Implementation and Field Testing of Improved Bridge Parapet Designs

Amy E. Kalabon
Cleveland State University

Follow this and additional works at: https://engagedscholarship.csuohio.edu/etdarchive

Part of the Civil and Environmental Engineering Commons

How does access to this work benefit you? Let us know!

Recommended Citation
https://engagedscholarship.csuohio.edu/etdarchive/398

This Thesis is brought to you for free and open access by EngagedScholarship@CSU. It has been accepted for inclusion in ETD Archive by an authorized administrator of EngagedScholarship@CSU. For more information, please contact library.es@csuohio.edu.
IMPLEMENTATION AND FIELD TESTING OF IMPROVED BRIDGE PARAPET DESIGNS

AMY E. KALABON

Bachelor of Civil Engineering
Cleveland State University
May 2013

submitted in partial fulfillment of requirements for the degree
MASTER OF SCIENCE IN CIVIL ENGINEERING
at the
CLEVELAND STATE UNIVERSITY
May 2014
We hereby approve the thesis of

Amy Kalabon

Candidate for the Master of Science in Civil Engineering degree

This thesis has been approved for the Department of

Civil and Environmental Engineering

and the

CLEVELAND STATE UNIVERSITY

College of Graduate Studies by

________________________________________
Norbert Delatte

________________________________________
Lutful Khan

________________________________________
Mehdi Jalalpour

________________________________________
Student’s Date of Defense
ACKNOWLEDGMENT

This study was sponsored by the Ohio Department of Transportation (ODOT), under a research contract entitled “Development, Field Testing and Implementation of Improved Bridge Parapet Designs,” State Job No. 134818, Agreement No. 25969. The research was also supported by the Civil and Environmental Engineering Department, the Washkewicz College of Engineering, and the College of Graduate Studies at Cleveland State University.

Completion of this study was greatly aided by several key individuals from ODOT. The research team would like to acknowledge and thank the following individuals for their specific contributions: Jim Farrell, Mark Sakian, Tom Beutler, and Brian Negrea for their support, insight, assistance, and coordination to make site visits possible; technical liaisons Richard Walters, Randy Over, Michael Kubek, Dale Crowl, and Walter Gratz for their technical insight and suggestions; Richard Orient for his guidance and knowledge out in the field; and Jacob Bailosky for his assistance in obtaining construction plans and any other needed data.
IMPLEMENTATION AND FIELD TESTING OF IMPROVED BRIDGE PARAPET DESIGNS

AMY E. KALABON

ABSTRACT

Premature cracking of concrete bridge parapets is a potentially complex problem, with a number of possible causes. Identifying the cause of premature cracking, and avoiding this problem in the future has several benefits, including: a potential cost savings for the district, improving the safety of these structures in future construction, and increasing the overall understanding of parapets. The objective of this study was to analyze the reasons for uncontrolled cracking in order to establish an improved parapet design, and provide recommendations to the Ohio Department of Transportation (ODOT) to prevent such cracking in the future. Previous research carried out a forensic investigation of four bridges in Northeast Ohio that exhibited extensive parapet cracking. In many cases, vertical cracks appeared between control joints. The study evaluated a number of hypotheses as to the causes of cracking, which were utilized in developing modifications to implement on test parapets for continued research.

Potential factors examined in this study to continue research included: properties of the concrete mixtures used, construction methods, joint details, composite structural action, and durability of the concrete and reinforcement. A total of 22 test parapets were constructed as part of this project to evaluate different approaches to address premature cracking. In this study, 15 of the 22 parapets were constructed and examined. Not enough information was gathered thus far on the use of deeper saw cuts through glass fiber reinforced polymer (GFRP) reinforcement or field cut steel...
reinforcement to determine if this modification is a cost-effective choice. The parapets that included polypropylene fibers in the mixture did not perform any differently than the parapets without fiber in regards to early age cracking. Fibers may not have been needed with the concrete mixture that was used to prevent shrinkage or thermal cracking, but it may prove to be an efficient modification in the future by improving the durability and service life of parapets. Reducing the joint spacing over the negative moment regions of the bridge is an important modification that should be included in the design of concrete bridge parapets.
TABLE OF CONTENTS

ACKNOWLEDGMENT ........................................................................................................ iii

ABSTRACT ............................................................................................................................. iv

LIST OF TABLES ..................................................................................................................... x

LIST OF FIGURES .................................................................................................................. xi

CHAPTER

I. INTRODUCTION AND RESEARCH OBJECTIVES ............................................................. 1
  1.1 ODOT Problem Statement .......................................................................................... 1
  1.2 Study Objectives ......................................................................................................... 2
  1.3 Research Methodology ............................................................................................... 3
  1.4 Benefits and Potential Application of Research Results ............................................. 3
  1.5 Organization of this Report ......................................................................................... 3

II. BACKGROUND AND LITERATURE REVIEW .................................................................. 5
  2.1 Observations from Other ODOT Districts ................................................................. 5
  2.2 Observations from Other State DOTs ......................................................................... 6

III. EXPERIMENTAL DESIGN .............................................................................................. 9
  3.1 Field Testing Plan ....................................................................................................... 12
    3.1.1 Concrete Mixture .................................................................................................. 13
    3.1.2 Ultrasonic Pulse Velocity Meter ........................................................................ 14
    3.1.3 Concrete Maturity Sensors .................................................................................. 16
    3.1.4 Concrete Cylinder Samples ................................................................................ 18

IV. OVERVIEW OF BRIDGE CASE STUDIES .................................................................... 19
  4.1 Eastbound Big Creek Bridge (LAK-90-16.41R) ......................................................... 20
    4.1.1 Overview ............................................................................................................. 20
    4.1.2 Contractor Information ...................................................................................... 21
    4.1.3 Designed Bridge Dimensions .......................................................................... 21
  4.2 Eastbound Paine Creek Bridge (LAK – 90 – 20.03 R) ................................................ 23
    4.2.1 Overview ............................................................................................................. 23
    4.2.2 Contractor Information ...................................................................................... 23
    4.2.3 Designed Bridge Dimensions .......................................................................... 24
  4.3 Eastbound Paine Road Bridge (LAK – 90 – 21.10 R) .................................................. 25
    4.3.1 Overview ............................................................................................................. 25
7.1 Cost ......................................................................................................................... 108
7.2 Type of Reinforcement .......................................................................................... 109
7.3 Polypropylene Fiber .............................................................................................. 111
7.4 Joint Spacing ........................................................................................................ 112

VIII. CONCLUSIONS AND RECOMMENDATIONS ................................................. 115

8.1 Results of Implemented Modifications ................................................................. 115
   8.1.1 Type of Reinforcement .................................................................................. 115
   8.1.2 Polypropylene Fiber .................................................................................... 116
   8.1.3 Joint Spacing ............................................................................................ 116

8.2 Recommendations ................................................................................................. 117
   8.2.1 Design Recommendations ........................................................................ 117
   8.2.2 Construction Recommendations ............................................................... 118
   8.2.3 Recommendations for Future Research ..................................................... 119

REFERENCES .............................................................................................................. 122
LIST OF TABLES

Table 1: Summary of Lake County Test Sites ................................................................. 11
Table 2: Concrete Mixture Proportions ........................................................................ 13
Table 3: Summary of Bridges ....................................................................................... 20
Table 4: EB Hermitage north parapet UPV velocities .................................................. 58
Table 5: EB Hermitage north parapet maturity sensor temperature data ..................... 60
Table 6: EB Hermitage south parapet UPV velocities .................................................... 62
Table 7: EB Hermitage south parapet maturity sensor temperature data ................. 63
Table 8: EB Auburn north parapet maturity sensor temperature data ......................... 66
Table 9: WB Paine Road north parapet maturity sensor temperature data ................... 70
Table 10: WB Paine Road south parapet UPV velocities ............................................. 75
Table 11: WB Paine Road south parapet maturity sensor temperature data ............... 77
Table 12: WB Paine Creek north parapet UPV velocities ............................................. 78
Table 13: WB Paine Creek north parapet maturity sensor temperature data ............... 81
Table 14: WB Paine Creek south parapet UPV velocities ........................................... 85
Table 15: WB Paine Creek south parapet maturity sensor temperature data ............... 88
Table 16: South Marginal north parapet maturity sensor temperature data ............... 94
Table 17: South Marginal south parapet maturity sensor temperature data ............... 99
Table 18: Modification cost per linear foot ................................................................... 109
Table 19: Percentage of early age joint cracking with respect to joint depth .......... 110
Table 20: Percentage of cracked joints with respect to fiber use ............................... 112
Table 21: Summary of Crack Inspections ................................................................... 114
Table 22: Summary of parapet modifications for continued research ....................... 120
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>James Ultrasonic Pulse Velocity Meter</td>
<td>15</td>
</tr>
<tr>
<td>2</td>
<td>Maturity Sensor Attached to Reinforcement</td>
<td>17</td>
</tr>
<tr>
<td>3</td>
<td>Data Provided by Maturity Sensors</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>Eastbound Big Creek Bridge Construction Plans, Profile</td>
<td>22</td>
</tr>
<tr>
<td>5</td>
<td>Eastbound Big Creek Bridge Construction Plans, Parapet Cross Section</td>
<td>22</td>
</tr>
<tr>
<td>6</td>
<td>Eastbound Paine Creek Bridge Plans, Profile</td>
<td>24</td>
</tr>
<tr>
<td>7</td>
<td>Eastbound Paine Creek Bridge Plans, Parapet Cross Section</td>
<td>25</td>
</tr>
<tr>
<td>8</td>
<td>Eastbound Paine Road Bridge Plans, Profile</td>
<td>27</td>
</tr>
<tr>
<td>9</td>
<td>Eastbound Paine Road Bridge Plans, Parapet Cross Section</td>
<td>27</td>
</tr>
<tr>
<td>10</td>
<td>Eastbound Hermitage Road Bridge Plans, Profile</td>
<td>29</td>
</tr>
<tr>
<td>11</td>
<td>Eastbound Hermitage Road Bridge Plans, Parapet Cross Section</td>
<td>30</td>
</tr>
<tr>
<td>12</td>
<td>Eastbound Auburn Road Bridge Plans, Profile</td>
<td>32</td>
</tr>
<tr>
<td>13</td>
<td>Eastbound Auburn Road Bridge Plans, Parapet Cross Section</td>
<td>32</td>
</tr>
<tr>
<td>14</td>
<td>Westbound Paine Road Bridge Plans, Profile</td>
<td>34</td>
</tr>
<tr>
<td>15</td>
<td>Westbound Paine Road Bridge Plans, Parapet Cross Section</td>
<td>35</td>
</tr>
<tr>
<td>16</td>
<td>Westbound Paine Creek Bridge Plans, Profile</td>
<td>37</td>
</tr>
<tr>
<td>17</td>
<td>Westbound Paine Creek Bridge Plans, Parapet Cross Section</td>
<td>37</td>
</tr>
<tr>
<td>18</td>
<td>South Marginal Bridge Plans, Profile</td>
<td>39</td>
</tr>
<tr>
<td>19</td>
<td>South Marginal Bridge Plans, Parapet Cross Section</td>
<td>39</td>
</tr>
<tr>
<td>20</td>
<td>Westbound Big Creek Bridge Plans, Profile</td>
<td>41</td>
</tr>
<tr>
<td>21</td>
<td>Westbound Big Creek Bridge Plans, Parapet Cross Section</td>
<td>42</td>
</tr>
<tr>
<td>22</td>
<td>Westbound Auburn Road Bridge Plans, Profile</td>
<td>44</td>
</tr>
<tr>
<td>23</td>
<td>Westbound Auburn Road Bridge Plans, Parapet Cross Section</td>
<td>44</td>
</tr>
<tr>
<td>24</td>
<td>Westbound Hermitage Road Bridge Plans, Profile</td>
<td>46</td>
</tr>
<tr>
<td>25</td>
<td>Westbound Hermitage Road Bridge Plans, Parapet Cross Section</td>
<td>47</td>
</tr>
<tr>
<td>26</td>
<td>EB Big Creek Bridge North Parapet Crack</td>
<td>49</td>
</tr>
<tr>
<td>27</td>
<td>EB Big Creek south parapet crack</td>
<td>50</td>
</tr>
<tr>
<td>28</td>
<td>Crack along top of parapet</td>
<td>50</td>
</tr>
<tr>
<td>29</td>
<td>EB Paine Creek north parapet crack near control joint</td>
<td>51</td>
</tr>
<tr>
<td>30</td>
<td>Looking at EB Paine Creek north parapet crack from adjacent bridge</td>
<td>52</td>
</tr>
<tr>
<td>31</td>
<td>EB Paine Road north parapet crack propagating out of control joint</td>
<td>53</td>
</tr>
<tr>
<td>32</td>
<td>EB Paine Road 2\textsuperscript{nd} crack found between joints</td>
<td>54</td>
</tr>
<tr>
<td>33</td>
<td>Spalling on EB Paine Road north parapet along location of horizontal reinforcement</td>
<td>55</td>
</tr>
<tr>
<td>34</td>
<td>EB Hermitage Road north parapet surface cracks</td>
<td>57</td>
</tr>
<tr>
<td>35</td>
<td>EB Hermitage Road north parapet typical bug holes</td>
<td>58</td>
</tr>
<tr>
<td>36</td>
<td>EB Hermitage south parapet condition</td>
<td>61</td>
</tr>
<tr>
<td>37</td>
<td>EB Hermitage south parapet winter temperature fluctuations</td>
<td>64</td>
</tr>
<tr>
<td>38</td>
<td>WB Paine Road north parapet performance of saw cuts</td>
<td>68</td>
</tr>
<tr>
<td>39</td>
<td>Rubbing the WB Paine Road north parapet</td>
<td>69</td>
</tr>
<tr>
<td>40</td>
<td>WB Paine Road north parapet winter temperature fluctuations</td>
<td>71</td>
</tr>
</tbody>
</table>
Figure 41: Consolidation of the concrete on WB Paine Road south parapet ................. 72
Figure 42: WB Paine Road south parapet bug holes ............................................ 73
Figure 43: Surface cracks found on WB Paine Road south parapet .......................... 73
Figure 44: WB Paine Road rubbed south parapet .................................................. 74
Figure 45: WB Paine Creek north parapet crack looking down from top of parapet..... 80
Figure 46: WB Paine Creek north parapet crack ..................................................... 81
Figure 47: WB Paine Creek north parapet crack zoomed in view ............................. 81
Figure 48: WB Paine Creek south parapet poor consolidation at the surface .......... 84
Figure 49: WB Paine Creek south parapet holes on the surface .............................. 85
Figure 50: WB Paine Creek Bridge Profile .............................................................. 87
Figure 51: South Marginal Bridge with vandal protection fences ............................ 90
Figure 52: Placement of maturity sensors ............................................................... 90
Figure 53: South Marginal north parapet crack at VPF post base plate............... 92
Figure 54: South Marginal north parapet cracks where control joint terminates ...... 93
Figure 55: South Marginal north parapet mid-panel cracking ............................... 95
Figure 56: South Marginal north parapet mid-panel cracking ............................... 95
Figure 57: South Marginal north parapet mid-panel cracking ............................... 96
Figure 58: South Marginal north parapet mid-panel cracking ............................... 96
Figure 59: South Marginal north parapet small cracking ..................................... 97
Figure 60: South Marginal south parapet mid-panel crack ................................. 100
Figure 61: South Marginal south parapet VPF post base plate crack ................. 100
CHAPTER I
INTRODUCTION AND RESEARCH OBJECTIVES

The Ohio Department of Transportation (ODOT) has identified widespread premature cracking of concrete bridge parapets on recently constructed bridge decks. Within ODOT District 12, there is an extensive number of bridges displaying premature cracking. District 12 is located in Northeast Ohio, covering the areas of Cuyahoga County, Geauga County, and Lake County. By developing an improved concrete bridge parapet design, a solution can be implemented to help address this problem.

1.1 ODOT Problem Statement

In District 12 alone, 27 bridges were found exhibiting premature cracking to varying degrees. The decks on which these problem parapets were poured appear to be performing as anticipated and little correlation existed between deck characteristics; some are on short spans, while others are longer spans, and some decks are skewed. Multiple contractors and concrete suppliers were involved for these 27 bridges. The District continues to design and construct these concrete bridge parapets similarly every year. While parapets can be replaced without bridge deck replacement, resorting to
this as a solution produces a large as well as wasted cost for the District. In 2002, District 12 had to replace the parapet on a bridge over I-271 without replacing the deck at a cost of approximately $140,000, which did not include sealing, fence, and expansion joint repairs. Eventually, the deck will need to be replaced producing a large sunk cost. Severely cracked parapets are a safety concern, and the potential cost to the Department to remove and replace parapets is significant.

1.2 Study Objectives

The overall objective of this study was to develop improved concrete bridge parapet designs to mitigate cracking. Reasons for uncontrolled bridge parapet cracking were determined in previous research. Prior to the start of this project, changes were implemented to the current bridge parapet design in an effort to reduce cracking, and these changes will be included in the design of the control parapets. Additional design modifications will be incorporated on thirteen bridge parapets. In order to fulfill the objective, the following goals were identified:

- Identify all relevant construction procedures potentially contributing to concrete parapet cracking.
- Determine which design modifications, if any, are most significant in preventing premature cracking on ODOT District 12 bridges.
- Provide results of which design modifications mitigate overall cracking of bridge parapets as well as recommendations for future research.
1.3 Research Methodology

ODOT developed a list of design modifications to incorporate on thirteen bridge parapets. The modifications included the addition of polypropylene microsynthetic fibers to the concrete mixture, the substitution of glass fiber reinforced polymer (GFRP) or field cut steel reinforcement instead of conventional continuous steel reinforcement along with the use of 3.5 inch (89 millimeter) deep saw cut joints, and shortening the spacing of the control joints in tension zones. The 3.5 inch (89 mm) deep control joints were assigned in combination with the GFRP or field cut steel reinforcement in order to perform the deeper cut. The performance of thirteen parapets incorporating one or more of these modifications will be monitored and compared to nine additional parapets acting as controls.

