0.000119 in</td><td>Max Load = 12135 lb</td><td>Max Stress = 61801 psi</td></tr>
<tr><td colspan="2">Slip at 10 kip = 0.000935 in</td><td colspan="2">Apparent Yield Stress ~ 60 ksi</td></tr>
<tr><td colspan="2">Description of the test</td><td colspan="2">Picture after test</td></tr>
<tr><td colspan="2"></td><td colspan="2">
</td></tr>
</table>

<table>
<tr><th colspan="4">Bond Test Summary of specimen E3</th></tr>
<tr><td colspan="2">Bar Size: #4
Bar Type: Black Bonded Length: 4 in</td><td colspan="2">Cast Date: 12-11-2019
Test Date: 02-12-2020</td></tr>
<tr><td colspan="4">Concrete Compressive Strength</td></tr>
<tr><td>Test Age(days)</td><td colspan="2">No. of Cylinders</td><td>Avg. compressive strength (psi)</td></tr>
<tr><td>7</td><td colspan="2">2</td><td>3345</td></tr>
<tr><td>14</td><td colspan="2">2</td><td>4389</td></tr>
<tr><td>21</td><td colspan="2">2</td><td>4985</td></tr>
<tr><td>28</td><td colspan="2">3</td><td>5017</td></tr>
<tr><td>56 (G3 & T3)</td><td colspan="2">1</td><td>7429</td></tr>
<tr><td>63 (B3 & E3)</td><td colspan="2">2</td><td>6940</td></tr>
<tr><td colspan="2">Load – Slip (back of specimen)</td><td colspan="2">Load – Disp (front of specimen)</td></tr>
<tr><td colspan="2">
</td><td colspan="2">
</td></tr>
<tr><td colspan="2">Slip at 4 kip = 0.000764 in</td><td>Max Load = 12234 lb</td><td>Max Stress = 62309 psi</td></tr>
<tr><td colspan="2">Slip at 10 kip = 0.0048375 in</td><td colspan="2">Apparent Yield Stress ~ 60 ksi</td></tr>
<tr><td colspan="2">Description of the test</td><td colspan="2">Picture after test</td></tr>
<tr><td colspan="2"></td><td colspan="2"></td></tr>
</table>

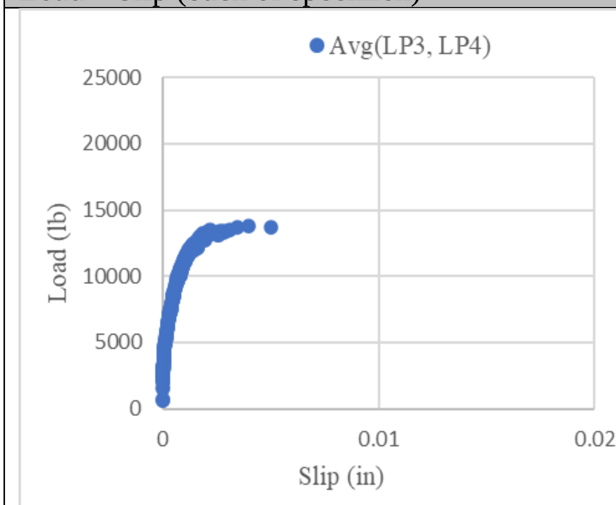
<table>
<tr><th colspan="3">Bond Test Summary of specimen G3</th></tr>
<tr><td>Bar Size: #4
Bar Type: Continuously Galvanized
Bonded Length: 4 in</td><td colspan="2">Cast Date: 12-11-2019
Test Date: 02-05-2020</td></tr>
<tr><th colspan="3">Concrete Compressive Strength</th></tr>
<tr><td>Test Age(days)</td><td>No. of Cylinders</td><td>Avg. compressive strength (psi)</td></tr>
<tr><td>7</td><td>2</td><td>3345</td></tr>
<tr><td>14</td><td>2</td><td>4389</td></tr>
<tr><td>21</td><td>2</td><td>4985</td></tr>
<tr><td>28</td><td>3</td><td>5017</td></tr>
<tr><td>56 (G3 & T3)</td><td>1</td><td>7429</td></tr>
<tr><td>63 (B3 & E3)</td><td>2</td><td>6940</td></tr>
<tr><th>Load – Slip (back of specimen)</th><th colspan="2">Load – Disp (front of specimen)</th></tr>
<tr><td>
</td><td colspan="2">
</td></tr>
<tr><td>Slip at 4 kip = 0.0001045 in</td><td>Max Load = 14652 lb</td><td>Max Stress = 74620 psi</td></tr>
<tr><td>Slip at 10 kip = 0.0020115 in</td><td colspan="2">Apparent Yield Stress ~ 74 ksi</td></tr>
<tr><th>Description of the test</th><th colspan="2">Picture after test</th></tr>
<tr><td></td><td colspan="2">
</td></tr>
</table>

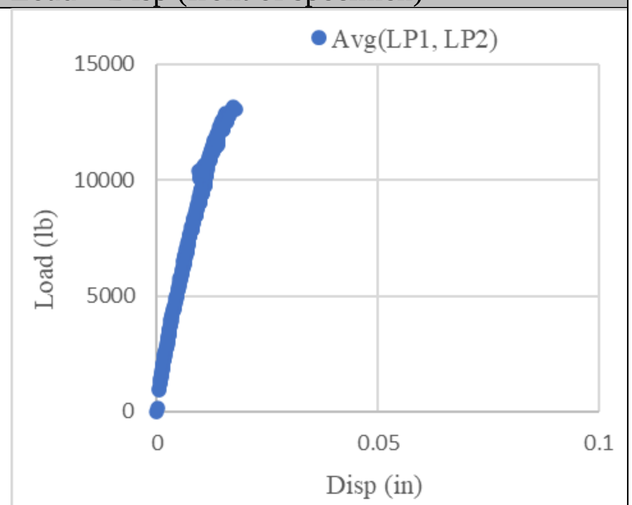
Bond Test Summary of specimen T3	
Bar Size: #4 Bar Type: Textured epoxy Bonded Length: 4 in	Cast Date: 12-11-2019 Test Date: 02-05-2020

Concrete Compressive Strength

Test Age(days)	No. of Cylinders	Avg. compressive strength (psi)
7	2	3345
14	2	4389
21	2	4985
28	3	5017
56 (G3 & T3)	1	7429
63 (B3 & E3)	2	6940

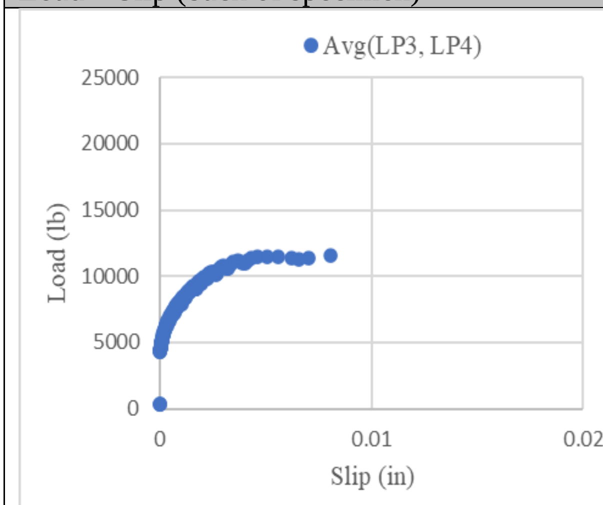
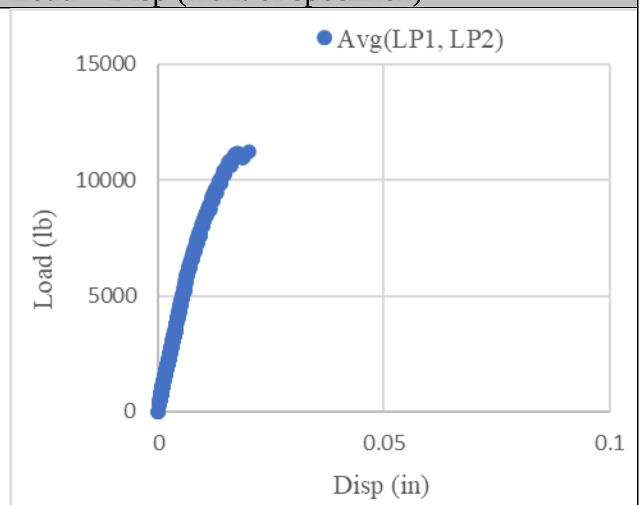
Load – Slip (back of specimen)	Load – Disp (front of specimen)





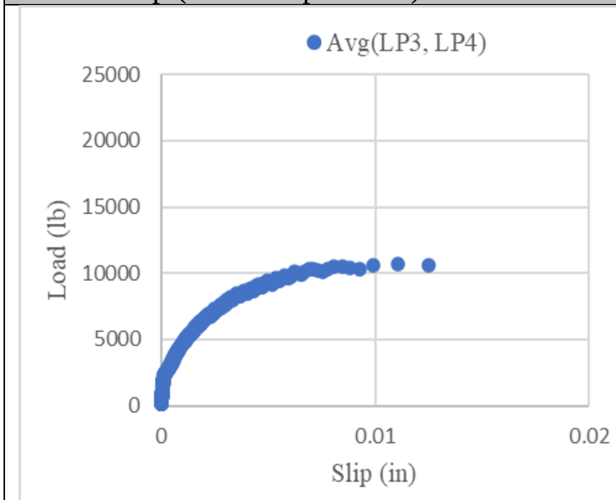
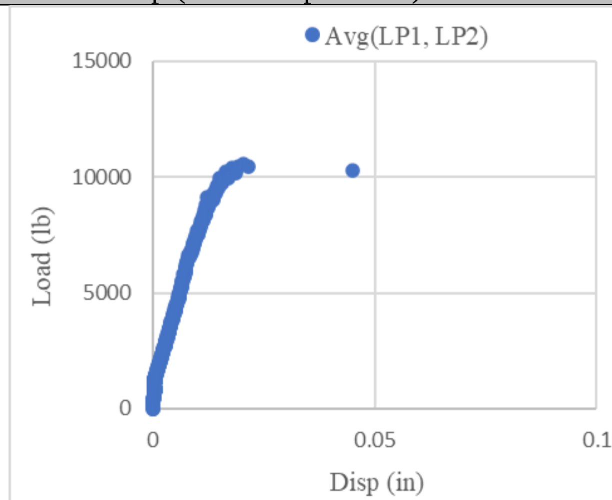
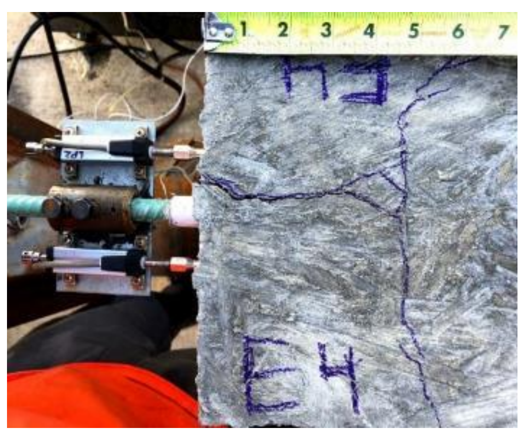
Slip at 4 kip = 8.8E-05 in	Max Load = 13145 lb	Max Stress = 66946 psi
Slip at 10 kip = 0.0008335 in	Apparent Yield Stress ~ 66 ksi	

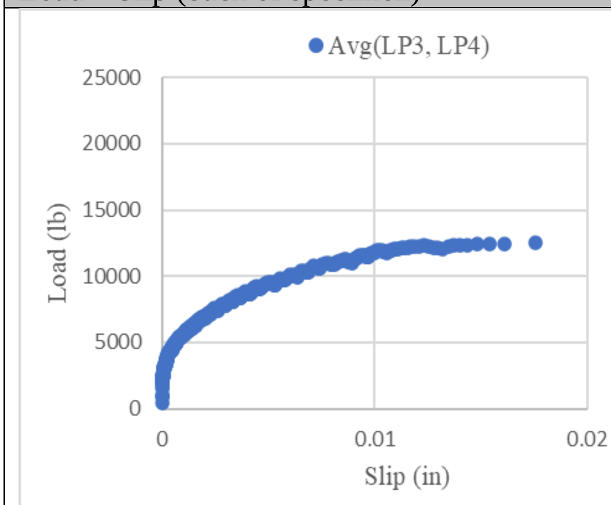
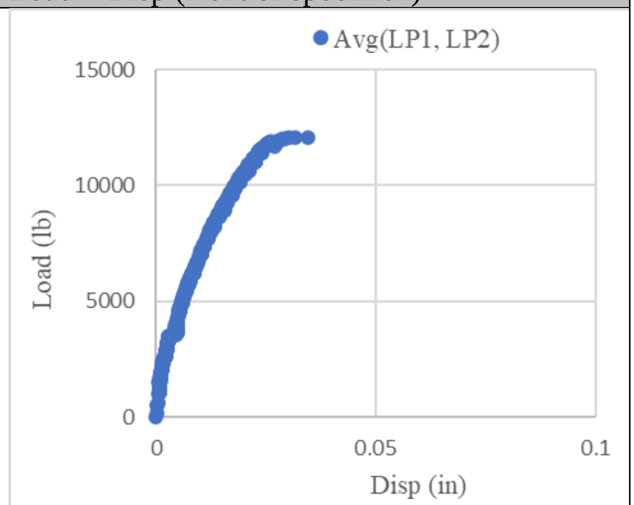
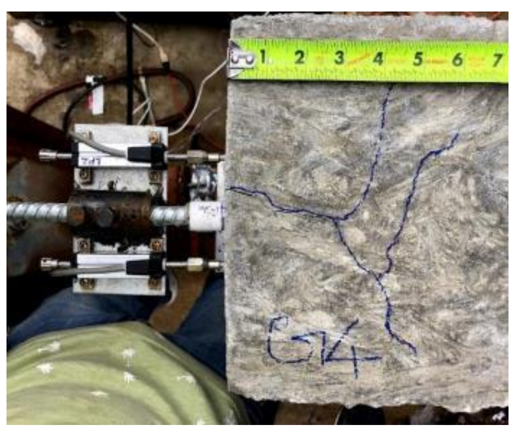
Description of the test	Picture after test
	

Bond Test Summary of specimen B4		
Bar Size: #4 Bar Type: Black Bonded Length: 4 in		Cast Date: 01-29-2019 Test Date: 02-18-2020
Concrete Compressive Strength		
Test Age(days)	No. of Cylinders	Avg. compressive strength (psi)
7	2	3710
14	2	4367
20 (B4)	1	5122
21 (G4)	2	4291
23 (T4)	2	4567
24 (E4)	2	4457
Load – Slip (back of specimen)	Load – Disp (front of specimen)	
		
Slip at 4 kip = 1E-05 in	Max Load = 11223 lb	Max Stress = 57160 psi
Slip at 10 kip = 0.002489 in	Apparent Yield Stress ~ 56 ksi	
Description of the test	Picture after test	

	 1 2 3 4 5 6 7

Bond Test Summary of specimen E4		
Bar Size: #4 Bar Type: Smooth Epoxy Bonded Length: 4 in	Cast Date: 01-29-2019 Test Date: 02-22-2020	
Concrete Compressive Strength		
Test Age(days)	No. of Cylinders	Avg. compressive strength (psi)
7	2	3710
14	2	4367
20 (B4)	1	5122
21 (G4)	2	4291
23 (T4)	2	4567
24 (E4)	2	4457

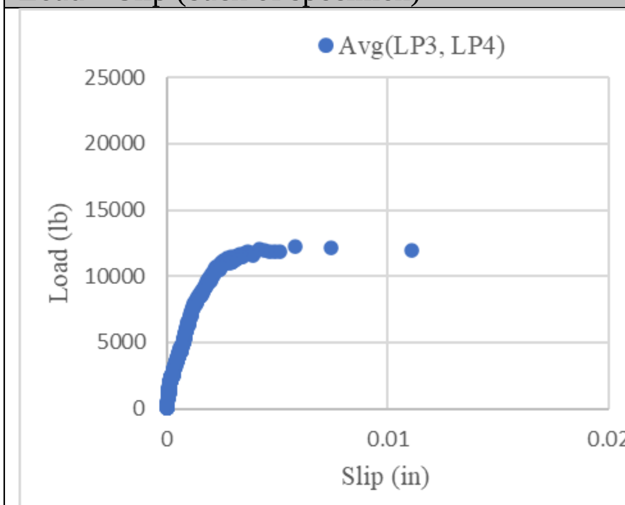
Load – Slip (back of specimen)	Load – Disp (front of specimen)	
		
Slip at 4 kip = 0.000787 in	Max Load = 10561 lb	Max Stress = 53787 psi
Slip at 10 kip = 0.0067075 in	Apparent Yield Stress ~ 53 ksi	
Description of the test	Picture after test	
		

