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ANALYSIS OF UNCONTROLLED CONCRETE BRIDGE PARAPET CRACKING

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ABSTRACT

The Ohio Department of Transportation has recently identified the problem of wide-spread premature cracking of concrete bridge parapets throughout its District 12 region (Northeast Ohio). Many of the bridge decks that contain these prematurely cracked parapets are of relatively recent construction. In severe cases, replacement of the parapet may be required before replacement of the bridge deck itself. This incurs a sunk cost upon the bridge owner, as the parapets will again be replaced during the regularly scheduled replacement of the bridge deck. In a recent instance, the replacement of a cracked parapet (without replacing the deck) cost District 12 approximately $140,000. In addition, parapet walls are a crucial safety feature of roadway bridge construction, and severe deterioration of these barriers could introduce a significant safety hazard.

Premature cracking of concrete bridge parapets is a potentially complex problem, with a number of possible causes. The objective of this study was to determine the reasons for uncontrolled concrete bridge parapet cracking, and to provide recommendations to ODOT to prevent such cracking in the future. Potential factors examined in this study included: properties of the concrete mixtures used, construction methods, joint details, composite structural action, and durability of the concrete and reinforcement. Identifying the cause of, and avoiding this problem in the future, has several benefits, including: a potential cost savings for the district, increasing the safety of these structures in future construction, and increasing the overall understanding of the durability of these structures.

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1.1 ODOT Problem Statement

There appears to be wide-spread premature cracking of bridge concrete parapets on relatively recently constructed bridge decks. District 12 has identified 27 bridges exhibiting premature cracking of bridge concrete parapets to varying degrees. Bridge concrete parapets can be replaced without bridge deck replacement, and the decks on which these problem parapets were poured appear to be performing as anticipated. A cursory review of District 12 parapets shows little correlation between deck characteristics; some are on short spans, while others are longer spans, and some are on skews. Also, multiple contractors and concrete suppliers were involved. The District continues to design and construct these bridge concrete parapets similarly every year. The District did replace one cracked parapet (without replacing the deck) and the cost was about $140,000. Cracked parapets are a safety concern, and the potential cost to the Department to remove and replace parapets could be significant.

1.2 Study Objectives

The overall objective of this study was to determine the reasons for uncontrolled bridge deck parapet cracking, and to provide recommendations to ODOT to prevent such cracking in the future. Cracking of concrete bridge parapets is a potentially complex problem, and could be caused by a number of possible factors. To fulfill these objectives, the following goals were identified:

- Identify all relevant factors potentially contributing to concrete parapet cracking.
- Determine the factors that are most probable and/or most significant in causing premature cracking on ODOT District 12 bridges.
- Provide recommendations to ODOT for repair and future prevention of this type of deterioration.

1.3 Research Methodology

A forensic engineering approach was used to achieve the objectives of this study. The steps performed in this process are summarized below.

1. Perform a literature review to obtain background information regarding the history of this problem and the factors involved.
2. Develop case studies for the four District 12 bridges identified for this study.
3. Develop a list of hypotheses for the causes of parapet cracking on District 12 bridges.
4. Perform a desk study of available records to refine the list of hypotheses and identify additional details for the case studies.

5. Perform site visits involving observation of field conditions, comparison as-built to planned conditions, measurement and mapping of parapet cracks, and various types of nondestructive testing.
6. Analyze the results of the previous steps to determine the most likely causes of parapet cracking.

1.4 Benefits and Potential Application of Research Results

Bridge deck parapets are replaced when it is necessary to replace the bridge deck itself, as they sit on top of the deck and are constructed after the deck. District 12 had to replace the parapet on a bridge over I-271 in 2002 at a cost of $139,705.75 which did not include sealing, fence and expansion joint repairs. So, if the parapet needs to be replaced prior to the deck, that cost is wasted when the deck is ultimately replaced.

By determining the specific causes of concrete parapet cracking on District 12 bridges, it is possible to identify applicable measures for the repair and prevention of this type of cracking. Recommendations can then be made to ODOT that will ultimately help reduce bridge life-cycle costs caused by prematurely cracked bridge parapets.

1.5 Organization of this Report

This report consists of seven chapters, beginning with this introduction. The second chapter is the Literature Review. The third chapter covers the Bridge Case Studies, which examines the history and condition of the four District 12 bridges that have been identified for the purposes of this study. The fourth chapter provides the Hypotheses, and summarizes all of the various factors that could potentially contribute to the cracking of concrete bridge parapets. The fifth chapter, Field Observations and Analysis, describes the field work carried out, including: observations, crack measurements and mapping, calculation of crack statistics, and non-destructive tests. The sixth chapter, Conclusions and Recommendations, provides an explanation for the factors which have been identified as the most likely causes of cracked concrete parapets on the bridges in this study. The seventh and final chapter, Implementation Plan, outlines suggested measures for ODOT to help reduce or eliminate the problem of prematurely cracked bridge parapets in the future.

CHAPTER II

BACKGROUND AND LITERATURE REVIEW

The literature review for this study covered three main topics: observations from other State DOTs, causes of cracking, and correlation to other published research studies. A search was performed to identify any other state DOTs that may have experienced similar problems or conducted similar studies with regard to cracked parapets. Literature regarding the technical details associated with general cracking of concrete structures was reviewed to familiarize the researchers with the current body of knowledge on this subject. Finally, other relevant research studies from academic and other sources were reviewed to identify any possible correlation to the objectives of this study.

2.1 Observations from Other State DOTs

Literature from several DOTs has confirmed that the recent problem of concrete parapet cracking is not exclusive to Ohio bridges. Several states have identified symptoms similar to the conditions present on the bridges under investigation in this study. Some states have already implemented changes to their design and construction procedures to prevent these problems. The available documentation from these states' recent studies of concrete parapet cracking is summarized below.

2.1.1 Illinois Department of Transportation

In 2003 the Illinois Department of Transportation and the Federal Highway Administration performed a joint process review on bridge parapet construction. The identification of uncontrolled vertical cracks in recently constructed bridges led to the need for the process review, which evaluated the durability of these structures and cited several causes of parapet cracking. One of these causes was the inadequate spacing of control joints in the parapets. IDOT subsequently issued a policy change that specified a maximum spacing of 20 feet (6.1 m) between joints in the upper portion of parapets (Anderson, 2004a).