1.4 Benefits and Potential Application of Research Results

By developing an improved concrete parapet design, a solution can be implemented to the widespread problem in northeast Ohio of premature cracking of bridge parapets. The use of an improved parapet design can ultimately help reduce bridge life-cycle costs as well as prevent early replacement of parapets, which can add up to $140,000 in wasted expenses.

1.5 Organization of this Report

This report consists of eight chapters, beginning with this introduction. The second chapter is the Literature Review. The third chapter covers the Experimental Design, which explains the project in coordination with ODOT, procedures used in the field, and the key elements used in the experimental plan in order to identify which modifications
were beneficial in reducing bridge parapet cracking. The fourth chapter gives the Overview of the Bridge Case Studies providing the basic information, contractor information, and important dimensions of all the bridges included in this study. The fifth chapter, Field Observations, describes the field work carried out, including observations, crack surveys, concrete tests, non-destructive tests, and any additional data gathered. The sixth chapter provides the Summary and Discussion of Observations, providing review and analysis of the vast amount of data gathered in the field. The seventh chapter, Analysis, looks at costs and evaluates the effectiveness of the modifications implemented on the experimental parapets by comparing them to the control parapets. The eighth and final chapter, Conclusions and Recommendations, determines which modifications were effective, ineffective, or inconclusive, and provides recommendations in design, construction, and future research.
CHAPTER II
BACKGROUND AND LITERATURE REVIEW

This study is a continuation of research performed by Bazzo (2013) on “Uncontrolled Concrete Bridge Parapet Cracking”. His research determined the factors causing parapet cracking and provided implementation recommendations that were taken into consideration for this study. Additional information was gathered from other ODOT districts and state DOTs to determine how bridge parapets within those states are designed. Other DOTs were contacted to determine how concrete parapets in those areas perform in regards to cracking.

2.1 Observations from Other ODOT Districts

Additional information regarding parapet cracking was collected from ODOT District 8, located in the Southwest portion of Ohio near Cincinnati. According to Brandon Collett, PE and structures planning engineer, many bridge parapets located in their district also suffer from prominent vertical cracking. Many of the older bridges with these cracks were constructed with the use of slip forming. This practice is currently not used for parapets with ODOT, but will be allowed starting in 2014. District 8 also shows
concern that older bridges also received a through joint, which allows for an air gap between parapets, but with time these parapets were also subject to severe cracking near the joints. Finally, it has been observed that many of their bridges with a longer span length are subject to the worst cracking. Although parapet cracking is extensive in ODOT district 8, Brandon Collett, PE argues that the vertical cracks are just an eye sore and not a maintenance issue. Instead, the cracking that really causes problems is horizontal cracking and cracking due to vandal protection fences (VPFs).

2.2 Observations from Other State DOTs

A total of fourteen other state DOT bridge parapet specifications were reviewed. Of the fourteen other DOTs, four of them did not significantly differ from ODOT’s specifications. The ten remaining state DOT bridge parapet specifications were then reviewed to identify differences from ODOT specification. The three main differences found between these other state DOTs and ODOT’s specifications are the amount of concrete cover required, the amount of horizontal rebar required, and the spacing of deflection joints.

First, the amount of cover for vertical and horizontal rebar, as stated by the ODOT specification is a minimum of 2 inches (50 mm). From the other DOTs reviewed, five of them require a different amount of cover. Idaho (ITD 2010) and California (California 2010) only require 1 inch (25 mm) of cover, while Montana (MDT 2012) and Missouri (MODOT 2012) specify 1.5 inches (38 mm) of cover. Michigan (MDOT 2013), however, requires the greatest amount of cover, 3 inches (76 mm).
ODOT and all of the other state DOTs use No. 5 (16 mm) reinforcement for their horizontal bars except for Maryland. Maryland’s DOT specifies that eight pieces of horizontal rebar are to be used, but the top four pieces are to be No. 7 (22 mm) rebar and the bottom four pieces are to be No. 8 (25 mm) rebar (MDOT 2012). The amount of horizontal rebar used also varies among many of the state DOTs. ODOT specifies that eight pieces of continuous No. 5 (16 mm) rebar are to be used. The DOTs for Idaho and Missouri specify that seven continuous pieces of No. 5 (16 mm) rebar are to be used. Alabama’s DOT also specifies seven continuous pieces, but it is placed in a zigzag type pattern within the parapet. Michigan’s DOT requires the least amount of rebar, with only five continuous pieces.

There are also a few DOTs that require more reinforcement than specified by ODOT. Arkansas DOT specifies that nine continuous pieces be used (AHTD 2003), and the Montana DOT specifies ten pieces. The DOT that requires the most amount of horizontal rebar is California. Thirteen pieces of rebar are used in parapets in California. Five pieces are placed along the sloped side of the parapet and an additional five down the straight side, but the bottom three horizontal bars down the straight side are doubled.

Finally, only a few DOTs had control joint information readily available on their site. Missouri’s DOT requires that joints are spaced every 12 feet (3.7 m). It is also specified that the joints are to be filled with 0.25 inches (6 mm) of bituminous joint filler. The DOT for Arizona requires that joint spacing does not exceed 10 feet (3 m). Arizona’s DOT also specifies that 0.5 inches (13 mm) of bituminous joint filler is used (AZDOT
2012). Minnesota’s DOT does not specify a minimum spacing for control joints, but notes that the maximum spacing is 20 feet (3.7 m).

In addition, many state DOTs allow slipforming of parapets, which has not been allowed in Northeast Ohio for several years. The Indiana DOT placed a moratorium on the use of slipforming parapets, which was later lifted (Anderson 2004; IDOT 2011). Transportation agencies in Michigan (Staton and Knauff 2007), Wisconsin (Battaglia et al.), and Connecticut (Georges 2005) also investigated bridge parapet performance. Additional information on state practices is provided by Hedges (2014).
For the purposes of this study, ODOT incorporated design modifications to thirteen parapets for eleven bridges within District 12. These bridges were undergoing deck and parapet replacement between the years of 2012 and 2014. Of the field test sites, ten bridges were located in Lake County, east of downtown Cleveland, and the eleventh bridge was the South Marginal Road overpass over I-90 in downtown Cleveland. In 2012, three Lake County bridges, Big Creek, Paine Creek, and Paine Road, underwent deck and parapet replacement. In 2013, five bridges were constructed leaving three bridges to be completed in 2014. For each bridge, the north and south parapets provided different test conditions, which resulted in a total sample of 22 bridge parapets. All of the Lake County bridges were half width construction, built one side at a time with traffic maintained on the other side.

The six Lake County bridge parapets that were constructed in 2012 were built as controls following contract plans with no modifications. In 2013, the north parapet wall of South Marginal Road Bridge in Cleveland and two parapets constructed in 2014
served as controls. These nine parapets had standard 1.5 inch (38 mm) deep saw cut joints spaced between 6 and 10 feet (1.8 and 3 m). The other thirteen parapet test sites had one or more of four modifications. The modifications ODOT incorporated into the parapet designs included the addition of synthetic polypropylene fibers to the concrete mix, the substitution of GFRP reinforcement instead of conventional steel reinforcement combined with the use of 3.5 inch (89 mm) deep saw cuts, field cutting of the steel reinforcement with 3.5 inch (89 mm) deep saw cuts to weaken the joints and promote control joint cracking, and reduced joint spacing over the negative tension regions of the bridge. The Lake County field test sites and their respective modifications are summarized in Table 1. Each bridge in Lake County was given a specific ODOT identification. The “R” or “L” assigned at the end of this identification represents the bridge’s location with respect to the right or left side of the center line. The “R” represents the bridges on the eastbound side of I-90 and the “L” represents bridges located on the westbound side of traffic.

For the addition of microsynthetic polypropylene fibers into the concrete mixture, seven out of eight test sites used a fiber dosage of 1 pound per cubic yard (0.59 kilogram per cubic meter) of concrete. The final site, the south parapet wall of LAK-90-20.03L Paine Creek, used double the dosage at 2 pounds per cubic yard (1.19 kg/m³) of concrete.
Table 1: Summary of Lake County Test Sites

<table>
<thead>
<tr>
<th>Bridge Number</th>
<th>Const. Year</th>
<th>Parapet</th>
<th>Experimental Treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Per Plans, Control</td>
</tr>
<tr>
<td>LAK-90-16.41R, Big Creek</td>
<td>2012</td>
<td>N X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>LAK-90-20.03R, Paine Creek</td>
<td>2012</td>
<td>N X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>LAK-90-21.10R, Paine Road</td>
<td>2012</td>
<td>N X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>LAK-90-13.70R, Hermitage Road</td>
<td>2013</td>
<td>N X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>LAK-90-14.87R, Auburn Road</td>
<td>2013</td>
<td>N X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>LAK-90-21.10L, Paine Road</td>
<td>2013</td>
<td>N X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>LAK-90-20.03L, Paine Creek</td>
<td>2013</td>
<td>N X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>LAK-90-16.41L, Big Creek</td>
<td>2014</td>
<td>N X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>LAK-90-14.87L, Auburn Road</td>
<td>2014</td>
<td>N X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
</tr>
<tr>
<td>LAK-90-13.70L, Hermitage Road</td>
<td>2014</td>
<td>N X</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S</td>
<td></td>
</tr>
</tbody>
</table>

Five test sites include Aslan 100 GFRP Rebar manufactured by Aslan FRP. According to Hughes Brothers, the producers of Aslan FRP, the GFRP rebar has a tensile strength of at least 100 ksi (690 MPa) for No. 5 and No. 6 (16 and 19 mm) bars, and an elastic modulus of 6,700 ksi (46,200 MPa). Although the strength of the GFRP is thus nearly twice that of Grade 60 reinforcing steel, it lacks the ductility of steel. The elastic modulus is less than 25% of that of reinforcing steel, therefore the GFRP will offer much less resistance to the development and opening of control joints. In other words, the GFRP may allow cracking to occur at the control joints more so than reinforcing steel. GFRP is also highly corrosion resistant.
Eight of the experimental sites included a 3.5 inch (89 mm) deep saw cut with variable spacing. It is important to note that the 3.5 inch (89 mm) deep saw cuts cannot be properly performed unless either GFRP rebar or field cut steel rebar are also used because steel reinforcing bars are usually too close to the concrete surface for a saw cut that deep without damaging the steel. For the 3.5 inch (89 mm) deep saw cuts, the joint spacing was 5 to 6 feet (1.5 to 1.8 m) in the tension zones, over bridge piers, and 10 to 15 feet (3 to 4.6 m) at other locations. The tension zones are defined on the plans as extending between 10 and 40 feet (3 and 12 m) on either side of a pier.

3.1 Field Testing Plan

Visits to the sites constructed in 2013 took place before parapet construction, during concrete placement, during formwork removal and saw cutting operations, and periodically after construction. The main data of interest were cracks in the parapets, as well as whether joints functioned properly to control cracking.

Before parapet construction, site visits occurred to attach maturity sensors to the reinforcement as well as to check for proper installation of the rebar. During concrete placement, concrete cylinder samples were made, and documentation was gathered on the weather, the procedures used by the construction workers, and behavior of the concrete. As soon as the formwork was removed and control joints were cut, the parapet walls were analyzed for cracks, proper consolidation of the concrete, and accurate control joint depths and spacing. Ultrasonic pulse velocity (UPV) tests were also performed. After curing was completed, site visits were made to collect information from the maturity sensors, inspect the parapets for additional cracking,
perform UPV tests, and determine whether the control joints were functioning properly by initiating cracking at the joints.

### 3.1.1 Concrete Mixture

The same concrete mixture was used for all of the bridges, with the exception of the addition of microsynthetic polypropylene fibers. The mixture proportions are shown in Table 2.

**Table 2: Concrete Mixture Proportions**

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Quantity lb/yd$^3$</th>
<th>Quantity kg/m$^3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement (portland type I)</td>
<td>400</td>
<td>237</td>
</tr>
<tr>
<td>Slag cement</td>
<td>170</td>
<td>101</td>
</tr>
<tr>
<td>Silica fume</td>
<td>30</td>
<td>18</td>
</tr>
<tr>
<td>Total cementitious content</td>
<td>600</td>
<td>355</td>
</tr>
<tr>
<td>Coarse aggregate #57</td>
<td>1,300</td>
<td>771</td>
</tr>
<tr>
<td>Intermediate coarse aggregate #8</td>
<td>350</td>
<td>207</td>
</tr>
<tr>
<td>Fine aggregate (natural sand)</td>
<td>1,280</td>
<td>759</td>
</tr>
<tr>
<td>Water</td>
<td>258</td>
<td>153</td>
</tr>
</tbody>
</table>

Slag cement is used as a cement replacement. Concrete produced using slag cement will set slower than concrete produced from only portland cement. The concrete may take longer to gain strength. However, the heat caused by hydration will be lower and the temperature of the concrete will be better controlled. Slag cement also provides higher resistance to attacks by sulfate and other chemicals. Microsilica, or silica fume, is used to create low permeability concrete by filling the void space between cement particles. Like slag cement, silica fume increases the concrete’s resistance to the ingress of chemicals.

The water to cementitious ratio (w/cm) was 0.43. The concrete mixtures used air entraining and superplasticizer admixtures, as well as retarders in hot weather. On the
one hand, this concrete has a relatively high content of cementitious material of 600 lb/yd$^3$ (355 kg/m$^3$), which would tend to promote shrinkage. On the other hand, the concrete uses a blend of #57 coarse aggregate (1 inch or 25 mm maximum size) and #8 intermediate aggregate (3/8 inch or 9.5 mm maximum size) in order to optimize gradation to reduce paste requirements and shrinkage cracking.

ODOT is now implementing quality control, quality assurance (QC/QA) mix requirements. The new specifications replace Class C, Class S, and Class HP concrete with Classes QC1, QC2, QC3, and QC4 concrete (ODOT 2013). Concrete bridge parapets used a Class HP concrete and will now be replaced with Class QC2 concrete. The new specification requires coarse aggregate absorption greater than 1% and adds well graded aggregate proportions, as previously stated, to help eliminate shrinkage cracking and lower the required amount of cementitious materials.

3.1.2 Ultrasonic Pulse Velocity Meter

The James Ultrasonic Pulse Velocity (UPV) Meter, shown in Figure 1, is a nondestructive instrument that was used during this study. This nondestructive method is based on the fact that the pulse velocity of compression waves in a concrete body is related to the elastic properties of the material. The UPV Meter is commonly used as a way to estimate strength; however for purposes of this study, the UPV was used as a quality control measure to study uniformity of the concrete and to determine the extent of cracking at the control joints.
The UPV has two transducers, a transmitter and a receiver. The transmitter sends an ultrasonic wave through the concrete. When ultrasonic waves are introduced into a material, they travel in a straight line and at a constant speed until they encounter a surface. When the wave is received by the other transducer, a velocity is calculated based on the amount of time it took to reach the receiver. The velocity of the wave depends on the consolidation of the concrete and the path the wave was forced to take to reach the other transducer. Therefore, if the transducers were placed over a cracked control joint, a very low apparent velocity would be observed, if any signal was received at all. A high velocity would represent a control joint that did not crack. The high velocity relates to good consolidation and consistency of the concrete as well as absence of internal cracks or defects. Using this concept, the UPV was used to estimate the quality and consistency of the concrete along the parapet and to determine the percentage of control joints that cracked along each parapet.

Figure 1: James Ultrasonic Pulse Velocity Meter
In order to establish the performance of the control joints, UPV tests were performed at each joint after the parapet was cured. If the velocity was found to be similar to the velocity over an area with no cracks, it was assumed that the control joint was not cracked and therefore was not functioning as designed. If the apparent velocity was measured to be considerably slower than the average velocity of the concrete, then the wave sent through the concrete had to find a way around a crack or void, suggesting that the joint had probably cracked.

3.1.3 Concrete Maturity Sensors

The rate of hydration of cement is greatly affected by both time and temperature, so the strength gain of concrete is also largely controlled by these two factors. These factors are likewise related to the quality of the concrete. Very high or low temperatures, including large changes in temperature, can severely affect the concrete’s strength and can cause uneven temperature distributions. Large differences in temperature across a parapet can result in cracking and reduce its durability. Due to the significance of temperature, multiple maturity sensors were embedded within the concrete of each bridge parapet by attaching them to the reinforcement before the concrete was placed. This is shown in Figure 2. Using Command Center technology, the temperature history and maturity of the parapets were captured to assess their potential role in parapet cracking.
With the use of this technology, temperature data were collected during concrete placement, as the concrete cured, and after the parapet had been exposed to the environment. The highest temperature the concrete reached as well as any significant temperature changes were gathered from the sensors to look for anything unusual that may lead to cracking in the future. The graph shown in Figure 3 is an example of the data that the sensors capture. The concrete for this parapet was placed on July 1st. During its seven day curing period, the concrete reaches its highest temperature of just under 110°F (°C), and it then drops as the hydration process slows down. The parapet was then exposed to the environment on July 8th, when the cure was taken off. This can also be seen in the graph because at this point the temperatures begin to fluctuate.
more. In this case, the concrete should not experience any affects or cracking from temperature because it did not experience any large temperature differentials nor did it hit an extreme high or low temperature.