<table>
<tr><th colspan="3">Bond Test Summary of specimen G4</th></tr>
<tr><td colspan="2">Bar Size: #4
Bar Type: Continuously Galvanized
Bonded Length: 4 in</td><td>Cast Date: 01-29-2019
Test Date: 02-19-2020</td></tr>
<tr><td colspan="3">Concrete Compressive Strength</td></tr>
<tr><td>Test Age(days)</td><td>No. of Cylinders</td><td>Avg. compressive strength (psi)</td></tr>
<tr><td>7</td><td>2</td><td>3710</td></tr>
<tr><td>14</td><td>2</td><td>4367</td></tr>
<tr><td>20 (B4)</td><td>1</td><td>5122</td></tr>
<tr><td>21 (G4)</td><td>2</td><td>4291</td></tr>
<tr><td>23 (T4)</td><td>2</td><td>4567</td></tr>
<tr><td>24 (E4)</td><td>2</td><td>4457</td></tr>
<tr><td colspan="2">Load – Slip (back of specimen)</td><td>Load – Disp (front of specimen)</td></tr>
<tr><td colspan="2">
</td><td>
</td></tr>
<tr><td colspan="2">Slip at 4 kip = 0.000395 in</td><td>Max Load = 12086 lb | Max Stress = 61555 psi</td></tr>
<tr><td colspan="2">Slip at 10 kip = 0.006934 in</td><td>Apparent Yield Stress ~ 61 ksi</td></tr>
<tr><td colspan="2">Description of the test</td><td>Picture after test</td></tr>
<tr><td colspan="2"></td><td>
</td></tr>
</table>

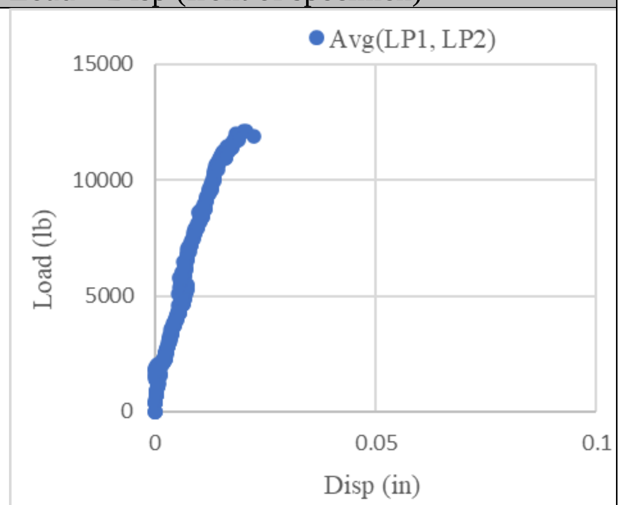
Bond Test Summary of specimen T4	
Bar Size: #4 Bar Type: Textured Epoxy Bonded Length: 4 in	Cast Date: 01-29-2019 Test Date: 02-21-2020

Concrete Compressive Strength		
Test Age(days)	No. of Cylinders	Avg. compressive strength (psi)
7	2	3710
14	2	4367
20 (B4)	1	5122
21 (G4)	2	4291
23 (T4)	2	4567
24 (E4)	2	4457

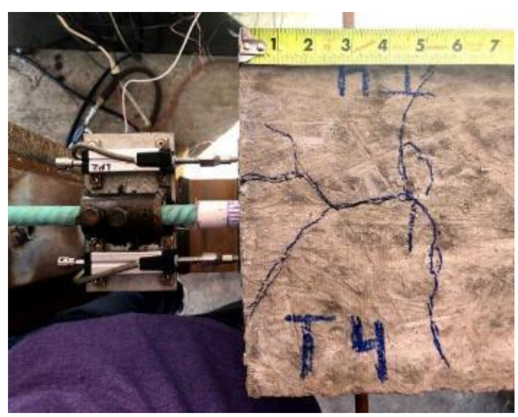
Load – Slip (back of specimen)

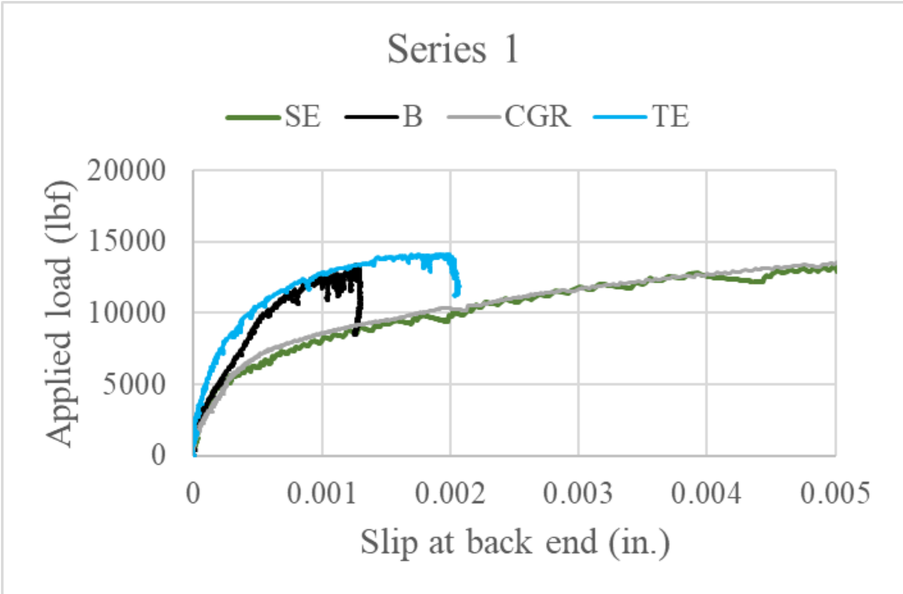


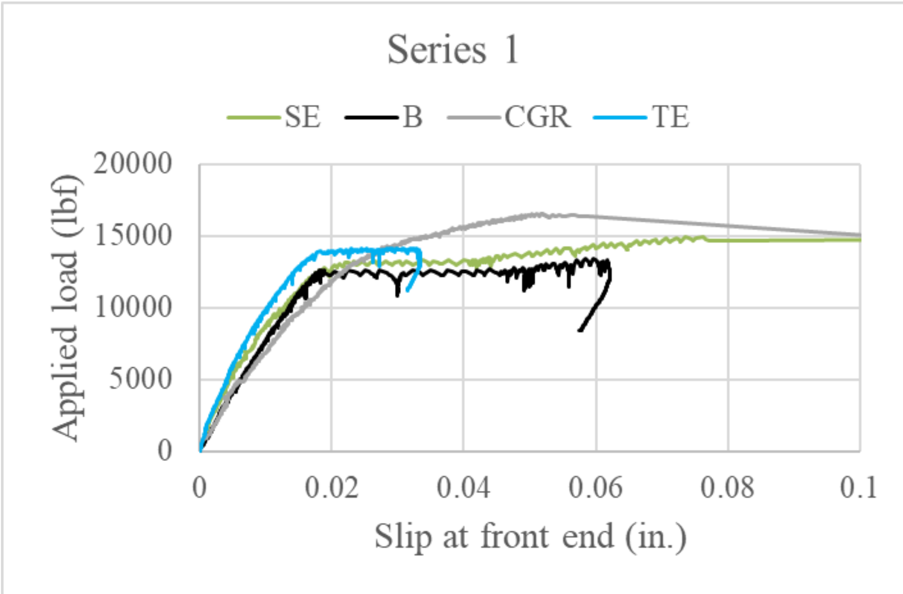
Load – Disp (front of specimen)

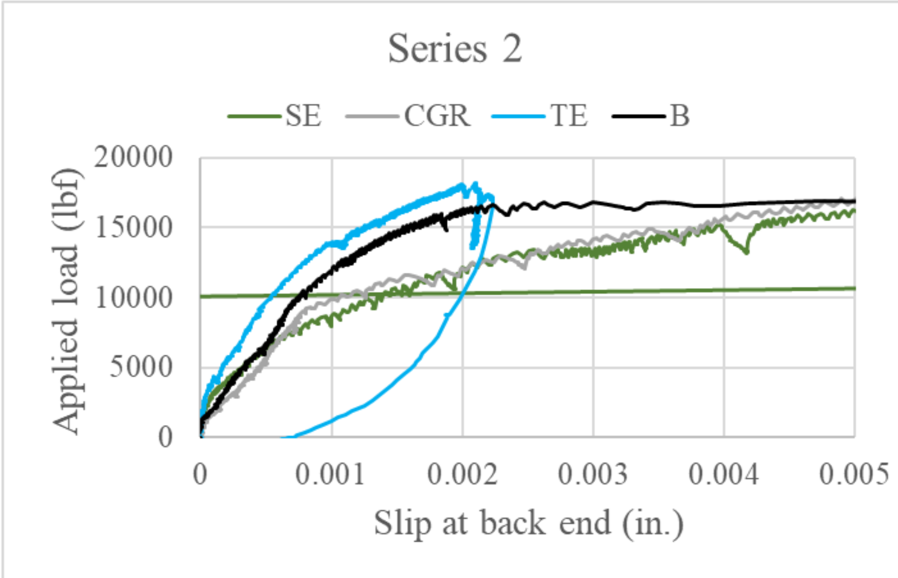


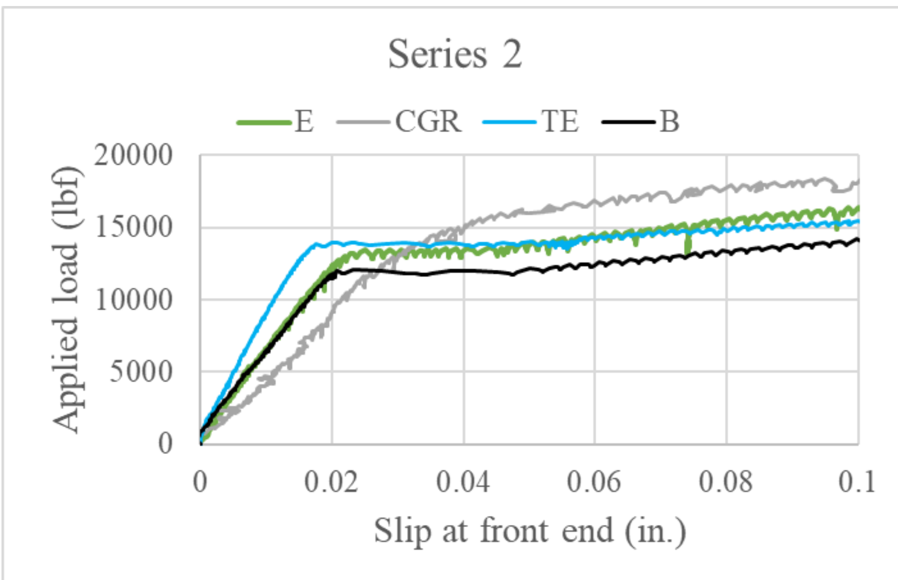
Slip at 4 kip = 0.00051 in	Max Load = 12134 lb	Max Stress = 61796 psi
Slip at 10 kip = 0.0020305 in	Apparent Yield Stress ~ 61 ksi	

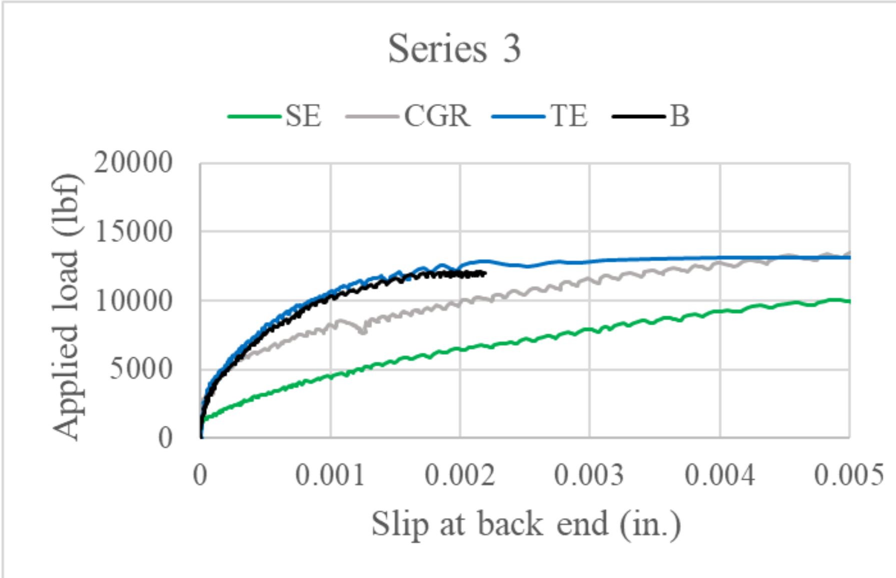
Description of the test	Picture after test
	

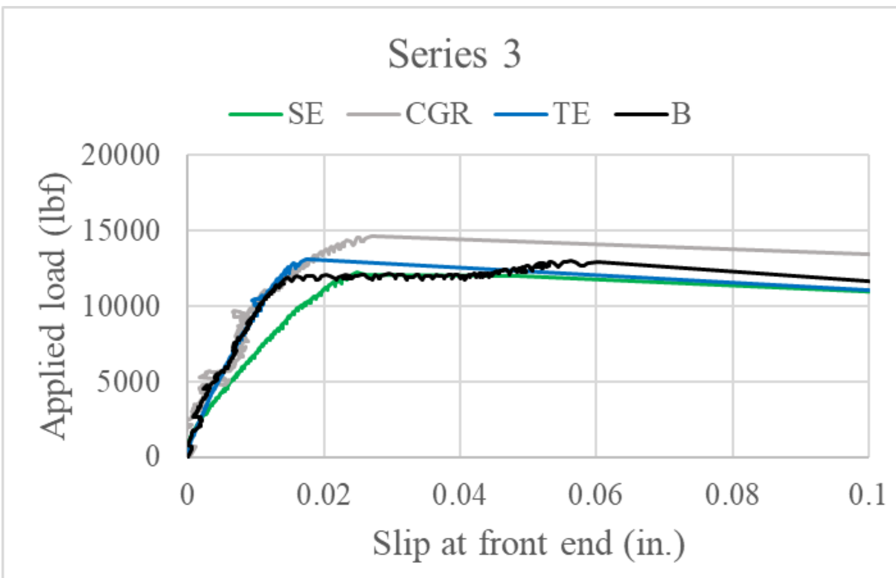

Series 1
SE
B
CGR
TE
Applied load (lbf)
20000
15000
10000
5000
0
0
0.001
0.002
0.003
0.004
0.005
Slip at back end (in.)

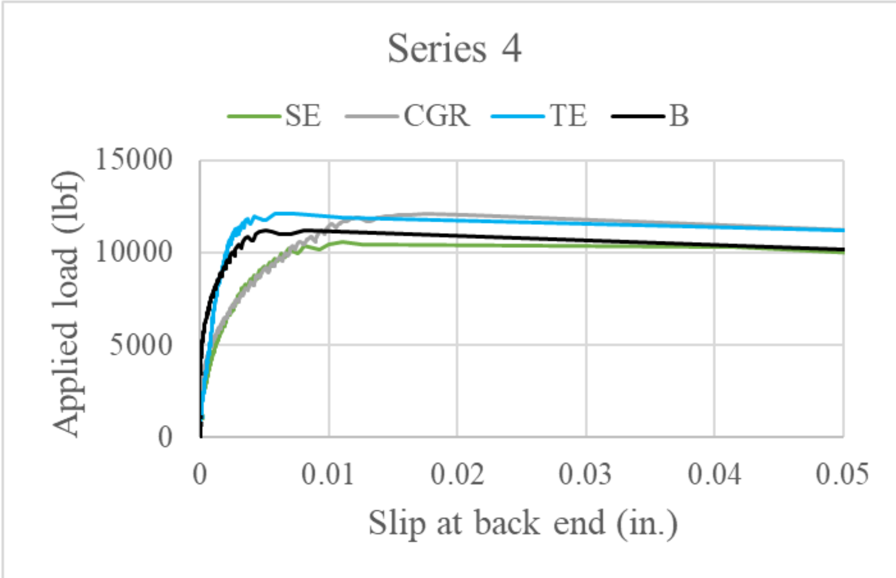

Series 1
SE
B
CGR
TE
Applied load (lbf)
20000
15000
10000
5000
0
0
0.02
0.04
0.06
0.08
0.1
Slip at front end (in.)