Another cause of parapet cracking cited in the IDOT process review was insufficient concrete consolidation in parapets constructed using the slipform method. This type of deterioration was not found in parapets built using traditional construction techniques. In response, IDOT issued a temporary moratorium on the slipforming of parapets in 2004. The moratorium listed several requirements that had to be met in order to lift the moratorium, including developing construction procedures, reinforcement details, concrete mix designs, and quality control procedures to ensure adequate consolidation, uniformity, and quality workmanship for slipformed parapets (Anderson, 2004b) (Anderson, 2007).

In 2007 IDOT issued the *Guide Bridge Special Provision Number 61*, which specified the policy changes to the IDOT Construction Specifications resulting from the slipform moratorium. These new specifications were intended to prevent premature cracking of parapets built using the slipforming process. A few of the key specifications are summarized below: (IDOT, 2011):

- The speed of the slipform machine may not exceed 3 feet (0.9 m) per minute.
- Interruptions in delivery of concrete from the trucks to the slipform machine may not exceed 15 minutes.
- Intersections of reinforcement within the parapet must be completely tied to maintain rigidity during the concrete pour.
- Glass Fiber Reinforcement Polymer shall be used across sections where the sawcut control joints will be located.
- Joints shall not be spaced greater than 20 feet (6.1 m).
- A minimum 4 inch (100 mm) gap shall be provided in the horizontal reinforcement at the locations where the sawcut control joints will be located.
- Sawing of joints shall take place after the concrete has sufficiently hardened but before shrinkage cracking occurs, and no later than 8 hours after placement.
- Concrete shall be covered with a continually wetted curing material within 30 minutes of the slipforming operation and a soaker hose shall be placed on the top surface of the parapet.

2.1.2 Michigan Department of Transportation

In 2007 the Michigan Department of Transportation published a report titled "Performance of Michigan's Concrete Barriers." The main objectives of the report were to identify the different types of barrier designs, evaluate the field performance of different barrier designs, and identify potential factors that may contribute to the premature deterioration of these structures. The report stated that “many of the current generation barriers in-service on MDOT roadways are deteriorating at a rate much greater than expected compared to 20 years ago” (Staton & Knauff, 2007). The types of deterioration investigated in the MDOT report closely resemble the problems identified on Ohio bridge parapets.

The MDOT report outlined the changes in concrete barrier designs that have been in use in the state of Michigan over the last several decades. Background information about some of the common mechanisms of concrete deterioration was also provided. This information, along with field observations of various in-service concrete bridge barriers, was used to identify several probable factors causing the premature deterioration of concrete bridge barriers. These factors are summarized below (Staton & Knauff, 2007):

- Modern solid face parapet designs allow snow and deicing chemicals to be trapped against the interior face of the parapet
- Slipform construction methods expose freshly poured concrete barriers to more severe early age shrinkage stresses than traditional formed cast-in-place methods
- Freeze-thaw durability of concrete structures has decreased with the increasing use of blast furnace slag and high absorptive coarse aggregates in concrete mixtures
- The increasing use of deicing chemicals on roadways has increased the speed of chloride induced corrosion of concrete and reinforcement

The report makes several recommendations for policy changes to help prevent these problems in the future.

2.1.3 Connecticut Department of Transportation

In 2005 the Connecticut Department of Transportation issued a memorandum to its Bridge Design Standard Practices concerning parapet cracking. The memorandum stated that an increase in parapet cracking had been noticed due to the elimination of paraffin coated joints in bridge parapet designs. The new standard practice proposed that paraffin coated joints once again be included in bridge parapets to control excessive shrinkage cracking (Georges, 2005).

2.2 Causes of Cracking

Technical literature about the causes of cracking of concrete is quite extensive. Various reports from the American Concrete Institute (ACI) as well as many other sources provide detailed discussions about the physical and chemical mechanisms that initiate and propagate cracks in concrete structures. A broad overview of these mechanisms is provided in the following sections, for the purpose of identifying key concepts and terminology relating to the current state-of-the-art of concrete cracking. A commonly accepted definition states that concrete cracks when the tensile stresses that develop in the concrete member exceed the tensile strength of the concrete. Tensile stresses can be created by a wide variety of factors which can be grouped into the categories of mechanical loading, shrinkage, and environmental factors.

2.2.1 Mechanical Loading

Mechanical loading of a concrete member can occur through static loads, dynamic loads, and fatigue. Static loads can be described as the dead loads and live loads acting on the structure, while dynamic loads include impact forces and vibrations. These types of loads create cracks, beginning with the development of micro-cracking between components of the concrete matrix. Micro-cracking is thought to occur because concrete is a composite material. The concrete matrix is composed of aggregate and a cement paste matrix. Since these components have different elastic properties, the stress-strain response of the concrete matrix behaves in a nonlinear fashion due to the different contributions of each component. As the magnitude of loading on the member increases, the micro-cracks combine to form full visible cracks at the high stress regions within the member. The development of visible cracks corresponds to the increase in the rate of strain in the concrete as the load increases (TRB, 2006).

Cyclic loading and unloading of a structure can cause additional stresses in the structure through the phenomenon of fatigue. While the strength of the concrete is sufficient to resist a few applications of the applied loads, after many cycles of loading and unloading, the micro-cracks may eventually combine to form a macro-crack. Due to the composite nature of concrete, the effect of fatigue stresses on concrete structures is not well understood. However, reinforced concrete structures exhibit a significantly greater resistance to fatigue than unreinforced concrete, due the concrete strain being limited by the contribution of the reinforcing steel (TRB, 2006).

