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Effect of Latex Modified Concrete Overlays With Reduced Surface Preparation on the Load Distribution and Flexural Strength of Channel Girders

Samuel Dodd
sbdodd@g.clemson.edu

EFFECT OF LATEX MODIFIED CONCRETE OVERLAYS WITH REDUCED SURFACE PREPARATION ON THE LOAD DISTRIBUTION AND FLEXURAL STRENGTH OF CHANNEL GIRDERS

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Samuel Byron Dodd
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Brandon E. Ross, Committee Chair
Thomas E. Cousins
Michael W. Stoner

ABSTRACT

This thesis investigates the use of a Latex Modified Concrete (LMC) overlay to increase the strength of prestressed channel girders and enhance their ability to distribute load. The research conducted in this thesis involved material testing of several different LMC mixes and flexural testing of an LMC overlay and girder system. The material testing was used to determine a reasonable LMC mix design and surface preparation method to be used for the overlay. Based on material testing it was concluded that a rapid-set mix and pressure washing of the girder surfaces were a reasonable mix design and surface preparation for the overlay construction. Both the material and flexural testing showcased a sufficient bond between the overlay and existing girders under service loads, implying that LMC overlays do not require as invasive surface preparation methods to be structurally effective. However, flexural testing found the overlay delaminated prior to ultimate failure, indicating a stronger bond is required for the overlay to increase flexural capacity. The flexural testing did determine that the LMC overlay increased the ability of the girder system to distribute load, especially when combined with transverse post-tensioning. Overall, the outcomes of the laboratory testing conducted for this thesis indicate LMC overlays are a promising option for bridge repair, rehabilitation, and strengthening.

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CHAPTER ONE

INTRODUCTION

Project Origin

Bridges are among the most important assests of a community's infrastructure and serve as connectors for multiple aspects of the economy – transit, shipping, rail, and many others. Often, they are used to span the same bodies of water which enabled the initial rise of the community around them. Despite their importance, bridges have the capacity to be one of the most neglected sectors of a community's infrastructure. This trend is especially true within the United States of America. Every four years the American Society of Civil Engineers (ASCE) releases a report on the state of the United States infrastructure – the 2021 report card gave the nation's bridges a C (Ard et al., 2021).

The state of South Carolina contains approximately 9,410 of the nation's more than 617,000 bridges. Of these, nearly 11% are rated as structurally deficient – roughly 3.5% higher than the national average (Ard et al., 2021). In an effort to address this issue, the South Carolina Department of Transportation (SCDOT) has funded multiple projects, both within itself and with partner universities, to investigate methods to repair, rehabilitate, and strengthen the existing bridge infrastructure within the state. In recent years, these projects have investigated a specific bridge design composed of thirty foot long, simple span, prestressed channel girders (Figure 1.1). While the SCDOT has multiple types of prestressed channel girders, this research focuses on the skinny-leg variety which has narrower legs than the other type and only one set of prestressing strands in each leg. This bridge type accounts for approximately 450 of the 9,410 bridges in South Carolina (Gunter, 2016). The majority of these bridges were built in the 1960s when the design truck load was lower than the current standards (Eubanks, 2023). Due to the smaller design load, many of these bridges have become under designed for current traffic loads and therefore requiring load postings and limits on these bridges (Eubanks, 2023).

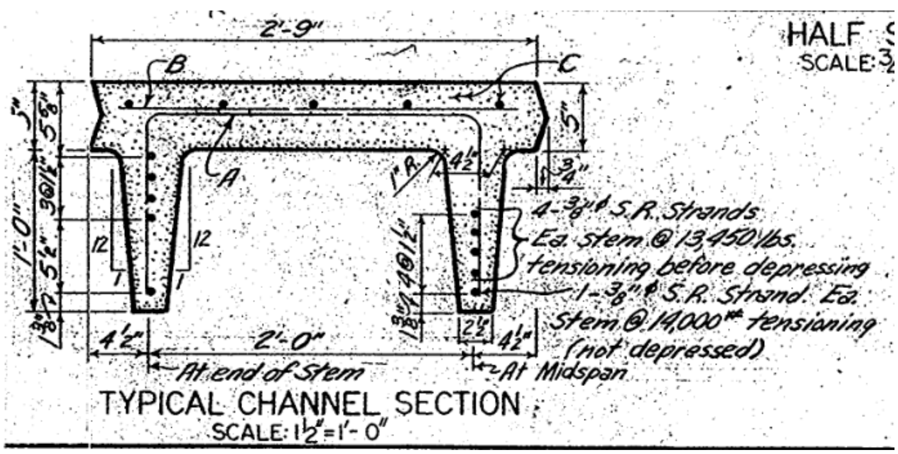

Figure 1.1: Skinny Leg Channel Girder Cross Section

In order to increase the strength of the affected bridges, SCDOT funded projects have investigated many different methods for bridge enhancement, most of which can be divided into two main categories. The first of these is improving the flexural strength of individual bridge members. One method for this is the addition of an overlay to the existing members. Another method is adding some form of external strengthening reinforcement along an individual structural member. An example of this option can be found in research conducted by the University of South Carolina (USC) on the feasibility of attaching aluminum channels to the inside webs of channel girders (Henderson, 2023).

The second of these categories is improving the load distribution of the structural system. This improved load distribution reduces the load on a specific girder by helping "share" the applied, local load more evenly onto the other members within the system. While there are multiple ways to achieve this, one option explored by researchers at Clemson University entailed using transverse post-tensioning to increase the distribution within a channel girder system (Eubanks, 2023).

This thesis will evaluate the ability of Latex Modified Concrete, a common bridge repair material, to improve both load distribution and flexural strength. Latex Modified Concrete (LMC) is a variant of standard concrete which replaces some of the water in the concrete mix with a latex admixture. LMC is typically used for bridge deck repair thanks to its corrosion resistance and the beneficial freeze-thaw performance it provides the bridge (Sprinkel, Michael M., 1984). Currently, LMC's use in repair requires destructive methods of surface preparation such as hydro demolition (BASF, 2020). The large loss of concrete caused by these methods reduces LMC's ability to add additional strength to a bridge as it must first replace the concrete lost from the surface preparation rather than add new concrete, preventing the overlay from increasing the flexural strength of the bridge. This research will evaluate the efficacy of an LMC overlay with non-destructive surface preparation methods in adding both flexural strength and load distribution capabilities to a girder system.

Purpose, Scope, and Objectives

The purpose of this research is twofold. First, the research aims to determine if less invasive means of surface preparation will allow an existing concrete structure to develop a sufficient bond with an LMC overlay for the overlay to become fully engaged in the structure's performance under load. Second, this thesis investigates how well the LMC overlay increases the flexural capacity and load distribution of the existing structure. The initial bond capabilities of the LMC were evaluated via direct tension pull-off tests performed on test pours for a variety of LMC mix designs and surface preparations. Based on this initial testing, a mix design and surface preparation method were chosen to be cast as an overlay on a transversely post-tensioned, three-girder system. This system was then run through multiple different flexural tests to evaluate the flexural strength and load distribution capabilities of the LMC overlay. These flexural tests were conducted in a laboratory setting and data collection included the load in the post-tensioning (when applicable), load applied to the system, and vertical displacement. Other measurements, such as horizontal displacement or strain, were not recorded.

The specific objectives of this thesis are listed below:

1.) Evaluate the ability of LMC to achieve a sufficient bond with an existing concrete structure with less invasive surface preparation than the industry standard.

2.) Evaluate the ability of a sufficiently bonded LMC overlay to enhance load distribution between three channel girders.

3.) Evaluate the flexural strength gain provided by an LMC overlay to an individual channel girder.

Thesis Organization

This thesis is organized into five chapters. Chapter one presents the origin of this line of research, the thesis' purposes and objectives, and organization. Chapter two presents relevant background information on some of the main topics investigated and used by this thesis – latex modified concrete, bond strength, and load distribution. Chapter three discusses the initial material testing and its results. Chapter four presents the methods and results from the flexural testing of the LMC overlay. Finally, chapter five goes over the research's conclusions, limitations, and final recommendations made to the SCDOT.

CHAPTER TWO

LITERATURE REVIEW AND BACKGROUND

Latex Modified Concrete

As of 2013, Latex Modified Concrete overlays were the second most common overlay material in the United States behind only asphalt overlays (Lane, 2017). As asphalt has nearly no capability to increase the strength of a bridge, Latex Modified Concrete overlays are a popular overlay which has the potential to increase the strength of the under-designed bridges in South Carolina. The SCDOT's previous experience with Latex Modified Concrete overlays is the main reason they were chosen as the item of research for this thesis. Ideally, the discovery of strength gain capabilities from Latex Modified Concrete will enable its quicker adoption due the familiarity of governments and contractors with its mixing and application.

Latex Modified Concrete (LMC) is a variant of portland cement concrete (PCC) which replaces some of the water in a typical PCC with a latex emulsion admixture. This admixture forms a plastic film within the concrete which gives LMC several properties that make it more beneficial to bridges than standard PCC (Sprinkel, Michael M., 1984). LMC is often used on overlays rather than PCC due to its better freeze-thaw performance and higher resistance to chloride intrusion (Sprinkel, Michael M., 1984). LMC has also been shown to have higher tensile, compressive, and flexural strengths than standard PCC (Sprinkel, Michael M., 1984). This strength increase is thought to arise from the concrete's lower w/c ratio and an increased bond strength between the paste and aggregate. LMC has also been used in bridge repair due to its lesser impact on the bridge’s self-weight as opposed to other concrete types. Only around 1.5” of LMC is required to achieve the same cover effect of 2” of standard PCC thanks to its increased resistance to chloride instrusion (Suskawang and Nassif, 2020). LMC overlays also perform well in terms of longevity – an evaluation of LMC overlays in Virginia found that LMC overlays could have service lives of twenty years or longer (Sprinkel, Michael, 1992).

These benefits have allowed LMC to be used on highway bridges as an overlay material for the past 60 years and throughout the United States (Sprinkel, Michael M., 1984). Historically, LMC has been viewed as a material to be used for bridge repair and protection rather than a way to increase the flexural strength of a bridge (Kuhlmann, 1985). A hallmark of this repair process, across structures, is rigorous surface preparation of the existing deck via methods such as sandblasting or hydro demolition (BASF, 2020). Combining the deep and destructive surface preparation with the typical thinness of an LMC overlay results in the LMC overlays failing to provide any significant increase in the strength of the structure (Harries et al.,). However, these thin overlays are still found to be structurally composite with the existing structure (Harries et al.,). The successful application of an LMC overlay with less destructive surface preparation would enable it to provide all its previously mentioned benefits in addition to increasing the flexural strength of the bridge.

Bond Strength

For the research conducted as a part of this thesis, a successful bond strength is defined as a bond which enables the LMC overlay to increase the load distribution performance and/or flexural capacity of the existing structure. The bond between the LMC and the existing structure can still be the first item to fail, but it may still increase the original flexural capacity of the structure. The ability of the bond to meet this qualification can be evaluated two ways. The first is a direct method: conducting bond tests on a test area and comparing the results to a bond strength threshold established by the literature. The second method is by constructing an overlay and testing the system flexure, thereby evaluating the performance of the bond based on the structural performance of the overlay. This research will evaluate the bond both ways. The first method will be used to determine the proper LMC mix and surface preparation method to use in flexural testing. The bond will then be evaluated via the second method during the flexural testing of the system under service and ultimate loads.

In order to use the direct evaluation method, a bond test type and a threshold for bond strength must be established. The bond test chosen for this research was the pull-off test outlined by ASTM C1583 (ASTM, 2020)) (Figure 2.1). This bond test was chosen due to the ease of both specimen preparation and testing process.

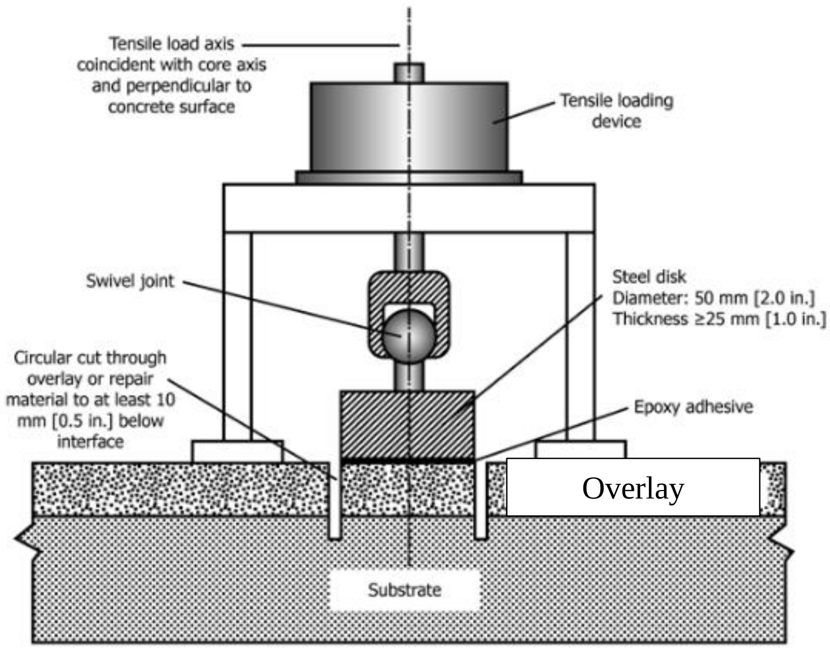

Figure 2.1: ASTM C1583 Pull Off Test

Bond strength between concrete layers is a function of multiple different factors, the primary of which are surface preparation and material properties (EL Afandi et al., 2023). A paper researching the effect of substrate texture and moisture content on bond strength found their average seven-day bond strength for medium level surface preparation to be 211 ± 90 psi (Toledo and Newtson, 2021). In 2004, a paper comparing the experimental and finite element analysis (FEA) results of LMC pull-off testing reported bond strengths ranging from 235 psi to 347 psi (Yun et al., 2004). Both of these papers evaluated bond strength via a direct tension pull off test and help establish a precedent on typical bond strengths for overlays. Acceptable bond strength ranges also exist throughout the literature. A presentation given by researchers from the University of Pittsburgh states a minimum direct tensile bond strength for ensuring a sound interface ranges from 100 psi to 200 psi (Harries et al.,). This minimum range is corroborated by the American Concrete Institute's (ACI) Guide to Materials Selection for Concrete Repair which lists the typical range for seven-day direct tensile testing as 150 psi to 250 psi (ACI Committee 546, 2014). Based on the minimum acceptable range given by ACI and the range exhibited by Yun et al., the target bond strength for a materials sample to qualify for the overlay testing was set at 200 psi.

Load Distribution

A key aspect of a structural system's behavior is the way it distributes load between its members. Load distribution is helpful within a structural system because it reduces the load felt by any individual member (Gunter, 2016). Load distribution is the physical phenomena wherein load applied to an individual structural member is distributed to other members in the system, thereby increasing the overall capacity of the structure See Figure 2.2 below for a representation of the effect of this phenomenon in a structural system.

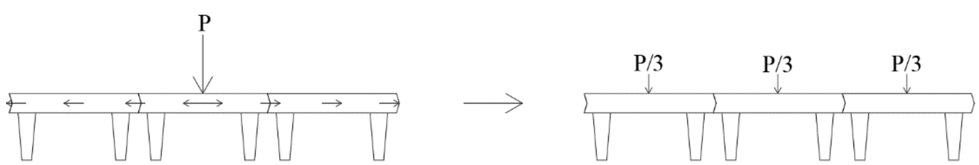

Figure 2.2: Representation of the Effect of Load Distribution

Many different parts of the structural system can help distribute load – shear keys, tie rods, and deck overlays are just a few key components (Gunter, 2016). However, these components often do very little to help distribute load on their own, especially over longer periods of time. Due to this inability to distribute load, it is necessary to explore other means to enhance the load distribution between girders in a bridge.

In order to analyze load distribution, its effects on structural systems, and the ability of different methods to enhance its capabilities, there must be some way to quantify its physical behavior. While there are several ways to accomplish this, the most common method is via load distribution factors. Load distribution factors can be calculated theoretically when designing a structure or determined experimentally from an existing structure (American Association of State Highway and Transportation Officials, 2014). The research conducted in this thesis focuses on experimental load distribution factors. Experimental load distribution factors are primarily functions of two properties: stiffness and deflection (Eubanks, 2023). The standard equation for load distribution factors can be found below in Eqn 1 where DF_i represents the load distribution factor for an individual member, δ_i represents the deflection of an individual member, k_i represents the stiffness of an individual member, and n represents the total number of members in the system.

$$DF_i = \frac{\delta_i * k_i}{\sum_{i=1}^{i=n} \delta_i * k_i}$$

Eqn 1: Load Distribution Factor Equation

This equation calculates the load distribution factor for an individual girder as the fraction of the individual girder's deflection as compared to the system's total deflection weighted by the girder's stiffness. A higher distribution factor indicates poor load distribution whereas a lower distribution factor indicates improved load distribution. If all the members of a system have the same or similar experimental stiffnesses, Eqn 1 can be simplified by removing the stiffness factor, resulting in Eqn 2 where DF_i represents the load distribution factor for an individual member, δ_i represents the deflection of an individual member, and n represents the total number of members in the system.

$$DF_i = \frac{\delta_i}{\sum_{i=1}^{i=n} \delta_i}$$

Eqn 2: Simplified Load Distribution Factor Equation

Eqn 2 provides a simple and effective way to quickly evaluate the capabilities of a system to distribute load. This version of the load distribution factor equation will be used to calculate the load distribution factors presented in this paper. Previous research conducted at Clemson University verified the stiffnesses of the girders used in this testing varied by no more than 1.5%, enabling the use of Eqn 2 (Eubanks, 2023).

One project conducted at Clemson University explored the use of transverse post-tensioning to increase load distribution between girders. In this project, three decommissioned channel girders were placed next to each other and transversely post-tensioned at three points where tie rods used to hold the girders together. The strands were stressed at three levels – negligible load, fifteen kips, and thirty kips (Eubanks, 2023). When the strands were stressed to thirty-kips, there was a noticeable increase in load distribution between girders and engaged the shear keys causing no damage to the girders (Eubanks, 2023).