Figure 3: Data Provided by Maturity Sensors

3.1.4 Concrete Cylinder Samples

Concrete cylinder samples were collected in order to verify that the UPV values obtained out in the field were reasonable. UPV tests on the cylinders were performed on the same day the UPV was done on the parapets to make an accurate comparison. The cylinders were also used to find compressive strength values to compare to ODOT’s compressive strength values. In the case that cylinder samples could not be obtained, compressive strength values were acquired from the District’s cylinder tests.
CHAPTER IV
OVERVIEW OF BRIDGE CASE STUDIES

Between the years of 2012 and 2014, eleven bridges in District 12 were planned for full deck and parapet replacements. ODOT selected these bridges to use as test sites for purposes of this study. Data for these eleven bridges have been collected, which include general structural information as well as designed bridge dimensions and characteristics. A brief summary of data related to these bridges is shown in Table 33.
Table 3: Summary of Bridges

<table>
<thead>
<tr>
<th>Bridge</th>
<th>City</th>
<th>Bridge Limits (ft., m)</th>
<th>No. of Spans</th>
<th>Max. Span Length (ft., m)</th>
<th>No. of Traffic Lanes Carried</th>
<th>Year Built</th>
</tr>
</thead>
<tbody>
<tr>
<td>LAK-90-16.41R, Big Creek</td>
<td>Painesville</td>
<td>344.5, 105.0</td>
<td>3</td>
<td>140.0, 42.67</td>
<td>2</td>
<td>1960</td>
</tr>
<tr>
<td>LAK-90-20.03R, Paine Creek</td>
<td>Painesville</td>
<td>496.10, 151.21</td>
<td>3</td>
<td>188.0, 57.30</td>
<td>2</td>
<td>1960</td>
</tr>
<tr>
<td>LAK-90-21.10R, Paine Road</td>
<td>Painesville</td>
<td>137.99, 42.06</td>
<td>3</td>
<td>58.17, 17.73</td>
<td>2</td>
<td>1960</td>
</tr>
<tr>
<td>LAK-90-13.70R, Hermitage Road</td>
<td>Painesville</td>
<td>160.58, 48.94</td>
<td>3</td>
<td>60.0, 18.29</td>
<td>2</td>
<td>1961</td>
</tr>
<tr>
<td>LAK-90-14.87R, Auburn Road</td>
<td>Painesville</td>
<td>148.82, 45.36</td>
<td>3</td>
<td>63.25, 19.28</td>
<td>3</td>
<td>1960</td>
</tr>
<tr>
<td>LAK-90-21.10L, Paine Road</td>
<td>Painesville</td>
<td>113.63, 34.63</td>
<td>3</td>
<td>46.0, 14.02</td>
<td>2</td>
<td>1960</td>
</tr>
<tr>
<td>LAK-90-20.03L, Paine Creek</td>
<td>Painesville</td>
<td>488.29, 148.83</td>
<td>3</td>
<td>188.5, 57.45</td>
<td>2</td>
<td>1960</td>
</tr>
<tr>
<td>South Marginal Road</td>
<td>Cleveland</td>
<td>228.02, 69.5</td>
<td>4</td>
<td>68.0, 20.73</td>
<td>2</td>
<td>1959</td>
</tr>
<tr>
<td>LAK-90-16.41L, Big Creek</td>
<td>Painesville</td>
<td>344.5, 105.0</td>
<td>3</td>
<td>140.0, 42.67</td>
<td>2</td>
<td>1960</td>
</tr>
<tr>
<td>LAK-90-14.87L, Auburn Road</td>
<td>Painesville</td>
<td>159.28, 48.55</td>
<td>3</td>
<td>63.24, 19.28</td>
<td>3</td>
<td>1960</td>
</tr>
<tr>
<td>LAK-90-13.70L, Hermitage Road</td>
<td>Painesville</td>
<td>136.5, 41.61</td>
<td>3</td>
<td>60.0, 18.29</td>
<td>2</td>
<td>1961</td>
</tr>
</tbody>
</table>

4.1 Eastbound Big Creek Bridge (LAK-90-16.41R)

4.1.1 Overview

The Big Creek Bridge is an eastbound Interstate – 90 Highway bridge in Painesville, Ohio. It was originally built in 1960.

4.1.1.1 Inventory Number and Structural File Number

In the ODOT Bridge Inventory, the Eastbound Big Creek Bridge is identified as follows:
Bridge Inventory Number: LAK – 90 – 16.14 R

Structural File Number: 4304659 (R)

4.1.1.2 Structure Type

The bridge is a twin continuous steel plate girder bridge with a reinforced concrete deck and substructure with semi-integral abutments.

4.1.2 Contractor Information

The deck and superstructure rehabilitation took place in 2012. The contractor for the rehabilitation was Allega, Inc. with Great Lakes Construction Company as the subcontractor for all bridge work. The ready mix concrete supplier was Osborne, Inc. In addition to parapet replacement, a new widened non-composite reinforced concrete deck was constructed on the existing steel girders.

4.1.3 Designed Bridge Dimensions

4.1.3.1 Length

The total length of the bridge is 344.5 feet (105 m). It consists of three spans of the following lengths: 90’ – 0”, 140’ – 0”, and 110’ – 0” (27.4 m, 42.7 m, 33.5 m). The bridge profile is shown in Figure 4.

4.1.3.2 Width

The total section width of the bridge is 47 feet (14.3 m), with a roadway width of 44 feet (13.4 m).
4.1.3.3 Parapet Dimensions

The height of each parapet is 3.5 feet (1.07 m). The top width of each parapet is 10 inches (254 mm) and reaches a width of 1.5 feet (457.2 mm) at the base of the parapet.

The parapet detail is shown in Figure 5.

Figure 4: Eastbound Big Creek Bridge Construction Plans, Profile

Figure 5: Eastbound Big Creek Bridge Construction Plans, Parapet Cross Section
4.2  Eastbound Paine Creek Bridge (LAK – 90 – 20.03 R)

4.2.1  Overview

The Paine Creek Bridge is an eastbound Interstate – 90 Highway bridge located in Painesville, Ohio. It was originally built in 1960.

4.2.1.1  Inventory Number and Structural File Number

In the ODOT Bridge Inventory, the Eastbound Paine Creek Bridge is identified as follows:

Bridge Inventory Number: LAK – 90 – 20.03 R

Structural File Number: 4304772 (R)

4.2.1.2  Structure Type

The bridge structure is a twin continuous steel plate girder bridge with reinforced concrete deck and substructure.

4.2.2  Contractor Information

The deck and superstructure rehabilitation took place in 2012. The contractor for the rehabilitation was Allega, Inc. with Great Lakes Construction Co. as the subcontractor for all bridge work. The ready mix concrete supplier was Osborne, Inc. In addition to parapet replacement, a new widened non-composite reinforced concrete deck was constructed on the existing steel girders.
4.2.3 Designed Bridge Dimensions

4.2.3.1 Length
The total length of the bridge is 496.1 feet (151.2 m). It consists of three spans of the following lengths: 150’ – 0”, 188’ – 0”, 150’ – 0” (45.72 m, 57.3 m, 45.72 m). A profile of the bridge is shown in Figure 6.

4.2.3.2 Width
The total section width of the bridge is 47 feet (14.3 m), with a roadway width of 44 feet (13.4 m).

4.2.3.3 Parapet Dimensions
The height of each parapet is 3.5 feet (1.07 m). The top width of each parapet is 10 inches (254 mm) and reaches a width of 1.5 feet (457.2 mm) at the base of the parapet. The parapet detail is shown in Figure 7.

Figure 6: Eastbound Paine Creek Bridge Plans, Profile
4.3 Eastbound Paine Road Bridge (LAK – 90 – 21.10 R)

4.3.1 Overview

The Paine Road Bridge is an eastbound Interstate – 90 Highway bridge located in Painesville, Ohio. It was originally built in 1960.

4.3.1.1 Inventory Number and Structural File Number

In the ODOT Bridge Inventory, the Eastbound Paine Road Bridge is identified as follows:

Bridge Inventory Number: LAK – 90 – 21.10 R

Structural File Number: 4304802
4.3.1.2 Structure Type
The bridge structure consists of a three span continuous steel beam bridge with a reinforced concrete deck and substructure with semi-integral abutments.

4.3.2 Contractor Information
The deck and superstructure rehabilitation took place in 2012. The contractor for the rehabilitation was Allega, Inc. with Great Lakes Construction Co. as the subcontractor for all bridge work. The ready mix concrete supplier was Osborne, Inc. In addition to deck and parapet replacement, the superstructure was raised and the approach slabs, deck expansion joints, and backwalls with semi-integral abutments were replaced.

4.3.3 Designed Bridge Dimensions

4.3.3.1 Length
The total length of the bridge is 137.99 feet (42.06 m). It consists of three spans of the following lengths: 37’ – 7”, 58’ – 2”, 37’ – 7” (11.45 m, 17.73 m, 11.45 m). A profile of the bridge is shown in Figure 8.

4.3.3.2 Width
The total section width of the bridge is 47 feet (14.3 m), with a roadway width of 44 feet (13.4 m).

4.3.3.3 Parapet Dimensions
The height of each parapet is 3.5 feet (1.07 m). The top width of each parapet is 10 inches (254 mm) and reaches a width of 1.5 feet (457.2 mm) at the base of the parapet. The parapet detail is shown in Figure 9.
Figure 8: Eastbound Paine Road Bridge Plans, Profile

Figure 9: Eastbound Paine Road Bridge Plans, Parapet Cross Section
4.4  Eastbound Hermitage Road Bridge (LAK – 90 – 13.70 R)

4.4.1  Overview

The Hermitage Road Bridge is an eastbound Interstate – 90 Highway bridge in Painesville, Ohio. It was originally built in 1961.

4.4.1.1  Inventory Number and Structural File Number

In the ODOT Bridge Inventory, the Eastbound Hermitage Road Bridge is identified as follows:

Bridge Inventory Number: LAK – 90 – 13.70 R

Structural File Number: 4304322

4.4.1.2  Structure Type

The bridge structure consists of a three span continuous steel beam bridge with a reinforced concrete deck and substructure with semi-integral abutments.

4.4.2  Contractor Information

The deck and superstructure rehabilitation took place in 2013. The contractor for the rehabilitation was Allega, Inc. with Great Lakes Construction Co. as the subcontractor for all bridge work. The ready mix concrete supplier was Osborne, Inc. In addition to deck and parapet replacement, the superstructure was raised and the approach slabs, deck expansion joints, and backwalls with semi-integral abutments were replaced.
4.4.3 Designed Bridge Dimensions

4.4.3.1 Length

The total length of the bridge is 160.58 feet (48.94 m). It consists of three spans of the following lengths: 47’ – 4”, 60’ – 0”, 47’ – 10” (14.43 m, 18.29 m, 14.58 m). A profile of the bridge is shown in Figure 10.

4.4.3.2 Width

The total section width of the bridge is 59 feet (18.0 m), with a roadway width of 56 feet (17.1 m).

4.4.3.3 Parapet Dimensions

The height of each parapet is 3.5 feet (1.07 m). The top width of each parapet is 10 inches (254 mm) and reaches a width of 1.5 feet (457.2 mm) at the base of the parapet. The parapet detail is shown in Figure 11.

Figure 10: Eastbound Hermitage Road Bridge Plans, Profile
4.5 Eastbound Auburn Road Bridge (LAK – 90 – 14.87 R)

4.5.1 Overview

The Auburn Road Bridge is an eastbound Interstate – 90 Highway bridge in Painesville, Ohio. It was originally built in 1960.

4.5.1.1 Inventory Number and Structural File Number

In the ODOT Bridge Inventory, the Eastbound Auburn Road Bridge is identified as follows:

Bridge Inventory Number: LAK – 90 – 14.87 R

Structural File Number: 4304446
4.5.1.2 Structure Type
The bridge structure consists of a three span continuous steel beam bridge with reinforced concrete deck and substructure.

4.5.2 Contractor Information
The deck and superstructure rehabilitation took place in 2013. The contractor for the rehabilitation was Allega, Inc. with Great Lakes Construction Co. as the subcontractor for all bridge work. The ready mix concrete supplier was Osborne, Inc. In addition to deck and parapet replacement, the superstructure was raised and the approach slabs, expansion joints, and backwalls were replaced.

4.5.3 Designed Bridge Dimensions

4.5.3.1 Length
The total length of the bridge is 160.58 feet (48.94 m). It consists of three spans of the following lengths: 41’ – 7.25”, 63’ – 3.44”, 41’ – 7.5” (12.68 m, 19.29 m, 12.69 m). A profile of the bridge is shown in Figure 12.

4.5.3.2 Width
The total section width of the bridge varies and the roadway width varies between 74’ – 1.13” and 84’ – 9.88” (22.58 m and 84.82 m).

4.5.3.3 Parapet Dimensions
The height of each parapet is 3.5 feet (1.07 m). The top width of each parapet is 10 inches (254 mm) and reaches a width of 1.5 feet (457.2 mm) at the base of the parapet. The parapet detail is shown in Figure 13.
Figure 12: Eastbound Auburn Road Bridge Plans, Profile

Figure 13: Eastbound Auburn Road Bridge Plans, Parapet Cross Section
4.6  **Westbound Paine Road Bridge (LAK – 90 – 21.10 L)**

4.6.1  **Overview**

The Paine Road Bridge is a westbound Interstate – 90 Highway bridge in Painesville, Ohio. It was originally built in 1960.

4.6.1.1  **Inventory Number and Structural File Number**

In the ODOT Bridge Inventory, the Eastbound Paine Road Bridge is identified as follows:

Bridge Inventory Number: LAK – 90 – 21.10 L

Structural File Number: 4304837

4.6.1.2  **Structure Type**

The bridge structure consists of a three span continuous steel beam bridge with reinforced concrete deck and substructure with semi-integral abutments.

4.6.2  **Contractor Information**

The deck and superstructure rehabilitation took place in 2013. The contractor for the rehabilitation was Allega, Inc. with Great Lakes Construction Co. as the subcontractor for all bridge work. The ready mix concrete supplier was Osborne, Inc. In addition to deck and parapet replacement, the superstructure was raised and the approach slabs, deck expansion joints, and backwalls with semi-integral abutments were replaced.
4.6.3 Designed Bridge Dimensions

4.6.3.1 Length
The total length of the bridge is 113.63 feet (34.63 m). It consists of three spans of the following lengths: 31’ – 3”, 46’ – 0”, 31’ – 3” (9.53 m, 14.02 m, 9.53 m). A profile of the bridge is shown in Figure 14.

4.6.3.2 Width
The total section width of the bridge is 47 feet (14.3 m), with a roadway width of 44 feet (13.4 m).

4.6.3.3 Parapet Dimensions
The height of each parapet is 3.5 feet (1.07 m). The top width of each parapet is 10 inches (254 mm) and reaches a width of 1.5 feet (457.2 mm) at the base of the parapet. The parapet detail is shown in Figure 15.

![Figure 14: Westbound Paine Road Bridge Plans, Profile](image-url)
4.7 Westbound Paine Creek Bridge (LAK – 90 – 20.03 L)

4.7.1 Overview

The Paine Creek Bridge is a westbound Interstate – 90 Highway bridge in Painesville, Ohio. It was originally built in 1960.

4.7.1.1 Inventory Number and Structural File Number

In the ODOT Bridge Inventory, the Westbound Paine Creek Bridge is identified as follows:

Bridge Inventory Number: LAK – 90 – 20.03 L

Structural File Number: 4304748 (L)
**4.7.1.2 Structure Type**

The bridge structure is a twin continuous steel plate girder bridge with reinforced concrete deck and substructure.

**4.7.2 Contractor Information**

The deck and superstructure rehabilitation took place in 2013. The contractor for the rehabilitation was Allega, Inc. with Great Lakes Construction Co. as the subcontractor for all bridge work. The ready mix concrete supplier was Osborne, Inc. In addition to parapet replacement, work included a new widened non-composite reinforced concrete deck on existing steel girders.

**4.7.3 Designed Bridge Dimensions**

**4.7.3.1 Length**

The total length of the bridge is 488.29 feet (148.83 m). It consists of three spans of the following lengths: 150’ – 9.88”, 188’ – 5.88”, 149’ – 2.75” (45.97 m, 57.45 m, 45.49 m). A profile of the bridge is shown in Figure 16.

**4.7.3.2 Width**

The total section width of the bridge is 47 feet (14.3 m), with a roadway width of 44 feet (13.4 m).

**4.7.3.3 Parapet Dimensions**

The height of each parapet is 3.5 feet (1.07 m). The top width of each parapet is 10 inches (254 mm) and reaches a width of 1.5 feet (457.2 mm) at the base of the parapet. The parapet detail is shown in Figure 17.
4.8 South Marginal Road Bridge (CUY – 90 – 18.15)

4.8.1 Overview

The South Marginal Bridge is an overpass bridge over I – 90 in downtown Cleveland.

It was originally built in 1959.
4.8.1.1 Inventory Number and Structural File Number

In the ODOT Bridge Inventory, the South Marginal Bridge is identified as follows:

Bridge Inventory Number: CUY – 90 – 18.15

Structural File Number: 1808192

4.8.1.2 Structure Type

The bridge structure consists of continuous steel beams with composite reinforced concrete deck and reinforced concrete substructure.

4.8.2 Contractor Information

The deck and superstructure rehabilitation took place in 2013. The contractor for the rehabilitation was Cuyahoga Bridge and Road, Inc., and the ready mix concrete supplier was Tech Ready Mix, Inc. In addition to parapet replacement, work included a new composite concrete deck on existing beams, refurbishment of pier bearings, and replacement of abutment bearings, end frames, abutment backwalls, and approach slabs, as well as patching and sealing of the substructure concrete.

4.8.3 Designed Bridge Dimensions

4.8.3.1 Length

The total length of the bridge is 228.02 feet (69.50 m). It consists of four spans of the following lengths: 45’ – 0”, 68’ – 0”, 68’ – 0”, 45’ – 0” (13.72 m, 20.73 m, 20.73 m, 13.72 m). A profile of the bridge is shown in Figure 18.

4.8.3.2 Width

The total section width of the bridge is 31 feet (9.45 m), with a roadway width of 24 feet (7.32 m) and a safety curb width of 2 feet (0.61 m) on either side.
4.8.3.3 Parapet Dimensions

The height of each parapet is 3.5 feet (1.07 m). The top width of each parapet is 10 inches (254 mm) and reaches a width of 1.5 feet (457.2 mm) at the base of the parapet.

The parapet detail is shown in Figure 19.

Figure 18: South Marginal Bridge Plans, Profile

Figure 19: South Marginal Bridge Plans, Parapet Cross Section
4.9  **Westbound Big Creek Bridge (LAK – 90 – 16.41 L)**

4.9.1  **Overview**

The Big Creek Bridge is a westbound Interstate – 90 Highway bridge in Painesville, Ohio. It was originally built in 1960.

4.9.1.1  **Inventory Number and Structural File Number**

In the ODOT Bridge Inventory, the Westbound Paine Creek Bridge is identified as follows:

Bridge Inventory Number: LAK – 90 – 16.41 L

Structural File Number:  4304624 (L)

4.9.1.2  **Structure Type**

The bridge structure consists of a twin continuous steel plate girder bridge with reinforced concrete deck and substructure with semi-integral abutments.