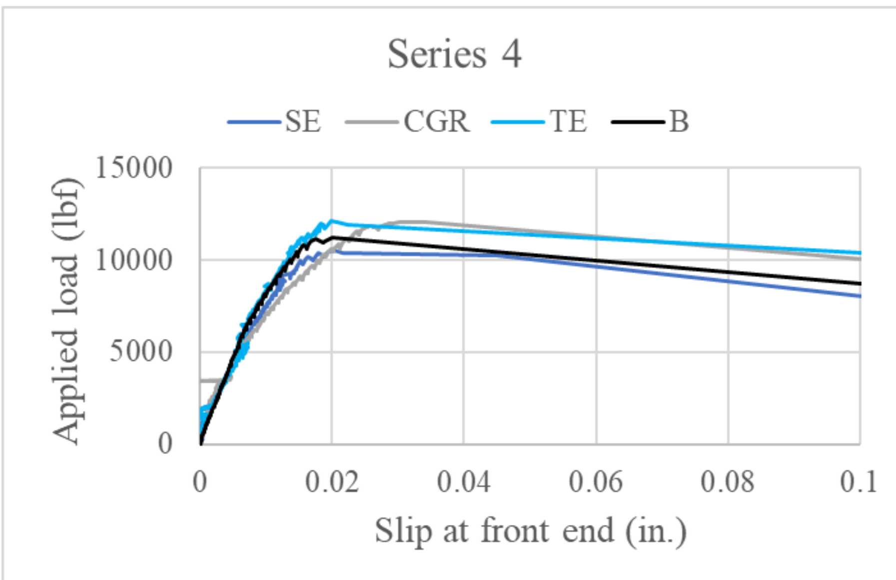

Series 2
SE
CGR
TE
B
Applied load (lbf)
20000
15000
10000
5000
0
0
0.001
0.002
0.003
0.004
0.005
Slip at back end (in.)


Series 2
E
CGR
TE
B
Applied load (lbf)
20000
15000
10000
5000
0
0
0.02
0.04
0.06
0.08
0.1
Slip at front end (in.)

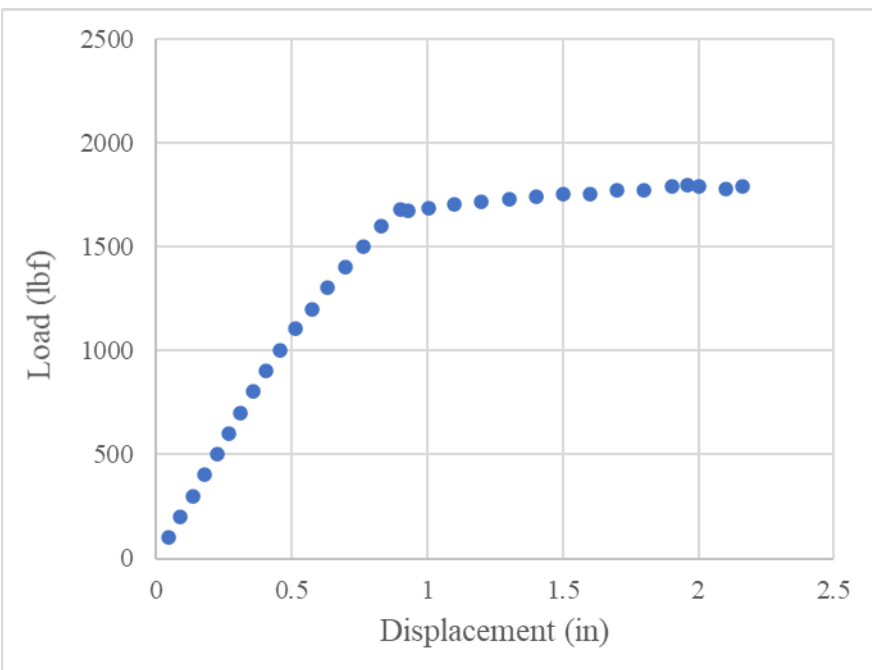

Series 3
SE
CGR
TE
B
Applied load (lbf)
20000
15000
10000
5000
0
0
0.001
0.002
0.003
0.004
0.005
Slip at back end (in.)


Series 3
SE
CGR
TE
B
Applied load (lbf)
20000
15000
10000
5000
0
0
0.02
0.04
0.06
0.08
0.1
Slip at front end (in.)

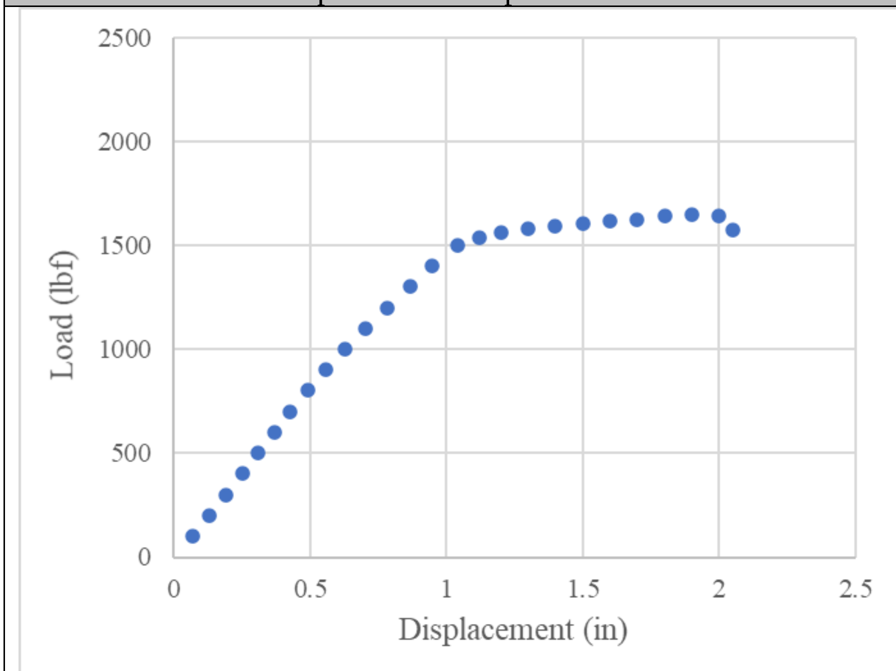

Series 4
SE
CGR
TE
B
Applied load (lbf)
15000
10000
5000
0
0
0.01
0.02
0.03
0.04
0.05
Slip at back end (in.)

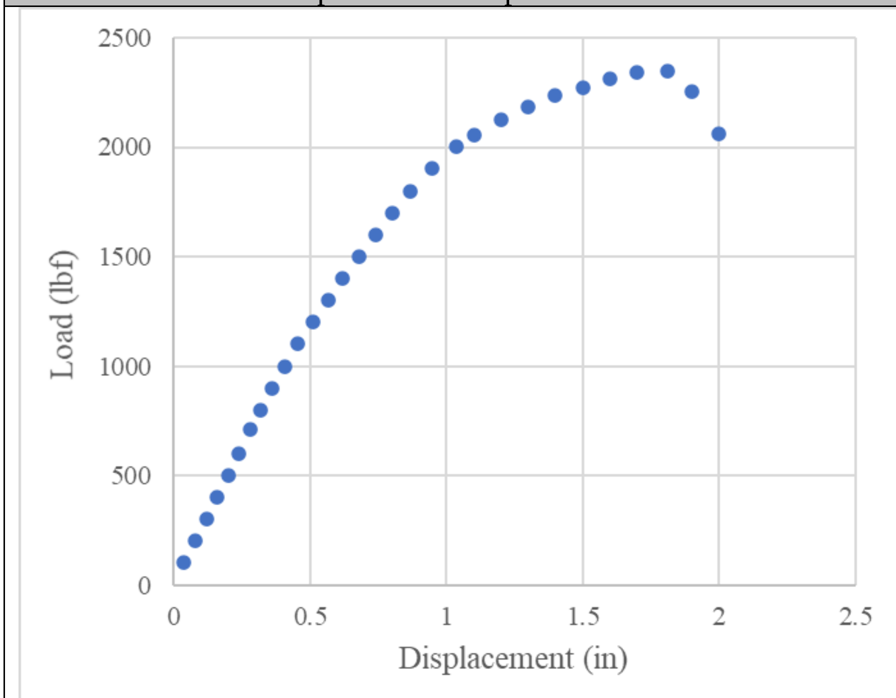

Series 4
SE
CGR
TE
B
Applied load (lbf)
15000
10000
5000
0
0
0.02
0.04
0.06
0.08
0.1
Slip at front end (in.)

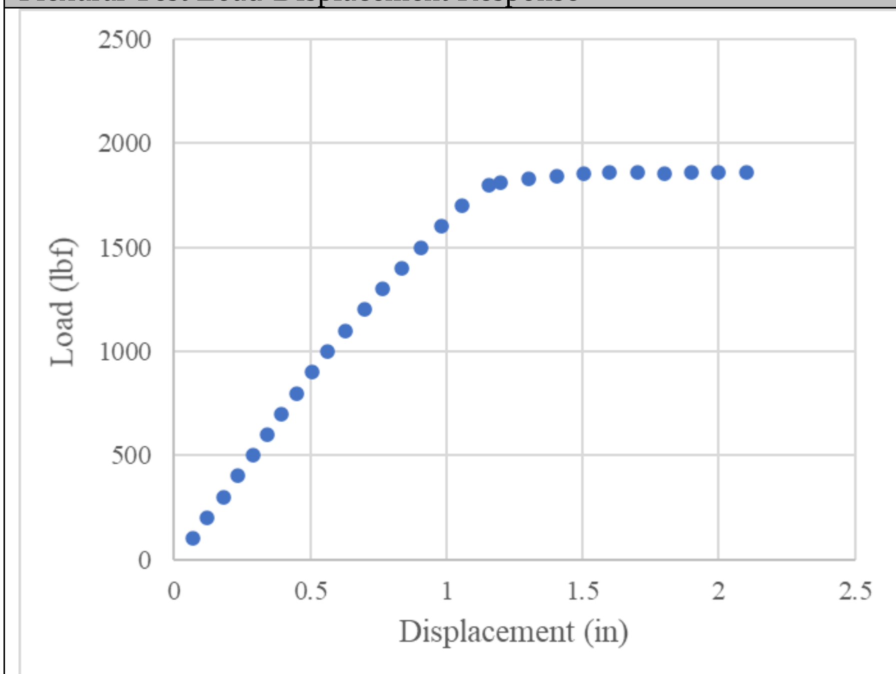
APPENDIX D – STATIC LOAD BEAMS

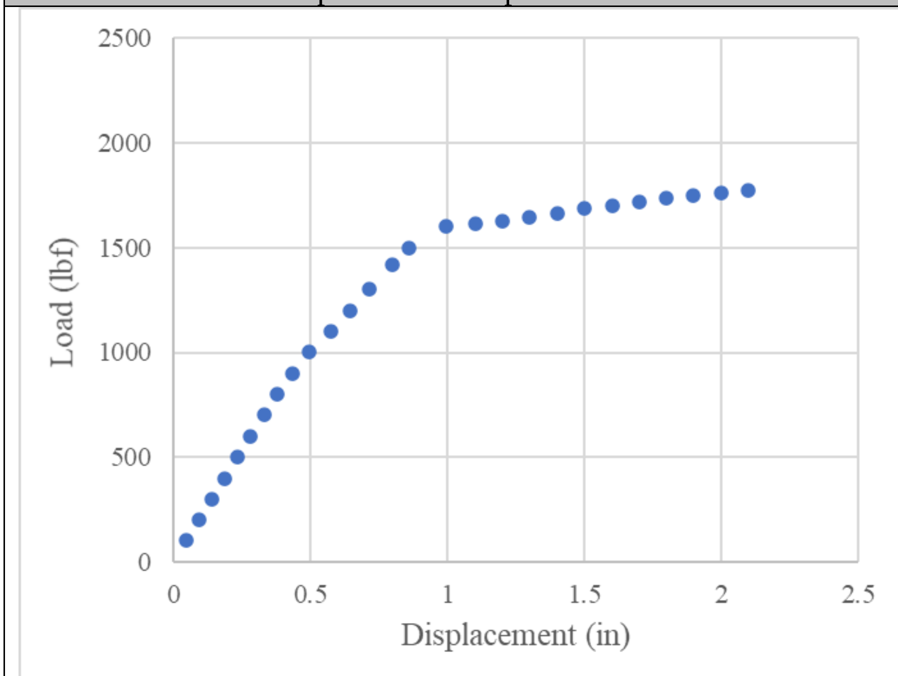
“Static Load Beam” Test Summary of specimen B1-L		
Bar Size: #4 Bar Type: Black	Cast Date: 10-07-2019 Static Load Test: 04-07-2020 Flexural Test: 06-11-2020	
Static Load Measurements	Value	
Number of cracks (total both sides)	28	
Length of cracks (total both sides)	35.87 in.	
Average spacing between cracks (sides only)	4 in.	
Average width of cracks (sides only)	0.005 in.	
Maximum crack width	0.01in.	
Area of cracks (total both sides)	0.096 in.^{2}	
Displacement at day 7	0.366 in.	
Flexural Test Load-Displacement Response	Parameter	Value
	Displacement at 250 lb	0.11 in.
	Displacement at 500 lb	0.22 in.
	Displacement at 750 lb	0.33 in.
	Peak Load	1795 lb.
	Transformed MOI	12.77 in.^{4}
	Cracked MOI	3.28 in.^{4}
	28-Day Compressive Strength	5070 psi

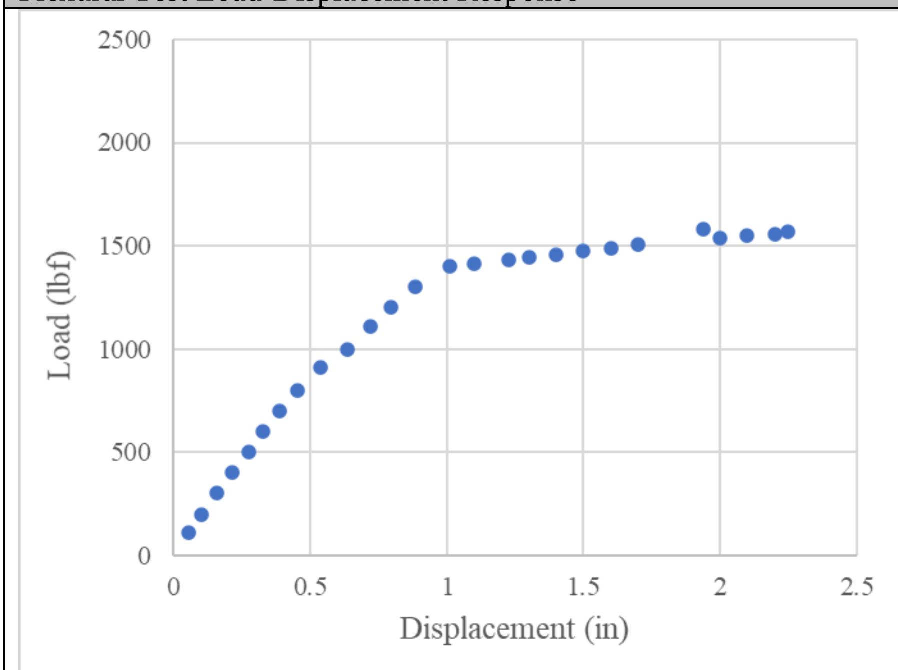
“Static Load Beam” Test Summary of specimen E1-L	
Bar Size: #4 Bar Type: Smooth Epoxy	Cast Date: 10-07-2019 Static Load Test: 04-07-2020 Flexural Test: 06-11-2020
Static Load Measurements	**Value**
Number of cracks (total both sides)	25
Length of cracks (total both sides)	36.06 in.
Average spacing between cracks (sides only)	3.78 in.
Average width of cracks (sides only)	0.006 in.
Maximum crack width	0.011 in.
Area of cracks (total both sides)	0.12 $in.^2$
Displacement at day 7	0.443 in.