Other methods of enhancing load distribution on existing bridge systems also exist. Two of these were investigated by researchers at Virginia Tech University (Halbe et al., 2015). The first of these involved epoxying a Kevlar mesh over an existing shear key to improve the shear key's durability and lifespan (Halbe et al., 2015). In the second of these options a six-inch by six-inch by 4-inch area was left exposed at a shear key, exposing a shear stirrup. A piece of reinforcement was then used to splice together the shear keys and the whole area, including the shear key, was filled with Ultra-High Performance Concrete (Halbe et al., 2015). This research found both of these options performed better than the original connection status and enhanced load distribution (Halbe et al., 2015).

Structural overlays may also help with load distribution but can be ineffective due to reflective cracking along the longitudinal joints between members. The risk of this reflective cracking arises from the negligible tensile strength of concrete with no tension steel and its limited ability to resist any loads which seek to pull the overlay or girders apart. The addition of other methods to increase load distribution, such as transverse post-tensioning, could help reduce the risk of reflective cracking by providing resistance to these pulling forces and strengthening the structural system as a whole.

Flexural Strength of Girders with Latex Modified Concrete Overlays

Other than preliminary work done by researchers at the University of Pittsburgh investigating the requirements for the composite behavior of LMC overlays and an underlying structure, no research was found investigating the flexural strength of structural systems with LMC overlays (Harries et al.,).

CHAPTER THREE

MATERIAL TESTING

Planned Mixes

Prior to performing the flexural testing, it was necessary to determine if LMC could achieve a successful bond with less invasive surface preparation. To that end, three LMC mix designs were proposed and tested. Mix designs one and two were provided by NHM Constructor's and Modified Concrete Suppliers LLC, contractors who had previous experience mixing LMC for the SCDOT. These mixes also conformed to the SCDOT's specifications for LMC overlays. (SCDOT, 2007). The third mix design was taken from a Virginia Department of Transportation (VDOT) presentation on "Rapid Overlays for Deck Preservation" (Sprinkel, Michael M., 2012). See Table 3.1 below for the proportions of each mix design and the amount of each that was made.

Table 3.1: Proposed Mix Designs

	Mix 1	Mix 2	Mix 3
CTS Rapid Set Cement (lb)	0	80	80
Type 1 Cement (lb)	80	0	0
Latex Modifier (lb)	25.3	25.3	24.9
Fine Aggregate (lb)	196	175	195
Coarse Aggregate (lb)	154	151	142
Water (lb)	15.2	18.8	16.7
Volume (ft^3)	3.28	3.28	3.28

All three mixes used the same coarse aggregate (#789 Washed Stone, Figure 3.1), fine aggregate (manufactured sand, Figure 3.2), Latex Admixture (Figure 3.3) and tap water. Each mix varied slightly in their amounts of each material. The principal difference between the mix designs was the type of cement. Mix one used standard, type

I portland cement while mixes two and three used CTS Cement Co. Rapid Set Cement (conforms to ASTM C1600 (ASTM, 2023)). Mix one was chosen in order to create a baseline for the behavior of a standard setting concrete mix with an added latex admixture. The usage of rapid-set cement in mixes two and three was meant to model a bridge repair scenario where the repair needed to be done quickly and therefore required a quick setting cement. While mix two alone was capable of simulating this scenario, mix three was also chosen in order to have a comparison to a mix that did not conform to SCDOT specifications. Due to mix three's original creation by VDOT, it conformed to their standards rather than SCDOT's.

Figure 3.1: #789 Washed Stone Sample

Figure 3.2: Manufactured Sand Sample

Figure 3.3: Latex Admixture

Planned Material Testing

There were two material properties of interest for the LMC mix testing: compressive strength and bond strength. Workability and set time were not planned to be directly measured but rather simply observed qualitatively. The compressive strength of the mixes was tested via a standard compression test based on ASTM C39 (ASTM, 2021). Each of the three mixes were planned to be tested at one-, three-, and seven-day strength with four cylinders being tested at each time stamp for a total of thirty-six compression tests. These cylinders were to be standard 4” by 8” cylinders (Figure 3.4).

Figure 3.4: Standard 4” x 8” Cylinder

The bond strength of the mixes was tested via a standard pull-off test based on ASTM C1583 (ASTM, 2020) The pull-off tests were performed on two-inch diameter specimens cored from a two-foot, three-inch square test area (Figure 3.5). The two-inch diameter specimens were cored through the LMC overlay and then one inch into the existing girder.

Figure 3.5: Test Area with Cores

The pull off testing was performed for two types of surface preparation. In both methods, the surfaces were initially cleaned with a broom. In method one, the surface of the test area was pressure washed with a small, electric pressure washer (Figure 3.6). In method two, the surface of the girder was scarified longitudinally and perpendicularly with a steel wire brush (Figure 3.7). Figure 3.8 presents the concrete appearance after the different surface preparation methods. Between the different mix designs and surface preparation methods, a total of six test areas were planned to be made. The bond strength of each test area was planned to be tested at three and seven-day strengths. Six pull-off tests were planned for each test area at each timestamp, resulting in a planned total of seventy-two pull-off tests. A summary of the planned material testing can be found below in Table 3.2.

Figure 3.6: Pressure Washer used in Material Testing

Figure 3.7: Steel Brush used in Material Testing

Figure 3.8: Typical Pressure Washed (Left) and Steel Brushed (Right) Test Areas

Table 3.2: Summary of Planned Material Testing

			Mix Design		
			One	Two	Three
Number of Compression Tests		1 Day Strength	4	4	4
		3 Day Strength	4	4	4
		7 day Strength	4	4	4
Number of Pull Off Tests	Steel Brush Surface Preparation	3 Day Strength	6	6	6
		7 Day Strength	6	6	6
	Pressure Washed Surface Preparation	3 Day Strength	6	6	6
		7 Day Strength	6	6	6

Specimen Casting and Preparation

The specimens for materials testing were cast on May 22, 2023. Mix one was mixed first and several issues were encountered. The aggregate received from Vulcan was fairly saturated with water which was not accounted for when portioning the materials for mix one. Therefore, the water content of mix one was too high, and the mix was extremely fluid. Despite the high moisture content, the test areas and cylinders were cast without any major issues (Figure 3.9 , Left). Mix two was cast second and an attempt was made to adjust the mix design for the high moisture content of the aggregate. However, this attempt overcorrected, and the mix was far too stiff. While there was an attempt to cast the cylinders and test areas only the cylinders were usable – the mix set too rapidly to successfully pour and finish the test areas (Figure 3.9, Center). Given the issues with mixes one and two, it was decided to not proceed with mix three and reattempt mix two. This time, the moisture content was decreased to around two-thirds of the originally planned water content to adjust for the aggregate. Revised mix two had acceptable moisture content and allowed for a smooth casting of the test areas and some cylinders (Figure 3.9, Right). Emphasis was placed on the placement of LMC for the bond test areas, therefore the mix set before all the planned cylinders could be cast. For all tests the bond test areas were cleaned and dried after their surface preparation.

Figure 3.9: Mix One (Left), Mix Two (Center), and Mix 3 (Right) Material Testing Areas

After the test areas and cylinders were cast, they had to be prepared for their respective testing processes. The cylinders set in their molds next to the pull-off test areas until they were tested. As cylinders were removed from their molds for the seven-day tests, many of them turned out to be poorly consolidated and therefore unsuitable for testing. Due to these consolidation issues cylinders were only tested at seven- and twenty-eight-day strength.

In order to perform pull-off testing, the specimens had to be prepared no less than two days before the desired timestamp in order to give the epoxy time to harden. This meant that the specimens for three-day bond strength needed to be prepared after only setting for one day. However, mix one had gained so little strength at one day that the mix itself broke under the force of the core drill. This poor performance of mix one led to its elimination as a suitable material to investigate for flexural testing. The rationale for this decision came from two factors. One, the poor performance of mix one made it impossible to make a judgement on its performance at a large scale. Secondly, many cases of bridge repair require a quick timeline and a mix that cannot gain enough strength after twenty-four hours to resist the force of a core drill will be unsuitable to use on a bridge. Both test areas for mix two (successful) were successfully poured, but only one test area yielded specimens for bond testing. Five specimens were successfully prepared from the test area for pressure washing and mix two (successful) (Figure 3.10). On the first attempt to prepare a specimen for the steel brushed, mix two (successful) test area the core drill slipped off its bearings, damaging both the in-progress specimen and coring bit. Unfortunately, the lab contained no spare bits, so in order to ease comparisons in data all pull-off testing was postponed to seven-day strength. Upon the purchase of new coring bits, attempts to prepare specimens for the steel brushed, mix two (successful) test area failed. The steel brush method of surface preparation created a bond which could not resist the rotary force of the core drill (Figure 3.11). Accordingly, the steel brush method of surface preparation was also removed from consideration for continued testing.

Figure 3.10: Successful Pull-Off Specimens

Figure 3.11: Broken Cores from the Steel Brush Test Area

At the conclusion of specimen preparation, the following specimens were successfully prepared for testing:

- Five pull-off tests from the mix two (successful), pressure washed test area
- Four cylinders from mix one

- Four cylinders from mix two
- Three cylinders from mix two (successful)

Material Testing Results

The five pull-off specimens were tested at seven-day strength on May 29, 2023. The specimens were tested with a Proceq digital pull-off tester to failure (Figure 3.12). Each specimen failed at the bond interface (Figure 3.13) with bond strengths ranging from 171 psi to 270 psi (Table 3.3). The average bond strength of the samples was 213 psi with a standard deviation of 37.2 psi. All pull-off tests failed at the interface of the precast girder and the LMC.

Table 3.3: Pull Off Testing Results

	Failure Stress (psi)
Spec 1	216
Spec 2	270
Spec 3	216
Spec 4	171
Spec 5	192
Average	213
Std Dev	37.2

Figure 3.12: Proceq Digital Pull-Off Tester

Figure 3.13: Typical Bond Failure of Pull-Off Specimens

Three cylinders from mix one and two and two cylinders from mix two (successful) were tested for compressive strength at seven-days (Figure 3.14). The results from these tests are presented below in Table 3.4. The average compressive strength for mixes one, two, and two (successful) at seven-day strength were 2530 psi, 7180 psi, and 6650 psi, respectively. The twenty-eight-day strengths for mix one, two, and two (successful) were 4830 psi, 8030 psi, and 7550 psi respectively.

Table 3.4: 7-Day Compression Testing Results

	Compressive Strength (psi)	
Mix 1	Spec 1	2370
	Spec 2	2570
	Spec 3	2660
	Average	2530
Mix 2	Spec 1	7110
	Spec 2	7030
	Spec 3	7410
	Average	7180
Mix 2 (Rev)	Spec 1	6570
	Spec 2	6720
	Average	6650

Figure 3.14: Typical Compression Test

Material Testing Discussion

The first result from the material testing to discuss is workability. The high moisture content of mix one resulted in it being highly workable and set time was no issue. The second mix had nearly no workability – nearly as soon as it came out of the mixer it began to set and was no longer workable. Mix two (successful) was more workable than mix two but set relatively quickly. While it was hoped to gather more certain data regarding the mix's workability, a lack of manpower and preparedness rendered this impossible. The experience gained in preparing the material testing specimens was invaluable for the later successful placement of the LMC overlay for flexural testing. The results from the compressive testing indicate that mix two (successful) is sufficiently strong to explore further as a strength-increasing overlay on a bridge deck. The stated compressive strength of the existing channel girders provided by SCDOT is 5000 psi, less than the seven-day strength of mix two (successful). To perform well near ultimate loads, the LMC overlay needs to have a comparable compressive strength to the existing concrete structure so that it can properly and effectively increase the strength of the structure. If the LMC overlay was much weaker than the existing structure it would crush long before the structure itself neared failure, eliminating its strength contributions and requiring the repair or even replacement of the overlay before the bridge itself reached a place where it needed to be replaced.

As discussed in chapter 2, section 3, the desired average bond strength at seven days was set at 200psi. The average bond strength at seven-days for the mix two (successful), pressure washed specimens was 212 psi, greater than the 200 psi previously established. In addition to the previously established bounds, the average bond strength was also compared to a recent review of concrete-to-concrete bond strength published in 2022 (EL Afandi et al., 2023). In this review of many different bond strength tests, including over 100 pull-off tests, the normalized tensile strength of direct pull-off tests for a bond between two samples of normal weight concrete was 0.26 for minimal surface preparation (EL Afandi et al., 2023). (See Appendix B for a description of how to calculate this normalized tensile strength using $\sqrt{f'_c}$). The same average normalized tensile strength value for the mix two (successful), pressure washed bond specimens was 0.25. Due to the inability to perform pull-off testing for mix one and mix two a normalized tensile strength value could not be calculated for them. The similarity between this value and the one found in the bond strength review serves as a final piece of evidence that pressure washing creates a successful bond between a standard concrete structure and LMC overlay. In conclusion, the high strength and acceptable bond of the pressure washed mix two (successful) provide suitable evidence to move forward with this mix design and surface preparation method for the flexural testing of an LMC overlay made with these parameters.

CHAPTER FOUR

LATEX MODIFIED CONCRETE OVERLAY TESTING

Overview of Latex Modified Concrete Overlay Testing

The second stage of this research involved placing and testing an LMC overlay on an existing, three channel girder system. This system contained seven main components: three skinny leg, pretensioned channel girders, three transverse post-tensioning strands, and a two-inch LMC overlay. The three skinny leg channel girders were taken from a decommissioned bridge and provided by the SCDOT. The girders were 30 feet long, 2'-3" wide, and spanned 27 feet between supports (see Appendix A for the girder plans provided by the SCDOT). These girders were designated as west, center, and east based on their locations relative to cardinal directions established in the lab space. In order to post-tension the girder system the eastern girder was slightly modified from its original condition. The shear key on the eastern edge of the eastern girder did not provide a flat surface on which the post-tensioning strands could bear. This issue was resolved by pouring small patches of mortar on the eastern girder around the holes where the strands passed through the girders. The three post-tensioning strands were low-relaxation, 0.6" diameter, seven-wire strands with a cross-sectional area of 0.217 in^2. These strands, which were post-tensioned transversely across the girders, were designated north, center, and south based on their locations relative to cardinal directions previously established in the lab space. The final item of the system was the two-inch LMC overlay placed directly on top of the channel girder system. The LMC overlay was set at two inches to as it provides a desirable increase in flexural strength but minimized the negative effect of self-weight on the flexural strength. Preliminary calculations indicated the net effect of a 2” LMC overlay would be approximately a 10% increase in flexural capacity (see Appendix E: Calculation of Moment Strength of Skinny Leg Channel Girders with LMC Overlays of Varying Thicknesses). Please see Figure 4.1 for a diagram of the system used in the flexural testing.

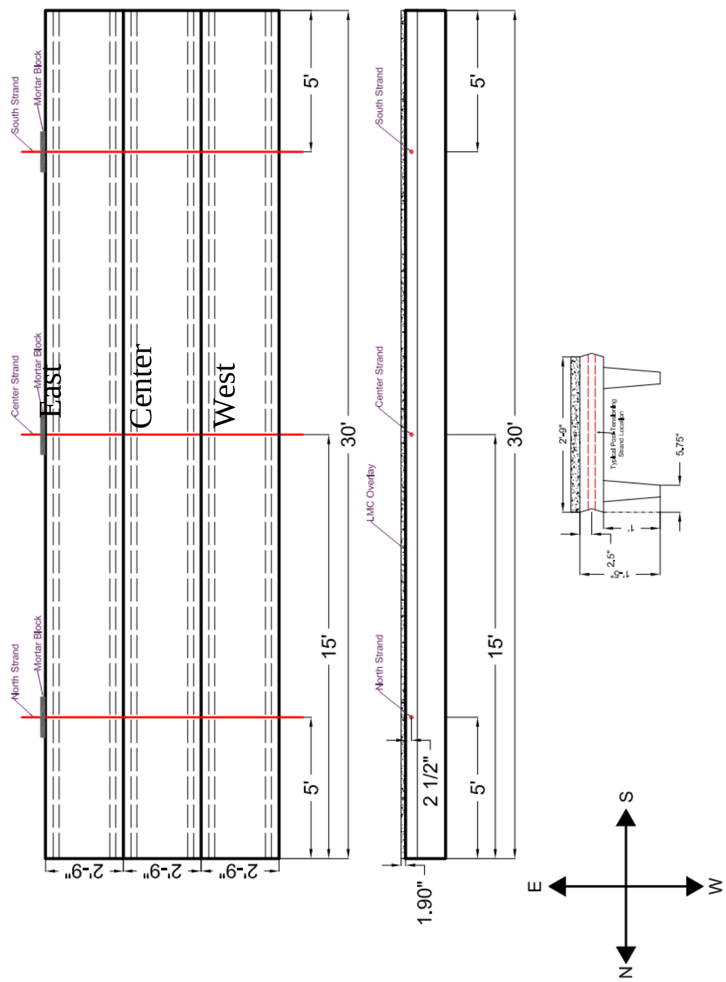

Figure 4.1: Overall System Layout

Two types of testing were conducted on the LMC overlay: basic material testing and flexural testing. The material testing consisted of cylinder compression tests (ASTM C39) and pull-off testing of specimens prepared from the overlay (ASTM C1583). These values were then compared with the results of the material testing in chapter three to evaluate the performance of the large slab relative to the smaller test pours. The flexural testing was divided into four stages: load distribution, joint durability, high load performance, and destructive testing. These four stages were then used to evaluate the structural performance of the LMC overlay.

Latex Modified Concrete Overlay Construction

The construction of the LMC overlay had four main stages: surface preparation, form construction, strand tensioning, and placing of overlay. The first stage of the LMC overlay's construction involved preparing the surfaces of the girders to facilitate a bond with the overlay. Based on the results of the materials testing, the surface was prepared with a 3000 psi pressure washer (Figure 4.2).

Figure 4.2: Pressure Washer Used in Surface Preparation

Each girder's surface was prepared individually following the same process: most residual asphalt was removed by a hand-held, pneumatic chisel (Figure 4.3) and then the girder surface was washed by the pressure washer. Not all of the asphalt was removed in an effort to simulate a lower-bound, quick and efficient repair job that could be easily repeated in the field. After the wash, the entire surface was pressure washed with the nozzle held approximately ¼" away from the surface (Figure 4.4), and finally the girder's surface was rinsed one last time.