2.2.2 Volumetric Stability

Volumetric stability refers to the stresses caused in a concrete member as a result of changes in the volume of the concrete member over time. Volume changes create internal tensile stresses within the concrete member, often resulting in cracking. The most notable sources of these volume changes are shrinkage and thermal changes and gradients. Shrinkage can occur in plastic concrete or in hardened concrete. Plastic shrinkage occurs when the surface of fresh concrete loses moisture faster than it can be replaced by the concrete’s natural bleed water. Shrinkage that occurs in hardened concrete is referred to as drying shrinkage, as it is caused by the gradual loss of moisture within the cement paste matrix over time. A special type of drying shrinkage, known as autogenous shrinkage, results from internal drying of concrete with low water-cementitious materials ratios. This is not likely to be a factor for bridge parapets. In general, the amount of shrinkage of any type is decreased when the concrete is under restraint, resulting in the development of higher stresses. Restraint can be internal or external, examples of which include reinforcing steel or formwork, respectively (ACI 224.1R, 2007).

Thermal changes and gradients create stresses due to differential expansion or contraction across a concrete member. As the local thermal deformations vary among sections of a concrete member, the corresponding volume changes create internal tensile stresses within the member, which can lead to cracking. Thermal gradients also contribute to the types of shrinkage discussed in the previous paragraph, since these mechanisms are highly sensitive to temperature. As with shrinkage, the effects of thermal gradients often increase in concrete members that are under greater restraint (ACI 224.1R, 2007).

Sawn joints are intended to allow the parapets to contract due to shrinkage and thermal effects without allowing additional cracking. However, if the joints are not fully effective or if they are too far apart, cracks may be expected to form between the joints due to these volumetric effects.

2.2.3 Environmental Factors

Various environmental factors can cause a concrete structure to crack during its lifetime. The most common of these factors include freeze-thaw attack, corrosion of the concrete, and corrosion of the steel reinforcement. Freeze-thaw attack occurs when tiny pockets of water within the concrete member freeze and subsequently expand, creating stress in the surrounding concrete. Freeze-thaw attack is of particular concern in regions where climatic temperatures frequently cycle between freezing and non-freezing.

Deterioration of concrete due to corrosion can occur in a variety of ways. One way is through chemical attack of the concrete matrix itself. Concrete is particularly susceptible to attack from sulfates and reaction with alkali materials, in addition to other chemicals. Corrosive compounds may occur naturally in the environment, or may be present from human interaction, such as through the use of deicing salts on roads. Reinforcing steel is also susceptible to various types of harmful chemical attacks. Corroded reinforcement often subsequently damages the surrounding concrete (Kovler, 2009).

2.3 Correlation to Other Published Research Studies

Literature from various research databases and other sources was searched using keywords relevant to the nature of this study. Many references were reviewed. These references describe various research studies, forensic investigations, and evaluations of construction methods. The content of these references can be organized into several key topics, summarized below.

2.3.1 Early Age Cracking of Concrete Barrier Walls

A research paper published by Canadian researchers in 2000 describes an investigation of the factors influencing early-age cracking in reconstructed concrete bridge barrier walls. Transportation professionals in Quebec had noticed many concrete bridge barriers exhibiting significant transverse cracking very shortly after construction. Researchers surveyed various transportation departments throughout North America, and their results showed that this problem was fairly widespread. Potential factors that govern cracking were analyzed by performing a case study of the parapet reconstruction on the Vachon Bridge in Quebec. Field observations and structural modeling showed that the parapets experienced noticeable cracking within only two days of the concrete placement. After several months, these cracks had propagated, along with the formation of new cracks (Cusson, 2000).

Field observations, along with a finite element model and sensitivity analysis of the parameters of the reconstructed parapet, were used to draw conclusions as to the probable causes of the widespread cracking in the newly constructed parapets. These conclusions are summarized below (Cusson, 2000) (Cusson, 2001):

- The main factor contributing to early age cracking of the barriers was thermal stresses due to large temperature gradients throughout the wall. The thermal stresses are attributed to high cement content of the concrete, use of different formwork materials on either side of the barrier (wood and steel), and removal of formwork after only 1 day.
- Autogenous shrinkage may have contributed to cracking due to the unnecessarily low water-to-cement ratio of the concrete.

- Since the bridge was opened to traffic only a few hours after the concrete for the barriers was allowed to set, traffic vibrations may have contributed to cracking at the midspans during a period of time where the concrete had not yet developed adequate strength.

2.3.2 Slipform Construction of Parapets

In 2006 the GOMACO Corporation, a manufacturer of slipform equipment, gave a presentation at the Midwest Concrete Consortium Meeting titled “Bridge Paving Equipment Update.” The purpose of the presentation was to inform the meeting participants of the recent problems of parapet wall cracking and bridge deck cracking as a result of slipform construction, and the design factors and construction methods associated with these problems. The presentation identified the following factors contributing to parapet wall cracking: concrete mix design, wall configuration, reinforcement cage design, vibrator placement within the slipform mold, and speed of the slipform machine (Clausen, 2006).

For each of these factors, the authors suggested several possible remedial actions. Tall straight wall configurations should be avoided, and radius shapes are favorable over chamfered shapes. Reinforcing steel should have adequate concrete cover, and too much steel in a parapet section should be avoided as it reduces the ability of the concrete to adequately consolidate around the steel. Reinforcement cages should be sufficiently rigid to prevent excessive movement during slipforming. Vibrators should not block the flow of concrete and should not come into contact with the steel. Finally, the speed of the slipform paver should be adjusted to be appropriate for the specific weather conditions, reinforcement configurations, and concrete mix properties of each individual project (Clausen, 2006).

2.3.3 Structural Action of Concrete Parapets

Several research papers were found which studied the composite structural action of a concrete bridge parapet and its contribution to the overall strength and stiffness of the bridge. One study hypothesized that bridge parapets will carry a portion of the live load stresses, even if they are not constructed compositely with the bridge deck. The researchers assessed this through several detailed finite element models of steel girder bridges. The finite element results showed that the overall stiffness of the structure can have an increase as high as 25% when the parapets act compositely with the deck, particularly when the loads are located toward the outside of the bridge, nearer to the parapets. It is expected that these stresses could cause significant cracking in the parapets, as most parapets are designed exclusively as barriers and are not designed for structural action of the bridge (Brenner, 2005).