4.9.2  **Contractor Information**

The deck and superstructure rehabilitation will take place in 2014. The contractor for the rehabilitation will be Allega, Inc. with Great Lakes Construction Co. as the subcontractor for all bridge work. The ready mix concrete supplier will be Osborne, Inc.

In addition to parapet replacement, work includes a new widened non-composite reinforced concrete deck on the existing steel girders.
4.9.3  Designed Bridge Dimensions

4.9.3.1  Length

The total length of the bridge is 344.5 feet (105.0 m). It consists of three spans of the following lengths: 90’ – 0”, 140’ – 0”, 110’ – 0” (27.43 m, 42.67 m, 33.53 m). A profile of the bridge is shown in Figure 20.

4.9.3.2  Width

The total section width of the bridge is 47 feet (14.3 m), with a roadway width of 44 feet (13.4 m).

4.9.3.3  Parapet Dimensions

The height of each parapet is 3.5 feet (1.07 m). The top width of each parapet is 10 inches (254 mm) and reaches a width of 1.5 feet (457.2 mm) at the base of the parapet. The parapet detail is shown in Figure 21.
4.10 Westbound Auburn Road Bridge (LAK – 90 – 14.87 L)

4.10.1 Overview

The Auburn Road Bridge is a westbound Interstate – 90 Highway bridge in Painesville, Ohio. It was originally built in 1960.

4.10.1.1 Inventory Number and Structural File Number

In the ODOT Bridge Inventory, the Auburn Road Bridge is identified as follows:

Bridge Inventory Number: LAK – 90 – 14.87 L

Structural File Number: 4304470

4.10.1.2 Structure Type

The bridge structure consists of a three span continuous steel beam bridge with reinforced concrete deck and substructure.
4.10.2 Contractor Information

The deck and superstructure rehabilitation will take place in 2014. The contractor for the rehabilitation will be Allega, Inc. with Great Lakes Construction Co. as the subcontractor for all bridge work. The ready mix concrete supplier will be Osborne, Inc. In addition to parapet replacement, work includes raising the superstructure and replacing the approach slabs, deck, expansion joints, and backwalls.

4.10.3 Designed Bridge Dimensions

4.10.3.1 Length

The total length of the bridge is 159.28 feet (48.55 m). It consists of three spans of the following lengths: 46’ – 8.13”, 63’ – 2.94”, 46’ – 9.25” (14.23 m, 19.28 m, 14.26 m). A profile of the bridge is shown in Figure 22.

4.10.3.2 Width

The total section width of the bridge varies, with a roadway width that varies between 54 feet (16.46 m) and 56.76 feet (17.3 m).

4.10.3.3 Parapet Dimensions

The height of each parapet is 3.5 feet (1.07 m). The top width of each parapet is 10 inches (254 mm) and reaches a width of 1.5 feet (457.2 mm) at the base of the parapet. The parapet detail is shown in Figure 23.
Figure 22: Westbound Auburn Road Bridge Plans, Profile

Figure 23: Westbound Auburn Road Bridge Plans, Parapet Cross Section
4.11  Westbound Hermitage Road Bridge (LAK – 90 – 13.70 L)

4.11.1  Overview

The Hermitage Road Bridge is a westbound Interstate – 90 Highway bridge in Painesville, Ohio. It was originally built in 1961.

4.11.1.1  Inventory Number and Structural File Number

In the ODOT Bridge Inventory, the Westbound Hermitage Road Bridge is identified as follows:

Bridge Inventory Number: LAK – 90 – 13.70 L

Structural File Number: 4304292

4.11.1.2  Structure Type

The bridge structure consists of a three span continuous steel beam bridge with a reinforced concrete deck and substructure with semi-integral abutments.

4.11.2  Contractor Information

The deck and superstructure rehabilitation will take place in 2014. The contractor for the rehabilitation will be Allega, Inc. with Great Lakes Construction Co. as the subcontractor for all bridge work. The ready mix concrete supplier will be Osborne, Inc.

In addition to parapet replacement, work includes raising the superstructure and replacing the approach slabs, deck, expansion joints, and backwalls with semi-integral abutments.
4.11.3 Designed Bridge Dimensions

4.11.3.1 Length

The total length of the bridge is 136.5 feet (41.61 m). It consists of three spans of the following lengths: 36’ – 0”, 60’ – 0”, 36’ – 0” (10.97 m, 18.29 m, 10.97 m). A profile of the bridge is shown in Figure 24.

4.11.3.2 Width

The total section width of the bridge is 59 feet (18.0 m), with a roadway width of 56 feet (17.1 m).

4.11.3.3 Parapet Dimensions

The height of each parapet is 3.5 feet (1.07 m). The top width of each parapet is 10 inches (254 mm) and reaches a width of 1.5 feet (457.2 mm) at the base of the parapet. The parapet detail is shown in Figure 25.

Figure 24: Westbound Hermitage Road Bridge Plans, Profile
Figure 25: Westbound Hermitage Road Bridge Plans, Parapet Cross Section
CHAPTER V
FIELD OBSERVATIONS

This chapter documents detailed field observations on completed bridge parapets, including data from UPV testing, cylinder sample testing, maturity results, and early age cracking.

5.1 Eastbound Big Creek Bridge

Both parapet walls on the eastbound Big Creek Bridge were constructed as experimental controls in 2012. Construction occurred before Cleveland State University was assigned the parapet study with ODOT, therefore site visits were not made during concrete placement or saw cutting operations. It is known that the parapets were constructed while traffic was using the other side of the bridge, and the control joints were cut on the day of concrete placement while the concrete was still green. Visits were made in February of 2014, to perform a crack survey.
5.1.1 North Parapet

Due to the narrow shoulder on this side of the bridge, it was not possible to safely perform a crack survey of the north parapet. However, when looking from the side of the south parapet, a large crack could be seen that formed midway between the control joints. A picture from the other side of the bridge was taken. It is hard to make out the crack, but it is circled in Figure 26. It is unknown exactly when this crack formed; however, the crack was discovered on September 30, 2013. The control joints were spaced 10 feet (3.0 m) apart along the length of the wall.

![Figure 26: EB Big Creek Bridge North Parapet Crack (Photograph provided by Lauren Hedges)](image)

5.1.2 South Parapet

A crack survey was performed on the south parapet of the eastbound Big Creek Bridge. The control joints on this bridge were spaced 10 feet (3.0 m) apart along the length of the parapet. Again, a crack was found midway between the control joints as displayed in Figure 27. Figure 28 is a picture looking down at the top of the parapet showing that the crack continued all the way through the thickness of the wall. It also
continued all the way down the back side of the parapet. This crack was not discovered until February 27, 2014, and it is unknown exactly when the crack formed.

Figure 27: EB Big Creek south parapet crack (Photograph provided by Lauren Hedges)

Figure 28: Crack along top of parapet (Photograph provided by Lauren Hedges)
5.2  Eastbound Paine Creek Bridge

Both parapet walls on the eastbound Paine Creek Bridge were constructed as experimental controls in 2012. Construction occurred before Cleveland State University was assigned the parapet study with ODOT, therefore site visits were not made during concrete placement or saw cutting operations. It is known that the parapets were constructed while traffic was using the other side of the bridge, and the control joints were cut on the day of concrete placement while the concrete was still green. Visits were made in February of 2014, to perform a crack survey.

5.2.1  North Parapet

It was not practical to close a lane on the two lane highway, so the wall was scanned for cracks while slowly driving next to it in order to inspect the parapet safely. The control joints were spaced approximately 9.5 feet (2.9 m) along the parapet. A crack was found in between the control joints in a location near a pier. The crack was not discovered until February 27, 2014. Figure 29 shows the crack from the front of the parapet, and Figure 30 was taken from the adjacent bridge showing the crack on the backside of the parapet.

Figure 29: EB Paine Creek north parapet crack near control joint (Photograph provided by Lauren Hedges)
5.2.2 South Parapet

The south parapet had too narrow a shoulder to safely get an up close view. A crack survey could not be performed.

5.3 Eastbound Paine Road Bridge

Both parapet walls on the eastbound Paine Road Bridge were constructed as experimental controls in 2012. Construction occurred before Cleveland State University was assigned the parapet study with ODOT, therefore site visits were not made during concrete placement or saw cutting operations. It is known that the parapets were constructed while traffic was using the other side of the bridge, and the control joints
were cut on the day of concrete placement while the concrete was still green. Visits were made in February of 2014, to perform a crack survey.

5.3.1 North Parapet

The north parapet had a large shoulder allowing a close view and crack survey to be taken. The control joints were spaced every 7.25 feet (2.2 m) creating a total of 18 joints. Two cracks were discovered on this parapet on February 27, 2014. The first crack, in Figure 31, propagated out of the third control joint from the west end. The joint was located halfway between the edge of the bridge and the pier. The second crack, in Figure 32, was found between the fourth and fifth control joints within the negative tension zone created by the pier.

Figure 31: EB Paine Road north parapet crack propagating out of control joint (Photograph provided by Lauren Hedges)
This parapet displayed a lot of spalling along the section of the parapet where the horizontal reinforcement is located. This may indicate there was not enough cover provided over the reinforcement. Figure 33 displays where the spalling began. As defined by the American Concrete Institute (ACI), spalling is “the development of a fragment, usually in the shape of a flake, detached from a larger mass by a blow, the action of weather, pressure, or expansion within the larger mass” (ACI Concrete Terminology 2014).
UPV tests were performed on the parapet as well as over the control joints. The average velocity of the concrete was calculated as 9,493 feet per second (2,893 meters per second) or approximately 9,500 fps (2,900 mps). Using this information, the velocities found over the control joints were used to determine which joints fully cracked, showed signs of cracking, or did not crack at all. A joint was labeled as cracked if the average velocity fell between no signal, or 0 fps, and 4,500 fps (1,370 mps). A velocity between 4,500 fps and 8,500 fps (2,590 mps) represented a partially cracked joint. Joints that were not cracked included velocities 8,500 fps or greater that fell near the concrete’s average velocity of 9,500 fps. Approximately 78% of the control joints fully cracked, 17% of the joints partially cracked, and 6% of the joints did not crack. One joint that did not crack was located near the west end of the bridge.

Figure 33: Spalling on EB Paine Road north parapet along location of horizontal reinforcement (Photograph provided by Lauren Hedges)
5.3.2 South Parapet

The south parapet had too narrow of a shoulder in order to safely get an up close view. A crack survey could not be performed.

5.4 Eastbound Hermitage Road Bridge

5.4.1 North Parapet

Three maturity sensors were attached to the reinforcement of the north parapet. The design of the reinforcement included both epoxy coated steel reinforcement and GFRP reinforcement. No. 5 (16 mm) steel bars were used as the vertical reinforcement, and No. 6 (19 mm) steel bars were used to connect the parapet to the deck. No. 5 (16 mm) GFRP bars were used for all the horizontal reinforcement except the single reinforcement at the top consisted of a No. 6 (19 mm) GFRP bar.

Concrete was placed on July 2, 2013, under significant cloud cover at 66°F (18.9°C) and 96% relative humidity. The first truck was tested at 5.8% air with a 6 inch (150 mm) slump and a concrete temperature of 77°F (25°C). Before placement, superplasticizer and a retarder were added to the concrete mix onsite. The concrete mixture did not contain any fiber. Three cylinder samples were taken for UPV and compressive strength testing.

Removal of the formwork and performance of the saw cuts took place the next day, approximately 20 hours after concrete placement. The saw cuts went 3.5 inches (889 mm) deep cutting through all of the GFRP reinforcement. The control joints were spaced between 5.83 and 6.08 feet (1.78 and 1.85 m) in negative tension zones and between 8.75 and 12.0 feet (2.67 and 3.66 m) in positive moment areas. Unlike most of
the other parapets, this parapet was kept continuously saturated during formwork removal and saw cutting.

When the forms were stripped, UPV was performed over the control joints and on the parapet before the wall was covered with wet burlap to cure for seven days. The parapet was also inspected for early age cracking. Other than flaws from formwork removal, no cracks were identified. Figures 34 and 35 show the bug holes and small surface cracks observed along the parapet.

Figure 34: EB Hermitage Road north parapet surface cracks (Photograph provided by Amy Kalabon)
Seven days later, after the wall cured, another site visit was made to take maturity sensor readings and complete UPV tests on the wall, over joints, and over any discovered cracks. No cracks were found during this site visit. The UPV velocities taken on the parapet and on the cylinder samples are displayed in Table 4.

Table 4: EB Hermitage north parapet UPV velocities

<table>
<thead>
<tr>
<th>Time</th>
<th>Average UPV Velocities</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>North Parapet</td>
</tr>
<tr>
<td>Day 1</td>
<td>11462 fps</td>
<td>3494 mps</td>
</tr>
<tr>
<td>Day 7</td>
<td>12561 fps</td>
<td>3829 mps</td>
</tr>
</tbody>
</table>
The velocities of the cylinder samples were used as verification of the values collected in the field. Due to the curing conditions in the lab, the cylinder samples were expected to produce higher velocities than the parapet.

Since the velocities of the parapet were in the appropriate range, average velocities over each control joint were recorded. These velocities were placed into three categories:

1. Cracked Joint
2. Partially Cracked Joint
3. Not Cracked Joint

A joint was labeled as cracked if the average velocity over that joint fell between “no signal” or 0 fps and 5,000 fps (1,500 mps). An average velocity from 5,000 fps to 10,000 fps (1,500 to 3,000 mps) represented a partially cracked joint. Joints that were not cracked included velocities greater than 10,000 fps (3,000 mps) that fell close to the average concrete velocity of 12,561 fps. Approximately, 18% of the joints cracked, 70% were partially cracked, and 12% were not cracked. It is expected that the partially cracked joints will fully crack in the future.

Three maturity sensors were placed on the bridge to determine temperatures of the concrete during placement and curing. One of the sensors was buried during concrete placement and another was damaged during construction. Table 5 displays the peak temperature and the initial drop in the temperature the concrete reached during the hydration process from the surviving maturity sensor.
Table 5: EB Hermitage north parapet maturity sensor temperature data

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Peak Temperature (*F/°C)</th>
<th>Initial Low Temperature after Peak (*F/°C)</th>
<th>Temperature Differential (*F/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hermitage (n) #2</td>
<td>124.7/51.5</td>
<td>78.8/26.0</td>
<td>45.9/25.5</td>
</tr>
</tbody>
</table>

5.4.2 South Parapet

Three maturity sensors were attached to the reinforcement of the south parapet of the Hermitage Road Bridge. As per design, the type of reinforcement used was epoxy coated steel reinforcement with No. 5 (16 mm) longitudinal and vertical bars, a single No. 6 (19 mm) longitudinal bar at the top of the parapet, and No. 6 (19 mm) bars tying the parapet to the deck.

Placement of the concrete occurred on October 15, 2013, under cloudy and foggy conditions at 60°F (15.6°C) and 78% relative humidity. One of the ready mix trucks was tested to ensure the quality of the concrete. The truck that was tested had concrete with a temperature of 62°F (16.7°C), a 6 inch (150 mm) slump, and an air content of 8%. If the air content had been above 8%, the truck would have been turned away. A factor contributing to the high air content of this concrete is the 1 lb/yd³ (0.59 kg/m³) of polypropylene fiber. Superplasticizer was added to the concrete before placement.

Three concrete cylinder samples were collected for UPV and compressive strength testing.

The forms were removed the same day the concrete was placed, right after placement was complete. With the concrete in this green stage, UPV tests could not be performed before the wall was prepared and covered to cure. Form removal and saw
cutting while the concrete is green will reduce the number of micro cracks that form during the first stages of hydration when the control joints have not yet been cut, and it allows the wall to be easily rubbed before it is left to cure. The control joints cut in this parapet were the typical 1.5 inch (38 mm) deep cuts, and were spaced from 5.25 to 6.42 feet (1.6 to 2 m) in negative tension areas and 11.83 to 12.33 feet (3.6 to 3.8 m) in positive moment areas.

After the parapet finished curing, a site visit was made to perform a crack survey and UPV tests. Due to rubbing, the parapet had no surface flaws such as holes or surface cracks created during removal of the formwork. The good condition of the parapet can be seen in Figure 36. No cracks were found; therefore UPV was only performed on the parapet and over the control joints. The average UPV velocities from both the parapet and the cylinder samples after curing are displayed in Table 6.

Figure 36: EB Hermitage south parapet condition (Photograph provided by Amy Kalabon)
Table 6: EB Hermitage south parapet UPV velocities

<table>
<thead>
<tr>
<th>Time</th>
<th>Average UPV Velocities</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Location</td>
</tr>
<tr>
<td></td>
<td>South Parapet</td>
</tr>
<tr>
<td>After Cure</td>
<td>8,797 fps</td>
</tr>
<tr>
<td></td>
<td>13,609 fps</td>
</tr>
</tbody>
</table>

The velocities of the cylinder samples were used as verification of the values collected in the field. Due to the curing conditions in the lab, the cylinder samples were expected to produce somewhat higher velocities than the parapet. However, the values of the cylinders in this case were much higher when compared to the parapet. Due to this, the ranges used to determine which category each control joint was placed into was adjusted. Again, the average velocities were placed into three separate categories:

1. Cracked Joint
2. Partially Cracked Joint
3. Not Cracked Joint

For this parapet, a joint was labeled as cracked if the average velocity over that joint fell between “no signal”, or 0 fps, and 3,000 fps (900 mps). An average velocity from 3,000 fps to 7,000 fps (2,100 mps) represented a partially cracked joint, and joints that were not cracked included velocities greater than 7,000 fps (2,100 mps) that fell close to the average concrete velocity of 8797 fps (2,681 mps). According to this adjusted system, only 6% of the joints cracked, 53% were partially cracked, and 41% did not crack.