Figure 4.3: Pneumatic Chisel

Figure 4.4: Pressure Washing Girder Surface

After the girder's surfaces were prepared, the girders were moved back inside the lab and the overlay's forms were constructed. These forms were made out of redhead concrete anchors and nominal 2" x 4" inch lumber (Figure 4.5).

Figure 4.5: Concrete Anchors used in Form Construction

Due to the mortar blocks cast around the east girder's shear keys the forms had to be divided into multiple pieces. A typical piece of the forms was installed via the following method: the redhead anchor was installed approximately ¾" below the top of the girder. Holes were then drilled in the nominally 2" x 4" lumber at the proper location to ensure two inches of the lumber extended above the girder surface. The lumber was then slid onto the anchor where a washer and nut secured the lumber to the girder. Small scab pieces of lumber were used to span the mortar blocks on the east girder and the corresponding areas on the west girder where the post-tensioning strand required bearing area. Smaller gaps (spalled concrete, imperfections in the wood, etc…) were patched with construction adhesive or tape. See Figure 4.6, Figure 4.7, Figure 4.8, Figure 4.9, and Figure 4.10 below for several pictures from the form construction process.

Figure 4.6: Installed Concrete Anchor

Figure 4.7: Typical Form Piece

Figure 4.8: Typical Slab over Mortar Block

Figure 4.9: Overall Picture of Nearly Complete Forms

Figure 4.10: Example of Tape used to Patch Section

After the construction of the forms, the strands had to be post-tensioned. Each strand was re-tensioned individually following a standard post-tensioning process. For a description of the general post-tensioning process see Appendix C. In this research, the load in each post-tensioning strand was recorded with load cells from Bridge Diagnostics Inc. and then monitored with their proprietary software. Table 4.1 below presents the initial post-tensioning force in each strand along with the post-tensioning forces a week later (overlay placing) and the average post-tensioning force throughout the overlay testing. The initial post-tensioning force was the force recorded in the strands after they had seated. The forces in each strand were recorded before each test on the overlay but showed little change. Therefore, the average of these forces is presented rather than each individual reading. All the post-tensioning force readings were taken with load cells mounted in-line with the strands.

Table 4.1: Strand Forces Over Time

Strand	***Initial Force (Kips)***	***Casting Day Force (Kips)***	***Average Testing Force (Kips)***
North	32.0	28.7	28.6
Center	31.3	30.5	30.4
South	32.4	31.2	31.0
Average	*31.9*	*30.1*	*30.0*

After the surface preparation, form construction, and transverse strand tensioning, the LMC overlay was placed. The LMC overlay was mixed by professionals from Modified Concrete LLC. A contractor was used to mix the overlay for several reasons. Principal among these was the desire to simulate the process as it might occur in actual application. Secondly, the placing of the overlay was a process well outside the personnel and equipment capabilities of the lab space, requiring the help of a contractor. Finally, the mix design used in the material testing and for the overlay had been previously used and provided by this contractor. Their familiarity with the mix and its placing was another reason for the decision to seek their assistance. Modified Concrete LLC provided labor and a truck containing the necessary water, cement, latex admixture, and mixer. The natural sand and #789 washed stone were purchased from Vulcan Materials company. The overlay was mixed on the truck and then poured on the girder system by a telehandler forklift rented from Blanchard Machinery (Figure 4.14). The girder surface had been dried and cleaned prior to the pouring of the overlay. See Figure 4.11, Figure 4.12, and Figure 4.13 below for pictures of the girder surface before the placement of the overlay.

Figure 4.11: Typical Surface of Girder Prior to Overlay

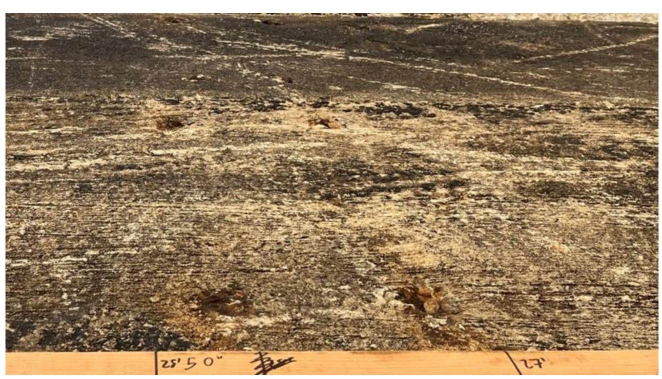

Figure 4.12: Typical Surface of Girder Prior to Overlay

Figure 4.13: Typical Surface of Girder Prior to Overlay

Figure 4.14: Telehandler Forklift and Bucket

The poured LMC was then spread via shovels, a home-made screed, and trowels (Figure 4.15 and Figure 4.16). This process was repeated multiple times due to the limited capacity of the telehandler bucket. Finally, the overlay was misted several times throughout the rest of the day to support curing. It should also be noted that a vibrator was not used in either the material testing or overlay placement. However, later destructive testing revealed good consolidation despite the inability to vibrate the mix during casting.

Figure 4.15: Spreading LMC with Shovels and Screed

Figure 4.16: Finishing LMC Overlay with Trowel

Materials Properties of the LMC Overlay

Three material properties of the LMC overlay were investigated: compressive strength, bond strength, and workability. Compressive strength was measured via 4” x 8” cylinders, similarly to the material testing done in chapter three. These cylinders were tested at one-day, three-day, seven-day, and twenty-eight-day strength. The results of these tests can be found in Table 4.2 (one of the seven-day strength cylinders contained an imperfection leading to the testing of the fourth cylinder). The pull off testing was also conducted similarly to the material testing in chapter three and was done at seven-day and twenty-eight-day strength. At each strength benchmark, five specimens were made and tested. These specimens were prepared in the same manner outlined in chapter three. See Table 4.3 for the results of the pull off testing. Workability was again observed rather than measured quantitatively but several important observations were made. First among these was the usefulness of continual misting of the overlay. At times it would begin to set and be difficult to smooth out but misting of the surface with additional water helped it regain its workability. The mix set within six hours and the formwork was removed within twenty-four hours of the overlay placement. Slump tests were performed, but unfortunately the data were lost and cannot be reported.

Table 4.2: Compressive Test Results

		Compressive Strength (psi)	***Average (psi)***
1 Day Strength	*Cylinder 1*	3540	*3720*
	Cylinder 2	3750	
	Cylinder 3	3860	
3 Day Strength	*Cylinder 1*	4170	*4310*
	Cylinder 2	4310	
	Cylinder 3	4460	
7 Day Strength	*Cylinder 1*	4690	*4660*
	Cylinder 2	4630	
	Cylinder 3	4660	
	Cylinder 4	4660	
28 Day Strength	*Cylinder 1*	5450	*5410*
	Cylinder 2	5430	
	Cylinder 3	5350	

Table 4.3: Pull Off Testing Results

	Specimen	Pull Off Strength (psi)	Failure Mode	Test Notes
7 Day Strength	1	54.5	Bond	Bond made with weak asphalt
	2	76.3	Bond	Bond made with weak asphalt
	3	N/A	Epoxy to Spec	Disk broke off specimen
	4	N/A	Epoxy to Spec	Disk broke off specimen
	5	115	Girder Failure	Concrete of under girder failed
28 Day Strength	1	180	Bond	None
	2	123	Bond	None
	3	120	Bond	Asphalt Present on Bond Surface
	4	102	Bond	Asphalt Present on Bond Surface

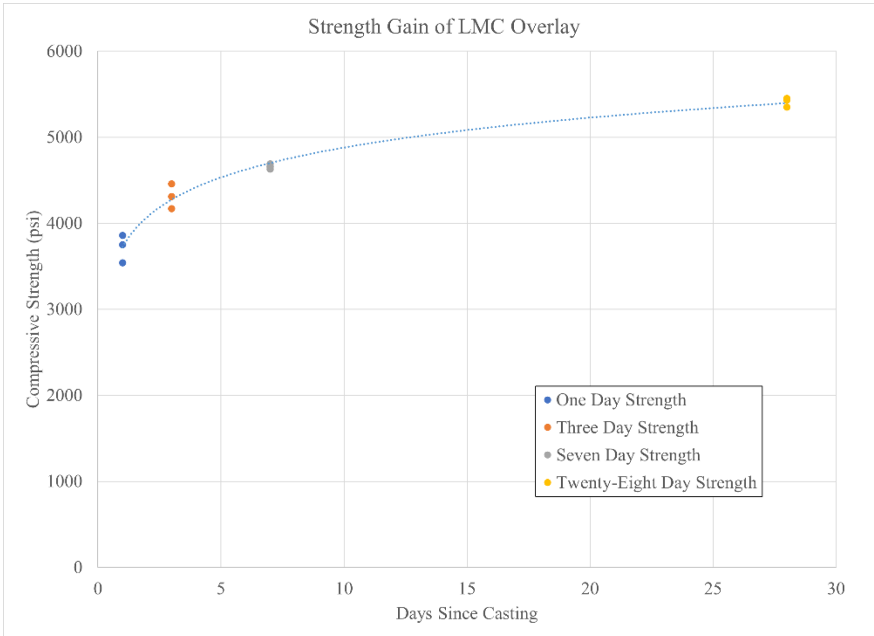

Figure 4.17: LMC Compressive Strength Over Time

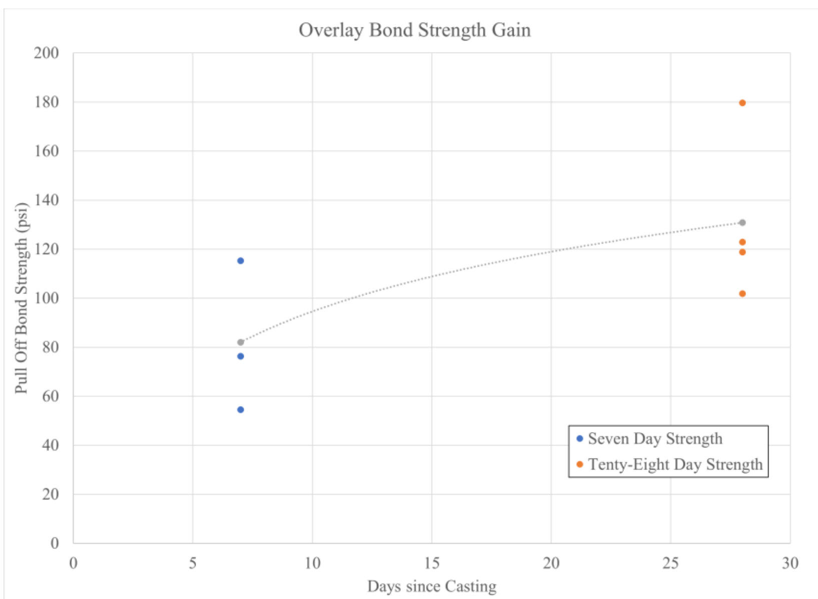

Figure 4.18: LMC Bond Strength Over Time

There are several items of note worth discussing from the material properties of the LMC overlay. First of these is the relatively low compressive strength of the overlay as compared to the test batches. While the true reason for this is unknown, the most probable reason is the use of natural sand for the overlay as opposed to the manufactured sand in the test batches. Manufactured sand is more angular than natural sand and can create a better bond withing the concrete itself, increasing the strength of the mix. The second item is the strength gain over time of the LMC overlay. As seen in Figure 4.17, the LMC overlay showcased a rapid gain in strength over three days which then quickly slowed down. This rapid initial strength gain is a result of the use of rapid set cement and evidenced in that the concrete reached nearly 80% of its twenty-eight-day strength at only three days. This is a beneficial property for bridge repair as it means the bridge could be opened much faster than with traditional concrete. The final item worth discussing is the relatively low bond strength values compared to the material testing. While the exact cause of this difference is also unknown, the most likely reason is poor bonding conditions on the channel girder system due to remaining asphalt, dirt/dust, or other similar factors (Figure 4.11, Figure 4.12, and Figure 4.13). See Figure 4.19 below for a typical surface of an overlay pull-off specimen.

Figure 4.19: Typical Bond Surface of Overlay Specimens

While these bond strengths are lower than what was expected based on the material testing, they do not fall outside the range of feasible values for the bond of LMC overlays placed in the field. In the same evaluation of LMC overlays previously discussed in chapter two, bond strength testing found tensile strengths ranging from just under 100 psi to over 400 psi (Sprinkel, Michael, 1992). This wide range of bond strength helps showcase the wide variability possible in bond strength of LMC overlays.

Flexural Testing Setup

Before discussing the testing and performance of the system, a discussion of the system's testing setup is required. A picture of the overall test setup can be found below in Figure 4.20 . The setup for the system testing can be divided into two sections: instrumentation and load application. The system was instrumented with six wire potentiometers (Figure 4.21), three load cells (Figure 4.22), and one pressure gauge (Figure 4.23). The six wire potentiometers were positioned at the midspan of the girders to measure midspan vertical deflections. Each girder received two wire potentiometers, with one glued to the inside of each girder's web. These wire potentiometers were labeled relative to two factors: the designation of the wire potentiometer's girder (west, center, or east) and whether the wire potentiometer was on the western or eastern web. For example, the wire potentiometer located on the western web of the center girder would be labeled as the CW wire potentiometer. The three load cells were used to measure the force in each post-tensioning strand over time. The load cells were labeled based on the designation given to the corresponding strand. However, only the center load cell data recorded continuously with the wire potentiometers. The north and south load cells were occasionally monitored during testing to ensure no drastic changes in the post-tensioning load occurred. Finally, the pressure gauge was attached directly to the pump which powers the hydraulic jack used to test the system. A digital readout of the hydraulic pressure in this jack was calibrated to the jack's force and used to drive the testing. See Figure 4.24 below for a labeled and dimensioned plan view of the system's instrumentation.

Figure 4.20: Overall Testing Setup

Figure 4.21: Typical Wire Potentiometer

Figure 4.22: Typical Load Cell

Figure 4.23: Hydraulic Pressure Gauge

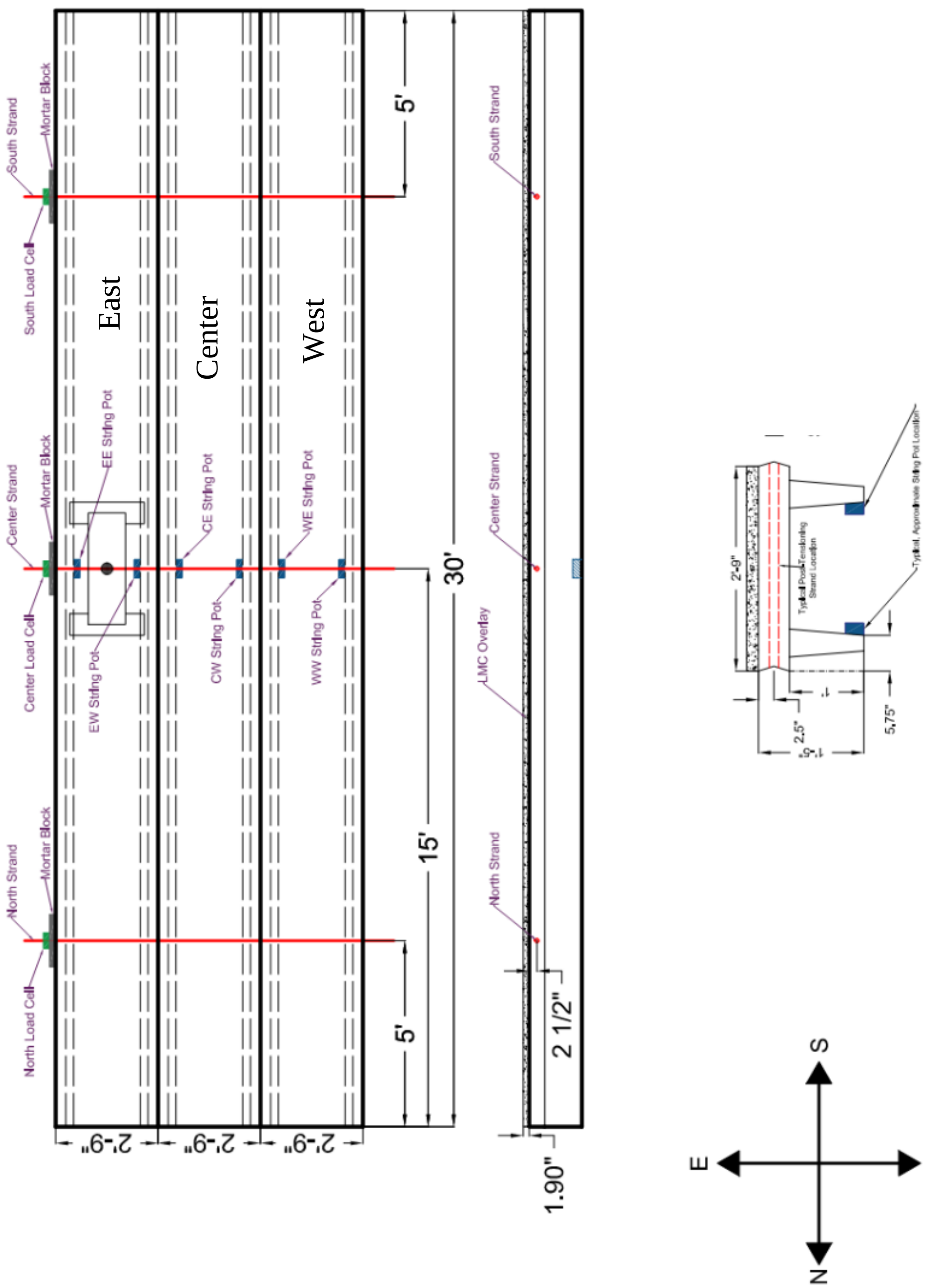

Figure 4.24: System Instrumentation Layout

The system was loaded in two-point bending using a hydraulic jack and steel spreader beam assembly which provided a constant moment region to develop at the midspan of the girders. The points of load application of the girders were three feet apart and in-line with the longitudinal centerline of the girder being testing. The three-feet distance was chosen to both coincide with harping in the pretensioned strands and to fit with available steel members in the lab. Elastomeric bearing pads were placed at every interface in the system. See Figure 4.25 below for a labeled, dimensioned diagram of the system's loading setup for a test loading the east girder. The setup for tests loading the center and west girders takes the same basic setup presented in Figure 4.25 but with the spreading system in line with the longitudinal centerline of the center and west girders respectively. While every flexural test used the same loading setup, some of the tests required different load thresholds. The load distribution and joint durability testing were service load tests. The service load for these tests was set at sixteen kips. This value is derived from the HL-93 design truck. This design truck has a back axle weight of thirty-two kips, a wheel spacing of six feet, and a minimum axle spacing of fourteen feet (American Association of State Highway and Transportation Officials, 2014). The loading value of sixteen kips was chosen to simulate one wheel line from the back axle of the design truck loading a single girder. The front axle was not considered as the axle spacing of an HL-93 truck was long enough that the front axle and back axle would not load the bridge at the same time.