Another study sought to measure the stiffening effects of parapets on the bridge structure with respect to the deflections caused by passages of super-heavy-weight vehicles, or superloads. Finite element models were developed to compare a bridge with parapets to an identical one without parapets. Results showed significantly smaller superload deflections in the bridge with parapets. It was also demonstrated that a continuous parapet would experience significant bending stresses in the negative moment regions of the bridge spans, as opposed to jointed parapets. Composite structural action of the parapets to this degree would be expected to initiate noticeable cracking of the parapets in the negative moment region of the bridge (Akinci, 2008).

2.3.4 Cracking of Concrete Bridge Decks

In recent years, many states have reported the problem of widespread cracking in concrete bridge decks. The number of cases of this type of deterioration seems to be on the rise. Many studies investigated the potential causes of bridge deck cracking, identified the most likely mechanisms, and made recommendations for preventative and remedial methods of this problem. Certain studies have focused on more specific scenarios of this phenomenon including early age bridge deck cracking, cracking of high performance concrete bridge decks, or transverse bridge deck cracking. Some DOTs have used the results of these studies to make appropriate changes to their design and construction procedures in an attempt to eliminate this problem.

Some of the conclusions made in these reports with regard to the causes of concrete bridge deck cracking are unique to particular circumstances. However, many conclusions are common among several studies, which reinforce the results of these investigations. Some of the main factors cited as causes of cracking in concrete bridge decks include the following: excessive drying shrinkage, autogenous shrinkage, and plastic shrinkage of high performance concretes (Miller, 2006) (Camisa, 2004); longitudinal restraint; and ambient conditions at the time of deck placement (French, 1999). Some of the key recommendations for future prevention of these problems include the following (Krauss, 1996):

- Use concrete mixes with larger aggregate sizes and higher water-to-cement ratios.
- Design more effective longitudinal reinforcement that use appropriate reinforcement sizes for sufficient consolidation.

- Minimize continuity of the deck over interior spans to limit shrinkage and reduce restraint of the concrete.
- Ensure the use of appropriate curing procedures and monitoring of ambient conditions

CHAPTER III

BRIDGE CASE STUDIES

For the purposes of this study, ODOT selected four bridges within District 12 to be examined in detail. They are: Canterbury Road over Interstate-90, Sheldon Road over Interstate-71, Spring Road over State Route 176, and Wagar Road over Interstate-90. These bridges all exhibit similar premature cracking of the concrete parapets, and are of relatively similar age. However, these bridges display minor variations in crack location, crack severity, structural dimensions, and construction details. These differences create an adequate sample of bridges to be examined in detail for this study. Case studies for these four bridges have been developed, which include general structural information, design and construction background, designed bridge dimensions, analysis of inspection and maintenance records, and field observations. A brief summary of data related to these bridges is shown in Table I.

Table I: Summary of Bridge Data

Bridge	Canterbury	Sheldon	Spring	Wagar
City	Westlake	Middleburg Heights/Brook Park	Cleveland	Rocky River
Total length (ft., m)	247.7 (75.5 m)	227 (69.2 m)	252 (76.8 m)	124.5 (37.9 m)
No. of spans	4	4	2	2
Max. span length (ft., m)	67.5 (20.6 m)	62.5 (19.1 m)	132 (40.2 m)	62.25 (19.0 m)
No. of traffic lanes carried	2	2	4	4
Year built/rehabilitated	2002	1999	1997	2001

3.1 Canterbury Road over Interstate-90

3.1.1 Overview

The Canterbury Road Bridge is an overpass of Interstate-90 in Westlake, Ohio. It was originally built in 1977. In 2002 the bridge deck and superstructure underwent major rehabilitation.

3.1.1.1 Inventory Number and Structural File Number

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

Bridge Inventory Number: CUY-90-0303

Structural File Number: 1807676

3.1.1.2 Functional Classification

The ODOT functional classification of the bridge is Local Road – Urban.

3.1.1.3 Structure Type

The bridge is a continuous composite steel beam bridge with reinforced concrete deck and substructure.

3.1.1.4 Major Repairs

The major rehabilitation work performed in 2002 included the following items:

1) Removal of deck, end crossframes, expansion joints, sidewalks, railings, backwalls, and approach slabs.
2) Placement of new abutment backwalls, sidewalks, deck, end crossframes, expansion joints, railings, approach slabs, and vandal protection fence.
3) Repair of damaged concrete abutment seats.
4) Repair of concrete slope protection.
5) Resetting of rocker bearings.
6) Sealing of concrete surfaces.
7) Repair of pressure relief joints.

3.1.1.5 Traffic Information

The bridge carries two lanes of traffic, with of one lane in either direction. Traffic data taken in 1999, which was used for the design of the 2002 rehabilitation, is as follows:

Current ADT:	5,600
Design Year ADT (2019):	7,600
Design Year ADTT:	152

Traffic data taken in the year 2002, which is listed in the ODOT bridge inventory, is as follows:

ADT: 14,266

ADTT: 285

3.1.2 Designer and Contractor Information

3.1.2.1 Original Construction

The designer of the original construction was Shaffer, Parrett and Associates. Design of the Bridge was completed in May 1973. The contractor for the original construction of the bridge was National Engineering. Construction was completed in July 1977.

3.1.2.2 Deck and Superstructure Rehabilitation

The designer of the major rehabilitation was Thomas Fok and Associates. Design of the rehabilitation was completed in February 2000. The contractor for the rehabilitation was Great Lakes Construction Company. The rehabilitation work was completed in November 2002.

3.1.3 Designed Bridge Dimensions

3.1.3.1 Length

Total length of the bridge is 247.70 feet (75.5 m). It consists of four spans of the following lengths: 54’-0”, 67’-6”, 67’-6”, and 54’-0” (16.5 m, 20.6 m, 20.6 m, 16.5 m). The bridge profile is shown in Figure 1.

3.1.3.2 Width

The total section width of the bridge is 38 feet (11.6 m), with a roadway width of 28 feet (8.5 m).

3.1.3.3 Parapet Dimensions

The height of each parapet is 32 inches (813 mm). The width of each parapet is 12 inches (305 mm). The parapet detail is shown in Figure 2.