The three maturity sensors placed on the bridge provided temperatures of the concrete during placement and curing. Table 7 displays the peak temperature and the initial drop in temperature the concrete reached during the hydration process.
Table 7: EB Hermitage south parapet maturity sensor temperature data

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Peak Temperature (*F/°C)</th>
<th>Initial Low Temperature after Peak (*F/°C)</th>
<th>Temperature Differential (*F/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hermitage (s) #1</td>
<td>99.5/37.5</td>
<td>70.7/21.5</td>
<td>28.8/16.0</td>
</tr>
<tr>
<td>Hermitage (s) #2</td>
<td>93.2/34.0</td>
<td>71.6/22.0</td>
<td>21.6/12.0</td>
</tr>
<tr>
<td>Hermitage (s) #3</td>
<td>95.0/35.0</td>
<td>72.5/22.5</td>
<td>22.5/12.5</td>
</tr>
</tbody>
</table>

On February 21, 2014, another site visit was made to the south parapet to perform UPV tests and a crack survey. Despite the very cold conditions, no cracks were found on the parapet.

UPV tests were performed on the parapet to see if the cold weather had initiated any additional cracking at the control joints. Before analyzing the velocities gathered from the control joints, the concrete’s average velocity was recalculated and found to have increased from 8,800 fps (2680 mps) to approximately 10,300 fps (3,140 mps). A joint was labeled as fully cracked if the velocity over the joint fell between 0 fps and 4,500 fps (1,370 mps), a partially cracked joint had a velocity between 4,500 fps and 8,500 fps (2,590 mps), and a joint was not cracked if it had a velocity of 8,500 fps or greater that fell near the average concrete velocity of 10,300 fps. Since the fall, the majority of the control joints were fully cracked or showed signs of cracking. Approximately 47% of the joints fell in the fully cracked category, 47% were partially cracked, and only 6% of the joints did not crack at all. With more control joints due to the smaller spacing over the negative tension areas, not all of the control joints needed to completely crack in order to properly control cracking along the parapet. So even though not all of the joints fully cracked, they are still functioning as designed by preventing cracking elsewhere on the parapet.
The wires from the three maturity sensors placed on this bridge were still intact during the site visit; however, only one of the sensors were able to provide readings from January 9, 2014 to February 21, 2014. A graph of the temperature fluctuations the parapet experienced during this time is displayed in Figure 37. Within this time, the parapet experienced a maximum temperature of 48.2°F (9°C) and a minimum temperature of 6.8°F (-14°C). Over the span of time since the parapet was placed in October, there was enough freeze-thaw action to cause the concrete to crack. With no cracks discovered along the length of the parapet, the parapet functioned as it was designed by limiting cracking to the joints.

![Figure 37: EB Hermitage south parapet winter temperature fluctuations](image)

5.5  Eastbound Auburn Road Bridge

5.5.1  North Parapet

Three maturity sensors were attached to the reinforcement on the north parapet of Auburn Road Bridge. The design of the reinforcement includes both epoxy coated steel reinforcement and GFRP reinforcement. No. 5 (16 mm) steel bars were used as the
vertical reinforcement, and No. 6 (19 mm) steel bars were used to attach the parapet to the deck. No. 5 (16 mm) GFRP bars were used for all the horizontal reinforcement, except that the single reinforcement at the top consisted of a No. 6 (19 mm) GFRP bar.

Concrete was placed on July 1, 2013, with no cloud cover, at 70°F (21°C) and 89% relative humidity. The temperature of the concrete was 77°F (25°C) with 7% air and a 4.75 inch (120 mm) slump. The concrete mixture did not contain any fiber. During formwork removal, one day after placement, the saw cuts were made at 3.5 inch (89 mm) depths cutting through all of the longitudinal GFRP reinforcement. The control joints were spaced at 3.25 to 6 feet (1.0 to 1.8 m) within negative tension zones, and 10 to 14 feet (3.0 to 4.3 m) along the rest of the parapet. No cracks were found; however there were small holes and many marks from the formwork.

A field visit was made after the seven-day curing period to perform UPV tests on the parapet where no flaws were present, over any identified cracks, and over each control joint. Again, no cracks were identified. Cylinder samples could not be collected for this parapet; however due to similar conditions, the concrete tests on Auburn Road were compared to the north parapet concrete tests and cylinder samples on Hermitage Road for verification. The average UPV velocity of the concrete was determined to be approximately 12,460 fps (3,798 mps). After verifying this velocity, the average velocities over each control joint were recorded. These velocities were placed into three categories:

1. Cracked Joint
2. Partially Cracked Joint
3. Not Cracked Joint

A joint was labeled as cracked if the average velocity over that joint fell between “no signal” or 0 fps and 5,000 fps (1,500 mps). An average velocity from 5,000 fps to 10,000 fps (1,500 to 3,000 mps) represented a partially cracked joint and joints that were not cracked included velocities greater than 10,000 fps (3,000 mps) that fell close to the average concrete velocity of 12,460 fps (3800 mps). Approximately 28% of the joints cracked, 61% were partially cracked, and only 11% were not cracked.

The joints that did not crack were located on either side of the bridge at the edge of the negative tension zones, approximately 10 feet (3 m) away from the piers. The parapet length is about 149 feet (45.4 m), and within that length, due to the new spacing method, there are 18 control joints. The most common specification calls for control joints to be spaced between 6 feet and 10 feet (1.8 m and 3.0 m) throughout the length of the parapet. If the conventional spacing was used, the parapet would only have around 12 control joints. With the extra joints as well as the 3.5 inch (89 mm) deep saw cuts through the GFRP bar, it appears that the majority of the joints cracked.

The three maturity sensors placed on the bridge provided temperatures of the concrete during placement and curing. Table 8 shows the peak temperature and the initial drop in temperature the concrete reached during the hydration process.

**Table 8: EB Auburn north parapet maturity sensor temperature data**

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Peak Temperature (°F/°C)</th>
<th>Initial Low Temperature after Peak (°F/°C)</th>
<th>Temperature Differential (°F/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Auburn (n) #1</td>
<td>108.5/42.5</td>
<td>86.9/30.5</td>
<td>21.6/12.0</td>
</tr>
<tr>
<td>Auburn (n) #2</td>
<td>108.5/42.5</td>
<td>88.7/31.5</td>
<td>19.8/11.0</td>
</tr>
<tr>
<td>Auburn (n) #3</td>
<td>108.5/42.5</td>
<td>87.8/31.0</td>
<td>20.7/11.5</td>
</tr>
</tbody>
</table>
All three maturity sensors were spaced evenly across the length of the parapet, and as shown in the table, they were consistent with each other. The parapet showed a small change in temperature during the initial phases of hydration, reducing the chances of any thermal cracking during this time.

5.5.2 South Parapet

The south parapet of Auburn Road Bridge was not constructed during the 2013 construction season due to weather conditions. This parapet will be finished along with westbound Big Creek Bridge, westbound Auburn Road Bridge, and westbound Hermitage Road Bridge in the 2014 season.

5.6 Westbound Paine Road Bridge

5.6.1 North Parapet

Three maturity sensors were attached to the reinforcement of the north parapet to provide temperature data of the concrete. The reinforcement was epoxy coated field cut steel rebar with No. 5 (16 mm) longitudinal and vertical bars, a No. 6 (19 mm) longitudinal bar at the top of the parapet, and No. 6 (19 mm) rebar tying the parapet into the deck.

The north parapet was placed on September 23, 2013 under cloudy conditions at 53°F (11.7°C) and 73% humidity. The first truck was tested before placement began. The tested concrete was 69°F (20.6°C) with a 5.25 inch (133 mm) slump and 6.2% air content. Unfortunately, cylinder samples were not collected. Superplasticizer was added to the concrete onsite along with a retarder.
Once concrete placement was finished, formork removal and saw cuts were performed while the concrete was still green as shown in Figure 38. The control joints were cut 3.5 inches (88.9 mm) deep through the horizontal field cut steel rebar. The joints were spaced 4.5 to 5.7 feet (1.37 to 1.74 m) in negative moment areas, and 11.25 to 13.7 feet (3.43 to 4.18 m) in positive moment areas. Right before the wall was covered with burlap to cure for seven days, the wall was rubbed (Figure 39).

Figure 38: WB Paine Road north parapet performance of saw cuts (Photograph provided by Amy Kalabon)
Due to the green state of the concrete, UPV tests could not be performed before curing took place. A site visit was made after curing in order to collect data from the maturity sensors, survey for cracks, and perform UPV tests. Without having cylinder samples to verify the UPV velocities taken from the parapet, the average velocity of the concrete was compared to the velocities found for the other Lake County bridges. The average velocity was 9,178 fps (2,800 mps), which seems low next to the other average parapet velocities. Taking this into account, the ranges used to determine which category the control joints fell into were readjusted for this parapet. A joint was labeled as cracked if the average velocity over that joint fell between “no signal”, or 0 fps, and 4,500 fps (1,370 mps). An average velocity from 4,500 fps to 9,000 fps (2,740 mps)
represented a partially cracked joint, and joints that were not cracked included velocities greater than 9,000 fps (2,740 mps) that fell close to the average concrete velocity of 9,178 fps (2,800 mps). Approximately, 31% of the control joints cracked, 54% were partially cracked, and 15% of the joints did not crack. The joints that did not show any signs of cracking were located at the ends of the bridge.

The three maturity sensors placed in the parapet provided the peak temperatures and the initial drop in temperature the concrete reached during curing as displayed in Table 9.

**Table 9: WB Paine Road north parapet maturity sensor temperature data**

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Peak Temperature (°F/°C)</th>
<th>Initial Low Temperature after Peak (°F/°C)</th>
<th>Temperature Differential (°F/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paine Road (n) #1</td>
<td>94.1/34.5</td>
<td>85.1/29.5</td>
<td>9.0/5.0</td>
</tr>
<tr>
<td>Paine Road (n) #2</td>
<td>95.9/35.5</td>
<td>85.1/29.5</td>
<td>10.8/6.0</td>
</tr>
<tr>
<td>Paine Road (n) #3</td>
<td>95.9/35.5</td>
<td>83.3/28.5</td>
<td>12.6/7.0</td>
</tr>
</tbody>
</table>

On February 21, 2014, a site visit was made to check the parapet for cracks. No cracks were found, and one of the maturity sensors was in good condition. It provided temperature readings from January 9, 2014 to February 21, 2014. During this time, the parapet experienced a maximum temperature of 44.6°F (7°C) and a minimum temperature of 5°F (-15°C). Figure 40 shows the temperature changes the concrete experienced. Since the parapet was placed in September, it has been through a lot of freeze-thaw cycles that might induce cracking. Just like the south parapet of the eastbound Hermitage Road Bridge, the design of this parapet functioned properly by limiting cracking to the control joints.
Prior to concrete placement, three maturity sensors were attached to the reinforcement of the south parapet. The type of reinforcement used was epoxy coated steel rebar with No. 5 (16 mm) longitudinal and vertical bars, a No. 6 (19 mm) longitudinal bar at the top of the parapet, and No. 6 (19 mm) bars tying the parapet into the deck.

Concrete was placed on June 17, 2013, with no cloud cover at 79°F (26.1°C) and 64% relative humidity. The first truck was tested before placement for the proper air content. At 5.8%, the truck was approved and three cylinder samples were taken for UPV and compressive strength testing. The temperature of the concrete was 76°F (24°C), and it had a slump of 3.5 inches (89 mm). The concrete mixture included 1 lb/yd³ (0.59 kg/m³) of polypropylene fiber. Therefore, a superplasticizer was added onsite to assist in proper consolidation around the rebar and at the top of the parapet without

Figure 40: WB Paine Road north parapet winter temperature fluctuations

5.6.2 South Parapet

Prior to concrete placement, three maturity sensors were attached to the reinforcement of the south parapet. The type of reinforcement used was epoxy coated steel rebar with No. 5 (16 mm) longitudinal and vertical bars, a No. 6 (19 mm) longitudinal bar at the top of the parapet, and No. 6 (19 mm) bars tying the parapet into the deck.

Concrete was placed on June 17, 2013, with no cloud cover at 79°F (26.1°C) and 64% relative humidity. The first truck was tested before placement for the proper air content. At 5.8%, the truck was approved and three cylinder samples were taken for UPV and compressive strength testing. The temperature of the concrete was 76°F (24°C), and it had a slump of 3.5 inches (89 mm). The concrete mixture included 1 lb/yd³ (0.59 kg/m³) of polypropylene fiber. Therefore, a superplasticizer was added onsite to assist in proper consolidation around the rebar and at the top of the parapet without
adding water to the mixture. Figure 41 is looking down in between the formwork showing how the concrete was consolidating around the reinforcement with the assistance of the added superplasticizer.

Figure 41: Consolidation of the concrete on WB Paine Road south parapet (Photograph provided by Amy Kalabon)

One vibrator was used during placement. It could not be used close to the surface of the wall without hitting the reinforcement. With a low slump of 3.5 inches (89 mm), the concrete consolidated poorly along the surface of the wall. This became more apparent once the forms were pulled. A way to address this is to rub the wall immediately after stripping the forms to make a continuous surface, removing any holes or pits. Stripping of the forms and saw cutting of the 1.5 inch (38 mm) deep control joints occurred 24 hours after concrete placement. Figures 42 and 43 show the holes and surface cracks
that were found after stripping the forms. The pits were found all the way across the wall ranging from 0.25 to 0.75 inches (6 to 19 mm) in diameter and 0.5 inches (13 mm) deep. These holes, as well as the flaws created by the formwork, were not rubbed out by the construction workers before placing the burlap on the wall. Typically, the wall is rubbed immediately after form removal before allowing the wall to cure for seven days. In this case, the parapet was “rubbed” sometime after the seven day cure. Since the concrete hardened by this point, paste was added to the wall to cover up the holes and flaws. Figure 44 shows how the parapet looked when the parapet is rubbed after the concrete has hardened.

Figure 42: WB Paine Road south parapet bug holes (Photograph provided by Amy Kalabon)

Figure 43: Surface cracks found on WB Paine Road south parapet (Photograph provided by Amy Kalabon)
The control joints cut in this parapet were the typical 1.5 inch (38 mm) deep cuts, but spaced 3.5 to 4.7 feet (1.1 to 1.4 m) in negative moment areas and 8 feet (2.4 m) in positive moment areas.

When the forms were stripped, UPV tests were performed on several areas of the parapet before it was covered with wet burlap to cure for seven days. The parapet was also inspected for early age cracking. No cracks were identified other than the flaws produced from poor consolidation at the surface and removal of the forms. Another field visit was made after curing was complete to perform UPV tests on the parapet where no flaws were present, over any identified cracks, and over each control joint. Two additional cracks, comparable to the crack in Figure 43, were found. The three cracks were determined to be insignificant surface cracks that initiated from holes that
were not rubbed out or from flaws created during removal of the formwork. The UPV test velocities from both the parapet and the cylinder samples before and after curing are displayed in Table 10.

Table 10: WB Paine Road south parapet UPV velocities

<table>
<thead>
<tr>
<th>Time</th>
<th>Average UPV Velocities</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>South Parapet</td>
<td>Concrete Cylinder Sample</td>
</tr>
<tr>
<td>Day 1</td>
<td>11,410 fps</td>
<td>3,478 mps</td>
</tr>
<tr>
<td></td>
<td>11,763 fps</td>
<td>3,585 mps</td>
</tr>
<tr>
<td>Day 7</td>
<td>11,863 fps</td>
<td>3,616 mps</td>
</tr>
<tr>
<td></td>
<td>13,261 fps</td>
<td>4,042 mps</td>
</tr>
</tbody>
</table>

The velocities of the cylinder samples were used as verification of the values collected out in the field. Due to the curing conditions in the lab, the cylinder samples were expected to produce somewhat higher velocities than the parapet. Since the velocities of the parapet were in the appropriate range, average velocities over each control joint were recorded. These velocities were placed into three categories:

1. Cracked Joint
2. Partially Cracked Joint
3. Not Cracked Joint

A joint was labeled as cracked if the average velocity over that joint fell between “no signal” or 0 fps and 5,000 fps (1,500 meter per second). An average velocity from 5,000 to 10,000 fps (1,500 to 3,000 mps) represented a partially cracked joint and joints that were not cracked included velocities greater than 10,000 fps (3,000 mps) that fell close to the average concrete velocity of 11,863 fps. Approximately 10% of the joints cracked, 20% were partially cracked, and 70% were not cracked. It is possible that the use of polypropylene fiber in the concrete mixture and 1.5 inch (38 mm) deep saw cuts kept
the control joints from cracking at early stages. It is expected that the partially cracked joints will crack completely in the future, but it is not known whether the joints that did not crack will crack and prevent cracking elsewhere on the parapet.

The control joints that showed signs of cracking were located directly over and in between the bridge piers. The joints that did not crack were located at the ends of the bridge, between the pier and the end expansion joints. A correlation between the condition of the control joints and the negative tension region could not be made. The negative tension region fell between 10 to 14 feet (3.05 to 4.27 m) on either side of the piers. Possibly due to the short length of the parapet, 113 feet (34.4 m), the negative tension region at the ends of the bridge may not have had a large impact on the parapet enough to cause all the control joints to crack. Also, using the smaller spacing method, there were 20 control joints cut in this parapet instead of 11 joints by the conventional spacing method. With the availability of additional control joints, it is possible that fewer of the joints needed to crack. Despite the number of control joints that cracked, the parapet functioned as designed up to this point by preventing any early age cracks from forming outside of a control joint.

The three maturity sensors embedded in the bridge provided temperatures of the concrete during placement and curing. Table 11 shows the peak temperature and the initial drop in temperature the concrete reached during the hydration process.
Table 11: WB Paine Road south parapet maturity sensor temperature data

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Peak Temperature (°F/°C)</th>
<th>Initial Low Temperature after Peak (°F/°C)</th>
<th>Temperature Differential (°F/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paine Road (s) #1</td>
<td>130.1/54.5</td>
<td>83.3/28.5</td>
<td>46.8/26.0</td>
</tr>
<tr>
<td>Paine Road (s) #2</td>
<td>125.6/52.0</td>
<td>81.5/27.5</td>
<td>44.1/24.5</td>
</tr>
<tr>
<td>Paine Road (s) #3</td>
<td>125.6/52.0</td>
<td>76.1/24.5</td>
<td>49.5/27.5</td>
</tr>
</tbody>
</table>

During placement and curing of the south parapet, the concrete reached high temperatures, due to summer conditions. All three sensors were consistent with each other showing a large change in temperature. This large temperature differential could possibly be the cause of potential future cracking.