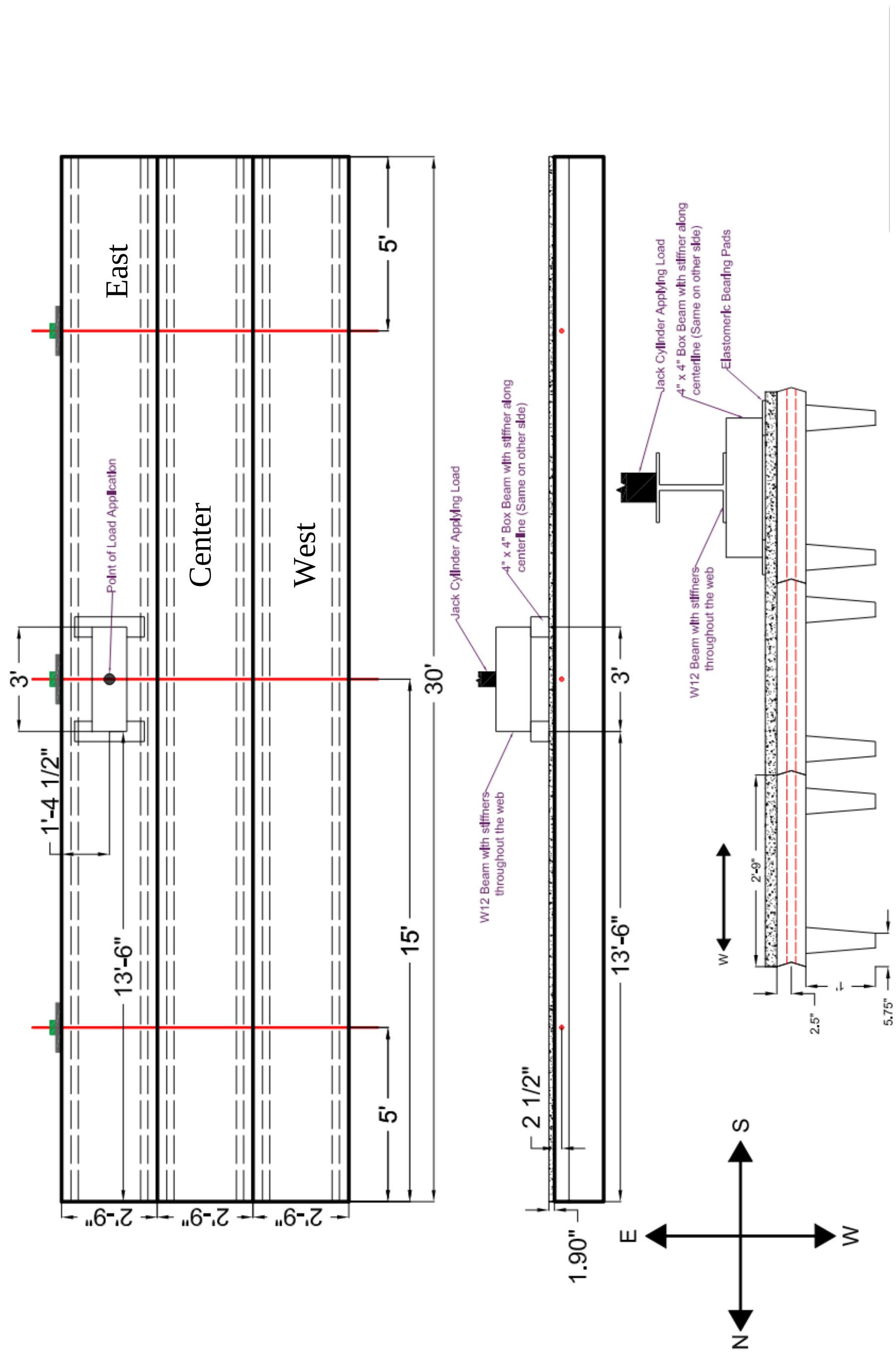

Figure 4.25: System Loading Plan, East Girder Loaded

Load Distribution Testing

The first set of flexural tests conducted on the system were load distribution tests. The principal goal of these tests was to determine the effect the addition of the LMC overlay would have on transverse load distribution in the channel girder system. Three separate tests were conducted to determine the load distribution capabilities of the system. In each test, the selected girder was loaded to or just past the sixteen-kip service load in three-kip increments. The effect of the LMC overlay was evaluated in two ways. The first evaluation method was visual and involved plotting the measured deflection (at multiple load steps) of the system along the east-west direction with and without the LMC overlay. These graphs were then normalized for the different loads to reduce the effect of the load on the visual appearance of the data. This method allows for easy visualization of the load distribution capabilities of the system and a visual comparison of the system’s behavior. The second evaluation method was quantitative and involved calculating and comparing the numerical distribution factors for the system with and without the LMC overlay. The first method of load distribution evaluation can be seen below in Figure 4.26, Figure 4.27, and Figure 4.28.

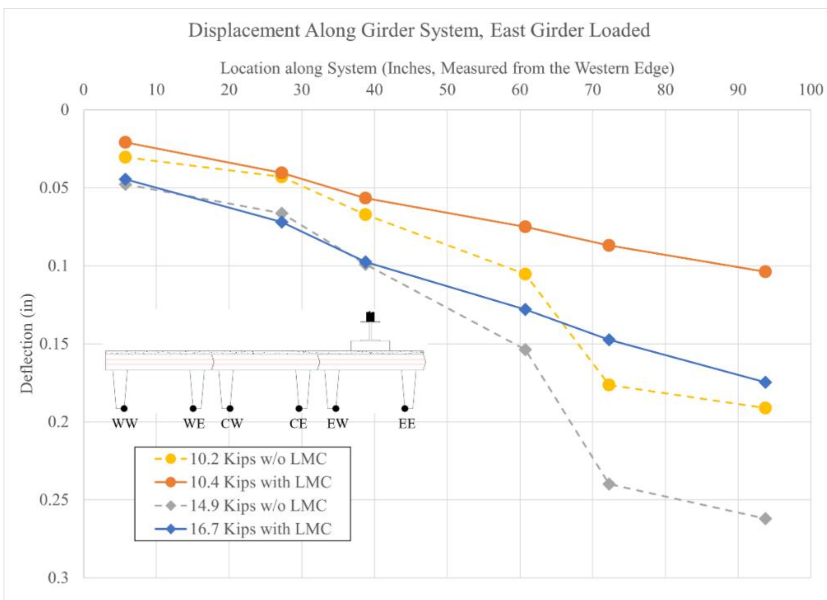

Figure 4.26: Load Distribution Test, East Girder Loaded

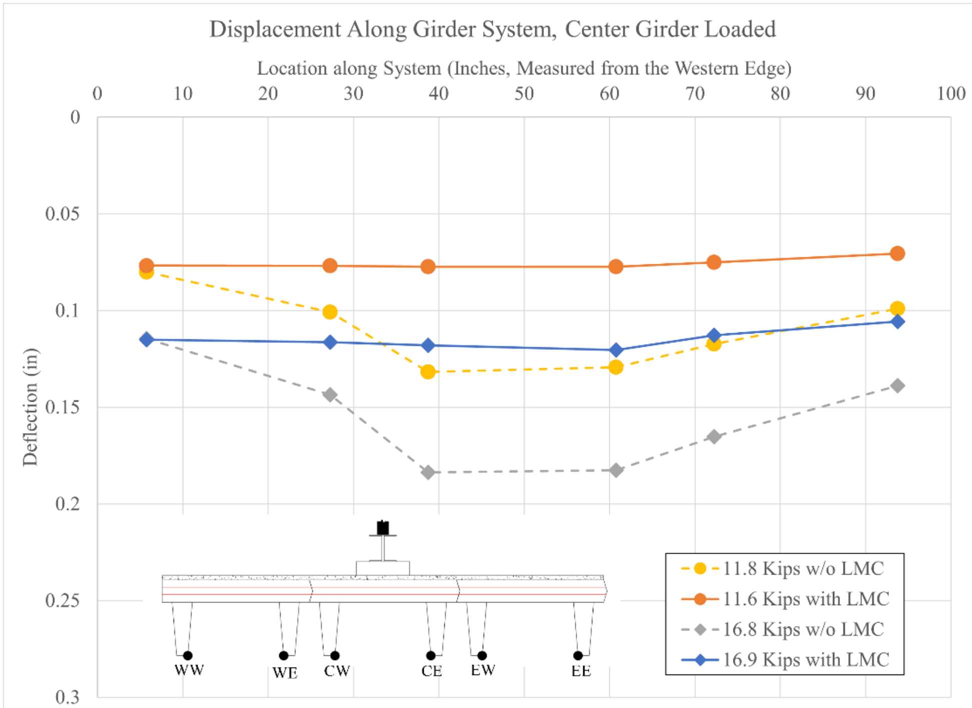

Figure 4.27: Load Distribution Test, Center Girder Loaded

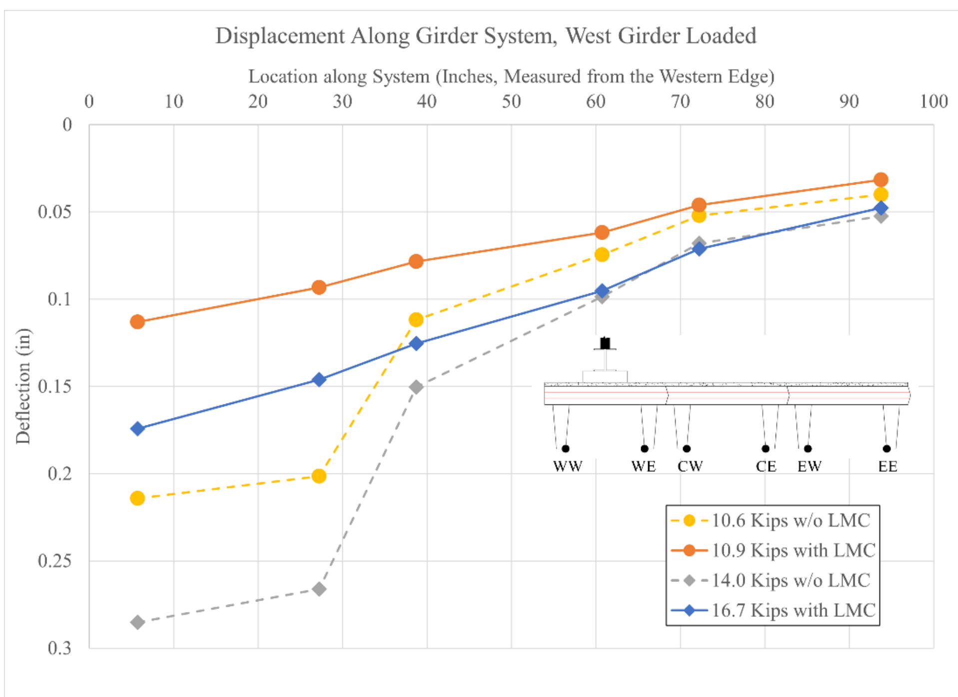

Figure 4.28: Load Distribution Test, West Girder Loaded

These figures graph the displacement of each sensor at certain load steps relative to their east-west position in the system. The dashed lines represent the displacement of the post-tensioned system with no LMC overlay while the solid lines represent the data from the system with the LMC overlay. Based on this data presentation, an increase in load distribution would correspond to a flatter line between the individual data points. Each of the above figures showcases this behavior, evidencing the improvement in load distribution capability given by the LMC overlay. However, the differences in behavior could also partly be due to the different load steps of the data. To that end, Figure 4.29, Figure 4.30, and Figure 4.31 below present the data normalized by load, giving deflections in inches per kip. Each of these plots showcase the same behavior as the original graphs, providing more evidence that the LMC overlay helps increase load distribution in the system. Data from tests without LMC were taken from Eubanks (2023). Eubanks used the same three girders are were used in the current thesis. Worth noting as well is previous research done by Eubanks also investigated the load distribution of this system with no transverse-post-tensioning. This investigation only loaded the eastern girder but found it to have a distribution factor of 98%, implying there was negligible load distribution present without transverse post-tensioning. The results of this test are added to Figure 4.29 below in order to see the effect of transverse post-tensioning on load distribution relative to the effect of the LMC overlay on load distribution.

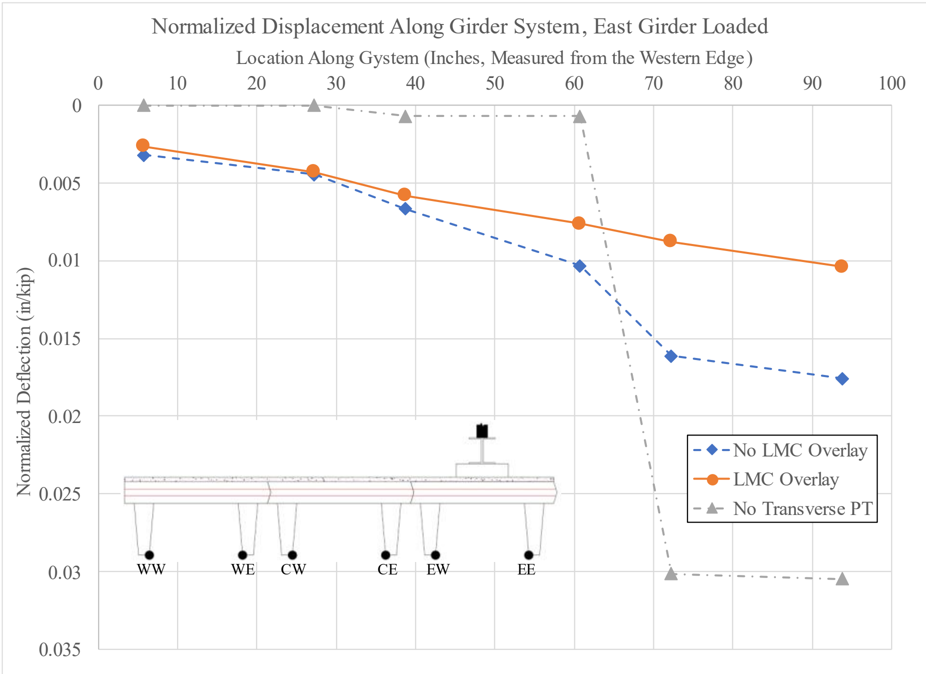

Figure 4.29: Normalized Load Distribution Data, East Girder Loaded

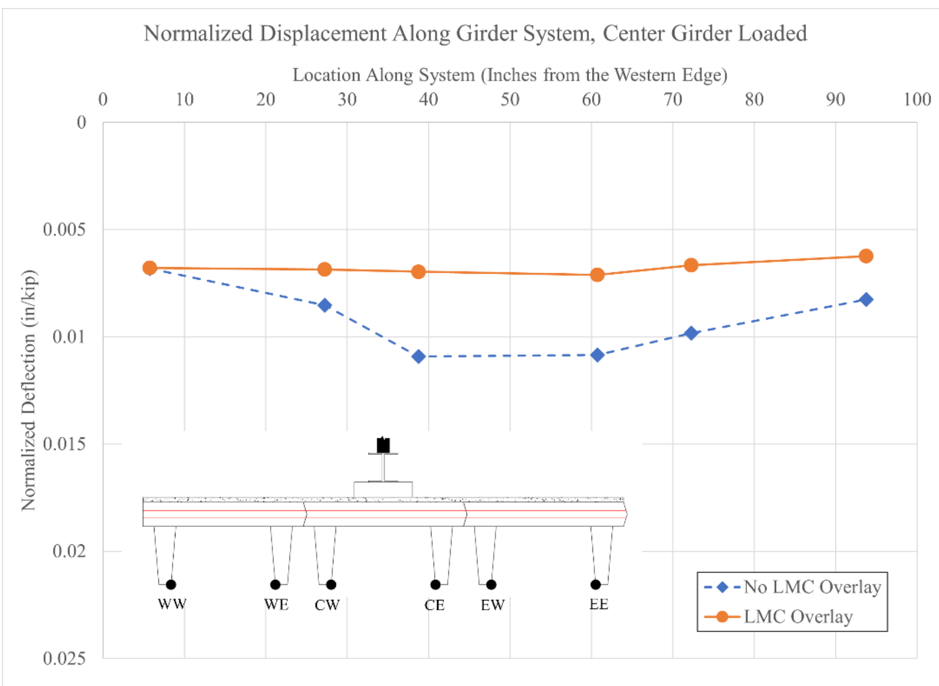

Figure 4.30: Normalized Load Distribution Data, Center Girder Loaded

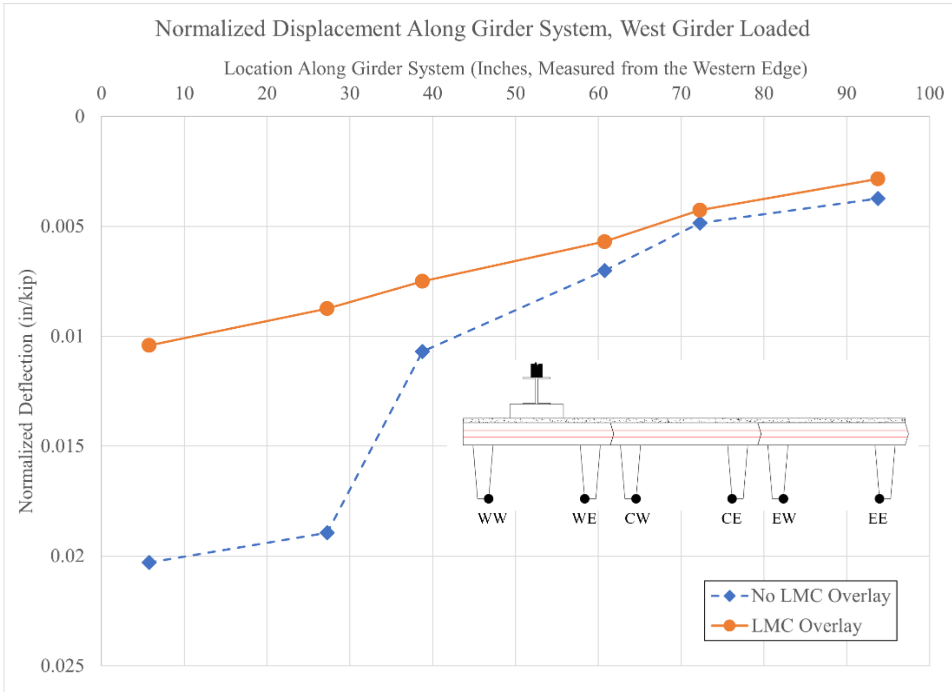

Figure 4.31: Normalized Load Distribution Data, West Girder Loaded

Numerical distribution factors were also calculated from each test using Eqn 2 (derived in Chapter 2). If the system experienced perfect load distribution, the max distribution factor ever recorded should be 0.333 as each girder would be sharing the load, and therefore deflection, equally. The critical distribution factors recorded for each girder are presented below in Table 4.4.