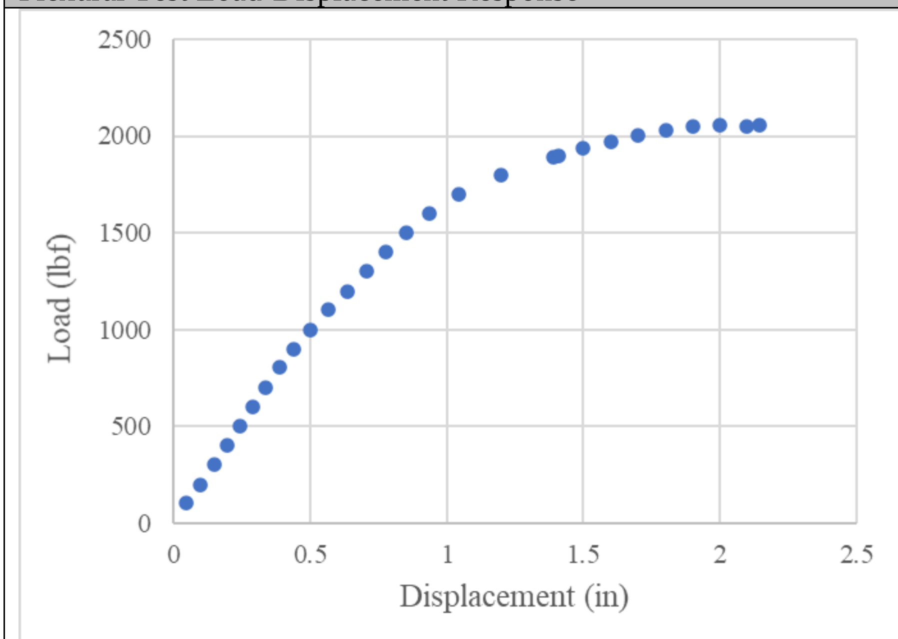
Flexural Test Load-Displacement Response	Parameter	Value
	Displacement at 250 lb	0.16 in.
	Displacement at 500 lb	0.31 in.
	Displacement at 750 lb	0.46 in.
	Peak Load	1650 lb.
	Transformed MOI	12.76 $in.^4$
	Cracked MOI	3.26 $in.^4$
	28-Day Compressive Strength	5070 psi

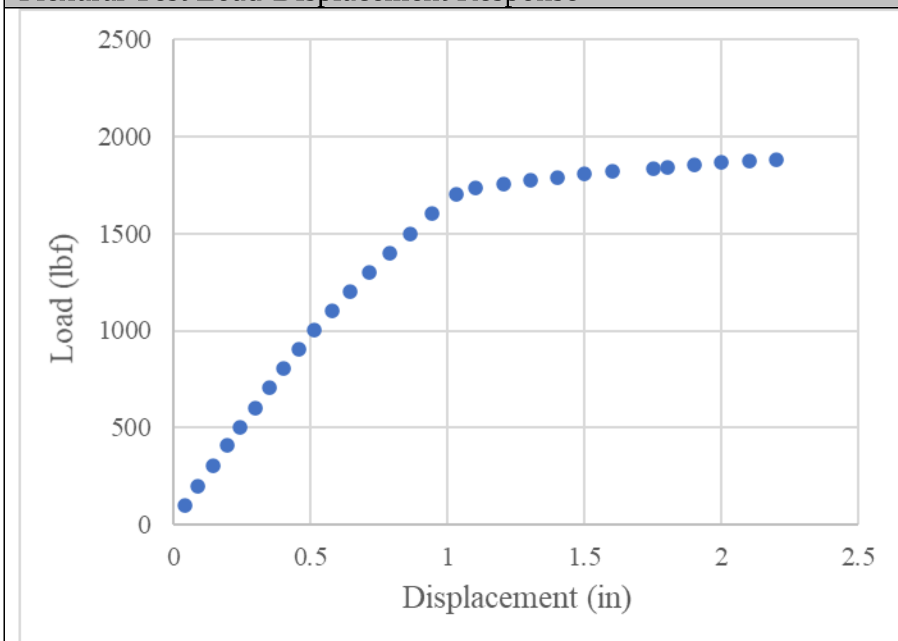
<table>
<tr><th colspan="3">“Static Load Beam” Test Summary of specimen G1-L</th></tr>
<tr><td>Bar Size: #4
Bar Type: Continuously Galvanized (CGR)</td><td colspan="2">Cast Date: 10-07-2019
Static Load Test: 04-07-2020
Flexural Test: 06-11-2020</td></tr>
<tr><th>Static Load Measurements</th><th colspan="2">Value</th></tr>
<tr><td>Number of cracks (total both sides)</td><td colspan="2">25</td></tr>
<tr><td>Length of cracks (total both sides)</td><td colspan="2">26.69 in.</td></tr>
<tr><td>Average spacing between cracks (sides only)</td><td colspan="2">4.72 in.</td></tr>
<tr><td>Average width of cracks (sides only)</td><td colspan="2">0.004 in.</td></tr>
<tr><td>Maximum crack width</td><td colspan="2">0.009 in.</td></tr>
<tr><td>Area of cracks (total both sides)</td><td colspan="2">0.059 $in.^2$</td></tr>
<tr><td>Displacement at day 7</td><td colspan="2">0.336 in.</td></tr>
<tr><th>Flexural Test Load-Displacement Response</th><th>Parameter</th><th>Value</th></tr>
<tr><td rowspan="7">
</td><td>Displacement at 250 lb</td><td>0.10 in.</td></tr>
<tr><td>Displacement at 500 lb</td><td>0.20 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.29 in.</td></tr>
<tr><td>Peak Load</td><td>2347 lb.</td></tr>
<tr><td>Transformed MOI</td><td>12.77 $in.^4$</td></tr>
<tr><td>Cracked MOI</td><td>3.32 $in.^4$</td></tr>
<tr><td>28-Day Compressive Strength</td><td>5070 psi</td></tr>
</table>

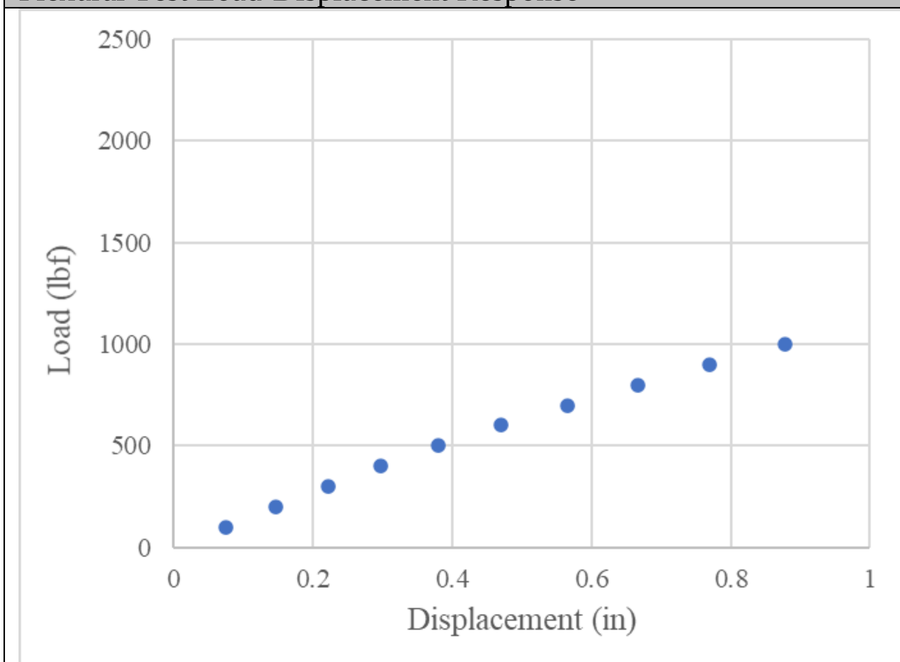
<table>
<tr><th colspan="3">"Static Load Beam" Test Summary of specimen T1-L</th></tr>
<tr><td>Bar Size: #4
Bar Type: Textured Epoxy</td><td colspan="2">Cast Date: 10-07-2019
Static Load Test: 04-07-2020
Flexural Test: 06-11-2020</td></tr>
<tr><th>Static Load Measurements</th><th colspan="2">Value</th></tr>
<tr><td>Number of cracks (total both sides)</td><td colspan="2">32</td></tr>
<tr><td>Length of cracks (total both sides)</td><td colspan="2">45.87 in.</td></tr>
<tr><td>Average spacing between cracks (sides only)</td><td colspan="2">2.89 in.</td></tr>
<tr><td>Average width of cracks (sides only)</td><td colspan="2">0.004 in.</td></tr>
<tr><td>Maximum crack width</td><td colspan="2">0.007 in.</td></tr>
<tr><td>Area of cracks (total both sides)</td><td colspan="2">0.097 in.^{2}</td></tr>
<tr><td>Displacement at day 7</td><td colspan="2">0.463 in.</td></tr>
<tr><th>Flexural Test Load-Displacement Response</th><th>Parameter</th><th>Value</th></tr>
<tr><td rowspan="7">
</td><td>Displacement at 250 lb</td><td>0.15 in.</td></tr>
<tr><td>Displacement at 500 lb</td><td>0.29 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.43 in.</td></tr>
<tr><td>Peak Load</td><td>1862 lb.</td></tr>
<tr><td>Transformed MOI</td><td>12.76 in.^{4}</td></tr>
<tr><td>Cracked MOI</td><td>3.25 in.^{4}</td></tr>
<tr><td>28-Day Compressive Strength</td><td>5070 psi</td></tr>
</table>

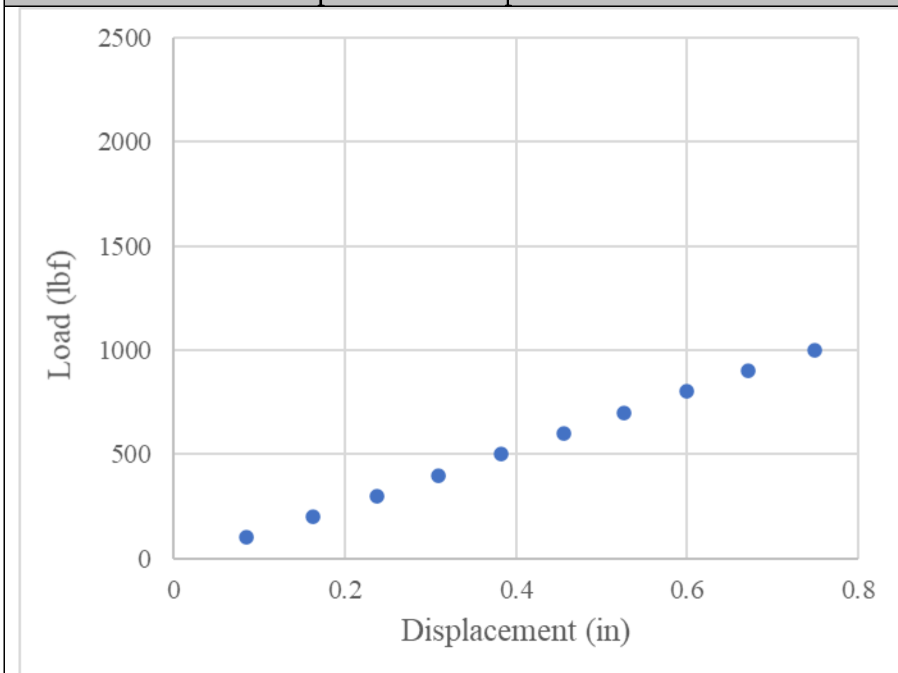
<table>
<tr><th colspan="3">“Static Load Beam” Test Summary of specimen B2-L</th></tr>
<tr><td>Bar Size: #4
Bar Type: Black</td><td colspan="2">Cast Date: 10-28-2019
Static Load Test: 06-09-2020
Flexural Test: 06-23-2020</td></tr>
<tr><th>Static Load Measurements</th><th colspan="2">Value</th></tr>
<tr><td>Number of cracks (total both sides)</td><td colspan="2">21</td></tr>
<tr><td>Total length of cracks (total both sides)</td><td colspan="2">36.102 in.</td></tr>
<tr><td>Average spacing between cracks (sides only)</td><td colspan="2">3.95 in.</td></tr>
<tr><td>Average width of cracks (sides only)</td><td colspan="2">0.004 in.</td></tr>
<tr><td>Maximum crack width</td><td colspan="2">0.007 in.</td></tr>
<tr><td>Area of cracks (total both sides)</td><td colspan="2">0.067 in.^{2}</td></tr>
<tr><td>Displacement at day 7</td><td colspan="2">0.523 in.</td></tr>
<tr><th>Flexural Test Load-Displacement Response</th><th>Parameter</th><th>Value</th></tr>
<tr><td rowspan="7">
</td><td>Displacement at 250 lb</td><td>0.11 in.</td></tr>
<tr><td>Displacement at 500 lb</td><td>0.23 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.35 in.</td></tr>
<tr><td>Peak Load</td><td>1770 lb.</td></tr>
<tr><td>Transformed MOI</td><td>12.75 in.^{4}</td></tr>
<tr><td>Cracked MOI</td><td>3.12 in.^{4}</td></tr>
<tr><td>28-Day Compressive Strength</td><td>5940 psi</td></tr>
</table>

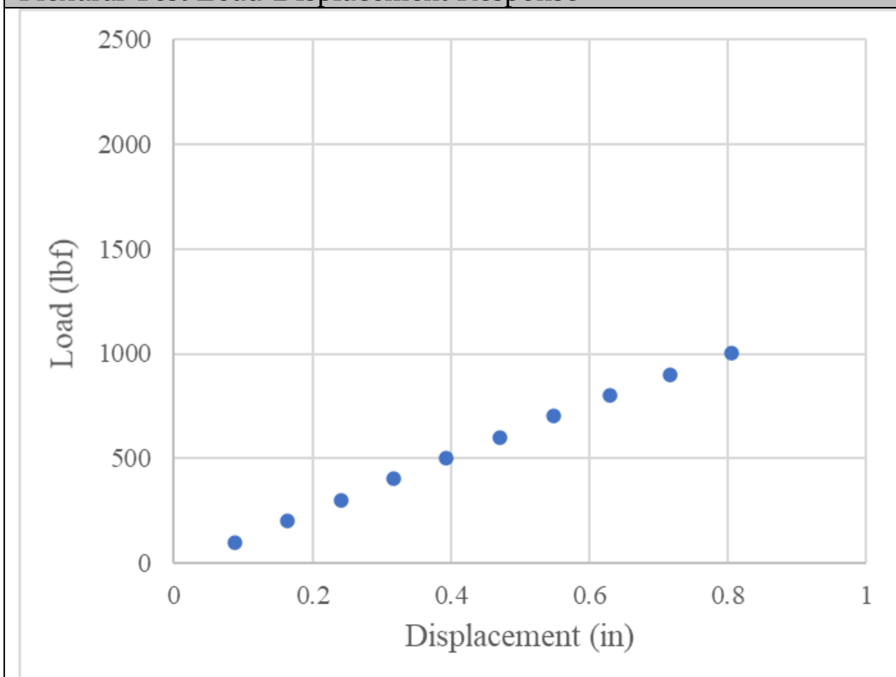
<table>
<tr><th colspan="3">“Static Load Beam” Test Summary of specimen E2-L</th></tr>
<tr><td>Bar Size: #4
Bar Type: Smooth Epoxy</td><td colspan="2">Cast Date: 10-28-2019
Static Load Test: 06-09-2020
Flexural Test: 06-23-2020</td></tr>
<tr><th>Static Load Measurements</th><th colspan="2">Value</th></tr>
<tr><td>Number of cracks (total both sides)</td><td colspan="2">19</td></tr>
<tr><td>Length of cracks (total both sides)</td><td colspan="2">38.307 in.</td></tr>
<tr><td>Average spacing between cracks (sides only)</td><td colspan="2">5.02 in.</td></tr>
<tr><td>Average width of cracks (sides only)</td><td colspan="2">0.004 in.</td></tr>
<tr><td>Maximum crack width</td><td colspan="2">0.007 in.</td></tr>
<tr><td>Area of cracks (total both sides)</td><td colspan="2">0.086 in.^{2}</td></tr>
<tr><td>Displacement at day 7</td><td colspan="2">0.564 in.</td></tr>
<tr><th>Flexural Test Load-Displacement Response</th><th>Parameter</th><th>Value</th></tr>
<tr><td rowspan="7">
</td><td>Displacement at 250 lb</td><td>0.12 in.</td></tr>
<tr><td>Displacement at 500 lb</td><td>0.28 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.44 in.</td></tr>
<tr><td>Peak Load</td><td>1580 lb.</td></tr>
<tr><td>Transformed MOI</td><td>12.74 in.^{4}</td></tr>
<tr><td>Cracked MOI</td><td>3.1 in.^{4}</td></tr>
<tr><td>28-Day Compressive Strength</td><td>5940 psi</td></tr>
</table>

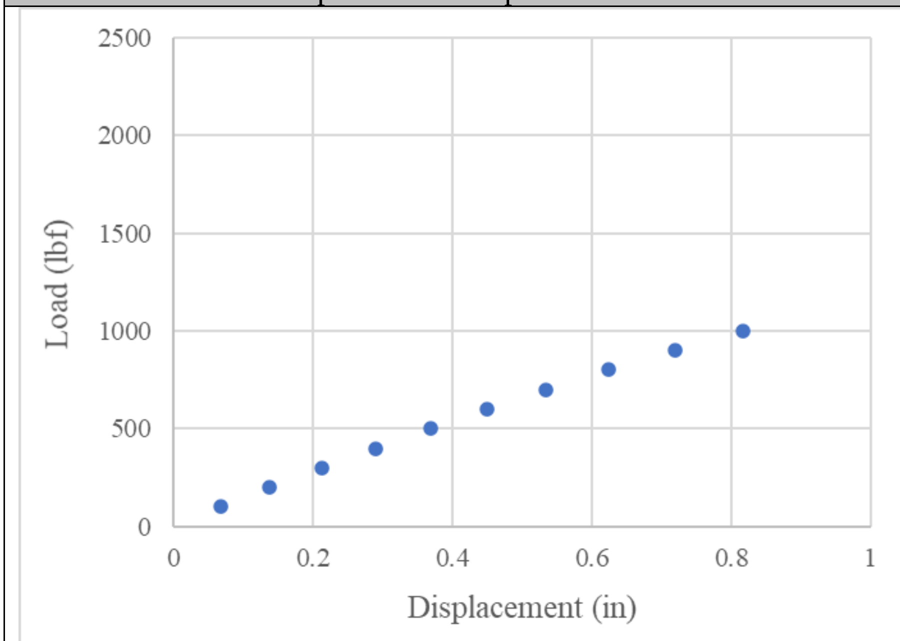
<table>
<tr><th colspan="3">“Static Load Beam” Test Summary of specimen G2-L</th></tr>
<tr><td>Bar Size: #4
Bar Type: Continuously Galvanized (CGR)</td><td colspan="2">Cast Date: 10-28-2019
Static Load Test: 06-09-2020
Flexural Test: 06-23-2020</td></tr>
<tr><th>Static Load Measurements</th><th colspan="2">Value</th></tr>
<tr><td>Number of cracks (total both sides)</td><td colspan="2">22</td></tr>
<tr><td>Length of cracks (total both sides)</td><td colspan="2">36.142 in.</td></tr>
<tr><td>Average spacing between cracks (sides only)</td><td colspan="2">3.86 in.</td></tr>
<tr><td>Average width of cracks (sides only)</td><td colspan="2">0.004 in.</td></tr>
<tr><td>Maximum crack width</td><td colspan="2">0.005 in.</td></tr>
<tr><td>Area of cracks (total both sides)</td><td colspan="2">0.069 in.^{2}</td></tr>
<tr><td>Displacement at day 7</td><td colspan="2">0.523 in.</td></tr>
<tr><th>Flexural Test Load-Displacement Response</th><th>Parameter</th><th>Value</th></tr>
<tr><td rowspan="7">
</td><td>Displacement at 250 lb</td><td>0.12 in.</td></tr>
<tr><td>Displacement at 500 lb</td><td>0.24 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.36 in.</td></tr>
<tr><td>Peak Load</td><td>2059 lb.</td></tr>
<tr><td>Transformed MOI</td><td>12.75 in.^{4}</td></tr>
<tr><td>Cracked MOI</td><td>3.15 in.^{4}</td></tr>
<tr><td>28-Day Compressive Strength</td><td>5940 psi</td></tr>
</table>