### 5.7 Westbound Paine Creek

#### 5.7.1 North Parapet

Five maturity sensors were attached to the reinforcement of the north parapet. No. 5 (16 mm) epoxy coated steel bars provided the longitudinal and vertical reinforcement with a single No. 6 (19 mm) rebar at the top of the parapet. No. 6 (19 mm) reinforcement was also used to tie the parapet to the deck.

Concrete for the north parapet was placed on September 30, 2013. When placement started, it was cloudy and rainy at 63°F (17.2°C) and 91% humidity. The first ready mix truck was tested before placing any concrete. The truck was approved with a 7% air content and 4.75 inch (120.7 mm) slump at a temperature of 70°F (21.1°C). Three cylinder samples were collected from this batch of concrete. The concrete mixture included 1 lb/yd³ (0.59 kg/m³) of polypropylene fiber, and so to assist with proper consolidation, superplasticizer was added onsite to the mix.
Formwork was removed once concrete placement was complete. As the forms were removed, saw cutting was performed in order to get the curing on as quickly as possible. The depth of the control joints were between 1.5 to 2 inches (38.1 to 50.8 mm) deep. The joints were spaced 4.67 to 8.5 feet (1.42 to 2.60 m) in negative tension areas and 10.67 to 16.08 feet (3.25 to 4.90 m) in positive moment areas. Before leaving the parapet to cure, the flaws from pulling off the formwork were rubbed out. Due to the green state of the concrete, UPV tests could not be performed.

After the parapet was cured, a site visit was made on October 16, 2013, to collect maturity data, look for cracks, and perform UPV tests. The UPV test velocities from both the parapet and the cylinder samples after curing are displayed in Table 12.

**Table 12: WB Paine Creek north parapet UPV velocities**

<table>
<thead>
<tr>
<th>Time</th>
<th>Average UPV Velocities</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>North Parapet</td>
</tr>
<tr>
<td>After Cure</td>
<td>9876 fps</td>
<td>3010 mps</td>
</tr>
</tbody>
</table>

The velocities of the cylinder samples were used as verification of the values collected out in the field. Due to the curing conditions in the lab, the cylinder samples were expected to produce somewhat higher velocities than the parapet.

Since the velocities of the parapet were in the appropriate range, average velocities over each control joint were recorded. These velocities were placed into three categories:

1. Cracked Joint
2. Partially Cracked Joint
3. Not Cracked Joint
A joint was labeled as cracked if the average velocity over that joint fell between “no signal” or 0 fps and 3,000 fps (900 mps). An average velocity from 3,000 fps to 7,000 fps (900 to 2,100 mps) represented a partially cracked joint and joints that were not cracked included velocities greater than 7,000 fps (2,100 mps) that fell close to the average concrete velocity of 9,876 fps (3,010 mps). Following this adjusted system, approximately 27% of the joints cracked, 63% were partially cracked, and 11% of the joints did not crack at all.

A crack was found on October 16, 2013, immediately after the parapet finished curing. It is shown in Figures 45, 46, and 47. The crack initiates from the control joint on the top of the parapet and follows the control joint down the side of the parapet until about a foot from the ground where it moves back into the joint. The crack does not appear on the outer side of the parapet. The crack width ranged from 0.004 to 0.007 inches (0.1 to 0.2 mm). With the depth of the control joints at approximately 1.5 inches (38 mm), it is possible that the control joint was not fully activated. The 1.5 inch deep (38 mm) saw cut may not have been accurate all the way through the joint, so where the cut was shallow, the crack was not able to continue through the joint. This crack may also represent a plane of weakness within the parapet, where a piece of vertical reinforcement may be located relatively close to the control joint or even right beneath the location of the crack. The amount of concrete cover on the reinforcement may not have been enough to prevent the crack from leaving the control joint by providing a path of least resistance. The UPV tests over the control joint and over the crack indicate that the control joint cracked and that the crack itself was deep. The concrete contained
1 lb/yd³ (0.59 kg/m³) of polypropylene fiber. Despite the use of 1.5 inch (38 mm) deep saw cuts, only about 11% of the control joints failed to crack. This, as well as the crack found, could be a result of the half-width construction. The amount of extra vibration and bouncing from traffic still using the bridge might result in additional cracking.

Figure 45: WB Paine Creek north parapet crack looking down from top of parapet
(Photograph provided by Amy Kalabon)
The five maturity sensors embedded in the bridge provided temperatures of the concrete during placement and curing. Table 13 displays the peak temperatures and the initial drops in temperature the concrete reached during the hydration process.

Table 13: WB Paine Creek north parapet maturity sensor temperature data

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Peak Temperature (°F/°C)</th>
<th>Initial Low Temperature after Peak (°F/°C)</th>
<th>Temperature Differential (°F/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paine Creek (n) #1</td>
<td>112.1/44.5</td>
<td>81.5/27.5</td>
<td>30.6/17.0</td>
</tr>
<tr>
<td>Paine Creek (n) #2</td>
<td>110.3/43.5</td>
<td>80.6/27.0</td>
<td>29.7/16.5</td>
</tr>
<tr>
<td>Paine Creek (n) #3</td>
<td>102.2/39.0</td>
<td>78.8/26.0</td>
<td>23.4/13.0</td>
</tr>
<tr>
<td>Paine Creek (n) #4</td>
<td>104.9/40.5</td>
<td>77.0/25.0</td>
<td>27.9/15.5</td>
</tr>
<tr>
<td>Paine Creek (n) #5</td>
<td>104.9/40.5</td>
<td>95.9/35.5</td>
<td>9.0/5.0</td>
</tr>
</tbody>
</table>

On February 21, 2014, a site visit was made to Paine Creek to inspect the parapet for any additional cracking. Due to the length of the bridge and the restriction to the shoulder between the parapet and oncoming traffic, the wall was inspected safely from...
inside an ODOT vehicle. No additional cracks were found along the parapet, showing good performance of the parapet’s design in response to the dramatic temperature changes over the winter.

5.7.2 South Parapet

Due to the length of this bridge, five maturity sensors were attached to the reinforcement of the south parapet. The type of reinforcement used was epoxy coated steel rebar with No. 5 (16 mm) longitudinal and vertical bars, a No. 6 (19 mm) longitudinal bar at the top of the parapet, and No. 6 (19 mm) bars tying the parapet into the deck.

The length of this parapet required concrete to be placed on two separate days, due to the lack of forms available. The first half of the parapet was placed on June 19, 2013 and the second half on June 24, 2013. During the first placement, the temperature was 67°F (19.4°C) with no cloud cover and 62% humidity. The first and third trucks were tested for proper air percentage. The first truck had 5.6% air, a concrete temperature of 74°F (23.3°C), and slump of 3.5 inches (89 mm). At 8.8% air content, the third truck was almost rejected due to high air content. Also, the concrete for the entire first half of the parapet was poured downhill. This proved to be inefficient because as construction workers finished the top of the parapet and moved down, the concrete kept flowing down the forms, requiring additional work. The first half was finished at a bulkhead approximately 288 feet (88 m) from the east expansion joint.

The second half of the parapet was placed with an outside temperature of 79°F (26.1°C), no cloud cover, and 61% relative humidity. The first truck had a high air
content of 7.8%, a 6.75 inch (170 mm) slump, and a temperature of 79°F (26.1°C). For both halves of the bridge, the forms were removed 24 hours after concrete placement and 1.5 inch (38 mm) deep control joints were cut, spaced 4 feet (1.2 m) in negative tension areas and 8 feet (2.4 m) in positive moment areas.

The concrete mixture used on the Paine Creek parapets contained 2 lb/yd³ (1.19 kg/m³) of polypropylene fibers. The product sold by BASF, MasterFiber F70, is a fibrillated polypropylene microsynthetic fiber manufactured from 100% virgin homopolymer polypropylene resins. The recommended dosage of MasterFiber F70 product provided by BASF (2010), as well as other producers of similar fibrillated microfiber products, is 1.5 lb/yd³ (0.89 kg/m³). The south parapet of Paine Creek exceeded the recommended dosage of fiber. This may have led to the high air contents. Typically, microfibers are coated in a surfactant in order to stop them from sticking together and collecting a charge in the machines during the drawing process. The surfactant coating can cause increased air entrainment, and therefore the increased dosage of fiber increased the amount of surfactant in the concrete.

One vibrator was used during placement. It could not be used close enough to the surface of the wall without hitting the reinforcement. With a low slump of 3.5 inches (89 mm), the concrete consolidated poorly along the surface of the first half of the wall, this became more apparent once the forms were pulled. A way to fix this is to rub the wall immediately after stripping the forms to make a continuous surface removing any holes or pits. This poor consolidation not only causes holes, like the ones on the Paine Road parapet, but it also causes a weak bond within the matrix of the concrete. It allows
large pieces to fall off the surface, as shown in Figures 48 and 49. The parapet had many flaws that looked like this, as well as numerous holes up to 0.25 inches (6 mm) in diameter and 0.25 to 0.75 inches (6 to 19 mm) deep across the entirety of the parapet. The parapet was not rubbed, except for a few severely flawed areas where paste was added after the concrete had already hardened.

Figure 48: WB Paine Creek south parapet poor consolidation at the surface (Photograph provided by Amy Kalabon)
On both halves of the parapet, the forms were stripped the next day, and UPV tests were performed on several areas of the parapet before it was covered with wet burlap to cure for seven days. The parapet was also inspected for early age cracking. Despite the many bug holes and flaws on the parapet, no cracks were found. Another field visit was made after the seven-day curing period to perform UPV tests on the parapet where no flaws were present, over any identified cracks, and over each control joint. Again, no cracks were identified. The UPV test velocities from both the parapet and the cylinder samples before and after curing are displayed in Table 14.

### Table 14: WB Paine Creek south parapet UPV velocities

<table>
<thead>
<tr>
<th>Time</th>
<th>Average UPV Velocities</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>South Parapet</td>
</tr>
<tr>
<td>Day 1</td>
<td>11617 fps</td>
<td>3541 mps</td>
</tr>
<tr>
<td>Day 7</td>
<td>12365 fps</td>
<td>3769 mps</td>
</tr>
</tbody>
</table>

**Figure 49: WB Paine Creek south parapet holes on the surface**
(Photograph provided by Amy Kalabon)
The velocities of the cylinder samples were used as verification of the values collected in the field. Due to the curing conditions in the lab, the cylinder samples were expected to produce somewhat higher velocities than the parapet. Since the velocities of the parapet were in the appropriate range, average velocities over each control joint were recorded. These velocities were placed into three categories:

1. Cracked Joint
2. Partially Cracked Joint
3. Not Cracked Joint

A joint was labeled as cracked if the average velocity over that joint fell between “no signal” or 0 fps and 5,000 fps (1,500 mps). An average velocity from 5,000 fps to 10,000 fps (1,500 to 3,000 mps) represented a partially cracked joint and joints that were not cracked included velocities greater than 10,000 fps (3,000 mps) that fell close to the average concrete velocity of 11,620 fps. Approximately 12% of the joints cracked, 41% were partially cracked, and 47% were not cracked. It is possible that the high dosage of polypropylene fiber in the concrete mixture and 1.5 inch (38 mm) deep saw cuts kept the control joints from cracking at early stages. It is expected that the partially cracked joints will fully crack in the future, but it is not known whether the joints that did not crack will crack and thus prevent cracking elsewhere on the parapet. Since Paine Creek is such a long bridge and was also exposed to the vibrations of traffic on the adjacent side throughout its construction, it is surprising that more of the joints did not crack.

Looking more closely, the majority of the joints that did not crack were located at the west end of the bridge, including the joints located over the west end pier or pier 1.
shown in Figure 50. About 40% of the joints located in between the piers, pier 1 and pier 2, did not crack. Between the east end of the bridge and pier 2, only 16% of the joints did not crack. With this significant difference between the sides of the bridge, the joints were analyzed again, but in two sections in regards to the two pours that took place. Fewer of the joints, about 26%, did not crack within the first 288 feet (88 m), from the east end of the bridge to the bulkhead, shown in Figure 50, where the first pour was finished. The second half of the parapet was poured on June 24, 2013. The second half was between the bulkhead and the west end of the bridge, and 72% of joints that did not crack within this section.

The control joint spacing on this bridge was 4 feet (1.2 m) over negative tension areas, and 8 feet (2.4 m) over the rest of the bridge. The 4 foot (1.2 m) spacing was extended out from each of the piers between 32 and 44 feet (9.8 and 13.4 m). The total
Parapet length is approximately 490 feet (150 m) long with 81 control joints. If conventional spacing was used, only 49 joints would have been cut. However, despite the number of control joints that were cut on this bridge, nearly 50% of them did not crack. It is not known whether this is due to the high amount of fiber used in the concrete mix, the shallow saw cut, the use of many closely spaced joints, or a combination of these factors. The design was effective at preventing early age cracking.

Five maturity sensors were installed on the Paine Creek parapet. The first three sensors were located within the first half of the parapet, providing temperatures during the first placement. The other two sensors were placed on the second half of the parapet. Unfortunately, the wires for the fifth sensor were buried during construction leaving only the fourth sensor to provide temperature readings for the second placement. Table 15 displays the peak temperatures and the initial drops in temperature the concrete reached at these four locations during the hydration process.

**Table 15: WB Paine Creek south parapet maturity sensor temperature data**

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Peak Temperature (°F/°C)</th>
<th>Initial Low Temperature after Peak (°F/°C)</th>
<th>Temperature Differential Peak (°F/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paine Creek (s) #1</td>
<td>115.7/46.5</td>
<td>86.0/30</td>
<td>29.7/16.5</td>
</tr>
<tr>
<td>Paine Creek (s) #2</td>
<td>107.6/42</td>
<td>86.0/30</td>
<td>21.6/12.0</td>
</tr>
<tr>
<td>Paine Creek (s) #3</td>
<td>109.4/43</td>
<td>88.7/31.5</td>
<td>20.7/11.5</td>
</tr>
<tr>
<td>Paine Creek (s) #4</td>
<td>132.8/56</td>
<td>91.4/33</td>
<td>41.4/23.0</td>
</tr>
</tbody>
</table>

The three sensors on the first half of the parapet were closely related, showing a slightly smaller change in temperature when compared to the second half. At sensor #4, during placement and curing of the second half of the parapet, the concrete reached a high peak temperature of 132.8°F (56°C). As a result, the concrete developed a large temperature differential, which could possibly cause cracking on this half of the bridge.
in the future. The high temperatures may also be the reason why the majority of the control joints did not crack on this section of the parapet. During and after curing of the parapet, about 21 days after placement, the temperature of the concrete remained high with an average of 80°F (26.7°C). Since the concrete did not fall to a lower temperature, the parapet did not experience an increase of stress due to contraction and therefore, the joints did not need to crack.

5.8 South Marginal Road Bridge

The South Marginal Road overpass bridge is located in downtown Cleveland, crossing over Interstate 90. On the South Marginal Bridge, the north parapet was a control following the typical ODOT design standards, and the south parapet included GFRP bars for vertical reinforcement to allow for a 3.5 inch (88.9 mm) deep saw cut joint. Unlike the Lake County bridges, both parapets have vandal protection fences (VPFs) on top of the parapets, as shown in Figure 51. The South Marginal Road overpass is the main access to the tailgating parking lot for the Cleveland Browns’ football fans. A lot of pressure was placed on the construction schedule by the city to complete this bridge before the start of the football season.
5.8.1 North Parapet

Three maturity sensors were placed deep in the center of the parapet on the steel reinforcement, as shown in Figure 52. The type of reinforcement used was epoxy coated steel rebar with No. 5 (16 mm) longitudinal and vertical bars, a No. 6 (19 mm) longitudinal bar at the top of the parapet, and No. 6 (19 mm) bars tying the parapet to the deck.
Concrete was placed on August 13, 2013 at 68°F (20°C) and 82% humidity under cloudy conditions. The first ready mix truck was tested with 5.1% air and a 4 inch (100 mm) slump. Three cylinder samples were taken from this truck. Before placing the concrete, superplasticizer was added to the mixture onsite. During placement, the workers started having trouble with the forms lifting up off the ground due to the pressure from the concrete. They were able to fix the forms before the second truck arrived. The second truck was tested for air content before placement, and it was rejected due to a low air content of 4.4%. As the concrete was poured into the forms, one vibrator was used to aid in proper consolidation of the concrete.

Due to the fast pace on the project, the front forms of the parapet were removed right after the concrete was placed. With the concrete still in its green state, the front of the wall could be rubbed out nicely giving the wall a proper finish. Unfortunately, the concrete was too green to perform any UPV tests on the wall. The back forms were left on until the following day when the saw cutting was performed. With the work under such a fast pace, it was not possible to gather UPV velocities before the wall was set to cure. Unlike the front of the parapet, the back was not rubbed when the formwork was removed the following day because the concrete already hardened by this point and the project was being rushed. Due to this, small pits and holes were found, similar to the ones found on the Lake County bridges that were not rubbed.

The north parapet wall was cured for only 2 days when the burlap was removed in order to put the cure on the south parapet. The wall was inspected for cracks and UPV
velocities were taken. A large crack was found beneath one of the vandal protection fence (VPF) post base plates. The crack, which was most likely caused during installation, is shown in Figure 53. Another crack was also found on the back side of the north parapet, near the third fence post base plate looking from the east. Since the crack was on the back of the parapet, a photo and UPV could not be taken of the crack.

![Figure 53: South Marginal north parapet crack at VPF post base plate (Photograph provided by Amy Kalabon)](image)

The UPV test velocities from both the parapet and the cylinder samples after cure were 6,700 fps (2,040 mps) and 13,292 fps (4,050 mps), respectively. Since the parapet only cured for 2 days, a large difference between the wall and the cylinders was expected. With such a low concrete velocity, the ranges used to determine which category a control joint fell in were adjusted. A joint was labeled as cracked if the average velocity over that joint fell between “no signal”, or 0 fps, and 3,000 fps (900 mps). An average velocity from 3,000 to 5,000 fps (900 to 1,500 mps) represented a
partially cracked joint, and joints that were not cracked had velocities greater than 5,000 fps that fell close to the average concrete velocity of 6,700 fps (2,040 mps). The control joints were cut 1.5 to 2 inches (38 to 51 mm) deep and were spaced approximately 10 feet (3 m) along the parapet. Using the adjusted ranges, about 36% of the joints fully cracked, 45% were partially cracked, and 18% did not crack. Of the four joints that did not crack, one of them showed surface crack found where the joint terminated about 2 inches (51 mm) above the bottom of the parapet. This is shown in Figure 50. Also, all of the control joints that were labeled as cracked or partially cracked showed cracking at the bottom of the parapet as in Figure 54.