Table 4.4: Critical Distribution Factor Summary

<table>
<tr><td></td><td colspan="3">Critical Distribution Factor (DF_{Cr})</td><td colspan="3">Δ_{DF}*</td></tr>
<tr><td>Girder</td><td>No PT</td><td>No LMC</td><td>LMC</td><td>No PT</td><td>No LMC</td><td>LMC</td></tr>
<tr><td>East</td><td>0.98</td><td>0.599</td><td>0.486</td><td>0.647</td><td>0.266</td><td>0.153</td></tr>
<tr><td>Center</td><td rowspan="2">Unknown</td><td>0.394</td><td>0.346</td><td rowspan="2">Unknown</td><td>0.061</td><td>0.013</td></tr>
<tr><td>West</td><td>0.578</td><td>0.485</td><td>0.245</td><td>0.152</td></tr>
</table>

*$\Delta_{DF}=DF_{Cr}-0.333$ (a measure of how close the DF was to perfect, 0.333)

In the table above, the larger Δ_{DF} for a girder, the worse the load distribution of that girder. The value of Δ_{DF}, decreased for all conditions when LMC was present, indicating improved load distribution due to the presence of the LMC overlay. The higher level of load distribution in the center girder as opposed to the east or west girders is a result of the girders position. The center girder has the ability to distribute load to the east and west girder simultaneously, improving its load distribution. In contrast, the east and west girders can only distribute load in one direction, limiting the amount of load distribution possible. Since the east and west girders have poorer load distribution than the center, the decision was made to load only edge girders for the remainder of the testing in order to evaluate the behavior of the system in worst-case scenarios.

Joint Durability Testing

One concern regarding the LMC overlay is the behavior and performance of the joints between the girders over time. In an effort to investigate this, a repeated load test was conducted at service loads for one hundred cycles. This test was setup with the spreader system on the east girder to simulate the constant loading and unloading an edge girder. As discussed previously, the edge girders can only distribute load in one direction. This inability to distribute load in multiple directions increases the risk of longitudinal joint damage, causing a repeated load of an edge girder to simulate a worst-case scenario for the system. During each cycle, the girder was loaded up to roughly sixteen kips and then quickly unloaded. Data was collected and analyzed at cycles one through five, ten, and then every tenth cycle up to 100 cycles. The overall stiffness of the system was calculated from each data set and then compared to the previous stiffness data. It was assumed any major change or deterioration in joint behavior would correlate to a change in the system's stiffness.

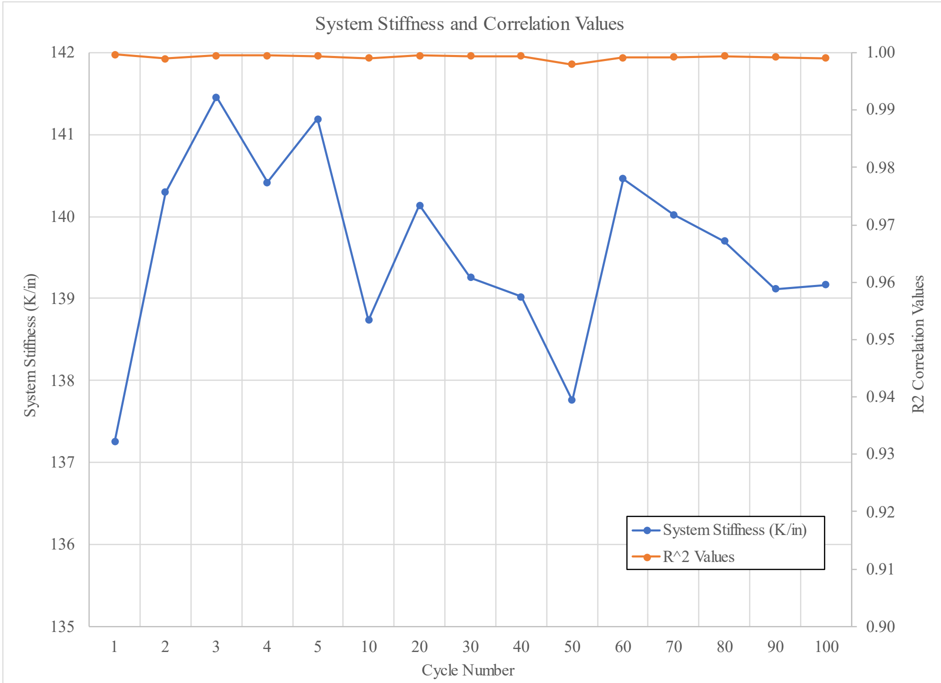

Figure 4.32: System Stiffness and Correlation over 100 Cycles

In Figure 4.32 above, cycle number is graphed on the x axis, with system stiffness (in K/in) on the lefthand y-axis and R^2 values plotted on the righthand y-axis. The system stiffness was calculated as the slope of the load vs displacement response for each measured cycle. The R^2 values are the corresponding correlation coefficients for each calculated slope. These R^2 values never drop below 0.99, which is evidence that the system's behavior was nearly always linear. More significantly, the system stiffness values also vary by no more than 4% throughout the testing, implying that very little deterioration, if any, occurred at the girder's joints. In addition to the load vs displacement data, the system was visually inspected and chain drug at each measured cycle to check for reflective cracking and overlay delamination. Throughout the cycles neither reflective cracking nor delamination was ever observed. While a 100-cycle test does not simulate the true lifespan of a bridge, the results presented here are encouraging and support the use of cyclic testing as a follow-up to the current research.

High Load Performance Test

The first two tests conducted on the system were service load tests meant to simulate typical events that the system might experience when used in the field. However, there was also a wish to understand how the system would perform when loaded past service loads and approaching failure. To that end, a high load test was conducted on the system. This test loaded the east girder in three-kip increments much like the load distribution tests, except with an initial loading to fifteen kips since the behavior of the system up to that load was known. Prior to the test's start, several stop criteria were laid out for the cessation of the test. In order of priority, they were:

- The north, center, and south strands recorded a load of 45 kips. This value was just over seventy-five percent of the strand's rupture force which was the limit the researchers were comfortable stretching the strands.
- "End of Comfort" was reached – namely, any situation where the researchers became uncomfortable to continue the test or deemed it unsafe to do so
- Delamination of the Overlay (checked by chain dragging the overlay every three-kip load step).
- Significant cracking of the system – flexural or reflective. The goal of this test was to determine the behavior of the system as it approached failure but not its ultimate failure load. To that end, both cracking and the delamination criteria prevented the test from causing a full flexural failure of the system.

- A load of thirty-seven kips was reached (this load was the sixteen-kip HL-93 design truck load times AASHTO's 1.33 dynamic load allowance and 1.75 load factor). This load is the highest theoretical load which can be applied to a bridge during design so if the system reached this load, it was deemed sufficient to cease the test.

The first stopping criteria reached during the test was the thirty-seven-kip load limit. However, the system had shown little change in behavior and the researchers determined it was safe to continue the test. At that point, the load limit was increased to sixty kips with the other stopping criteria remaining the same and in the same order of importance. As the test continued, the girders and overlay were monitored for flexural and reflective cracking in addition to delamination. However, the delamination check was ceased after a load of forty-five kips was reached due to concerns regarding the safety of chain dragging such a highly loaded system. At around fifty kips of load several small flexural cracks were noticed in the outside edges of the eastern and western girders. Finally, the system achieved its peak load at around fifty-seven kips. At this peak load, the LMC overlay experienced a rapid, destructive reflective cracking that spanned the entire length of the overlay (Figure 4.33). This reflective crack roughly followed the longitudinal joint between the east and center girders and penetrated through the entire overlay. Also, later removal of the post-tensioning slightly opened the reflective crack (Figure 4.34).

Figure 4.33: Reflective Cracking of LMC Overlay prior to removal of post-tensioning

Figure 4.34: Reflective Cracking of LMC Overlay after removal of post-tensioning

At the conclusion of the test, chain dragging of the reflective crack revealed only six to eight inches of overlay on each side of the crack delaminated. The chain dragging followed the standard procedure of dragging a steel chain over the surface and listening for the hollow sounds which indicate delamination. At the same time the reflective crack appeared, the force in each post-tensioning strand increased by around 1.5 kips. Figure 4.35 below presents the load-displacement curve for the high load test.

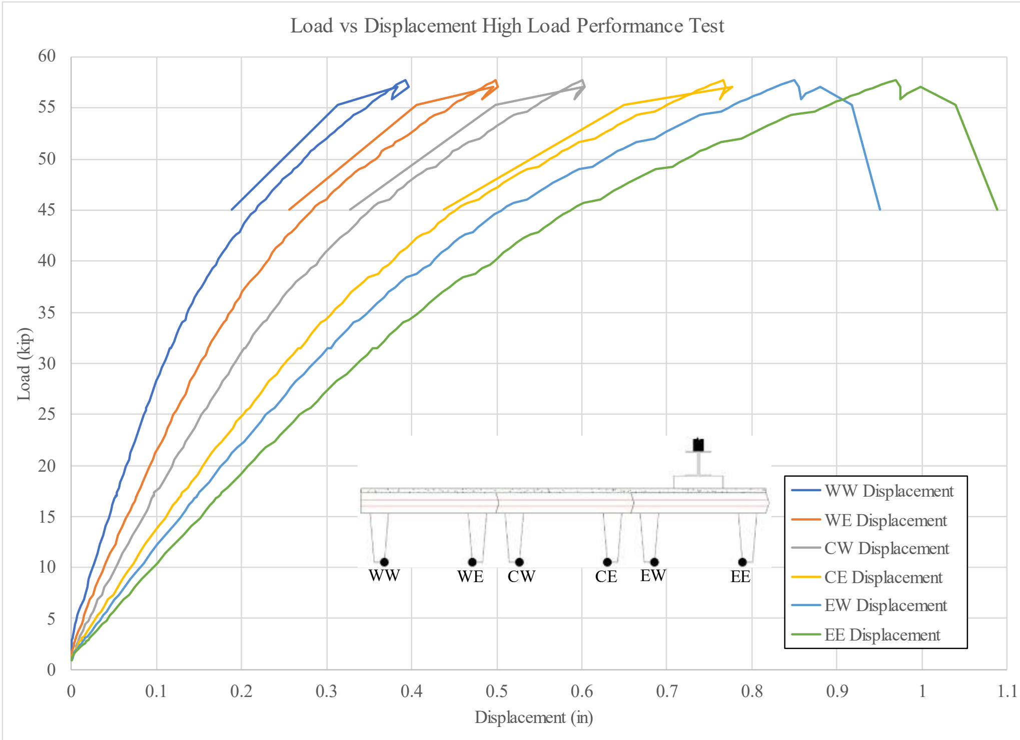

Figure 4.35: Load vs. Displacement Curve, High Load Test

There are several items worth discussing in Figure 4.35. At the system's peak load of 57 kips, the recorded displacement from the western and center girders decreases while it increases for the eastern girder. This seemingly odd behavior arises due to the longitudinal crack along the overlay. The loss of the LMC overlay reduces the capability of the eastern girder to distribute its load to the center and western girders. A reduction in the load shared to the center and western girders would also cause their displacements to reduce as well, matching the behavior shown in the graph. Similarly, the drop in load distribution would correlate to an increase in the load and displacement experienced by the eastern girder. While the eastern girder does showcase an increase in displacement, the entire system does not experience an increase in load. This is because the cracking of the overlay necessitates the load on the whole system to decrease while the load experienced individually by the eastern girder can still increase, satisfying all the behaviors required by simple mechanics. The drop in the system's ability to distribute load can also be seen below in Figure 4.36, a graph similar to those previously used to analyze load distribution.

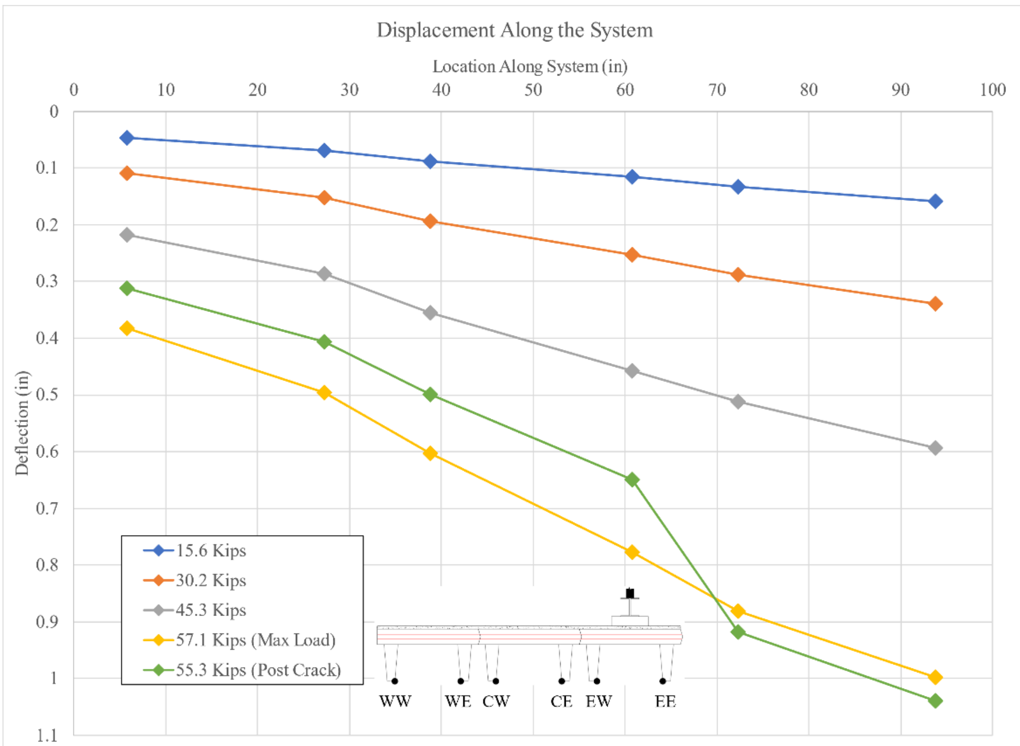

Figure 4.36: Load Distribution, High Load Test

In Figure 4.36 above, the most relevant load steps to examine are 57.1 kips and 55.3 kips. These two lines show the effect of the overlay cracking on load distribution. At 57.1 kips, the average difference between the eastern and western displacements is just over 0.6 inches. However, at 55.3 kips, directly after the overlay cracked, the difference increased to just under ¾ inches, an increase of roughly 25%.

The high load performance test of the LMC overlay presents several favorable outcomes. First, the overlay experienced minimal damage at loads much larger than the highest design load. Secondly, the presence of flexural cracks in the girders prior to any damage in the overlay indicates that the bond between the girder and overlay is strong enough to engage the strength of the girders before undergoing system-level structural damage. Finally, the lack of major change in the post-tensioning force indicates that failure of the post-tensioning strands and anchors were not the controlling failure mode of the system. One drawback of the LMC overlay's performance was its sudden failure. There was little warning that the overlay was about to crack. While the girders provide more than enough strength to prevent a total failure, brittle failure is always a concern in structures and should be monitored and accounted for in the design process.

Destructive Test – Flexural Strength

All three previous tests investigated the behavior of the system with both the LMC overlay and post-tensioning. It was also desired to investigate the behavior of the system without post-tensioning. To that end, the post-tensioning was removed in preparation for the destructive test. The cracking of the LMC overlay between the eastern and center girders was present during the final test. This test was designed to investigate the ability of the LMC overlay to distribute load without the presence of post-tensioning as well as the flexural strength added to a single girder by the overlay. This destructive test followed a similar pattern to the high load performance test. Once the overlay cracked the western girder was then tested to flexural failure. For this test, flexural failure was defined as when the girder became unable to carry load. This definition of flexural failure was popularly referred to as the "put it on the floor" philosophy during the test.