Figure 1: Canterbury Road Construction Plans, Profile

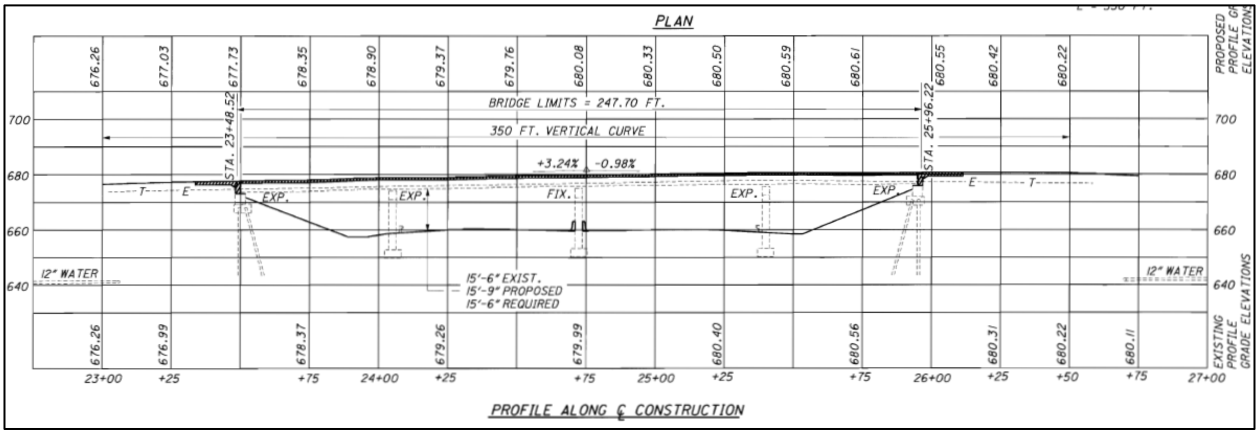
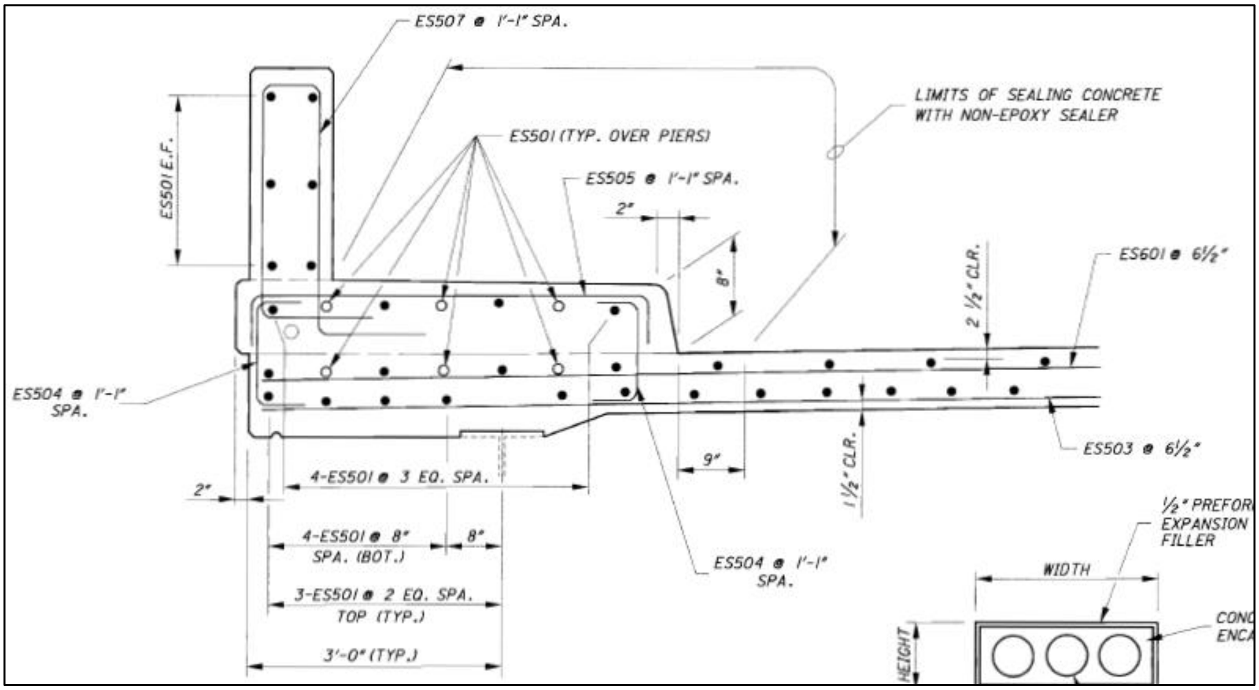


Figure 2: Canterbury Road Construction Plans, Parapet Cross Section



3.1.4 Analysis of Available Records

3.1.4.1 Inspection Records

Routine annual inspection records are available beginning in 1985. All inspection records since the 2002 rehabilitation specify a condition rating of “1” for the deck railings. According to the ODOT Manual of Bridge Inspection, this rating indicates deficiencies ranging from “new” to “some minor problems, minor impact damage.”

3.1.4.2 Maintenance Records

Repair and maintenance projects performed over the bridge’s lifetime including painting of structural steel, asphaltic concrete deck overlay, and deck replacement.

3.1.5 Field Observations and Measurements

Field observations regarding the bridge’s cracked concrete parapets were recorded during various site visits. Observations relevant to the location, severity, and potential causes of the cracked parapets are discussed below.

3.1.5.1 Qualitative Observations

Many vertical cracks appeared to be located approximately halfway between the sawcut control joints. Some of these cracks were continuous through the sidewalk and the bridge deck. This seems to indicate that the corresponding control joints were not functioning properly. Some of the transverse cracks in the bridge deck, sidewalk, or parapets appeared to redirect towards other cracks or control joints. This may indicate that the respective control joints were active, but provided an insufficient level of crack control for the given section of concrete.

Another common location of vertical parapet cracks was below or near the base plates of the vandal protection fence (VPF) posts. This may indicate that the connection details of the base plates have reduced the durability of the concrete parapet directly below them. In addition, many of the base plates are anchored into the parapets within a relatively short distance of the sawcut control joints, which may also contribute to the reduced durability of the concrete at these locations.