“Static Load Beam” Test Summary of specimen T2-L		
Bar Size: #4 Bar Type: Textured Epoxy	Cast Date: 10-28-2019 Static Load Test: 06-09-2020 Flexural Test: 06-23-2020	
Static Load Measurements	**Value**	
Number of cracks (total both sides)	28	
Length of cracks (total both sides)	48.78 in.	
Average spacing between cracks (sides only)	3.18 in.	
Average width of cracks (sides only)	0.004 in.	
Maximum crack width	0.007 in.	
Area of cracks (total both sides)	0.104 in.^{2}	
Displacement at day 7	0.597 in.	
Flexural Test Load-Displacement Response	**Parameter**	**Value**
	Displacement at 250 lb	0.11 in.
	Displacement at 500 lb	0.24 in.
	Displacement at 750 lb	0.38 in.
	Peak Load	1880 lb.
	Transformed MOI	12.74 in.^{4}
	Cracked MOI	3.08 in.^{4}
	28-Day Compressive Strength	5940 psi

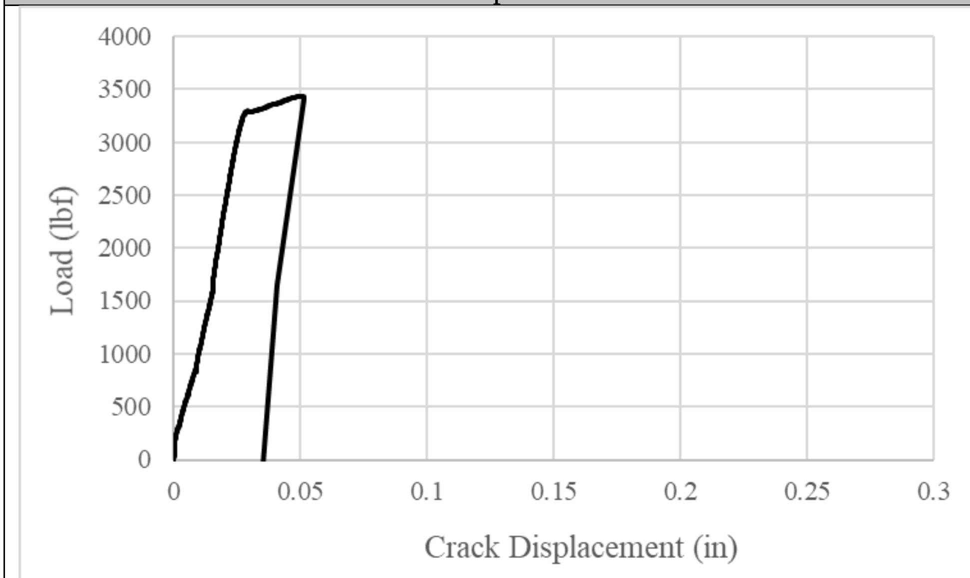
<table>
<tr><td colspan="3">“Static Load Beam” Test Summary of specimen B3-L</td></tr>
<tr><td>Bar Size: #4
Bar Type: Black</td><td colspan="2">Cast Date: 10-16-2020
Static Load Test: 12-10-2020
Flexural Test: 02-18-2021</td></tr>
<tr><td>Static Load Measurements</td><td colspan="2">Value</td></tr>
<tr><td>Number of cracks (total both sides)</td><td colspan="2">15</td></tr>
<tr><td>Length of cracks (total both sides)</td><td colspan="2">21.163 in.</td></tr>
<tr><td>Average spacing between cracks (sides only)</td><td colspan="2">4.587 in.</td></tr>
<tr><td>Average width of cracks (sides only)</td><td colspan="2">0.006 in.</td></tr>
<tr><td>Maximum crack width</td><td colspan="2">0.008 in.</td></tr>
<tr><td>Area of cracks (total both sides)</td><td colspan="2">0.058 $in.^2$</td></tr>
<tr><td>Displacement at day 7</td><td colspan="2">0.645 in.</td></tr>
<tr><td>Flexural Test Load-Displacement Response</td><td>Parameter</td><td>Value</td></tr>
<tr><td rowspan="7">
</td><td>Displacement at 250 lb</td><td>0.18 in.</td></tr>
<tr><td>Displacement at 500 lb</td><td>0.38 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.62 in.</td></tr>
<tr><td>Peak Load</td><td>---------</td></tr>
<tr><td>Transformed MOI</td><td>12.77 $in.^4$</td></tr>
<tr><td>Cracked MOI</td><td>3.27 $in.^4$</td></tr>
<tr><td>28-Day Compressive Strength</td><td>5139 psi</td></tr>
</table>

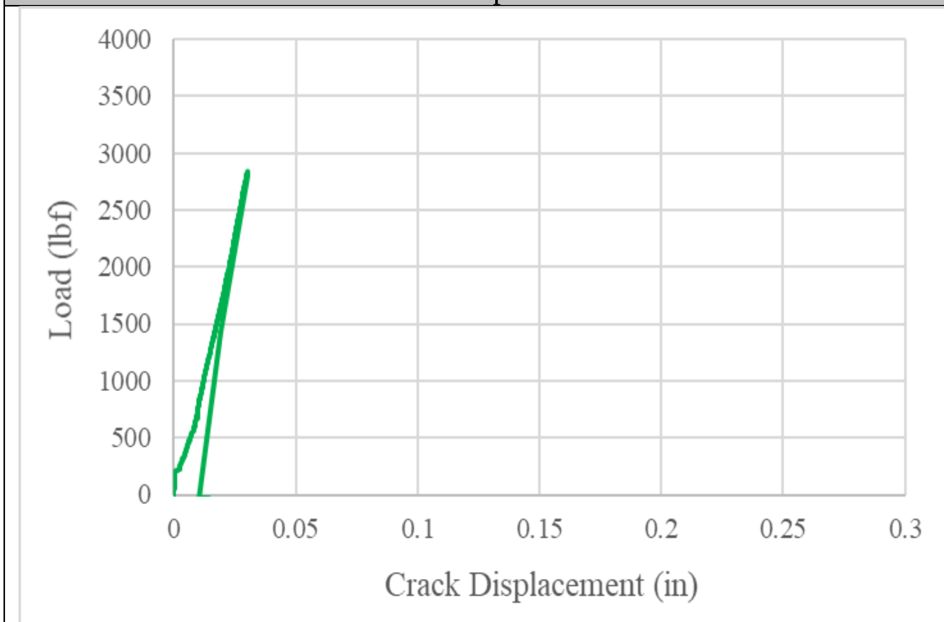
<table>
<tr><th colspan="3">“Static Load Beam” Test Summary of specimen E3-L</th></tr>
<tr><td>Bar Size: #4
Bar Type: Smooth Epoxy</td><td colspan="2">Cast Date: 10-16-2020
Static Load Test: 12-10-2020
Flexural Test: 02-18-2021</td></tr>
<tr><th>Static Load Measurements</th><th colspan="2">Value</th></tr>
<tr><td>Number of cracks (total both sides)</td><td colspan="2">23</td></tr>
<tr><td>Length of cracks (total both sides)</td><td colspan="2">32.48 in.</td></tr>
<tr><td>Average spacing between cracks (sides only)</td><td colspan="2">4.45 in.</td></tr>
<tr><td>Average width of cracks (sides only)</td><td colspan="2">0.007 in.</td></tr>
<tr><td>Maximum crack width</td><td colspan="2">0.012 in.</td></tr>
<tr><td>Area of cracks (total both sides)</td><td colspan="2">0.118 $in.^2$</td></tr>
<tr><td>Displacement at day 7</td><td colspan="2">0.79 in.</td></tr>
<tr><th>Flexural Test Load-Displacement Response</th><th>Parameter</th><th>Value</th></tr>
<tr><td rowspan="7">
</td><td>Displacement at 250 lb</td><td>0.2 in.</td></tr>
<tr><td>Displacement at 500 lb</td><td>0.38 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.57 in.</td></tr>
<tr><td>Peak Load</td><td>---------</td></tr>
<tr><td>Transformed MOI</td><td>12.76 $in.^4$</td></tr>
<tr><td>Cracked MOI</td><td>3.25 $in.^4$</td></tr>
<tr><td>28-Day Compressive Strength</td><td>5139 psi</td></tr>
</table>

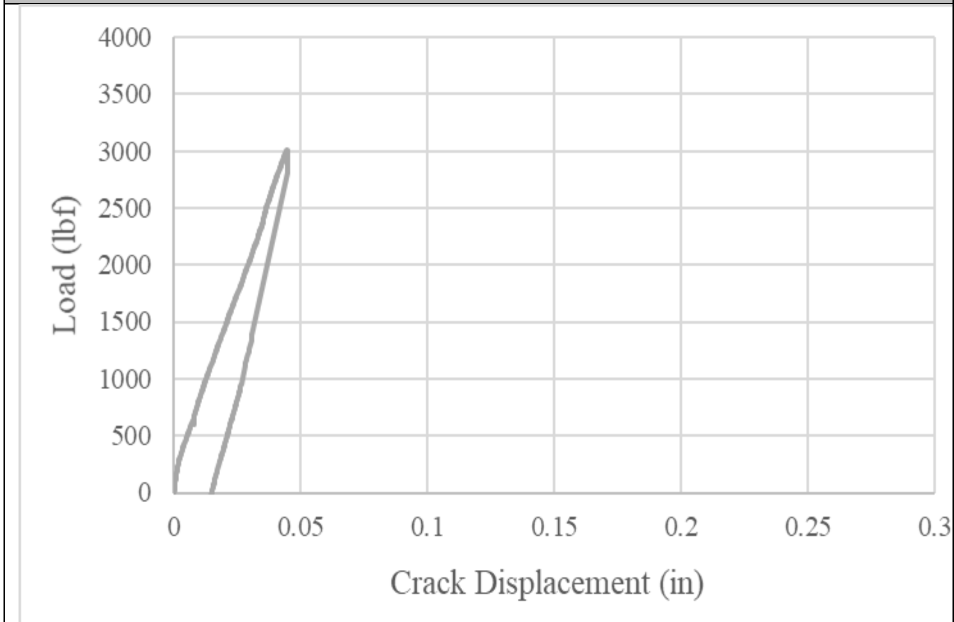
<table>
<tr><th colspan="3">“Static Load Beam” Test Summary of specimen G3-L</th></tr>
<tr><td>Bar Size: #4
Bar Type: Continuously Galvanized (CGR)</td><td colspan="2">Cast Date: 10-16-2020
Static Load Test: 12-10-2020
Flexural Test: 02-18-2021</td></tr>
<tr><th>Static Load Measurements</th><th colspan="2">Value</th></tr>
<tr><td>Number of cracks (total both sides)</td><td colspan="2">24</td></tr>
<tr><td>Length of cracks (total both sides)</td><td colspan="2">27.016 in.</td></tr>
<tr><td>Average spacing between cracks (sides only)</td><td colspan="2">3.76 in.</td></tr>
<tr><td>Average width of cracks (sides only)</td><td colspan="2">0.006 in.</td></tr>
<tr><td>Maximum crack width</td><td colspan="2">0.01 in.</td></tr>
<tr><td>Area of cracks (total both sides)</td><td colspan="2">0.085 in.^{2}</td></tr>
<tr><td>Displacement at day 7</td><td colspan="2">0.803 in.</td></tr>
<tr><th>Flexural Test Load-Displacement Response</th><th>Parameter</th><th>Value</th></tr>
<tr><td rowspan="7">
</td><td>Displacement at 250 lb</td><td>0.2 in.</td></tr>
<tr><td>Displacement at 500 lb</td><td>0.39 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.58 in.</td></tr>
<tr><td>Peak Load</td><td>---------</td></tr>
<tr><td>Transformed MOI</td><td>12.77 in.^{4}</td></tr>
<tr><td>Cracked MOI</td><td>3.3 in.^{4}</td></tr>
<tr><td>28-Day Compressive Strength</td><td>5139 psi</td></tr>
</table>

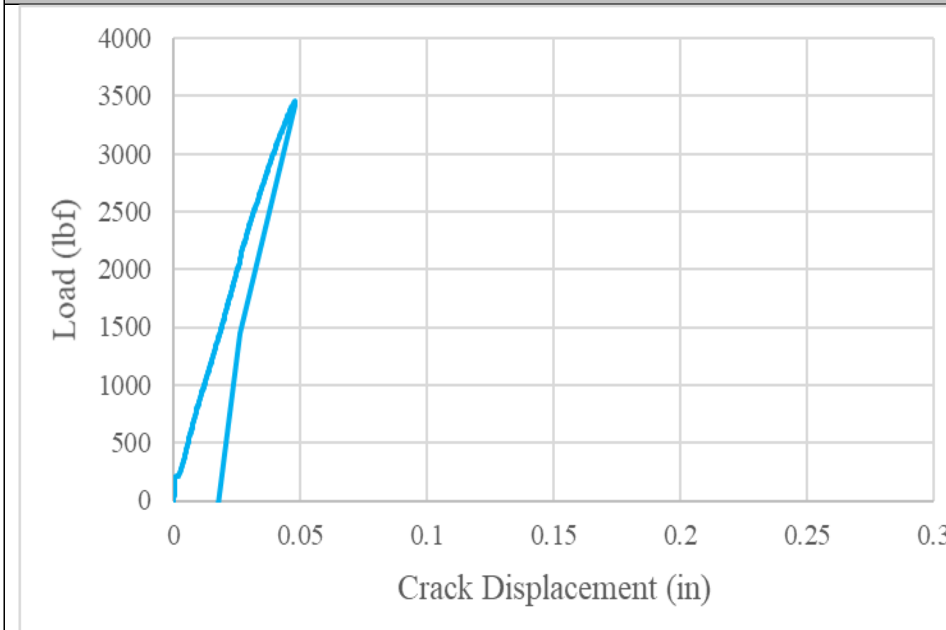
<table>
<tr><th colspan="3">“Static Load Beam” Test Summary of specimen T3-L</th></tr>
<tr><td>Bar Size: #4
Bar Type: Textured Epoxy</td><td colspan="2">Cast Date: 10-16-2020
Static Load Test: 12-10-2020
Flexural Test: 02-18-2021</td></tr>
<tr><th>Static Load Measurements</th><th colspan="2">Value</th></tr>
<tr><td>Number of cracks (total both sides)</td><td colspan="2">27</td></tr>
<tr><td>Length of cracks (total both sides)</td><td colspan="2">35.352 in.</td></tr>
<tr><td>Average spacing between cracks (sides only)</td><td colspan="2">3.94 in.</td></tr>
<tr><td>Average width of cracks (sides only)</td><td colspan="2">0.005 in.</td></tr>
<tr><td>Maximum crack width</td><td colspan="2">0.01 in.</td></tr>
<tr><td>Area of cracks (total both sides)</td><td colspan="2">0.091 $in.^2$</td></tr>
<tr><td>Displacement at day 7</td><td colspan="2">0.879 in.</td></tr>
<tr><th>Flexural Test Load-Displacement Response</th><th>Parameter</th><th>Value</th></tr>
<tr><td rowspan="7">
</td><td>Displacement at 250 lb</td><td>0.18 in.</td></tr>
<tr><td>Displacement at 500 lb</td><td>0.37 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.58 in.</td></tr>
<tr><td>Peak Load</td><td>---------</td></tr>
<tr><td>Transformed MOI</td><td>12.76 $in.^4$</td></tr>
<tr><td>Cracked MOI</td><td>3.23 $in.^4$</td></tr>
<tr><td>28-Day Compressive Strength</td><td>5139 psi</td></tr>
</table>