![Figure 54: South Marginal north parapet cracks where control joint terminates (Photograph provided by Amy Kalabon)](image)
Of the three maturity sensors embedded in the bridge, the wires for one of them were buried during construction, so only two of the sensors provided temperatures of the concrete during placement and curing. Table 16 shows the peak temperatures and the initial drops in temperature the concrete experienced during the hydration process.

Table 16: South Marginal north parapet maturity sensor temperature data

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Peak Temperature (°F/°C)</th>
<th>Initial Low Temperature after Peak (°F/°C)</th>
<th>Temperature Differential (°F/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.M. #1</td>
<td>104/40.0</td>
<td>85.1/29.5</td>
<td>18.9/10.5</td>
</tr>
<tr>
<td>S.M. #3</td>
<td>104/40.0</td>
<td>87.8/31.0</td>
<td>16.2/9.0</td>
</tr>
</tbody>
</table>

The sensors were consistent with each other, showing similar temperature readings.

During the weeks after the curing was taken off of the concrete, the parapet remained at a high temperature around 77°F (25°C). This could be because the parapet was not cured for the full 7 day span. It was also exposed to the environment a few times during its shortened curing time, without being watered down to lower temperatures. After the concrete was placed, without watering it down, the front forms were removed and the burlap was placed on the wall. The next day the burlap was removed entirely to take off the back forms and saw cut the control joints. Then the burlap was put back on the wall for one more day of curing.

A field visit took place on February 21, 2014 to check the parapet for cracking. Approximately 12 large cracks were found for the first time along the north parapet located midway between the joints and sometimes extending from the VPF post base plates. Examples of these types of cracks are shown in Figures 55 through 58.
Figure 55: South Marginal north parapet mid-panel cracking (Photograph provided by Amy Kalabon)

Figure 56: South Marginal north parapet mid-panel cracking (Photograph provided by Amy Kalabon)
Figure 57: South Marginal north parapet mid-panel cracking (Photograph provided by Amy Kalabon)

Figure 58: South Marginal north parapet mid-panel cracking (Photograph provided by Amy Kalabon)
There were many additional fine cracks elsewhere along the parapet, as shown in Figure 59, but most were too small to photograph.

![Figure 59: South Marginal north parapet small cracking](Photograph provided by Amy Kalabon)

5.8.2 South Parapet

Three maturity sensors were attached to the reinforcement of the south parapet. The reinforcement followed typical design plans using No. 5 (16 mm) GFRP bar as the longitudinal reinforcement, No. 5 (16mm) epoxy coated steel bars as the vertical reinforcement, a No. 6 (19 mm) GFRP bar at the top of the parapet, and No. 6 (19 mm) steel bars tying the parapet into the deck.

Concrete for the south parapet was placed on August 15, 2013 at 59°F (15°C) and 70% humidity under partly cloudy conditions. The second ready mix truck was tested with 6.7% air at 75°F (23.9°C). Three concrete cylinder samples were taken from this truck. Prior to placement, superplasticizer was added to the mixture to aid in
consolidation of the concrete. As soon as concrete placement was complete, the front forms were removed, the wall was rubbed, and then the wall was covered with burlap. The next day, the burlap was removed in order to take off the back forms and saw cut the control joints. The control joints were spaced between 4.8 and 5.17 feet (1.5 and 1.6 m) in negative moment areas and 8.25 to 10 feet (2.5 to 3.1 m) in positive moment areas. During saw cutting, the saw hit a piece of the vertical reinforcement in one of the control joints. This control joint was sealed extra carefully to avoid corrosion and accelerated cracking within the joint. The control joints were cut between 2.5 to 3.5 inches (64 to 89 mm) deep cutting through the GRFP bar. The wall was covered back up with the burlap to cure for 2 days.

After cure, the wall was inspected for cracks and UPV was performed. No cracks were identified. Due to the shortened curing of the parapet, it was expected that the UPV velocities of the cylinder samples would be higher than the velocities of the parapet. The average velocity of the cylinder was found to be 12,822 fps (3,900 mps) and the average velocity of the parapet was 7,101 fps (2,160 mps). With such a low concrete velocity, the ranges used to determine which category a control joint fell in were adjusted. A joint was labeled as cracked if the average velocity over that joint fell between “no signal”, or 0 fps, and 3,000 fps (900 mps). An average velocity from 3,000 fps to 5,000 fps (900 to 1,500 mps) represented a partially cracked joint and joints that were not cracked included velocities greater than 5,000 fps (1,500 mps) that fell close to the average concrete velocity of 7,101 fps (2,160 mps). A majority of the control joints had a crack that continued from where the saw cut terminated down to the bottom of
the parapet. About 11% of the joints cracked, 38% were partially cracked, and 51% of the joints did not crack. On this parapet, the saw cuts terminated between 5 and 6 inches (127 and 152 mm) above the bridge deck surpassing the typical 2 inches (51 mm). The shortened saw cuts in combination with poor curing may have made it harder for the control joints to fully crack.

Three maturity sensors embedded in the concrete provided temperatures of the concrete during placement and curing. Table 17 shows the peak temperatures and the initial drops in temperature the concrete reached during the hydration process.

<table>
<thead>
<tr>
<th>Sensor</th>
<th>Peak Temperature (*F/°C)</th>
<th>Initial Low Temperature after Peak (*F/°C)</th>
<th>Temperature Differential (*F/°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S.M. #4</td>
<td>107.6/42.0</td>
<td>87.8/31.0</td>
<td>19.8/11.0</td>
</tr>
<tr>
<td>S.M. #5</td>
<td>107.6/42.0</td>
<td>86.9/30.5</td>
<td>20.7/11.5</td>
</tr>
<tr>
<td>S.M. #6</td>
<td>109.4/43.0</td>
<td>86.9/30.5</td>
<td>22.5/12.5</td>
</tr>
</tbody>
</table>

On February 21, 2014, a field visit was made to inspect the parapet for cracks. Due to the quality of curing on this bridge, it is not a surprise that cracks were discovered even with the modifications that were implemented on the design of this parapet. However, the south parapet exhibited far less cracking than the north parapet. Two prominent cracks were found, among a few others that were too small to capture. One of the cracks, shown in Figure 60, was a full depth crack located midway between the control joints. The other crack, in Figure 61, extended downward from one of the VPF post base plates.
Figure 60: South Marginal south parapet mid-panel crack
(Photograph provided by Amy Kalabon)

Figure 61: South Marginal south parapet VPF post base
plate crack (Photograph provided by Amy Kalabon)
5.9  **Westbound Big Creek Bridge**

The parapets on the westbound Big Creek Bridge were to be constructed during the 2014 construction season.

5.10  **Westbound Auburn Road Bridge**

The parapets on the westbound Auburn Road Bridge were to be constructed during the 2014 construction season.

5.11  **Westbound Hermitage Road**

The parapets on the westbound Hermitage Road Bridge were to be constructed during the 2014 construction season.
CHAPTER VI

SUMMARY AND DISCUSSION OF OBSERVATIONS

There were many field observations made over the course of this project. This section summarizes the general observations made, as well as the trends that emerged between all of the parapets that were inspected.

6.1 General Observations

The Lake County bridges were all cured for the proper 7 day length. The South Marginal Bridge parapets were only cured for 2 days. As stated by PCA (Portland Cement Association 2014),

“Curing is the process in which the concrete is protected from loss of moisture and kept within a reasonable temperature range. This process results in concrete with increased strength and decreased permeability. Curing is also a key player in mitigating cracks, which can severely affect durability”.

The process of curing results in decreased permeability, and because the South Marginal Bridge did not have proper curing procedures there may be voids and internal microcracking within the concrete. The concrete cylinder samples provided an average
compressive strength of 6,400 psi (44 MPa), but because the cylinders had optimal curing conditions, the parapets may not have reached this strength while exposed to the conditions in the field. This assumption was supported by the results from the UPV meter. The UPV velocities found on both parapets of the South Marginal Bridge were extremely low, when compared to the velocities of the concrete cylinder samples as well as the velocities gathered from the Lake County bridge parapets. The average UPV of the concrete was around 6,900 fps (2,100 mps). The Lake County bridges had an average velocity between 9,000 to 13,000 fps (2,740 to 3,960 mps). The low velocity is generally related to low strength, which may be why the parapet cracked so easily during the installation of the vandal protection fence post base plate. Several cracks were found on the north parapet midway between control joints and extending from the VPF post base plates. Fewer cracks were found on the south parapet, but these were similar. It is important to note that this bridge is not a highway bridge like the Lake County bridges. It will not be subjected to the type of interstate highway traffic the Lake County bridges experience every day, therefore it will not undergo large amounts of vibrations and deflections. Even without significant traffic, the South Marginal Bridge parapets showed the most cracking out of all the inspected parapets.

The durability of the parapets may be increased when the parapet surface is rubbed. As shown by the parapets whose forms were removed 1 day after placement, there were many holes and voids along the surface of the parapet. Holes are also more likely to form along the surface if the concrete had a low slump, such as the 3.5 inch (89 mm) slump of the concrete for both the south parapets of WB Paine Road Bridge and WB
Paine Creek Bridge. If these holes cannot be rubbed out, they may be a reason for early deterioration of the concrete as deicing salt and other chemicals get into them and begin breaking down the concrete. Also, as the concrete experiences temperature changes, these areas on the surface will be the first to crack since the surface of the concrete has already been weakened. Removing the forms when the concrete is still green seems to be the more economical choice. It is easier to rub the wall, faster to cut the control joints, and the entire wall can be left to cure. In addition, cutting the control joints while the concrete is still green allows the construction workers to get ahead of the formation of any cracks as the concrete hydrates.

The location of the vertical reinforcement with respect to the control joints is important during saw cutting procedures. This may be impractical as well as too time consuming for construction workers to keep track of; however, this was demonstrated on the south parapet of the South Marginal Bridge when the saw hit part of the vertical reinforcement. Other than possibly exposing the reinforcement, the relation of the control joint to the vertical rebar can possibly cause cracking to occur. This may have been the case on the north parapet of the Paine Creek Bridge. It seemed that there was a plane of weakness created where the vertical reinforcement was located, making it easier for the concrete to crack along the reinforcement instead of at the control joint. If the location of the vertical rebar cannot be followed, the proper amount of cover must be provided.

Not enough water was used during the removal of the formwork and saw cutting procedures. A few of the parapets actually dried out and turned white before the
burlap was placed on the wall. It is important to keep the concrete cool and moist to allow proper curing, especially when the curing cannot be put on right away. Curing is the key to mitigate cracking.

In regards to cracking, all of the control parapets that could be inspected displayed uncontrolled cracking. The majority of the cracks found were discovered after being exposed to the harsh winter conditions of 2013-2014, with the exception of the north parapet on the WB Paine Creek Bridge. Two control parapets, the south parapets of the EB Paine Creek Bridge and the EB Paine Road Bridge, could not be safely inspected. Typically, the control parapets displayed mid-panel cracking, with a few cracks near a control joint or initiating from the control joint. Of the crack surveys that were performed, only two of the experimental parapets showed cracking, the north parapet of the WB Paine Creek Bridge and the south parapet of the South Marginal Bridge. The north parapet of the WB Paine Creek Bridge had a crack that initiated out of a control joint. This was a very early aged crack, and no other cracks were found along the length of the parapet after enduring the winter. The south parapet of the South Marginal Bridge had 2 large cracks, among some fine cracks. One crack initiated out from the VPF post base plate near the side where the bolts were installed to keep it in place. The other crack was a mid-panel crack. This cracking may not be due to the design, but due to the fact that the concrete did not receive proper curing. Since the bridge does not see heavy traffic, a combination of the poor cure and stresses put on the parapet from the VPF most likely caused the cracking to occur.
6.2 General Trends

The design of the reinforcement remained the same for all of the parapets. No. 6 (19 mm) epoxy coated steel reinforcement was used to tie the parapet into the deck, as well as provide reinforcement at the top of the parapet as a single horizontal bar. A single No. 6 (19 mm) GFRP bar was also used at the top of the parapet when GFRP replaced steel in the design. Whether the design of the parapet included No. 5 (16 mm) epoxy coated steel or GFRP bar for the horizontal reinforcement, the sizes remained equivalent to provide the proper amount of reinforcement. No. 5 (16 mm) epoxy coated steel rebar was also used as the vertical reinforcement in the parapets.

The concrete mixture used on all the parapets was the same, with the exception of adding polypropylene fibers for some parapets. When fibers were added to the concrete mixture, it proved difficult to keep the air content within allowable limits when compared to the mixes with no fiber. The slump of the concrete fell anywhere between 3.5 to 6 inches (88.9 to 152 mm) for all of the parapets, and the compressive strengths of the cylinder samples ranged from 4,860 psi to 6,700 psi (33.5 to 46.2 MPa). For safety reasons, the compressive strengths were important in making sure the parapets reached a proper strength. The cylinder samples were also very useful in providing a basis to verify the UPV velocities taken in the field.

The average UPV was a good indicator of the uniformity and quality of the concrete as in the instance of the South Marginal Road Bridge parapets. The low velocities gathered were not surprising, due to the shortened curing procedures used in order to complete construction on time. The UPV was also a great way to assess behavior of the
control joints. It was easy to tell the difference between a cracked joint and a joint with no signs of cracking at all. However, the velocity fell between the two extremes several times, making it difficult to define the joint as one or the other, so a third category of partially cracked joints was added.

The maturity sensors embedded in each parapet were consistent with each other, displaying even temperature distributions along the length of the parapets. The sensors showed the highest temperature the concrete reached during placement. The concrete of the two bridges that did not exhibit any cracking, the south parapets of the EB Hermitage Road Bridge and the WB Paine Road Bridge, never reached a temperature higher than 96°F (36°C). All of the other parapets easily exceeded 105°F (41°C) during the curing stages. The data from the sensors were also used to see if the concrete had any unusual behavior or experienced any large temperature differentials. The consistent temperatures among all the parapets helped to rule out temperature changes as a direct cause of any uncontrolled cracking. Months after placement, the sensors remained in good condition to gather additional data and document how the concrete responded to the winter. It was easy to see the parapets had endured the effects of freeze-thaw cycles. With the concrete undergoing volume changes due to the fluctuating temperatures, the parapets that did not show any uncontrolled cracking proved to have an effective design.
CHAPTER VII

ANALYSIS

The field observations and data gathered over the course of this project show a significant difference between the control and experimental parapets. This difference implies that one or some of the modifications included in the experimental parapet designs accomplished the goal to reduce parapet cracking. Since all of the modifications add cost, it is important to analyze what performed well and what proved to be ineffective.

7.1 Cost

The costs referred to represent the costs for this project only. Since the prices are a result of change orders, the amounts may be higher than normal; however these values were used as a reference in order to compare the implemented modifications. The costs per linear foot (0.3 m) for the modifications added to the bridges are shown in Table 18.
Table 18: Modification cost per linear foot (0.3 m)

<table>
<thead>
<tr>
<th>Modification</th>
<th>Bridges Included</th>
<th>Parapet</th>
<th>Cost of Change Order</th>
<th>Parapet Length (ft)</th>
<th>Cost per Linear Foot</th>
</tr>
</thead>
<tbody>
<tr>
<td>GFRP</td>
<td>EB Hermitage Road North</td>
<td>$2,250.36</td>
<td>160.41</td>
<td>$14.03/ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EB Auburn Road North</td>
<td>$1,726.53</td>
<td>147.74</td>
<td>$11.69/ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WB Big Creek North</td>
<td>$4,020.77</td>
<td>344.50</td>
<td>$11.67/ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>South Marginal South</td>
<td>$1,922.25</td>
<td>226.60</td>
<td>$8.48/ft</td>
<td></td>
</tr>
<tr>
<td>GFRP + 1 lb/yd³ Fiber</td>
<td>EB Auburn Road South</td>
<td>$2,443.46</td>
<td>154.52</td>
<td>$15.81/ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WB Big Creek South</td>
<td>$4,487.67</td>
<td>344.50</td>
<td>$13.03/ft</td>
<td></td>
</tr>
<tr>
<td>Field Cut Steel</td>
<td>WB Paine Road North</td>
<td>$1,329.09</td>
<td>113.13</td>
<td>$11.75/ft</td>
<td></td>
</tr>
<tr>
<td>Field Cut Steel + 1 lb/yd³ Fiber</td>
<td>WB Auburn Road South</td>
<td>$2,044.85</td>
<td>158.23</td>
<td>$12.92/ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WB Hermitage Road South</td>
<td>$1,763.45</td>
<td>136.78</td>
<td>$12.89/ft</td>
<td></td>
</tr>
<tr>
<td>1 lb/yd³ Fiber</td>
<td>EB Hermitage Road South</td>
<td>$217.35</td>
<td>160.72</td>
<td>$1.35/ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WB Paine Road South</td>
<td>$152.95</td>
<td>113.08</td>
<td>$1.35/ft</td>
<td></td>
</tr>
<tr>
<td></td>
<td>WB Paine Creek North</td>
<td>$652.05</td>
<td>488.27</td>
<td>$1.34/ft</td>
<td></td>
</tr>
<tr>
<td>2 lb/yd³ Fiber</td>
<td>WB Paine Creek South</td>
<td>$1,210.95</td>
<td>488.27</td>
<td>$2.48/ft</td>
<td></td>
</tr>
</tbody>
</table>

The prices include the cost of the material, shipping, labor, and the contractor’s markup for the change order. Looking at the table, the cost to add polypropylene fiber is insignificant compared to the addition of GFRP or field cut steel reinforcement. Since fiber does not have additional costs for labor or shipping, its price lies solely in the material itself. The price for the GFRP reinforcement changes for each parapet, but averages out to be around the same cost for field cut steel.

7.2 Type of Reinforcement

The type of reinforcement was used in correlation with the depth of the control joints. If the typical epoxy coated steel reinforcement was used, the control joints were cut 1.5 inches (38 mm) deep, and the use of GFRP or field cut steel reinforcement allowed a 3.5 inch (89 mm) deep cut.