Approximately half of the length of the parapet exhibited horizontal cracks located several inches below the top of the parapet. This depth likely corresponds to the top layer of longitudinal reinforcing steel in the parapet. This type of deterioration usually indicates the eventual spalling of the concrete cover above the top layer of reinforcement.

Many of the parapet cracks appear to have been filled with a type of patching material and subsequently painted over. In many locations, this paint layer is cracked as well around the perimeter of the concrete cracks. This chipping of the paint layer tends to make the cracks appear to be wider than they actually are. A few cracks show signs of rust staining, indicating the penetration of moisture and corrosion of the steel reinforcement.

3.1.5.2 Parapet Dimensions

The parapet height measured in the field was 32 inches (813 mm) for both parapets, which matches the design height. The measured parapet width for both parapets was approximately 13 inches (330 mm), which is slightly larger than the design width of 12 inches (305 mm). Spacing between the control joints in the parapets varied widely throughout the length of the bridge, but the typical control joint spacing is in the range of 70 to 96 inches (1.8 to 2.4 m).

3.2 Sheldon Road over Interstate-71

3.2.1 Overview

The Sheldon Road Bridge is an overpass of Interstate-71 and is located on the border of Middleburg Heights, Ohio and Brook Park, Ohio. It was originally built in 1966. In 1999 the bridge deck and superstructure underwent major rehabilitation.

3.2.1.1 Inventory Number and Structural File Number

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

Bridge Inventory Number: CUY-71-0787
Structural File Number: 1804294

3.2.1.2 Functional Classification

The ODOT functional classification of the bridge is Collector – Urban.

3.2.1.3 Structure Type

The bridge structure consists of 4-span continuous steel rolled beams composite with a reinforced concrete deck.

3.2.1.4 Major Repairs

The major rehabilitation work in 1999 included the following items:

1) Replacement of the existing deck with a reinforced concrete deck composite with the existing beams.
2) Installation of vandal protection fence mounted on parapets.
3) Rebuilding of wingwall parapets.
4) Sealing of the transverse expansion joints.
5) Replacement of approach slabs.
6) Replacement of abutment backwalls.

7) Fatigue retrofitting of welded cover plate ends.

8) Repair of existing abutments and piers.

3.2.1.5 Traffic Information

The bridge carries two lanes of traffic, consisting of one lane in either direction. Traffic data taken in 1993, which used for the design of the 1999 rehabilitation, is as follows:

Current ADT: 18,824

Design Year ADT (2013): 18,824

Design Year ADTT: 565

Traffic data taken in 2002, which is listed in the ODOT Bridge Inventory, is as follows:

ADT: 18,272

ADTT: 822

3.2.2 Designer and Contractor Information

3.2.2.1 Original Construction

The designer of the original construction was Pace Associates of Ohio. Design of the bridge was completed in July 1964. The contractor for the original construction of the bridge was Great Lakes Construction Company. Construction of the bridge was completed in July 1966.

3.2.2.2 Deck and Superstructure Rehabilitation

The designer for the major rehabilitation was Greiner Engineering. Design of the rehabilitation was completed in October 1993. The rehabilitation work was completed in July 1999.

3.2.3 Designed Bridge Dimensions

3.2.3.1 Length

Total length of the bridge is 227.02 feet (69.2 m). It consists of four spans of the following lengths: 50’-0”, 62’-6”, 62’-6”, and 50’-0” (15.2 m, 19.1 m, 19.1 m, 15.2 m). The bridge profile is shown in Figure 3.

3.2.3.2 Width

The total section width of the bridge is 40 feet (12.2 m), with a roadway width of 28 feet (8.5 m). The bridge cross section is shown in Figure 4.

3.2.3.3 Parapet Dimensions

The height of each parapet is 32 inches (813 mm). The width of each parapet is 12 inches (305 mm).

Figure 3: Sheldon Road Construction Plans, Profile

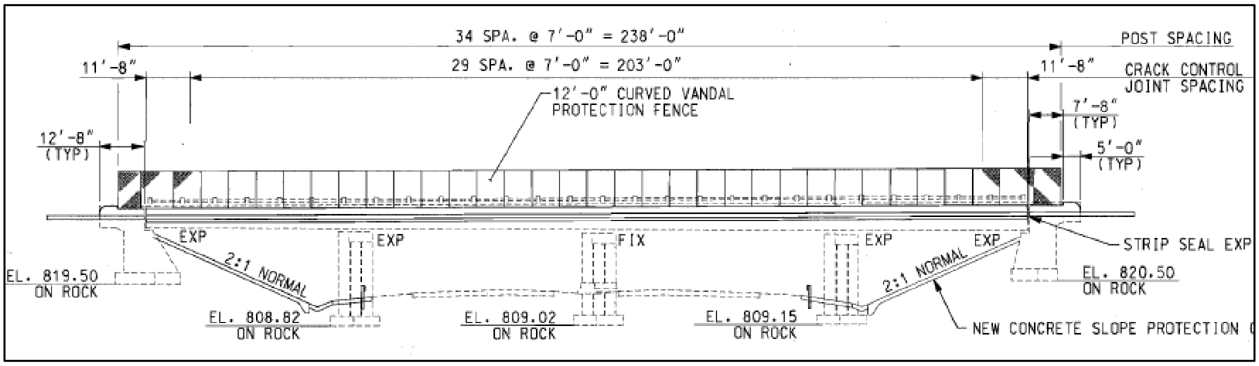
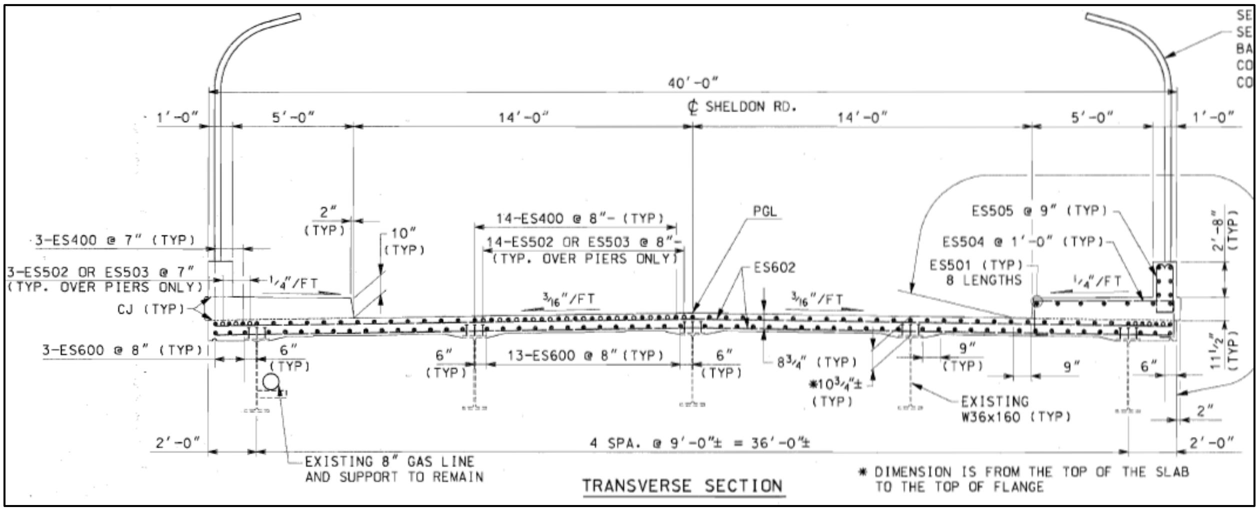