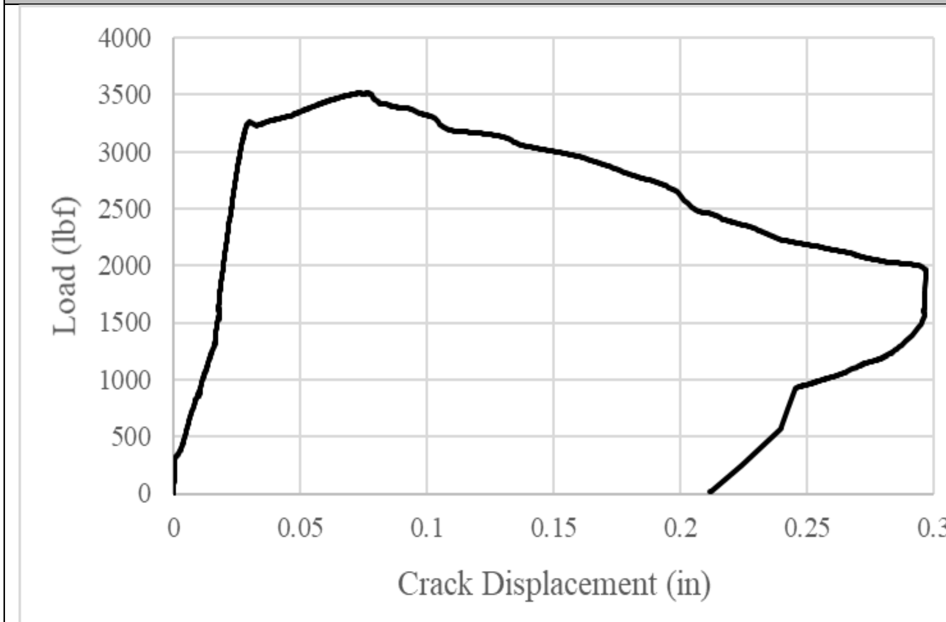
APPENDIX E – SHORT BEAMS

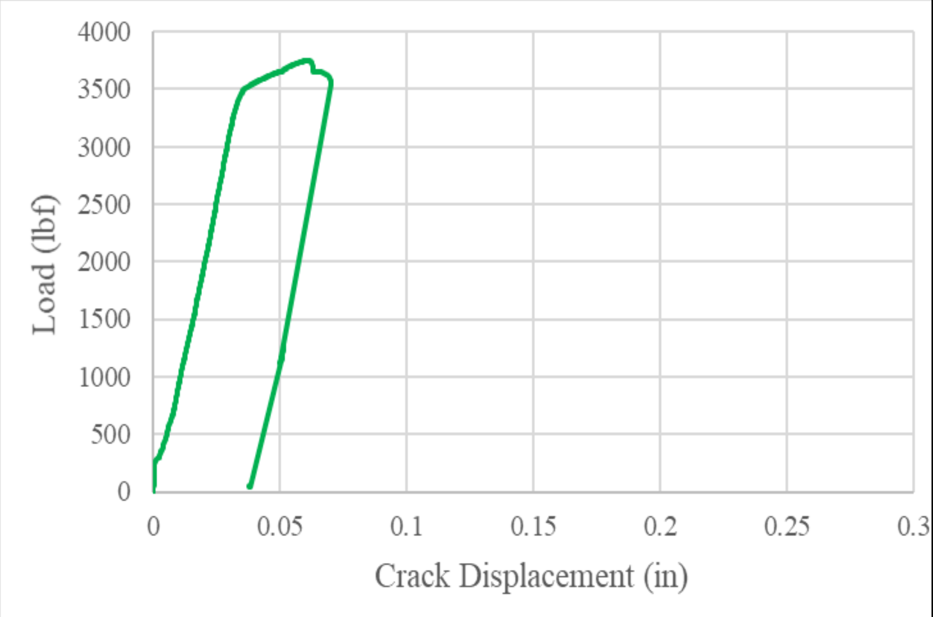
<table>
<tr><th colspan="3">“Short Beam” Test Summary of specimen B1-S</th></tr>
<tr><td>Bar Size: #4
Bar Type: Black</td><td colspan="2">Cast Date: 10-07-2019
Flexural Test Date: 07-20-2020</td></tr>
<tr><td>Flexural Test Load-Crack Width Response</td><td>Parameter</td><td>Value</td></tr>
<tr><td rowspan="7">
</td><td>Displacement at 500 lb</td><td>0.004 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.007 in.</td></tr>
<tr><td>Displacement at 1000 lb</td><td>0.01 in.</td></tr>
<tr><td>Peak Load</td><td>3435 lb.</td></tr>
<tr><td>Transformed MOI</td><td></td></tr>
<tr><td>Cracked MOI</td><td></td></tr>
<tr><td>28-Day Compressive Strength</td><td>5070 psi</td></tr>
</table>

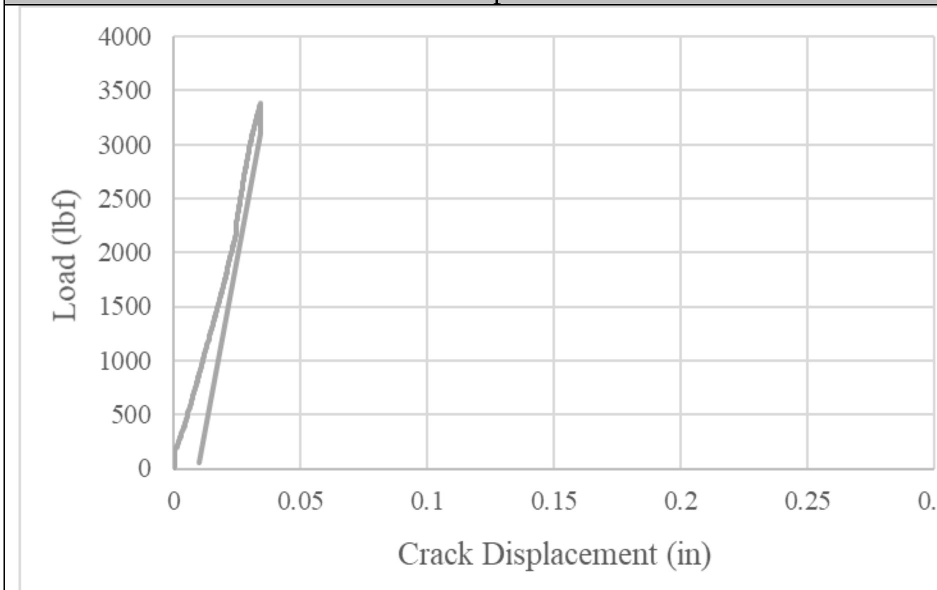
<table>
<tr><th colspan="3">“Short Beam” Test Summary of specimen E1-S</th></tr>
<tr><td>Bar Size: #4
Bar Type: Smooth Epoxy</td><td colspan="2">Cast Date: 10-07-2019
Flexural Test Date: 07-20-2020</td></tr>
<tr><td>Flexural Test Load-Crack Width Response</td><td>Parameter</td><td>Value</td></tr>
<tr><td rowspan="7">
</td><td>Displacement at 500 lb</td><td>0.007 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.01 in.</td></tr>
<tr><td>Displacement at 1000 lb</td><td>0.012 in.</td></tr>
<tr><td>Peak Load</td><td>2835 lb.</td></tr>
<tr><td>Transformed MOI</td><td></td></tr>
<tr><td>Cracked MOI</td><td></td></tr>
<tr><td>28-Day Compressive Strength</td><td>5070 psi</td></tr>
</table>

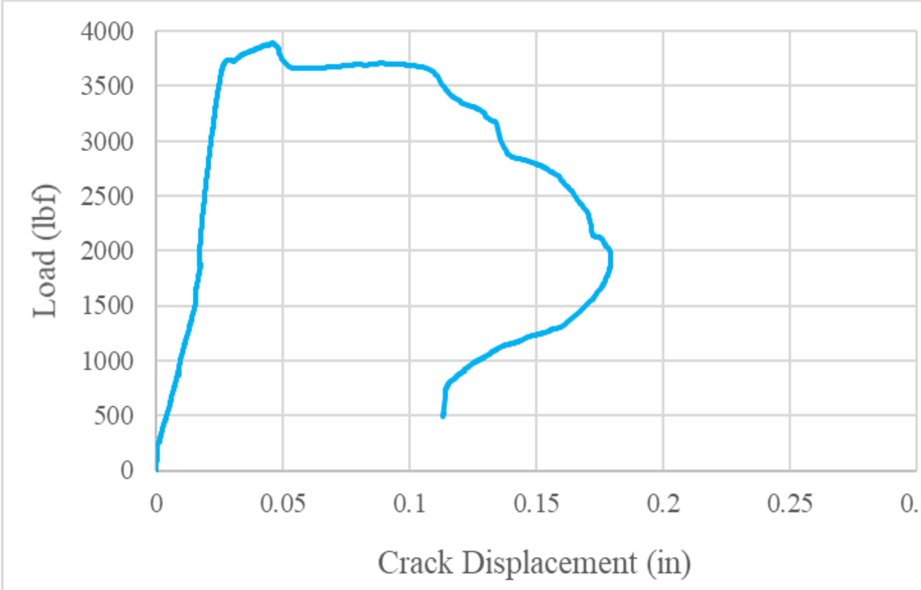
“Short Beam” Test Summary of specimen G1-S		
Bar Size: #4 Bar Type: Continuously Galvanized (CGR)	Cast Date: 10-07-2019 Flexural Test Date: 07-20-2020	
Flexural Test Load-Crack Width Response	Parameter	Value
	Displacement at 500 lb	0.005 in.
	Displacement at 750 lb	0.009 in.
	Displacement at 1000 lb	0.013 in.
	Peak Load	3003 lb.
	Transformed MOI	
	Cracked MOI	
	28-Day Compressive Strength	5070 psi

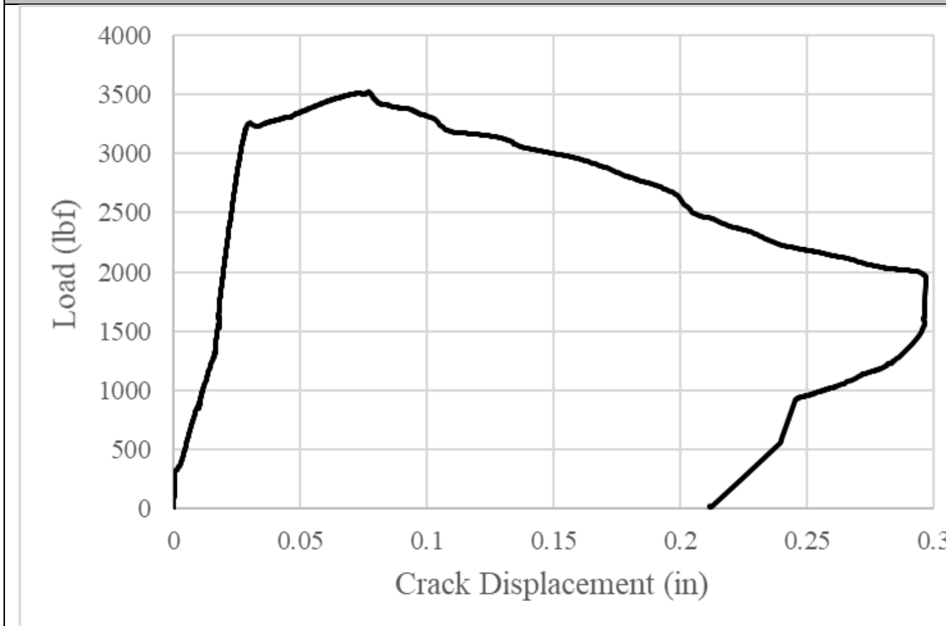
"Short Beam" Test Summary of specimen T1-S		
Bar Size: #4 Bar Type: Textured Epoxy	Cast Date: 10-07-2019 Flexural Test Date: 07-20-2020	
Flexural Test Load-Crack Width Response	Parameter	Value
	Displacement at 500 lb	0.006 in.
	Displacement at 750 lb	0.009 in.
	Displacement at 1000 lb	0.012 in.
	Peak Load	3455 lb.
	Transformed MOI	
	Cracked MOI	
	28-Day Compressive Strength	5070 psi

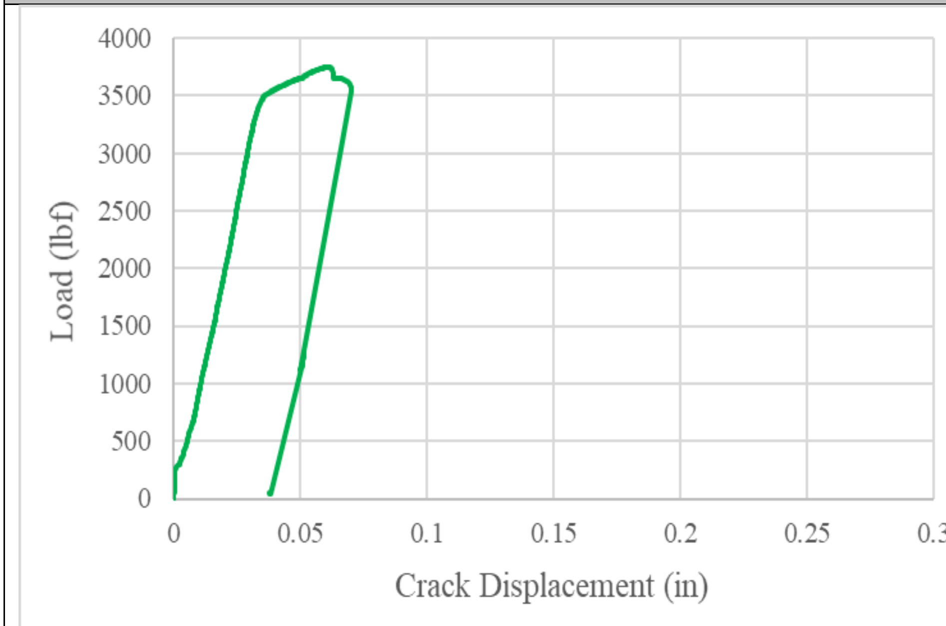
<table>
<tr><th colspan="3">“Short Beam” Test Summary of specimen B2-S</th></tr>
<tr><td>Bar Size: #4
Bar Type: Black</td><td colspan="2">Cast Date: 10-28-2019
Flexural Test Date: 07-22-2020</td></tr>
<tr><td>Flexural Test Load-Crack Width Response</td><td>Parameter</td><td>Value</td></tr>
<tr><td rowspan="7">
</td><td>Displacement at 500 lb</td><td>0.004 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.008 in.</td></tr>
<tr><td>Displacement at 1000 lb</td><td>0.011 in.</td></tr>
<tr><td>Peak Load</td><td>3519 lb.</td></tr>
<tr><td>Transformed MOI</td><td></td></tr>
<tr><td>Cracked MOI</td><td></td></tr>
<tr><td>28-Day Compressive Strength</td><td>5940 psi</td></tr>
</table>

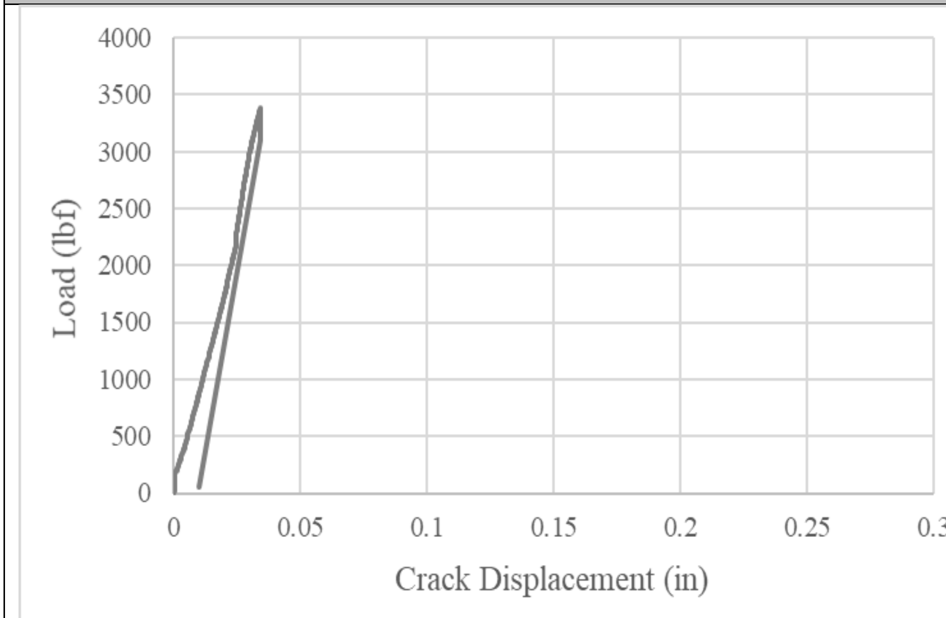
<table>
<tr><th colspan="3">“Short Beam” Test Summary of specimen E2-S</th></tr>
<tr><td>Bar Size: #4
Bar Type: Smooth Epoxy</td><td colspan="2">Cast Date: 10-28-2019
Flexural Test Date: 07-22-2020</td></tr>
<tr><td>Flexural Test Load-Crack Width Response</td><td>Parameter</td><td>Value</td></tr>
<tr><td rowspan="7">
</td><td>Displacement at 500 lb</td><td>0.005 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.008 in.</td></tr>
<tr><td>Displacement at 1000 lb</td><td>0.011 in.</td></tr>
<tr><td>Peak Load</td><td>3743 lb.</td></tr>
<tr><td>Transformed MOI</td><td></td></tr>
<tr><td>Cracked MOI</td><td></td></tr>
<tr><td>28-Day Compressive Strength</td><td>5940 psi</td></tr>
</table>