Unlike the other tests conducted on the overlay system, the destructive test occurred in multiple stages. While this segmentation was not planned, circumstances arose during testing which made it necessary. During the first stage of testing, the two-girder system was loaded up to roughly 30 kips in three kip increments with chain dragging at every three kips to check for delamination. The system was then unloaded, and chain dragged to verify that no delamination had occurred. The system was unloaded for this verification due to the concern that the high load on the system was preventing the chain drag from discovering any delamination. Since no delamination was found, the second stage of the test began. The system was then reloaded to thirty kips and subsequently loaded in three kip increments to roughly thirty-six kips, when the overlay failed in the same manner as it did in the high load test – a reflective crack spanning the length of the longitudinal joint between the west and center girders. After the overlay failed, the system was once again unloaded to investigate delamination around the crack. No delamination was found during the investigation. The third stage of the test began with reloading the western girder up to thirty-five kips. At this point the WW wire potentiometer reached its maximum displacement, so the system was once again unloaded while discussions were had on the best way to proceed. It was decided to use only the WE wire potentiometer to record the remaining displacement of the girder. The girder was then loaded up to thirty-five kips one more time (stage four) where the WE wire potentiometer also reached its maximum displacement as the girder had yielded and entered the plastic stage of its behavior. A yardstick was then placed next to the girder and approximate displacements were recorded up to the final failure of the girder at roughly thirty-nine kips and roughly four and a half inches of displacement. Figure 4.37 and Figure 4.38 below present the load displacement curves from stage 2 and stage 4. See Appendix D for the load displacement curves from stages 1 and 3 (along with extra plots from previous testing).

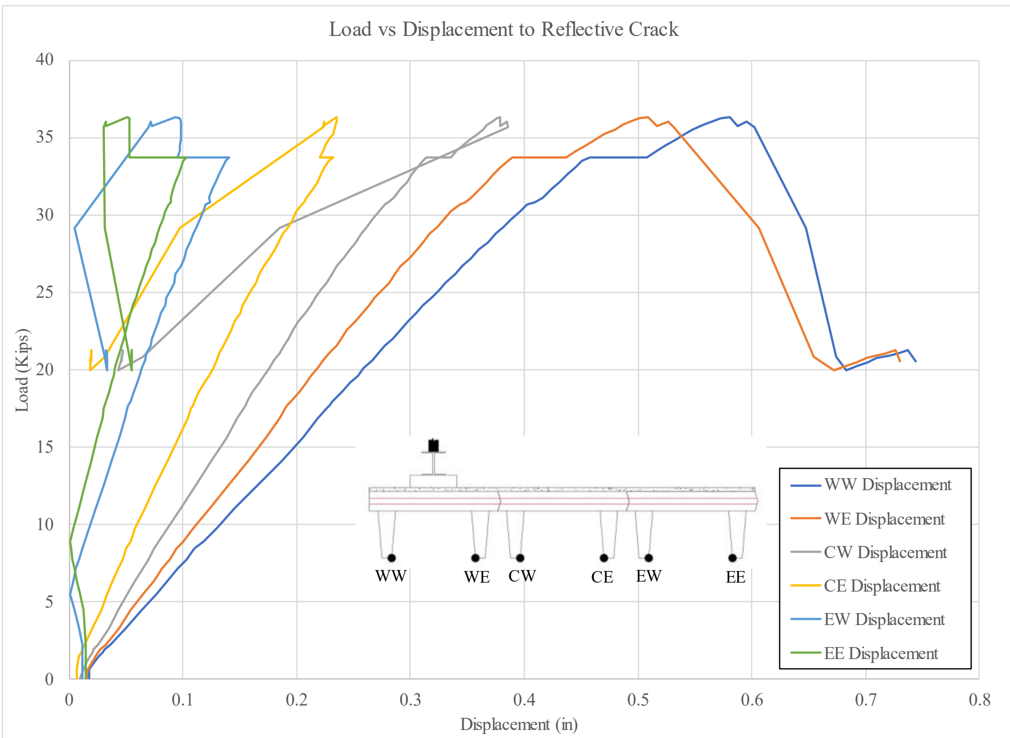

Figure 4.37: Stage 2 Load Displacement Curve, Destructive Test

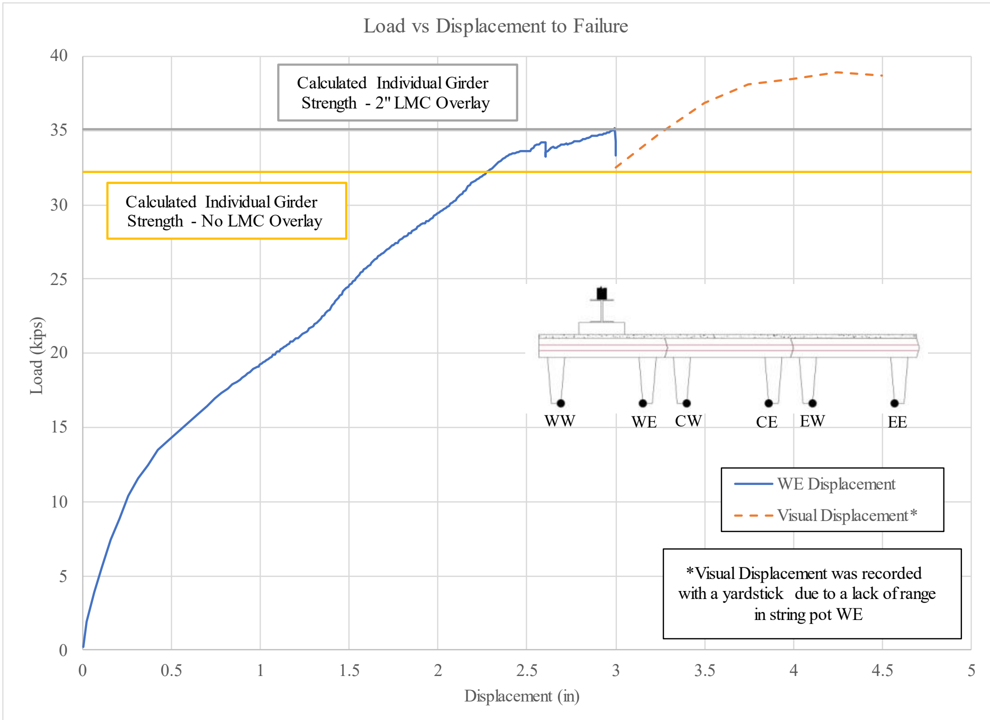

Figure 4.38: Stage 4 Load Displacement Curve, Destructive Tests

The final destructive test was designed to investigate two principal questions: how well the LMC overlay can increase the strength of an individual girder and how well the LMC overlay, with no assistance from post-tensioning, distributed load. The first of these questions unfortunately has no conclusive answer. As seen below in Figure 4.39 and Figure 4.40, the LMC overlay had debonded from the girder prior to the flexural failure of the beam. (The areas of delamination are highlighted in red boxes). This delamination implies that, in this test, the overlay did not contribute to the flexural strength of the girder at failure. However, it is worth mentioning that an increased bond strength could allow the overlay to remain bonded at failure, giving the overlay the ability to increase flexural strength.

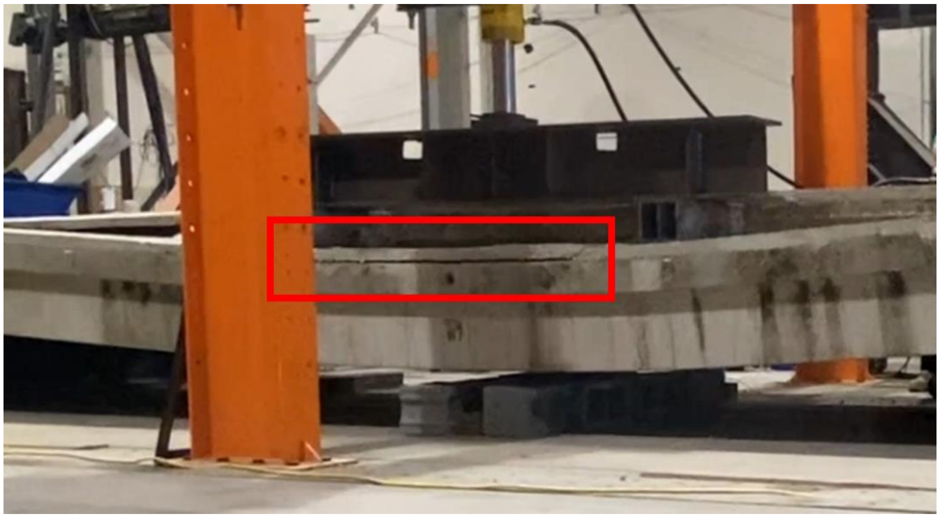

Figure 4.39: Delamination of Overlay Prior to Flexural Failure

Figure 4.40: Delamination of Overlay as Seen After Flexural Failure

Despite the physical behavior of the overlay indicating it did not impact flexural strength, the girder still failed at a load greater than its theoretical strength with and without the overlay (assuming the overlay remained bonded at failure). (See Appendix E for the calculation process for theoretical moment strength of the girder). This would loosely imply the overlay had a positive impact on final flexural strength. However, analysis of previous channel girder testing removes this loose implication.

Table 4.5: Comparison of Experimental Girder Strengths

	*Experimental Moment Capacity (Kip*ft)*	*Maxiumum Load (Kip)*
Max of Previous Girders (Eubanks 2023)	253	42.2
Min of Previous Girders (Eubanks 2023)	209	34.8
Average of Previous Girders (Eubanks 2023)	238	39.7
Destructive Test Result	233	38.9

Presented above in Table 4.5 is a comparison between the strength of the individual girder with the LMC overlay and the girders with no LMC overlay tested by Eubanks in 2023. As see in the table, the moment capacity of the individual girder with the LMC overlay is actually less than the average of four girders in good condition tested by Eubanks. In fact, the girder with the LMC overlay was weaker than all but one of the girders previously tested by Eubanks. Given that the strength of the girder with LMC lies within the range of girders previously tested by Eubanks, it is concluded that the LMC had little, if any, impact on the girder’s flexural strength. For a more detailed discussion of the mechanics of the overlay during testing, both with and without the presence of post-tensioning, see Appendix F.

Destructive Test – Load Distribution

While the LMC overlay did not perform as well as expected in strength gain, it did perform well in its load distribution capabilities, even without transverse post-tensioning. Figure 4.37 showcases this behavior well by exhibiting the same type of behavior at cracking of the overlay as Figure 4.35 from the high load performance test, albeit on a much larger scale. As soon as the overlay exhibited cracking, the ability of the center girder to take any of the load experienced by the western girder dropped to near zero. The reason for the much larger drop in the load distribution capabilities of the system is the lack of the post-tensioning. The large drop in the load distribution capabilities is seen more clearly below in Figure 4.41. Figure 4.41 presents the displacement of each string potentiometer along the system at certain load steps, including before and after the LMC overlay cracked. As seen in Figure 4.41, the west girder lost nearly all ability to distribute load once the overlay cracked. Overall, the LMC overlay did enhance the load distribution of the system even without the assistance of the post-tensioning.

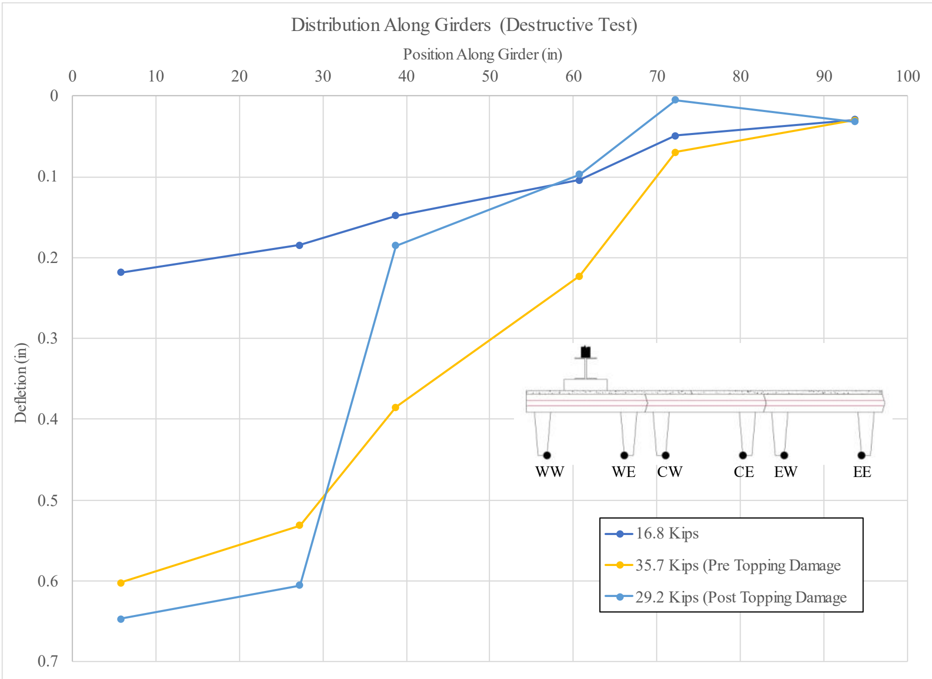

Figure 4.41: Load Distribution, Destructive Test

In contrast to the high load test, distribution factors were not calculated for the destructive test. The principal reason for this arose from the damage already caused to the system by the high load performance test. One of the issues with distribution factors is, numerically, they are a function of the number of members in a system. Given the damage to the eastern girder caused by the high load performance test, its contribution to the system was minimal. To that end, only a visual evaluation of load distribution was done in order to not obfuscate the ability of the overlay to enhance load distribution with numerical calculations based on data collected after the LMC joint between the east and center girders were already damaged.

CHAPTER FIVE

FINAL RECOMMENDATIONS AND CONCLUSIONS

Final Conclusions

Based on the research presented and its recommendations and limitations, the following conclusions can be made, based on the research's three initial objectives:

1.) Evaluate the ability of LMC to achieve a sufficient bond with an existing concrete structure with a less invasive surface preparation process.

2.) Evaluate the ability of a sufficiently bonded, two-inch LMC overlay to enhance the load distribution between three channel girders.

3.) Evaluate the strength gain provided by a two-inch LMC overlay to a single channel girder.

Conclusion 1: LMC Overlays can achieve a sufficient bond for service loads with an existing concrete structure with less invasive surface preparation methods than is currently the industry standard. However, the bond was insufficient to allow the overlay to increase the flexural strength of the system.

Conclusion 2: A two-inch LMC overlay is capable of enhancing the load distribution capabilities of a channel girder system. This ability is enhanced even more when combined with transverse post-tensioning between the girders. The combination of post-tension and LMC resulted in an improvement of load distribution of approximately 50% relative to previous lab tests without LMC and post-tensioning.

Conclusion 3: Cracking at the girder-LMC interface prior to flexural failure indicates the overlay had little, if any, impact on the ultimate flexural strength of the individual girder. However, it is possible that increased bond strength could enable the overlay to improve the flexural strength of an individual girder.

Research Limitations

While there are several promising results from the research reported in this thesis, there are several limitations which need to be discussed. Chief among these was the performance of the research in a lab setting. This lab setting is more controlled than a bridge and cannot simulate different environmental factors this system would experience when applied to a bridge. The research was also unable to investigate the long-term behavior and performance of this system. For this system to be applied to a real bridge, more knowledge on its long-term performance, including performance under repetitive loading and environmental durability, must be acquired. The final, major limitation of this research was its scale. It is not guaranteed that the results from the three-girder system will be realized in a full bridge. More research must be conducted on a full bridge to ensure the benefits hold true regardless of the number of girders.

Recommendations

Based on the research conducted and presented in this thesis, several recommendations can be made to the SCDOT regarding surface preparation, latex modified concrete overlays, and bridge rehabilitation.

First among these recommendations is conducting further research on the performance of overlays with minimal surface preparation. The research conducted in this thesis provides a proof of concept that less intensive surface preparation can provide a sufficient bond for a structural system at service loads. However, this proof of concept needs more extensive research before it can accurately be put into practice. Some of this testing should be done in the field in order to investigate how the bond performs in a less controlled environment. Other testing should evaluate performance under repetitive loading that mimics the loading experienced in the field. It would also be beneficial to investigate the contribution an overlay with a stronger bond can make to the flexural strength of an individual girder.

The second recommendation would be to install a transverse post-tensioning and LMC overlay system on a bridge which is closed to traffic and then conduct several field tests to ensure the benefits discovered in this research can be realized in the field. This research, based on lab tests of a three-girder system, can only provide preliminary evidence of behavior that should be replicated in a full bridge before the general application of this type of system rehabilitation. Another, similar recommendation would be to implement a combined LMC overlay and transverse post-tensioning system on an active bridge and implement a long-term monitoring plan. One of the main limitations of this research was its inability to evaluate how the system would behave over a long period of time. Items such as the bond and overlay behavior might change significantly over time and this should be investigated before the system can be applied broadly.

Third, materials and details that promote durability should be investigated. The uncoated strand and unprotected anchors used for post tensioning in this thesis project are not suitable for field conditions wherein corrosion is likely.

The final recommendation of this research would be to investigate the creation and verification of a finite element model (FEM) of a full bridge with an LMC overlay and transverse post-tensioning. A verified FEM of this system would help reduce the amount of costly and time-consuming field testing required to verify the results of this thesis.