Figure 4: Sheldon Road Construction Plans, Cross Section



3.2.4 Analysis of Available Records

3.2.4.1 Inspection Records

Routine annual inspection records are available beginning in 1985. All inspection records between 1985 and the deck rehabilitation in 2002 specify a condition rating varying between "1" and "2" for the deck railings. Following the deck rehabilitation in 2002, the deck railings were rated at "1," until 2004, after which the deck railings have consistently received a rating of "2." According to the ODOT Manual of Bridge Inspection, a condition rating of "1" indicates deficiencies ranging from "new" to "some minor problems, minor impact damage." A condition rating of "2" indicates deficiencies in the range of "structural elements show some minor deterioration, minor section loss, spalling" to "all primary structural elements are sound but have minor section loss, deterioration or spalling, a few post anchors are exposed due to fascia deterioration, minor impact damage."

3.2.4.2 Maintenance Records

Repair and maintenance projects performed over the bridge's lifetime include painting of structural steel and a deck overlay.

3.2.5 Field Observations and Measurements

Field observations regarding the bridge's cracked parapets were recorded during various site visits. Observations relevant to the location, severity, and potential causes of the cracked parapets are discussed below.

3.2.5.1 Qualitative Observations

Common locations of vertical parapet cracks include the middle of the section between control joints, and below the base plates of the VPF posts. Many cracks are clearly visible but are not wide enough to effectively measure the crack width. In general, cracks near the midpoint of control joint sections appear to be wider than the cracks located below the VPF base plates. A few cracks redirect toward other cracks or control joints. A few control joints have continuous cracks through the sidewalk and bridge deck. Map cracking is present along much of the inner face of the parapets. The sidewalks exhibit a significant amount of concrete scaling along the length of the bridge.

The east end of the bridge contains control joints spaced at 140 inches (3.6 m), while the west end contains control joints spaced at 84 inches (2.1 m). In general, the sections spaced at 140 inches (3.6 m) appear to contain more intermediate cracks. Many control joints appear to have a very thin layer of sealant, which was not nearly enough to fully seal the joint. The sawcut depth for the control joints varies widely throughout the height of a single control joint, as well as between one control joint to another. Variability of the sawcut depths is due to a number of factors, including: the paint layer over the parapets, partial sealing of the control joints, and small rocks and debris that had become wedged in the control joints.

In general, the south parapet wall appears to have wider and more continuous cracks compared to the north wall. On the south wall, nearly every section of parapet has one or two large vertical cracks located near the one-third points, or the middle third, of the section of wall between control joints. This seems to indicate an insufficient level of crack control provided by the control joints. On the north wall, more cracks appear near the base plates of the VPF posts, but many cracks also appear midway between control joints. This may indicate that the cracks that initiated near the VPF base plates helped to limit the severity of the mid-length cracking of control joint sections.

Some of the cracks located near the edge of the VPF base plates extend diagonally outward from the edge of the base plate, which may indicate some type of shearing mechanism due to restraint caused by the base plate. Additionally, many of the VPF posts are severely rusted near the base plate. In base plates that contain a crack directly below them, rust staining has extended down through the length of the crack. Many cracks appear to have been filled with an epoxy material in an attempt to repair them. In many cases the epoxy makes the cracks look worse than the non epoxy-filled cracks.

3.2.5.2 Parapet Dimensions

The parapet height measured in the field was 32 inches (813 mm) for both parapets, which matches the design height. The measured parapet width for both parapets was approximately 12 inches (305 mm) or slightly greater, which roughly matches the design width of 12 inches (305 mm). Spacing between control joints varied slightly along the bridge, but as mentioned above, the east end of the bridge typically contained control joints spaced at 140 inches (3.6 m), while the west end of the bridge typically contained control joints spaced at 84 inches (2.1 m). Sawcut depth measurements were highly inaccurate for reasons discussed above. However, the typical sawcut depth was in the range of 1/8 to ¼ inch (3 to 6 mm). Design specifications call for a one inch (25 mm) deep sawcut.

3.3 Spring Road over SR-176

3.3.1 Overview

The Spring Road Bridge is an overpass of State Route-176 (Jennings Freeway) in Cleveland, Ohio. It was built in 1997.

3.3.1.1 Inventory Number and Structural File Number

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

Bridge Inventory Number: CUY-176-1137

Structural File Number: 1810146

3.3.1.2 Functional Classification

The ODOT functional classification of the bridge is Collector – Urban.

3.3.1.3 Structure Type

The bridge structure is a continuous composite A572 painted plate girder with reinforced concrete deck and substructure with integral abutments.

3.3.1.4 Major Repairs

Repair projects performed over the bridge’s lifetime include a deck overlay.