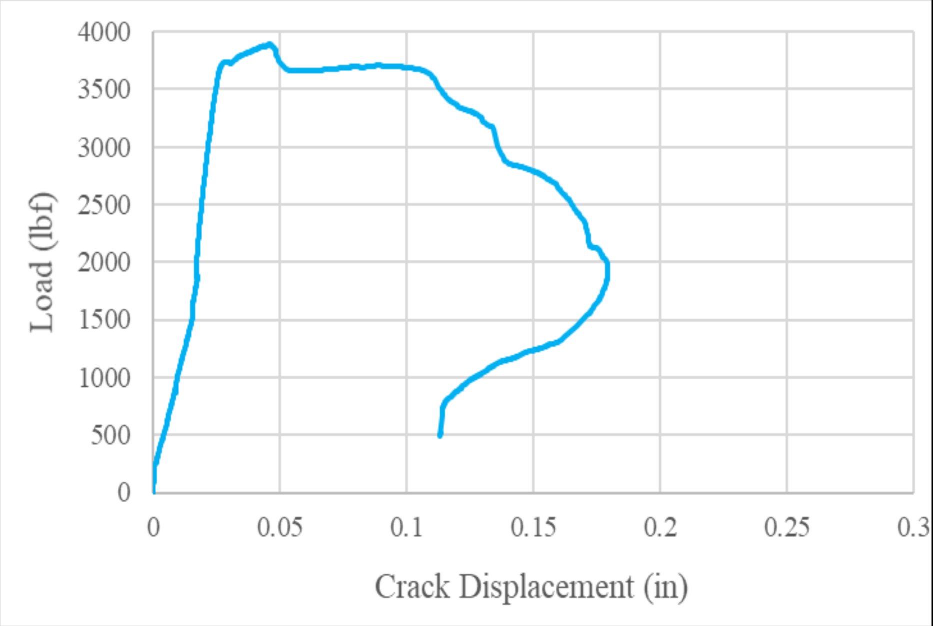
<table>
<tr><th colspan="3">“Short Beam” Test Summary of specimen G2-S</th></tr>
<tr><td>Bar Size: #4
Bar Type: Continuously Galvanized (CGR)</td><td colspan="2">Cast Date: 10-28-2019
Flexural Test Date: 07-22-2020</td></tr>
<tr><td>Flexural Test Load-Crack Width Response</td><td>Parameter</td><td>Value</td></tr>
<tr><td rowspan="7">
</td><td>Displacement at 500 lb</td><td>0.0053 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.0084 in.</td></tr>
<tr><td>Displacement at 1000 lb</td><td>0.0114 in.</td></tr>
<tr><td>Peak Load</td><td>3387 lb.</td></tr>
<tr><td>Transformed MOI</td><td></td></tr>
<tr><td>Cracked MOI</td><td></td></tr>
<tr><td>28-Day Compressive Strength</td><td>5940 psi</td></tr>
</table>

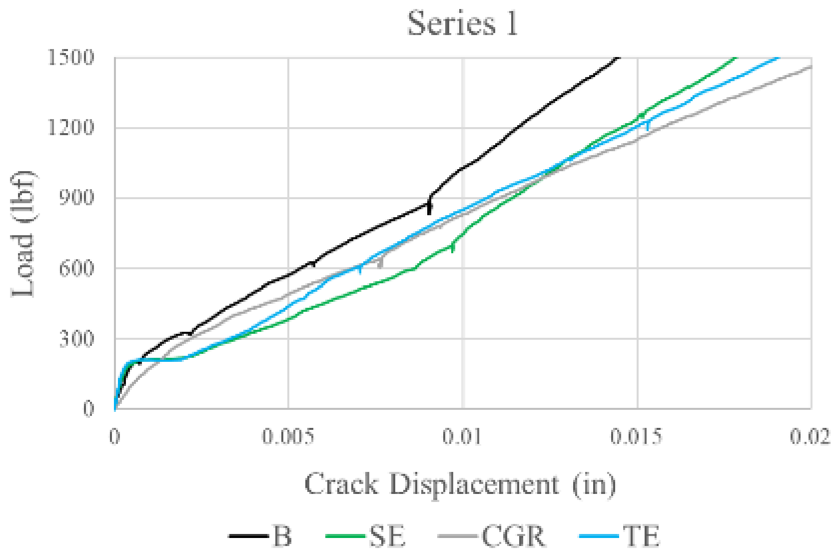
<table>
<tr><th colspan="3">“Short Beam” Test Summary of specimen T2-S</th></tr>
<tr><td>Bar Size: #4
Bar Type: Textured Epoxy</td><td colspan="2">Cast Date: 10-28-2019
Flexural Test Date: 07-22-2020</td></tr>
<tr><td>Flexural Test Load-Crack Width Response</td><td>Parameter</td><td>Value</td></tr>
<tr><td rowspan="7">
</td><td>Displacement at 500 lb</td><td>0.0040 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.0069 in.</td></tr>
<tr><td>Displacement at 1000 lb</td><td>0.0094 in.</td></tr>
<tr><td>Peak Load</td><td>3889 lb.</td></tr>
<tr><td>Transformed MOI</td><td></td></tr>
<tr><td>Cracked MOI</td><td></td></tr>
<tr><td>28-Day Compressive Strength</td><td>5940 psi</td></tr>
</table>

<table>
<tr><th colspan="3">“Short Beam” Test Summary of specimen B3-S</th></tr>
<tr><td>Bar Size: #4
Bar Type: Black</td><td colspan="2">Cast Date: 10-16-2020
Flexural Test Date: 07-23-2020</td></tr>
<tr><th>Flexural Test Load-Crack Width Response</th><th>Parameter</th><th>Value</th></tr>
<tr><td rowspan="7">
</td><td>Displacement at 500 lb</td><td>0.003 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.006 in.</td></tr>
<tr><td>Displacement at 1000 lb</td><td>0.008 in.</td></tr>
<tr><td>Peak Load</td><td>3569 lb.</td></tr>
<tr><td>Transformed MOI</td><td></td></tr>
<tr><td>Cracked MOI</td><td></td></tr>
<tr><td>28-Day Compressive Strength</td><td>5139 psi</td></tr>
</table>

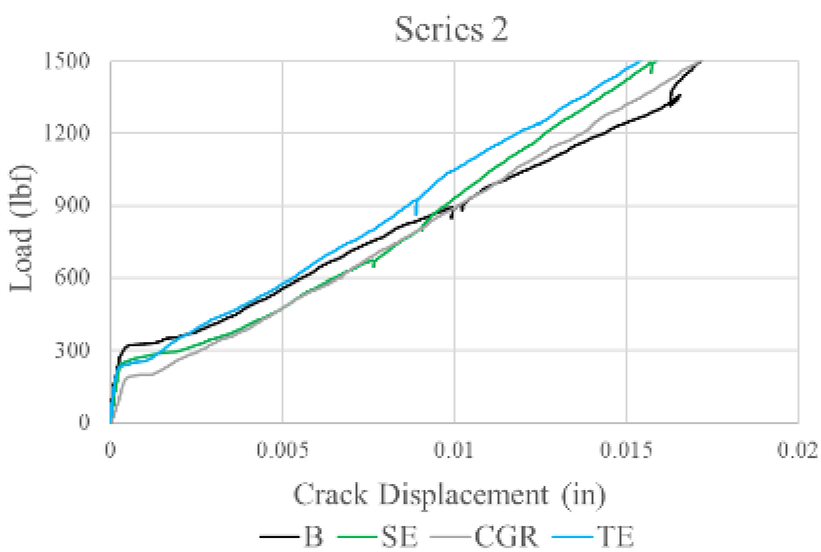
“Short Beam” Test Summary of specimen E3-S		
Bar Size: #4 Bar Type: Epoxy	Cast Date: 10-16-2020 Flexural Test Date: 07-23-2020	
Flexural Test Load-Crack Width Response	Parameter	Value
	Displacement at 500 lb	0.006 in.
	Displacement at 750 lb	0.011 in.
	Displacement at 1000 lb	0.014 in.
	Peak Load	3096 lb.
	Transformed MOI	
	Cracked MOI	
	28-Day Compressive Strength	5139 psi

“Short Beam” Test Summary of specimen G3-S		
Bar Size: #4 Bar Type: Galvanized	Cast Date: 10-16-2020 Flexural Test Date: 07-23-2020	
Flexural Test Load-Crack Width Response	Parameter	Value
	Displacement at 500 lb	0.005 in.
	Displacement at 750 lb	0.008 in.
	Displacement at 1000 lb	0.010 in.
	Peak Load	3683 lb.
	Transformed MOI	
	Cracked MOI	
	28-Day Compressive Strength	5139 psi

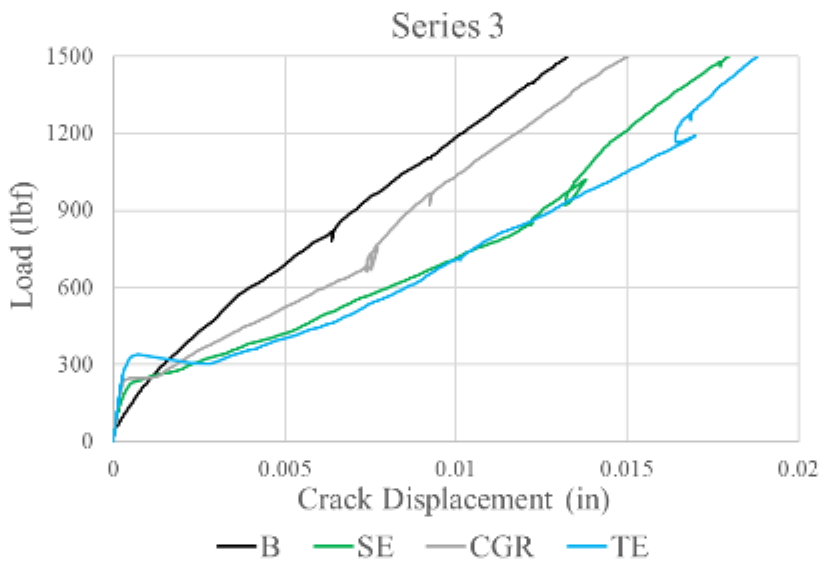
<table>
<tr><th colspan="3">“Short Beam” Test Summary of specimen T3-S</th></tr>
<tr><td>Bar Size: #4
Bar Type: Textured Epoxy</td><td colspan="2">Cast Date: 10-16-2020
Flexural Test Date: 07-23-2020</td></tr>
<tr><td>Flexural Test Load-Crack Width Response</td><td>Parameter</td><td>Value</td></tr>
<tr><td rowspan="7">
</td><td>Displacement at 500 lb</td><td>0.007 in.</td></tr>
<tr><td>Displacement at 750 lb</td><td>0.011 in.</td></tr>
<tr><td>Displacement at 1000 lb</td><td>0.014 in.</td></tr>
<tr><td>Peak Load</td><td>3772 lb.</td></tr>
<tr><td>Transformed MOI</td><td></td></tr>
<tr><td>Cracked MOI</td><td></td></tr>
<tr><td>28-Day Compressive Strength</td><td>5139 psi</td></tr>
</table>



Series 1
1500
1200
900
600
300
0
Load (lbf)
0
0.005
0.01
0.015
0.02
Crack Displacement (in)
B
SE
CGR
TE



Series 2
1500
1200
900
600
300
0
Load (lbf)
0
0.005
0.01
0.015
0.02
Crack Displacement (in)
B
SE
CGR
TE


Series 3
1500
1200
900
600
300
0
Load (lbf)
0
0.005
0.01
0.015
0.02
Crack Displacement (in)
B
SE
CGR
TE

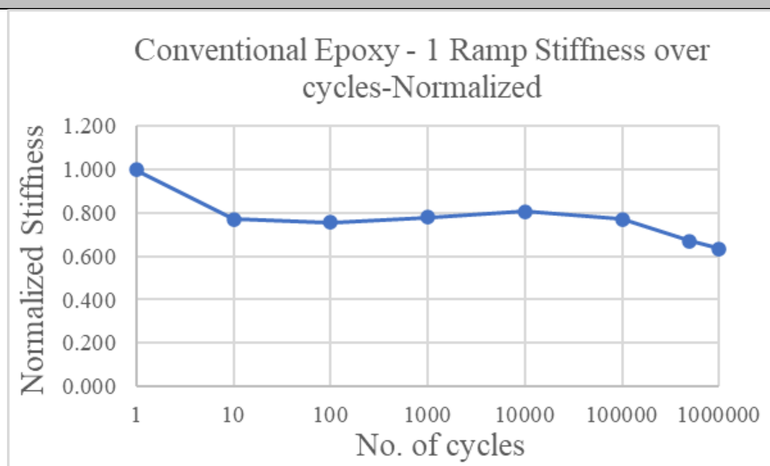
APPENDIX F – CYCLIC LOAD TEST

Cyclic Load Test Summary of specimen E1	
Bar Size: #4 Bar Type: Epoxy	Cast Date: 10-16-2020 Test Start Date: 01-08-2021 Test End Date: 01-18-2021

Concrete Compressive Strength		
Test Age(days)	No. of Cylinders	Avg. compressive strength (psi)
7	2	4050
14	2	4970
28	3	5140
91 (Age at testing of E1)	3	6690

Stiffness variation over million cycles	
Number of cycles	Stiffness k (lb/in)
1. Pre-crack	64415
2. 10 (Post-crack)	49705
3. 100	48741
4. 1000	50308
5. 10000	51899
6. 100000	49597
7. 500000	43095
8. 1000000	40810

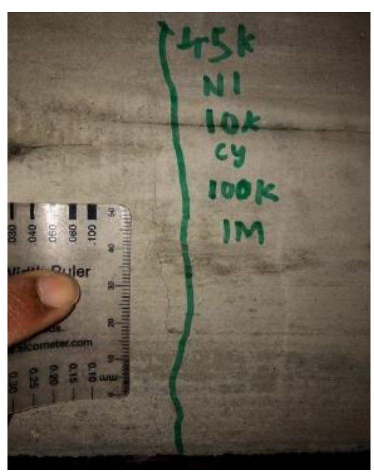
Stiffness vs Number of cycles (plot)



Description of the test

No cracks observed outside the loading points. The crack shown in the picture is located about 2 inches within the loading point.

Picture of cracks



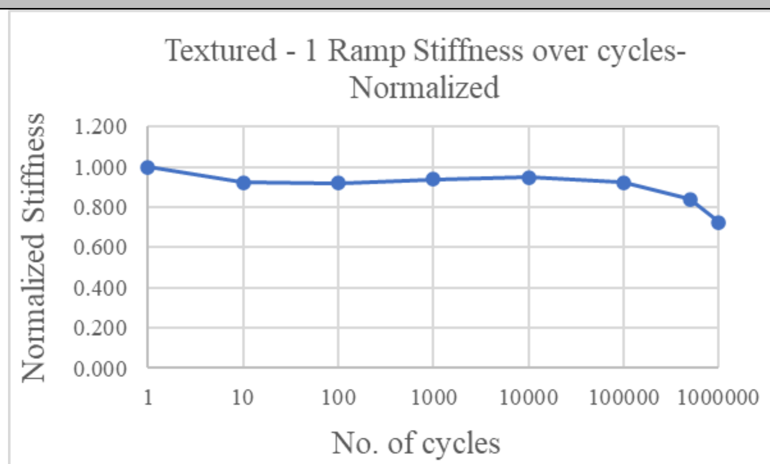
Cyclic Load Test Summary of specimen T1	
Bar Size: #4 Bar Type: Textured Epoxy	Cast Date: 10-16-2020 Test Date: 01-25-2021 Test End Date: 02-03-2021

Concrete Compressive Strength		
Test Age(days)	No. of Cylinders	Avg. compressive strength (psi)
7	2	4050
14	2	4970
28	3	5140
109 (Age at testing of T1)	3	6070

Stiffness variation over million cycles

Number of cycles	Stiffness k (lb/in)
1. Pre-crack	57297
2. 10 (Post-crack)	52950
3. 100	52638
4. 1000	53758
5. 10000	54408
6. 100000	52850
7. 500000	48083
8. 1000000	41595

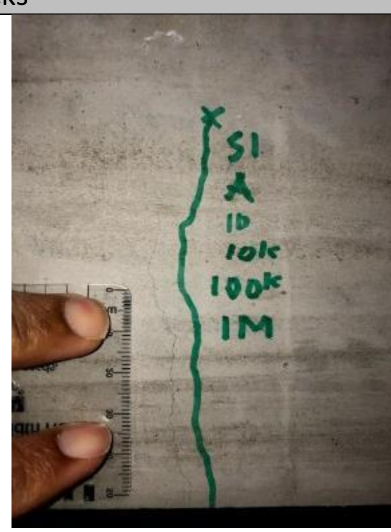
Stiffness vs Number of cycles (plot)



Description of the test

The specimen had a pre-crack under one of the threaded rods because of which the initial stiffness was less compared to that of other specimens. The pre-crack developed as the cracking load was applied to the specimen. Many cracks were observed in this specimen compared to all the specimens. The crack shown in the picture is located about 3 inches off the loading point.