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APPENDICES

Appendix A: Standard Plans for Skinny Leg Channel Girders

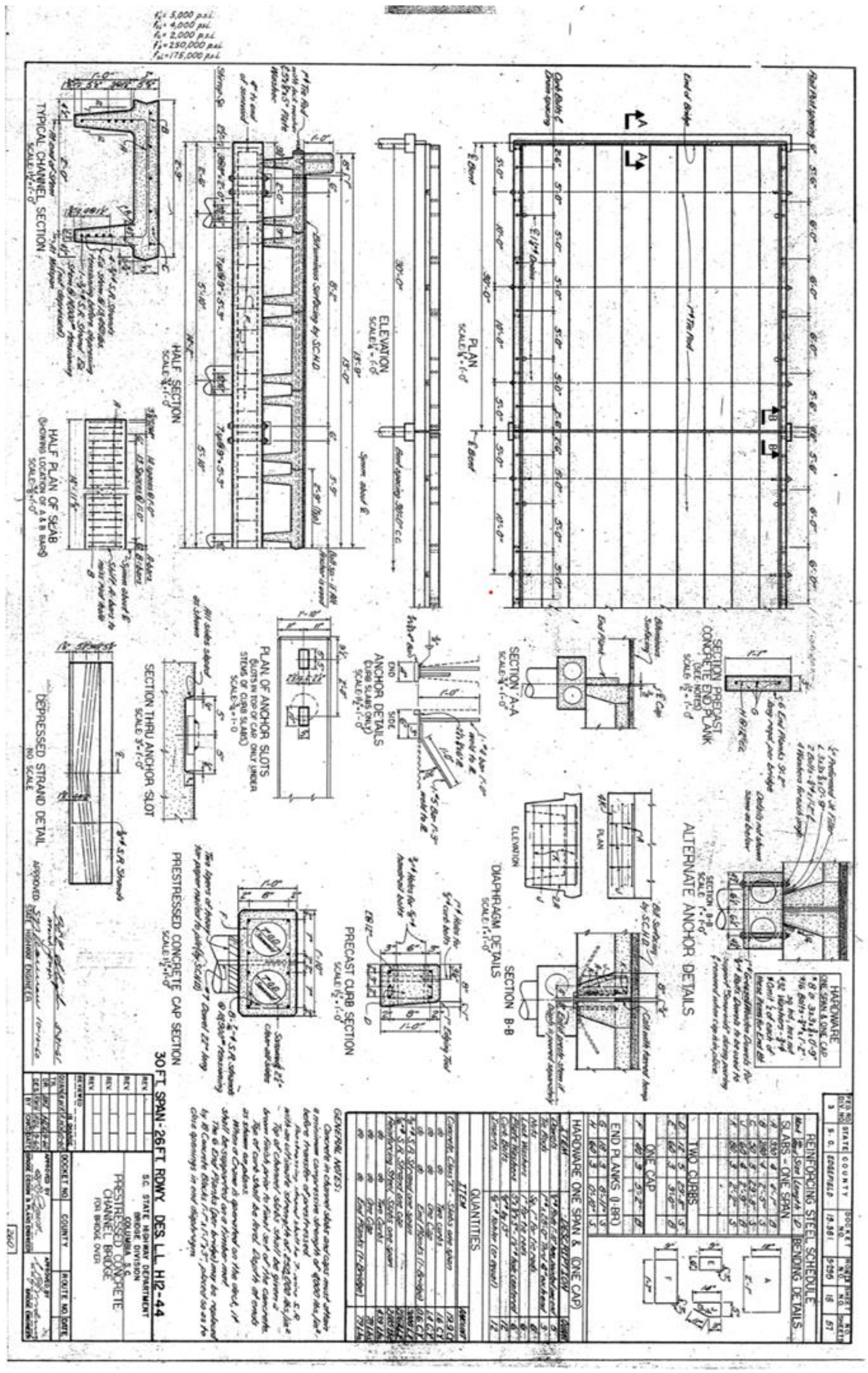

Figure A.1: Standard SCDOT Skinny Leg Channel Girder Plans

The SCDOT has many different types of girders and slabs used in its bridges throughout the state of South Carolina. This thesis conducted testing on their “skinny leg” channel girders. The standard plans of these girders are presented above (Figure A.1).

Appendix B: Normalized Tensile Strength Calculation

The process for calculating the normalized tensile strength for the specimens presented in Chapter 3 is taken from *Concrete-to-concrete bond strength: A review* written by M. El Afandi, S. Yehia, T. Landolsi, N. Qaddoumi, and M. Elchalakani in 2023. In an effort to reduce the effect of concrete compressive strength on the data, they normalized all bond tests by dividing the bond test result by the square root of the weaker compressive strength of the bonded materials (EL Afandi et al., 2023). This method was applied to many different types of bond tests but the equation for its application to pull off testing can be found below in Eqn 3.

$$\sigma_{TN} = \frac{\sigma_T}{\sqrt{f'_c}}$$

Eqn 3: Normalized Tensile Strength Equation

In Eqn 3 above, σ_{TN} represents the normalized tensile strength, σ_T represents the tensile strength reported by the pull-off test, and f'_c represents the compressive strength of the weaker concrete in the bonded system. This equation was used to calculate the normalized tensile strength for the specimens in chapter three with an f'_c of 5000 psi and σ_T values as presented in the Material Testing Discussion.

Appendix C: Post-Tensioning Process

Post-tensioning steel strands is a process that has multiple steps which must be done in a precise order to ensure both the safety of the individuals performing it and the efficacy of the force in the strands. Post-tensioning requires several unique pieces of equipment which must be procured before the process can start. These are strands, strand chucks, a hydraulic jack with a pump and pressure gauge, and a steel saddle. The strands and chucks can be purchased from several different manufacturers and the types purchased are up to the specifics of the job. The hydraulic jack, pump, and pressure gauge are the items used to physically stretch the strand to the desired force. These can also be purchased from several different manufacturers, but an important stipulation is the jack must have a hole which goes all the way through it in order to slide it on the strand. Finally, the most unique piece of equipment is the steel saddle. The steel saddle sits on the structure being post-tensioned and provides the reaction for the hydraulic jack to push against. These steel saddles are typically made to order for specific situations and depend on factors such as working area, available steel, and the orientation of the post-tensioning job (whether it is being done horizontally, vertically, or some other direction). Other useful, but not necessary, pieces of equipment are load cells to monitor the force in the strand, spacers, and a stand for the steel saddle (depending on the orientation of the job).

After the procurement of all the necessary equipment, there are still several items that are important to consider before post-tensioning. Chief among these is the distance the strand must be stretched to reach the required load. This distance is determined using Eqn 4 below:

$$\Delta = \frac{P*L}{A*E},$$

Eqn 4: Axial Deformation Equation

In Eqn 4, Δ is the elongation of the strand, *P* is the desired force in the strand, *L* is the length of the strand being stretched, *A* is the initial area of the strand, and *E* is the strand's modulus of elasticity. It is important to note that the shorter the strand length being stretched the smaller the elongation of the strand will be to reach the desired force. Short strand lengths can be very dangerous to post-tension as elongating the strand even just a quarter of an inch too long may lead to strand rupture.

After determining the required elongation of the strand and verifying it can be done precisely and safely, the physical act of post-tensioning can be performed. This process starts with inserting the strand through the structure and securing a strand chuck (and load cell if desired) on the dead end of the strand. After ensuring all the items are properly in place on the dead end, place spacers (if desired) and a non-secured chuck on the live end of the strand. After placing the spacers and chuck, slide the steel saddle on the strand so that it is resting on the structure. After the steel saddle is in place, slide the hydraulic jack, several spacers, and the final chuck on the remaining portion of the live end of the strand. Secure the outermost chuck and begin increasing the pressure in the hydraulic jack. Increase the pressure in the jack to the desired load and secure the chuck inside the steel saddle. Finally, release the pressure in the hydraulic jack and let the strand seat. This process has many areas where simple mistakes can be made, so it is recommended that any individual who wishes to perform post-tensioning consult a professional. In addition, this appendix is not meant to provide professional guidance on post-tensioning but rather to inform on the basic process used in post-tensioning.

Appendix D: Extra Graphs from Flexural Testing

There were several graphs generated throughout the flexural testing of the post-tensioned girder system that, while not relevant to the final conclusions of the research, merit inclusion in this thesis. These graphs, along with discussion if required, are presented here.

Load Distribution Testing

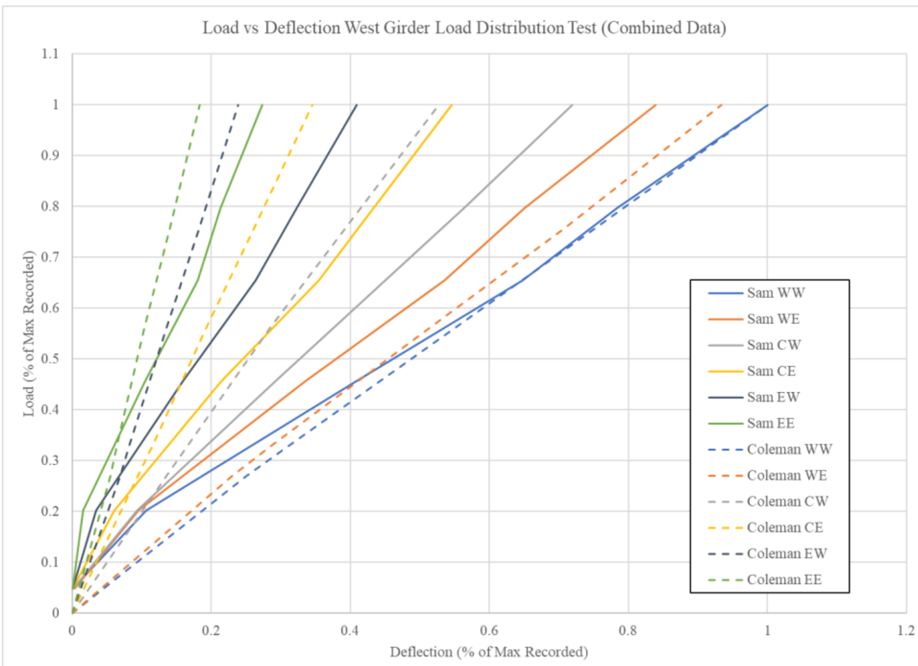

Figure D.1: Load Displacement Graph, Load Distribution Testing, West Girder Loaded

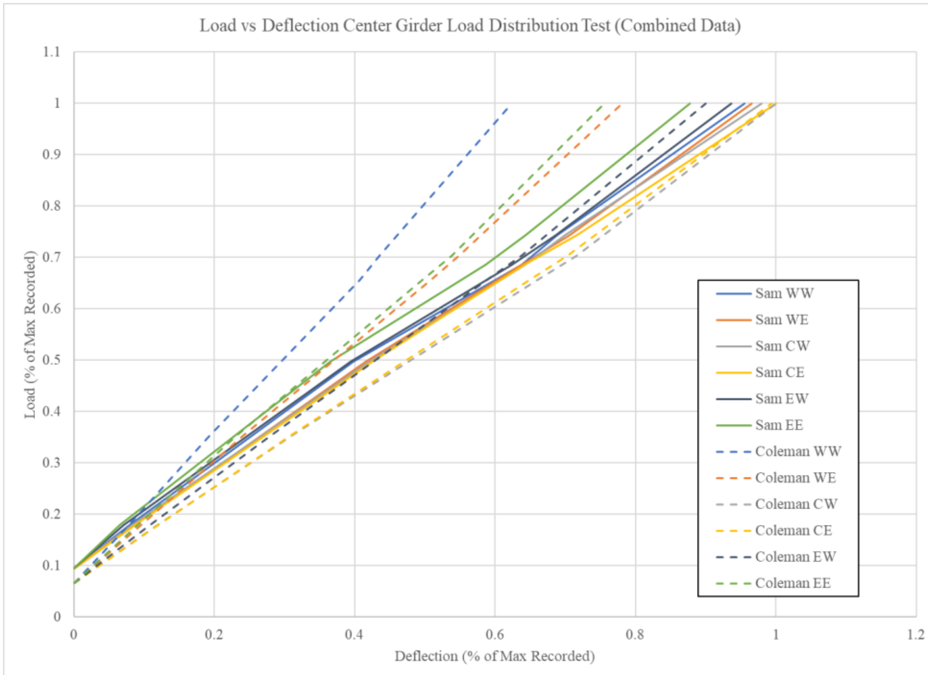

Figure D.2: Load Displacement Graph, Load Distribution Testing, Center Girder Loaded

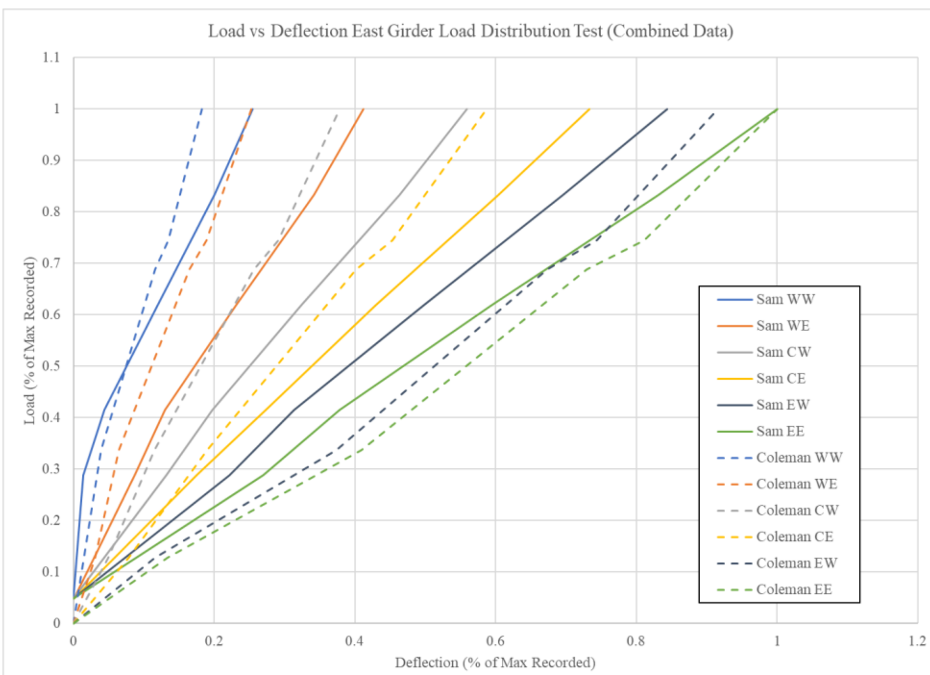

Figure D.3: Load Displacement Graph, Load Distribution Testing, East Girder Loaded

Joint Durability Testing

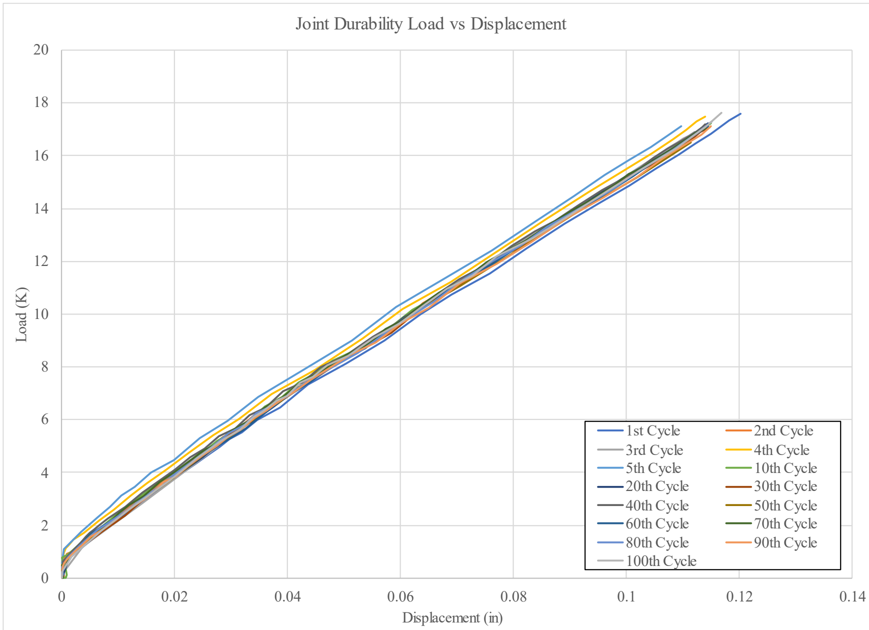

Figure D.4: Load vs Displacement Graph for Multiple Cycles, Joint Durability Testing