When comparing the parapets with the reinforcement modification, there does not seem to be a significant difference between the use of field cut steel reinforcement and
the GFRP reinforcement. Only one of the parapets had field cut steel reinforcement, therefore it is hard to properly analyze its effect. However, from the number of joints that cracked at early stages between the GFRP and field cut steel reinforcement, the field cut steel produced approximately 10%, or about 1 to 2 more cracked joints. Both modifications seem to cost about the same, averaging between $11.00 and $13.00 per linear foot (0.3 m). For this project, GFRP bar cost $3.74 per pound (0.45 kg), which includes the markups for the change order as well as shipping, and there is also a cost for labor, which is $57.70 per hour. For the field cut steel, the steel cost $0.62 per pound (0.45 kg), and labor cost $57.70 per hour plus the additional cost for an ironworker to cut through the steel at $78.26 per hour. If used more often, the cost of the GFRP bar may go down, and since it is less labor intensive, it might be a more economical choice over the field cut steel reinforcement.

The use of the 3.5 inch (89 mm) deep saw cuts with either the field cut steel or GFRP reinforcement increases the likelihood of joint cracking. The percentage of control joints that cracked during these early stages of the parapets are displayed in Table 19.

<table>
<thead>
<tr>
<th>Depth of Cut</th>
<th>Parapets Included</th>
<th>Average % of All Cracked Joints</th>
<th>Average % of Not Cracked Joints</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5 inches (38 mm)</td>
<td>- South Marginal North Steel</td>
<td>62.6</td>
<td>37.4</td>
</tr>
<tr>
<td></td>
<td>EB Hermitage South Steel</td>
<td>62.6</td>
<td>37.4</td>
</tr>
<tr>
<td></td>
<td>WB Paine Creek North Steel</td>
<td>62.6</td>
<td>37.4</td>
</tr>
<tr>
<td></td>
<td>WB Paine Creek South Steel</td>
<td>62.6</td>
<td>37.4</td>
</tr>
<tr>
<td></td>
<td>WB Paine Road South Steel</td>
<td>62.6</td>
<td>37.4</td>
</tr>
<tr>
<td>3.5 inches (89 mm)</td>
<td>WB Paine Road North Field Cut Steel</td>
<td>77.8</td>
<td>22.3</td>
</tr>
<tr>
<td></td>
<td>EB Auburn North GFRP</td>
<td>77.8</td>
<td>22.3</td>
</tr>
<tr>
<td></td>
<td>EB Hermitage North GFRP</td>
<td>77.8</td>
<td>22.3</td>
</tr>
<tr>
<td></td>
<td>- South Marginal South GFRP</td>
<td>77.8</td>
<td>22.3</td>
</tr>
</tbody>
</table>
As shown, about 15% more of the control joints that used the 3.5 inch (89 mm) deep saw cuts cracked within the first few weeks of placement. However, there is not a significant variation between the two saw cut depths to conclude that the 3.5 inch (89 mm) deep cut along with the field cut steel or GFRP reinforcement is a cost-effective choice. The parapets including the 3.5 inch (89 mm) deep saw cuts may not have displayed any uncontrolled cracking, but the experimental parapets with a 1.5 inch (38 mm) deep saw cut and closer joint spacing also did not display any cracking. Since the parapets including the 3.5 inch deep (89 mm) saw cuts also had the reduced joint spacing, it is not clear what specific impact the deeper saw cut has on a parapet to control cracking.

### 7.3 Polypropylene Fiber

The purpose for adding polypropylene fiber in the concrete mixture was to prevent temperature and shrinkage cracking. On the north parapet of the WB Paine Creek Bridge, a crack was found despite the use of 1 lb/yd$^3$ (0.59 kg/m$^3$) of fiber in the concrete. It was hypothesized that the concrete cracked due to a combination of the control joint not being fully activated, with only a 1.5 inch (38.1 mm) deep saw cut. Also, there was not enough cover over the vertical reinforcement that was located close to the joint. It is likely that the crack did not have to do with temperature or shrinkage cracking, therefore, the fiber met its purpose. However, the parapets with no fiber in the concrete mixture also did not show any signs of temperature or shrinkage cracking. From the data in Table 20, it seems that the use of fibers kept the control joints from
cracking. As a result, the use of polypropylene fiber may not be worth the added cost of $8.05 per cubic yard when adding 1 lb/yd\(^3\) (0.59 kg/m\(^3\)) of fiber or $14.95 per cubic yard when adding 2 lb/yd\(^3\) (1.19 kg/m\(^3\)) of fiber. For example, the south parapet of the WB Paine Creek Bridge was estimated as a total of 81 cubic yards (62 cubic meters) of concrete and with the addition of 2 lb/yd\(^3\) (1.19 kg/m\(^3\)) of polypropylene fiber, the cost of the fiber alone was approximately $1,210.95. Fiber may not be the most economical choice with the concrete mixture used in regards to early age cracking, but the use of fibers may prove to be a contributing factor to extend the service life and safety of bridge parapets.

### Table 20: Percentage of cracked joints with respect to fiber use

<table>
<thead>
<tr>
<th>Amount of Polypropylene Fiber</th>
<th>Parapets Included</th>
<th>Average % of All Cracked Joints</th>
<th>Average % of Not Cracked Joints</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Fiber</td>
<td>- South Marginal</td>
<td>81.2</td>
<td>18.8</td>
</tr>
<tr>
<td></td>
<td>EB Paine Road</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WB Paine Road</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EB Auburn Road</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EB Hermitage Road</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>- South Marginal</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 lb/yd(^3) (0.59 kg/m(^3))</td>
<td>EB Hermitage Road</td>
<td>71.3</td>
<td>29.0</td>
</tr>
<tr>
<td></td>
<td>WB Paine Creek</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>WB Paine Road</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 lb/yd(^3) (1.19 kg/m(^3))</td>
<td>WB Paine Creek</td>
<td>53.0</td>
<td>47.0</td>
</tr>
</tbody>
</table>

#### 7.4 Joint Spacing

Changing the joint spacing had a major effect on the performance of a parapet. Due to composite structural action, it is expected that a continuous parapet would experience significant tensile bending stresses in the negative moment regions of the bridge spans. This is supported by the results gathered from the control and experimental parapets. The control parapets had joints spaced evenly along the bridge
and did not increase the number of joints over the negative moment areas. With this spacing, all the control parapets showed uncontrolled mid-panel cracking. Little or no cracking was found on the experimental parapets, because there were more joints spaced closely together in the negative moment areas over the piers. The additional control joints in this region give the parapet the ability to flex or bend without cracking.

Most of the experimental parapets could not be examined for a second time after the winter due to safety concerns. However, the last time these parapets were inspected, no cracks had been found. The north parapet of the WB Paine Creek Bridge and the south parapet of the South Marginal Bridge were the two experimental parapets that showed uncontrolled cracking, but seemed to have cracked for reasons other than the joint spacing, as stated in the general observations. A summary of which parapets observed uncontrolled cracking is shown in Table 21.

Only two of the experimental parapets that could be examined after the winter were free of cracking. The south parapet of the EB Hermitage Road Bridge and the north parapet of the WB Paine Road Bridge did not have many factors in common. The south parapet of the EB Hermitage Road Bridge had 1.5 inch (38 mm) deep saw cuts, epoxy coated steel reinforcement, and 1 lb/yd³ (0.59 kg/m³) of polypropylene fiber in the mixture. The north parapet of the WB Paine Road Bridge had 3.5 inch (89 mm) deep saw cuts, field cut steel reinforcement, and no fiber in the mixture. The two similarities between these parapets were the shorter spacing of the control joints, and performing the saw cuts for the control joints while the concrete was still in a green state. The Hermitage parapet had control joints that were spaced 5.25 to 6.42 feet (1.6 to 1.9 m) in
negative moment areas and 11.83 to 12.33 feet (3.6 to 3.8 m) in positive moment areas.

The Paine Road parapet had control joints that were spaced 4.5 to 5.7 feet (1.4 to 1.7 m) in the negative moment areas and 11.25 to 13.7 feet (3.4 to 4.2 m) in positive moment areas. As shown by the close correlation of the spacing between these bridges, joint spacing is an important factor in crack control.

**Table 21: Summary of Crack Inspections**

<table>
<thead>
<tr>
<th>Bridge</th>
<th>Name</th>
<th>Parapet</th>
<th>Type</th>
<th>Last Visit</th>
<th>Type of Cracking</th>
</tr>
</thead>
<tbody>
<tr>
<td>EB</td>
<td>Big Creek</td>
<td>North</td>
<td>Control</td>
<td>February 21, 2014</td>
<td>Mid-panel</td>
</tr>
<tr>
<td>EB</td>
<td>Big Creek</td>
<td>South</td>
<td>Control</td>
<td>February 21, 2014</td>
<td>Mid-panel</td>
</tr>
<tr>
<td>EB</td>
<td>Paine Creek</td>
<td>North</td>
<td>Control</td>
<td>February 21, 2014</td>
<td>Mid-panel</td>
</tr>
<tr>
<td>EB</td>
<td>Paine Road</td>
<td>North</td>
<td>Control</td>
<td>February 21, 2014</td>
<td>Mid-panel/Joint</td>
</tr>
<tr>
<td>-</td>
<td>South Marginal</td>
<td>North</td>
<td>Control</td>
<td>February 21, 2014</td>
<td>Mid-panel/VPF Post</td>
</tr>
<tr>
<td>-</td>
<td>South Marginal</td>
<td>South</td>
<td>Experimental</td>
<td>February 21, 2014</td>
<td>Mid-panel/VPF Post</td>
</tr>
<tr>
<td>WB</td>
<td>Paine Creek</td>
<td>North</td>
<td>Experimental</td>
<td>February 21, 2014</td>
<td>Leaves Joint</td>
</tr>
<tr>
<td>EB</td>
<td>Hermitage Road</td>
<td>North</td>
<td>Experimental</td>
<td>October 15, 2013</td>
<td>None</td>
</tr>
<tr>
<td>EB</td>
<td>Hermitage Road</td>
<td>South</td>
<td>Experimental</td>
<td>February 21, 2014</td>
<td>None</td>
</tr>
<tr>
<td>EB</td>
<td>Auburn Road</td>
<td>North</td>
<td>Experimental</td>
<td>October 15, 2013</td>
<td>None</td>
</tr>
<tr>
<td>WB</td>
<td>Paine Road</td>
<td>North</td>
<td>Experimental</td>
<td>February 21, 2014</td>
<td>None</td>
</tr>
<tr>
<td>WB</td>
<td>Paine Road</td>
<td>South</td>
<td>Experimental</td>
<td>October 15, 2013</td>
<td>None</td>
</tr>
<tr>
<td>WB</td>
<td>Paine Creek</td>
<td>South</td>
<td>Experimental</td>
<td>October 15, 2013</td>
<td>None</td>
</tr>
</tbody>
</table>
CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

8.1 Results of Implemented Modifications

The modifications to the experimental bridge parapets were implemented to reduce uncontrolled cracking. Analysis of the available information suggests which modifications were effective, ineffective, or inconclusive.

8.1.1 Type of Reinforcement

The main purpose of using GFRP or field cut steel reinforcement with the 3.5 inch (89 mm) deep saw cut is to create a weakened plane at the control joint through the gap provided in the reinforcement, in order initiate cracking at the joints and reduce cracking elsewhere on the parapet. From the data gathered, this modification allowed more joints to crack at early stages, and prevented uncontrolled cracking. The 3.5 inch (89 mm) deep saw cut allowed 15% more joints to crack within the first few weeks of placement than the 1.5 inch (38 mm) deep cut. This modification is useful to control
early age cracking, but this alone is not enough information to determine whether a 3.5 inch (89 mm) deep saw cut is an economical and cost-effective choice when parapets with closer joint spacing produced similar results.

8.1.2 Polypropylene Fiber

The parapets with fiber showed no measurable improvement over the parapets without fiber in regards to preventing shrinkage and temperature cracking. From the temperatures provided by the maturity sensors, the concrete in the parapets did not experience significant enough temperature variations at early stages to cause thermal cracking. The absence of temperature and shrinkage cracking on the parapets without fibers may be due to the concrete mixtures used on all the parapets. For the parapets using this concrete mix, the fibers proved to be ineffective. With the use of a different concrete mixture, the addition of fibers may be more beneficial.

The use of polypropylene fibers may be efficient in extending the service life and safety of parapets as well as reduce life cycle costs. Fibers will enhance fatigue strength, and cracks caused by impact or freeze-thaw cycles will be better controlled.

8.1.3 Joint Spacing

Reducing the joint spacing over negative tension areas is essential to reduce uncontrolled bridge parapet cracking. This seems to be an important modification to include in the design of continuous bridge parapets. As shown by the results of the control parapets, parapets without enough control joints over the negative tension areas of the bridge tend to demonstrate uncontrolled cracking. However, since the experimental parapets with the reduced joint spacing were coupled with another
modification of either the polypropylene fibers or the deeper saw cut, it is hard to determine if this alone will solve uncontrolled bridge parapet cracking. In order to resolve this issue, recommendations have been made to modify the control parapets that were to be constructed during the 2014 construction season.

8.2 Recommendations

Based off of the data gathered, recommendations for the design as well as construction of concrete bridge parapets have been developed. This study will be continued through the next construction season, therefore recommendations for future research on this project are also provided.

8.2.1 Design Recommendations

The most optimal design of a bridge parapet, researched thus far, should include reducing the spacing of the control joints over negative tension regions of the bridge. The control parapets without this modification displayed uncontrolled cracking between control joints, while the experimental parapets did not. The concrete mixture design used throughout this study also proved to be robust by preventing temperature and shrinkage cracking without the use of polypropylene fibers.

It is uncertain if the use of GFRP or field cut steel reinforcement with a deeper saw cut is essential for providing crack control. There is no doubt that the modification will aid the parapet to crack at the control joints and reduce cracking elsewhere; however, it is inconclusive whether this modification is the most cost-effective.

The parapets including the addition of polypropylene fiber in the mixture did not perform any differently than the parapets without fibers in terms of early age cracking.
The addition of fibers proved unnecessary with the concrete mixture used. However, the use of fibers may prove to be beneficial in the future by extending the service life of the parapet through its enhanced fatigue strength, and reducing life cycle costs by improving control of cracks caused by impact or freeze-thaw cycles. If polypropylene fiber is used in the concrete mixture, the recommended dosage of 1.5 lb/yd$^3$ (0.89 kg/m$^3$) should be used to avoid any issues with the air content.

Cracking near the bolts on VPF post base plates occurred on both the north and south parapets of the South Marginal Bridge. This may be due to the shortened curing time the concrete experienced, but design details for the base plate anchorages, as well as when the base plates were anchored into the concrete may have caused the cracking. It is possible that drilling the bolt holes may have caused enough stress in the concrete to cause it to crack in these specific locations. Redesign of the post anchorage details or installations method may still be necessary to prevent cracking on parapets with vandal protection fences.

### 8.2.2 Construction Recommendations

It is important to pay attention to the slump of the concrete during placement. A low slump can cause poor consolidation, especially near the surface of the parapet. A superplasticizer should be added, if necessary, and vibrators should be used thoroughly to aid in consolidation of the concrete.

During removal of the formwork and saw cutting, the parapet should be watered to keep the concrete cool and prevent the occurrence of any shrinkage or temperature cracking. Also, saturated burlap must be placed on the parapet immediately to keep as...
much moisture as possible from evaporating. Getting the cure on quickly is an
important step.

Performing saw cuts for the control joints while the concrete is still in a green state
seems more effective than waiting one day after placement. This allows the
construction workers to intercept the formation of any cracks by providing a location for
the concrete to crack as it cures and hardens. It is also easier to rub the wall, faster to
cut the control joints, and the entire wall can be left to cure.

Once the formwork is removed and saw cuts are made, if the wall can be kept
saturated, rubbing should occur before allowing the concrete to cure. This way paste
does not need to be added to already hardened concrete, and it reduces the chance
that cracking will not initiate from any pits, holes, or flaws in existence on the parapet
surface. Rubbing the wall immediately will also make the parapet more aesthetically
pleasing.

Curing is the key to mitigating cracking. Therefore, allowing the parapet to cure in
saturated conditions for 7 days is vital to the outcome of the parapet, which was proven
by the South Marginal Road Bridge parapets.

8.2.3 Recommendations for Future Research

This study will continue over the next year to complete construction of the final
bridge parapets. The final seven parapets and the respective implemented
modifications are listed in Table 22.
As displayed in the table, two of the parapets will be controls. Since field visits could not be made to the controls constructed in 2012, field visits during and after placement of these two control parapets will provide important information that could not be gathered for the current study.

The experimental parapets include the 3.5 inch (89 mm) deep control joint with both the GFRP and field cut steel reinforcement. Field visits during and after construction should be made to make thorough observations and gather the appropriate data. UPV tests over the control joints should be performed within the first few weeks of placement and again, if possible, after the parapet has had more exposure to the environment. The UPV will help determine if the control joints are functioning, and can be used to compare the GFRP against the field cut steel reinforcement. Maturity sensors should be attached to the reinforcement of all the parapets before concrete placement to measure the temperature of the concrete during and after placement. If high temperature variations occur and thermal cracking is an issue on the control parapets, it will become clearer if the use of polypropylene fiber is effective in regards
to early age cracking. Crack surveys should be completed on all parapets after curing
and again months later.

If possible, the experimental parapets that were constructed during the 2013 season
should undergo additional crack inspections. The results may determine the long term
functionality of the GFRP or field cut steel reinforcement modification with the 3.5 inch
(89 mm) deep saw cuts to be more beneficial than using just the closer joint spacing
modification. If possible, the final two control parapets should be constructed to
include the reduced joint spacing. Based on the performance of these controls, the
overall effectiveness of the deeper saw cut can be analyzed and better determined.
REFERENCES


AZDOT. (2012). Bridge Highway Details. Arizona Department of Transportation.


Collett, B., “Parapet Cracking.” Message to Norbert Delatte. 19 June 2013. E-mail.


MDOT. (2012). Bridge Standards. Hanover: Maryland Department of Transportation.