Picture of cracks

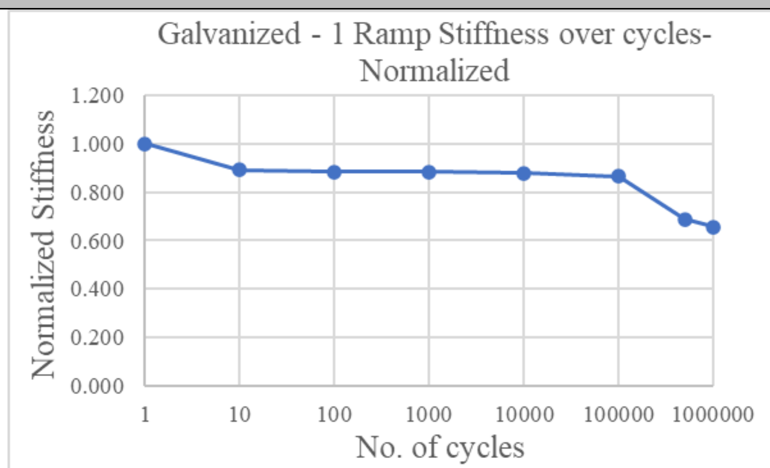


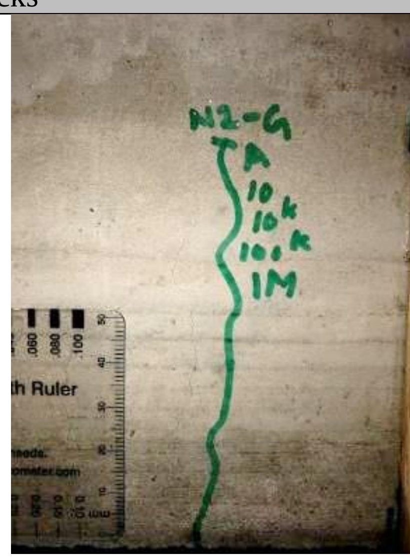
Cyclic Load Test Summary of specimen G1	
Bar Size: #4 Bar Type: Hot-dipped Galvanized	Cast Date: 10-16-2020 Test Date: 02-08-2021 Test End Date: 02-16-2021

Concrete Compressive Strength		
Test Age(days)	No. of Cylinders	Avg. compressive strength (psi)
7	2	4050
14	2	4970
28	3	5140
119 (Age at testing of E1)	3	6020

Stiffness variation over million cycles	
Number of cycles	Stiffness k (lb/in)
1. Pre-crack	64329
2. 10 (Post-crack)	57398
3. 100	56863
4. 1000	56762
5. 10000	56486
6. 100000	55596
7. 500000	44318
8. 1000000	42192

Stiffness vs Number of cycles (plot)



Description of the test	Picture of cracks
Two cracks were only observed in this specimen within the loading points. The crack shown in the picture is located about 4 inches off the loading point.	

APPENDIX G – BRIDGE DECK FIELD STUDY

Weather conditions during the deck pour

Weather parameter	Magnitude
Wind Speed (mph)	Calm in the beginning, 3-6 along NW and 6 along W during the completion
Weather condition	Fair and partly cloudy overall
Average Relative Humidity (%)	78
Average altimeter pressure (in)	29.80
Precipitation	None

LYCON - LYCON INC
1110 Harding St.
Janesville, WI 53545
Tel : (608) 754-7701

WISDOT HPC 4000 PSI #467 AE WR RET #65404540HPC

Date : **1/22/2020**

Mix Code : **65404540HPC** Description : **4000 PSI #467 AE WR HPC**

Revision Number : 20 Creation Date : 22 Jan 2020 Customer : LUNDA CONST CO. - Laremy Sacia Proj Mgr

Plant : OREGON-MADISON Created By : LYCON Project : I-39 1007-12-78 MADISON, WI

Specifications

Consistence Class : 3" Max W/C : 0.45 Max Agg Size : #4 & #67 ASTM C-33

Strength Class : 4000 Min Cement : 540 Air Class : FULL AIR

Location : I-39 1007-12-78 - MADISON, WI - STRUCTURES WISDOT HPC 4000 PSI #467 AE WR RET #65404540HPC

Material Type	Description	Supplier Source		Design Quantity	Specific Gravity	Volume ft3
Water	WATER	LYCON INC.-CITY - POTABLE WATER		27.8 gal	1.00	3.72
Cement	LAFARGE - CEMENT - BULK	LAFARGE NORTH AMERICA-MADISON - ALPE		432 lb	3.15	2.20
Slag	NEWCEM 100	LAFARGE NORTH AMERICA-MILWAUKEE - CH		108 lb	2.95	0.59
Fine Aggregate	FINE AGG/CONC SAND-TORP	55-53-018-JSG.PIT-JSG		1280 lb	2.63	7.80
Coarse Aggregate	3/4" LIMESTONE #67	YAHARA MATERIALS INC-55-13-008.BUCKEYE		1030 lb	2.65	6.23
Coarse Aggregate	1 1/2" LIMESTONE/CONC MIX	YAHARA MATERIALS INC-55-13-008.BUCKEYE		830 lb	2.65	5.02
Admixture	7920 - TYPE A-F W.R.	BASF-BASF		24 lq oz	-	-
Admixture	RETARDER	BASF-BASF		16 lq oz	-	-
Admixture	AIR ENTRAINING-FULL	BASF-BASF		2 lq oz	-	-
			Air Content	**6.00 %**	**--**	**1.63**
			Yield	**3912lb**	**--**	**27.18**

Design Properties

W/C Eq : 0.43 Density : 143.9 lb/ft3 ACF : 0.3 %

Cement Eq : 540 Chloride/Cem : 0.00 %

ALL WISDOT REQUIRED CONCRETE & AGGREGATES TESTING & REPORTING IS THE CONTRACTOR'S LUNDA CONST. CO. RESPONSIBILITY

Page 1

COUNTY MATERIALS CORPORATION

JANESVILLE

QUALITY CONTROL

MIX #	**JV-235**
D.O.T.	**WISDOT**
D.O.T. DESIGNATION	**SCC GRACE AIR #2**
DATE	
JOB #	
JOBNAME	

CONCRETE MIX DESIGN

Sack Content	8.5	sacks/cu.yd.	
Specified Strength:	8000	psi @ 28 days	
	6400	psi @ release	
Entrained Air:	1.5%		
Type Cement:	Type III LA		La Farge North America -Alpena Plant -4116-01
Water/Cement Ratio:	0.32		
Slump / Flow Spread	23-27"		
Admixtures:			
	11.25	oz/cwt	HRWR Grace Adva Cast 575 767-01
	3.75	oz/cwt	WE Grace VMAR
	2.75	oz/cwt	WR Grace Daravair 1400
		oz/100# cement	

MATERIALS	SPECIFIC GRAVITY		S.S.D # WEIGHT	Abs. VOL. cu.ft.	DENSITY SOURCE LB/CU.FT.
Cement III	3.15		800	4.07	196.56
Coarse 3/4"	2.646		1000	6.06	165.11
Coarse 3/8"	2.646		500	3.03	165.11
Fine	2.62		1455	8.90	163.49
Water	1	31.09	259	4.15	62.4
Air Max 6.0%				1.62	
TOTAL			4014	27.83	

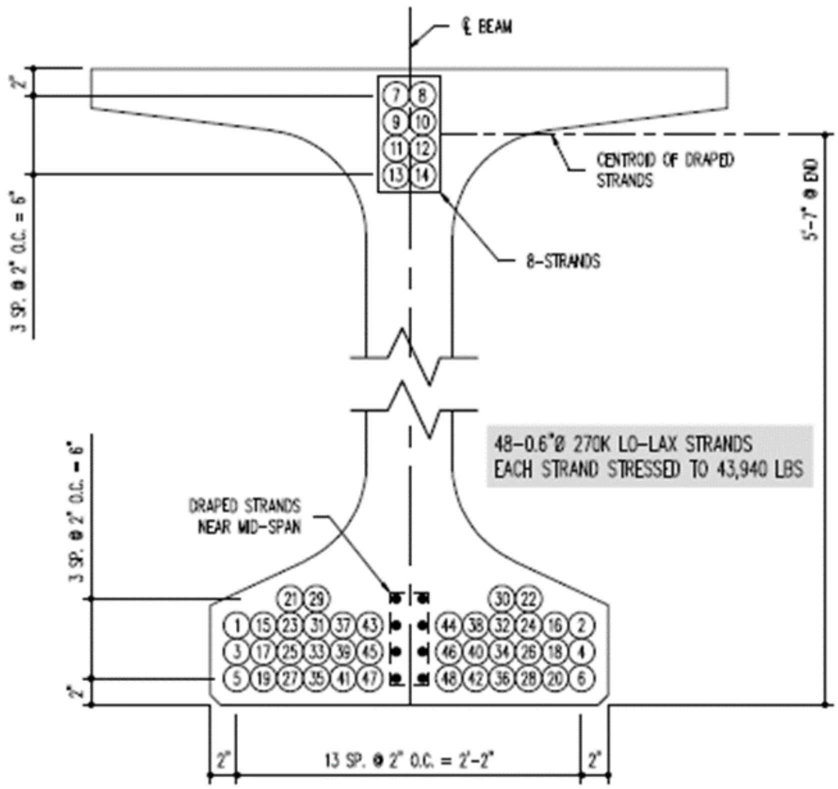
DESIGN STRENGTH	8000 psi @28 days

W/C	0.32	
Unit wt.	149	pcf
Yield	27	cf/cy

Fine	1455	49%
Total	2955	

By: *Brian Rowekamp*
Quality Control

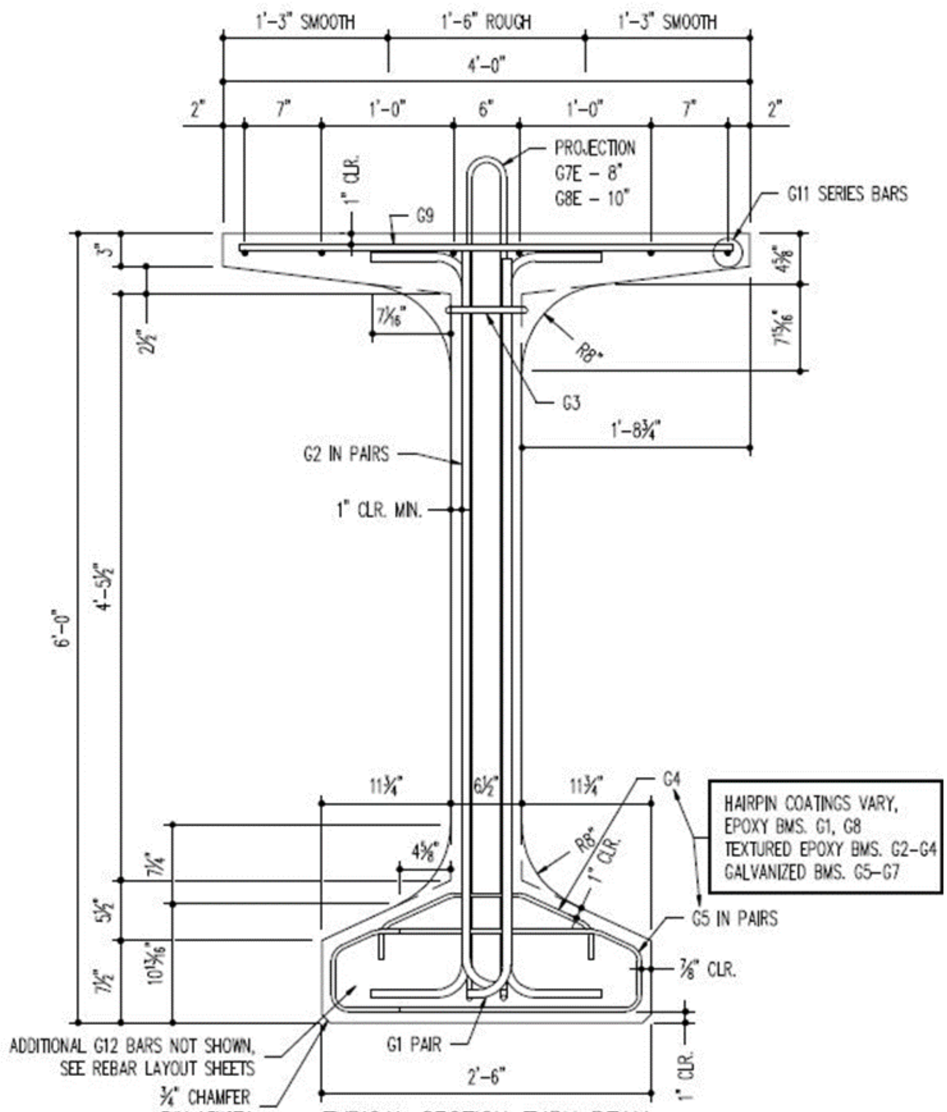
Noted:	Based upon aggregate in saturated surface dry condition. Correction necessary for free moisture
	The above mix is based on the consideration that the compressive strength results will equal or exceedthe strength shown above when cylinders are taken, handled and cured in accordance with ASTM C-31.
	If the correct procedures for testing are not followed or if the water/cement ratio is exceeded,(0.40 max.) this mix as shown above cannot be expected to produce the desired properties.



DESIGN STRAND PATTERN & RELEASE SEQUENCE

LOOKING AT BEAM END

SCALE: 1" = 1'-0"



TYPICAL SECTION THRU BEAM

NEAR END OF BEAM
HOLES, PLATES & INSERTS NOT SHOWN
B.A. = 6.3510 S.F.

Crack data in flange area							
Type of reinforcement	Girder End	Average crack width	Comparison Index (CI)	Avg CI	Max width	CI	Avg CI
Epoxy	G1N	0.339	0.949	1.011	0.480	0.809	1.106
	G1S	0.361	1.010		0.563	0.948	
	G8N	0.391	1.093		0.778	1.310	
	G8S	0.355	0.992		0.806	1.358	
Textured	G2N	0.329	0.919	0.936	0.373	0.627	0.857
	G2S	0.336	0.940		0.469	0.790	
	G3N	0.332	0.928		0.611	1.029	
	G3S	0.351	0.981		0.508	0.856	
	G4N	0.359	1.003		0.631	1.063	
	G4S	0.303	0.847		0.460	0.775	
Galvanized	G5N	0.407	1.139	1.056	0.553	0.931	1.073
	G5S	0.384	1.074		0.606	1.020	
	G6N	0.304	0.849		0.416	0.701	
	G6S	0.352	0.985		0.617	1.039	
	G7N	0.412	1.153		0.962	1.620	
	G7S	0.407	1.137		0.668	1.125	
Average overall		0.358			0.594		
Average Interior		0.355	0.992		0.620	1.044	
Average Exterior		0.361	1.008		0.568	0.956	
*	(yellow)	Interior ends on the stressing bed					
*	(red)	Exterior ends on the stressing bed					

Crack data in web area							
Type of reinforcement	Girder End	Average crack width	Comparison Index (CI)	Avg CI	Max width	CI	Avg CI
Epoxy	G1N	0.321	1.120	1.019	0.403	1.079	1.002
	G1S	0.260	0.905		0.381	1.018	
	G8N	0.313	1.090		0.392	1.049	
	G8S	0.276	0.961		0.322	0.861	
Textured	G2N	0.276	0.962	1.105	0.337	0.902	1.151
	G2S	0.252	0.878		0.332	0.887	
	G3N	0.286	0.998		0.512	1.370	
	G3S	0.450	1.567		0.526	1.408	
	G4N	0.294	1.024		0.465	1.245	
	G4S	0.344	1.199		0.409	1.094	
Galvanized	G5N	0.243	0.848	0.883	0.291	0.778	0.848
	G5S	0.270	0.940		0.371	0.993	
	G6N	0.227	0.791		0.298	0.797	
	G6S	0.239	0.831		0.280	0.748	
	G7N	0.231	0.803		0.292	0.782	
	G7S	0.311	1.084		0.370	0.989	
Average overall		0.287			0.374		
Average Interior		0.274	0.955		0.355	0.950	
Average Exterior		0.300	1.045		0.392	1.050	
*	(yellow)	Interior end on the stressing bed					
*	(red)	Exterior end on the stressing bed					