High Load Performance Test

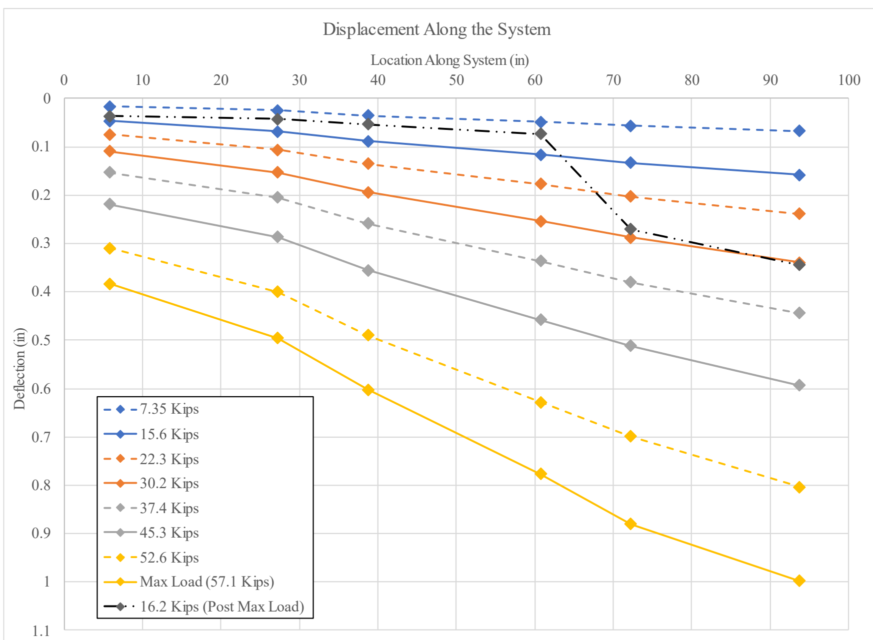

Figure D.5: Detailed Displacement Along the Girders, High Load Performance Test

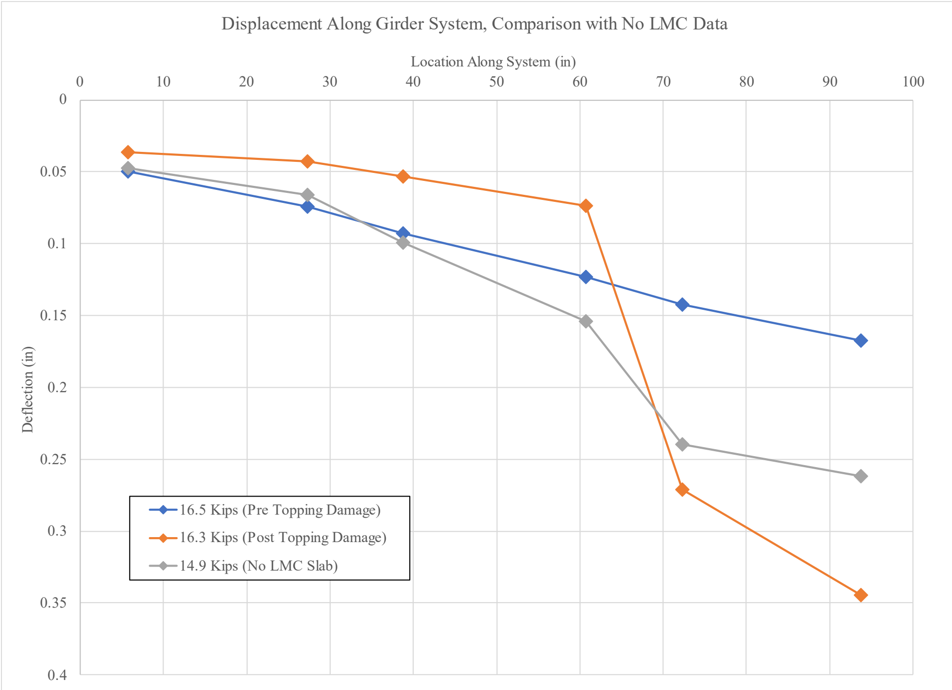

Figure D.6: Comparative Displacement Along the Girders, Multiple Tests

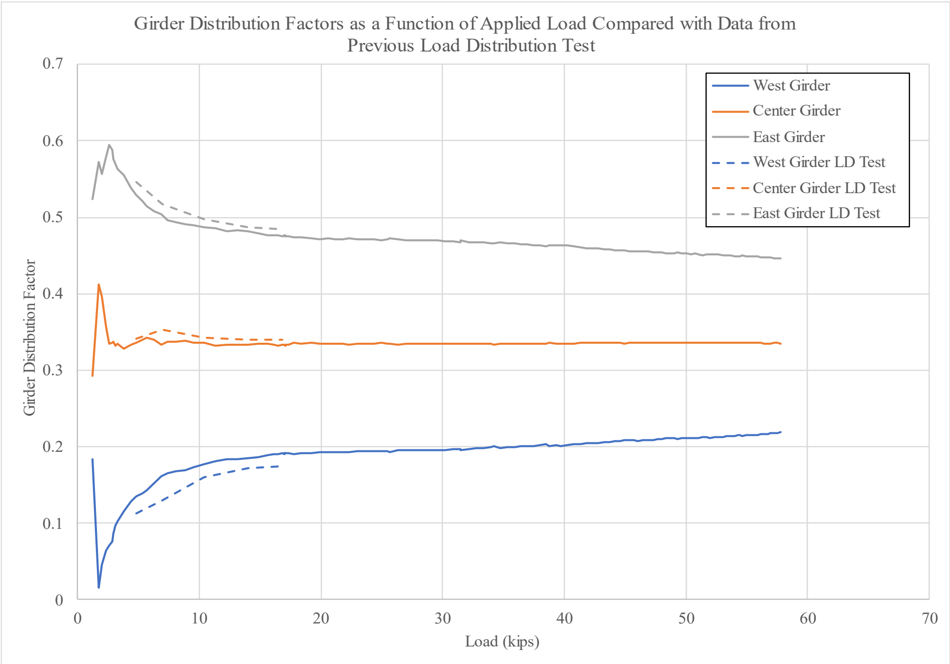

Figure D.7: Distribution Factors as a Function of Load, High Load Performance Test

Analysis of Figure D.7 reveals an interesting behavior of this system in that it experiences enhanced load distribution the higher the load placed on the structure. This increase in load distribution is extreme at lower loads, flattens out around twenty to thirty kips, and then picks back up after thirty to thirty-five kips. While not particularly applicable in design or rehabilitation, it is an interesting behavior to note and implies that, in the case of an extreme load, the structure would perform better than expected. This enhanced performance creates an extra degree of safety in the design which should be noted for future study.

Final Destructive Test

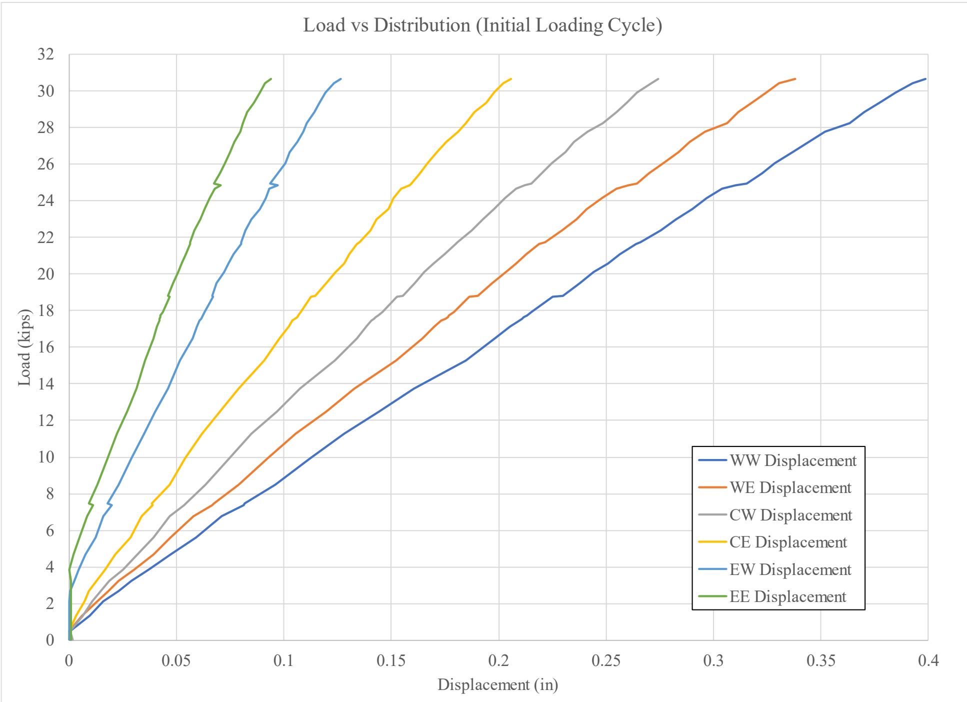

Figure D.8: Load Distribution Graph, Stage 1 of Destructive Test

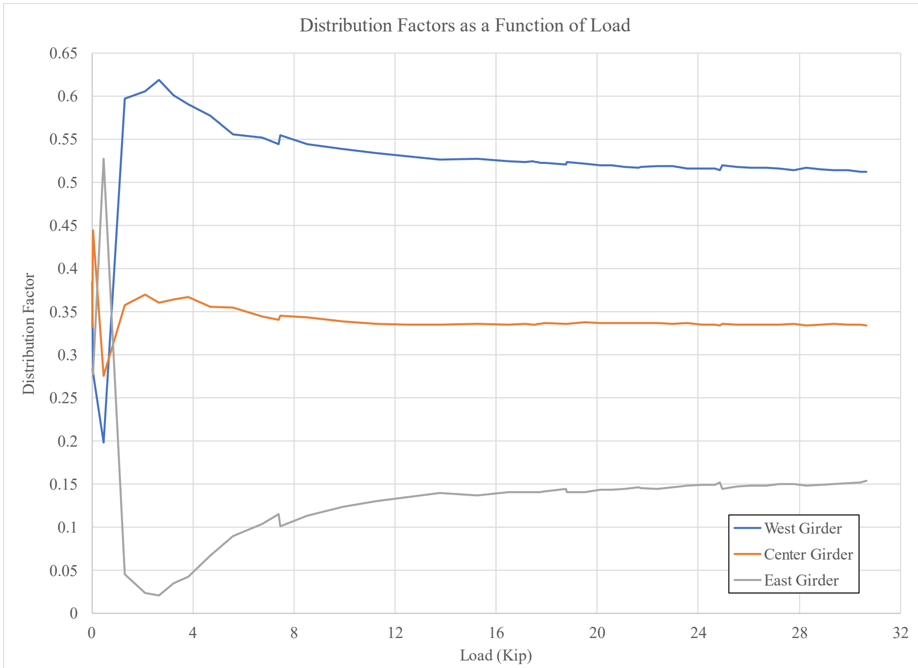

Figure D.9: Distribution Factors as a Function of Load, Stage 1 of Destructive Test

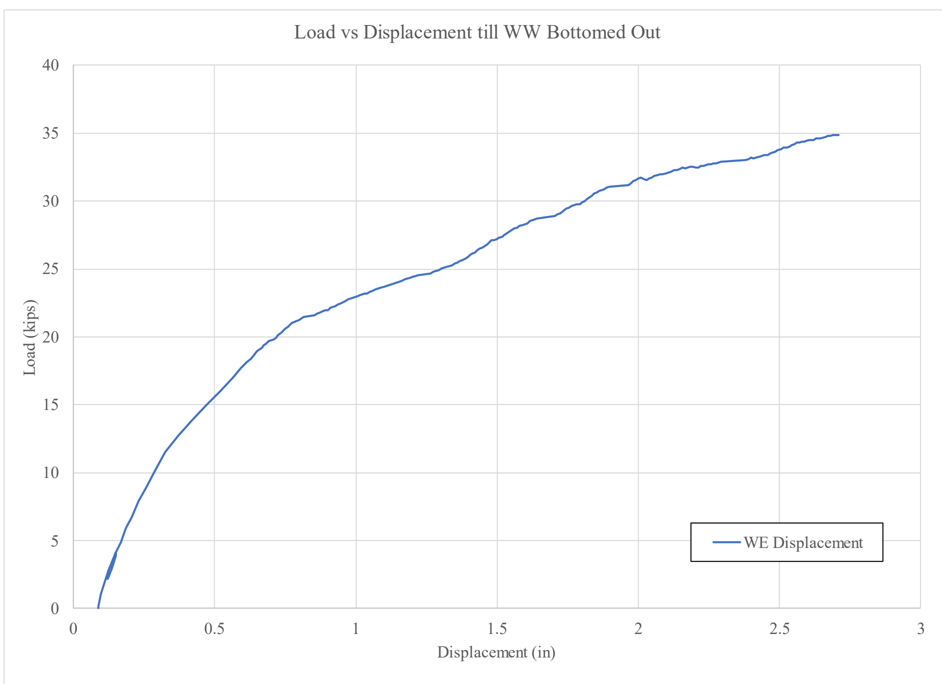

Figure D.10: Load vs Displacement Graph, Stage 3 of Destructive Test

Appendix E: Calculation of Moment Strength of Skinny Leg Channel Girders with LMC Overlays of Varying Thicknesses

The Calculation of the moment strength of skinny leg channel girders with LMC overlays of varying thicknesses is a factor of both the geometry of the girder and overlay and the available stress in the prestressed strands in the girders. This discussion also assumes the overlay remains bonded at failure and crushes rather than delaminates. While this did not occur during the destructive test, a discussion on the calculation of this theoretical strength is still merited. This appendix will present the calculation process for two cases: a girder with no overlay and a girder with a two-inch overlay.

For the girder with no overlay, the moment strength calculation is a function of the girder's geometry, the available force in the prestressing strands, and the location of interest along the girder. The location of interest for these calculations is directly under the points where the load is applied to the girder. These locations are where the applied moment is maximum while the moment strength has not reached its peak strength. There are two main equations used in the calculation of an individual girder's moment strength, presented below as Eqn 5 and Eqn 6.

$$a = \frac{f_{ps} * A_{ps}}{0.85 * f'_c * b}$$

Eqn 5: Calculation of Whitney Stress Block Depth

$$M_N = f_{ps} * A_{ps} * (d - {}^{a}/_{2})$$

Eqn 6: Nominal Moment Strength of Channel Girder

In these equations, the following variable definitions hold true, with constant values given in parenthesis:

- a: The depth of the Whitney Stress Block in girder
- f_{ps}: The available stress in the prestressing strands
- A_{ps}: Area of the prestressing strands in the girder (.217 in^2)
- f'_c: Compressive strength of the girder (5 ksi)
- b: width of the Whitney Stress Block (33 inches)
- M_N: Nominal Moment strength of the girder
- d: Depth from the top of the girder to the centroid of the prestressing force

All the values presented above are functions of the girder's geometry except f_{ps}. While there are many methods to calculate f_{ps}, the calculations presented here used the empirical method and found a f_{ps} value of 241 ksi at the location of interest. The depth of the prestressing centroid is also a function of the location of interest and was 12.27 inches at the location of interest. Based on the values given above, the Whitney Stress Block at the critical location was 1.38 inches which gives a moment strength of 186 kip*ft, or a maximum load of 31 kips.

In order to ease the calculation of the moment strength of a girder with a two inch overlay the Whitney Stress Block is assumed to lay solely in the overlay. This assumption must be checked before calculating the moment strength of the girder and overlay. The only difference in the calculation of the Whitney Stress Block from the process outline previously is the compressive strength of the overlay. Using the f'_c value for the overlay obtained via materials testing (5.4 ksi), the depth of the Whitney Stress

Block is 1.28 inches, which is less than the 2-inch overlay. Since the assumption regarding the Whitney Stress Block is correct the calculation of the moment strength proceeds the same as before, only with an adjusted value for the distance to the centroid of the prestressing force. This value must be increased by the thickness of the overlay, giving a new value of 14.27 inches. Using these adjusted values, the nominal moment strength of the girder with a two-inch overlay is 219 kip*ft, or a maximum load of 36.5 kips. This is approximately a 17% increase in strength without adjusting for the increase in self-weight. Accounting for the increased self-weight from the overlay this strength increase drops to about 8%, giving a maximum load of 33.6 kips.

Appendix F: Discussion on Stress States of LMC Overlay at Girder Joints

The performance of the individual girder during destructive testing revealed the weak link of the overlay-girder system to be the bond between the LMC overlay and the channel girders. While not relevant to the final conclusions of this thesis, some discussion of the mechanics of load distribution within the system, the effect of post-tensioning on these mechanics, and these mechanics effect on the stress state of the LMC overlay and bond at the girder joints would be beneficial to the understanding of this thesis and its implications for future research.

The load distribution in the channel girder system occurs in primarily two places – the shear keys of the girders and the LMC overlay. This distribution takes the form of these materials ability to resist the shear caused by the differential displacement between the loaded and unloaded girders. Figure F.1 below provides a pictorial representation of this phenomena and the effect transverse post-tensioning has on load transfer.

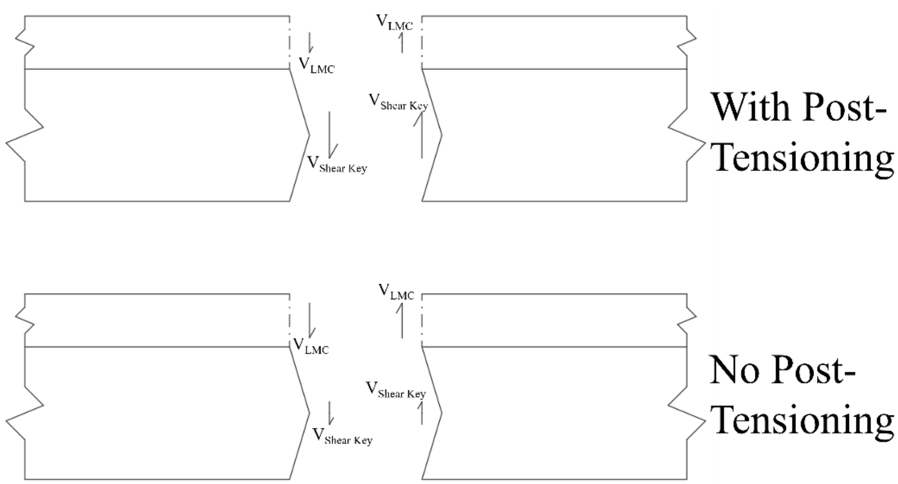

Figure F.1: Mechanics of Load Distribution

As seen above, the presence of post-tensioning increases the capacity of the shear keys to transfer load, increasing the overall capacity of the system and the applied load required to cause a reflective crack in the LMC overlay. In contrast, removal of the transverse post-tensioning lessens the ability of the shear key to transfer load, decreasing the system capacity and applied shear force, causing the reflective crack to develop. This mechanical analysis is supported by the behavior of the system during the system's flexural testing. With the transverse post-tensioning on the system the reflective crack did not develop on the overlay until a system load of 57 kips during the high load performance test. Upon the removal of the transverse post-tensioning, the overlay developed a reflective crack around 36 kips, roughly 65% of the load achieved with the post-tensioning. This behavior can also be seen in an analysis of the stress state of the LMC overlay at a girder joint, presented below in Figure F.2.

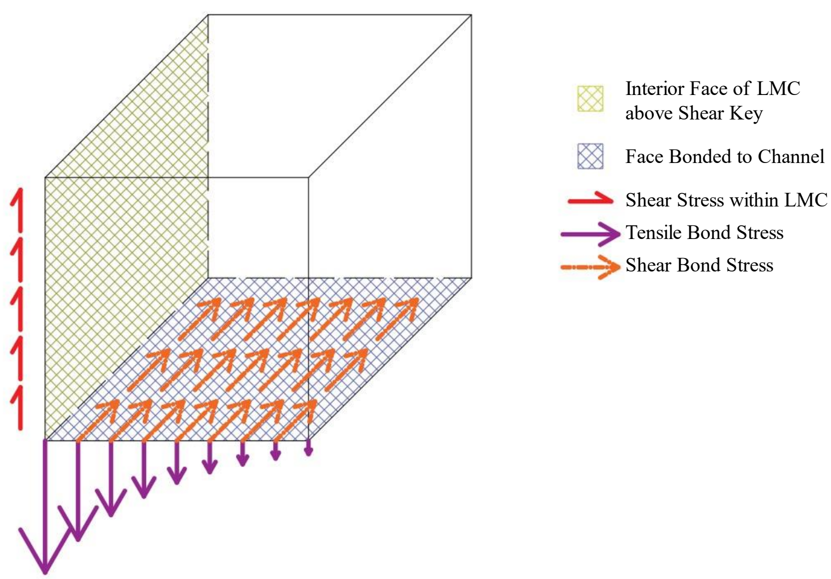

Figure F.2: Stress State of the LMC Overlay

Seen above in Figure F.2, at the joint the LMC overlay feels three stresses: a tensile and shear stress resisted by the bond and a shear stress within the overlay itself. The tensile stress on the bond is likely maximum adjacent to the joints between girders where load distribution occurs. The ability of the transverse post-tensioning to increase the load in the shear keys not only reduces the shear load within the overlay but also reduces the tensile stress on the bond between the overlay and girder, increasing the overall resistance of the overlay to both delamination and a reflective crack.