3.3.1.5 Traffic Information

The bridge carries four lanes of traffic, consisting of two lanes in either direction. The traffic data used for the design of the bridge is as follows:

Design Year ADT (2013): 10,570

Design Year ADTT: 951

Traffic data taken in the year 2002, which is listed in the ODOT bridge inventory, is as follows:

ADT: 11,520

ADTT: 230

3.3.2 Designer and Contractor Information

3.3.2.1 Original Construction

The designer of the bridge was Adache, Ciuni, Lynn and Associates. Design of the bridge was completed in August 1993. The contractor for the bridge's construction was Great Lakes Construction. Construction of the bridge was completed in July 1997.

3.3.3 Designed Bridge Dimensions

3.3.3.1 Length

Total length of the bridge is 252.00 feet (76.8 m). It consists of two spans of the following lengths: 132'-0" and 120'-0" (40.2 m, 36.6 m). The bridge profile is shown in Figure 5.

3.3.3.2 Width

The total section width of the bridge is 67 feet (20.4 m), with a roadway width of 52 feet (15.8 m). The bridge cross section is shown in Figure 6.

3.3.3.3 Parapet Dimensions

The height and width of each outer parapet are 28 inches and 12 inches (711 mm and 305 mm), respectively. The height and width of each inner parapet are 19 and 9 inches (483 and 229 mm), respectively, and is rounded off at the top.

Figure 5: Spring Road Construction Plans, Profile

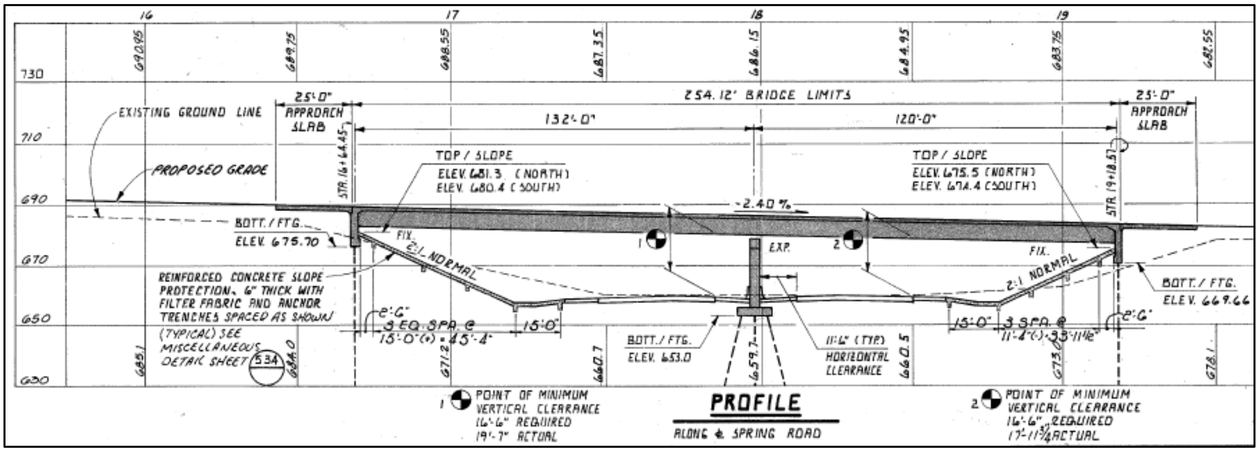
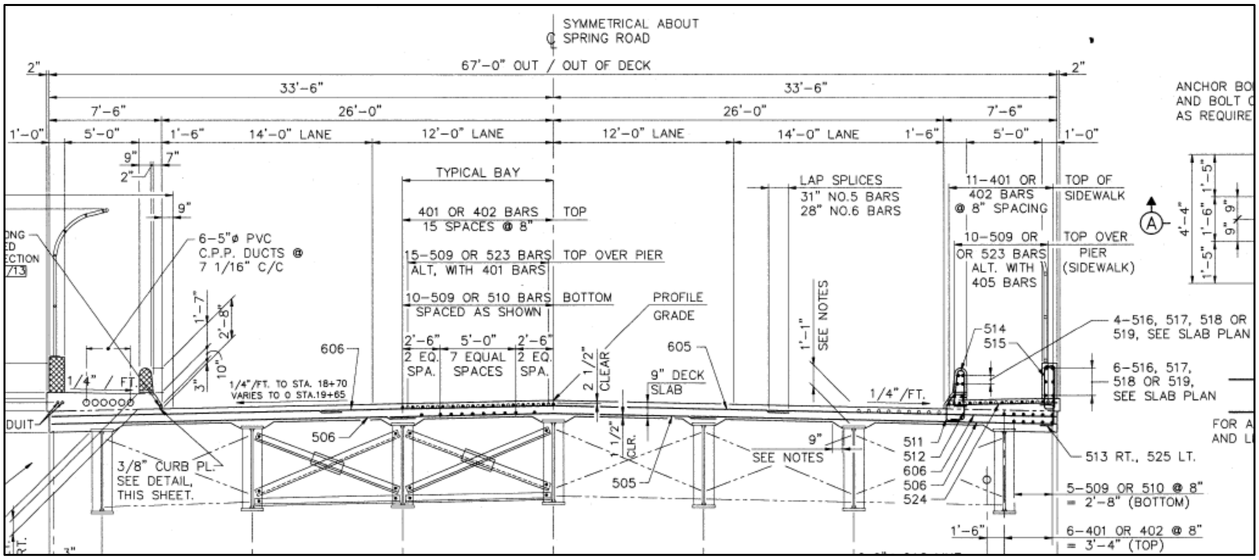


Figure 6: Spring Road Construction Plans, Cross Section



3.3.4 Analysis of Available Records

3.3.4.1 Inspection Records

Routine annual inspection reports are available since the construction of the bridge in 1997. All inspection records specify a condition rating of "1" for the deck railings. According to the ODOT manual of Bridge Inspection, a condition rating of "1" indicates deficiencies ranging from "new" to "some minor problems, minor impact damage."

3.3.4.2 Maintenance Records

Maintenance projects performed on the bridge include the sealing of concrete surfaces in 2002, in addition to the deck overlay noted earlier. Inspection records from the concrete surface sealing project in 2002 indicate that the sealing was performed only on the outer parapets, not the inner parapets between the sidewalk and the roadway.

3.3.5 Field Observations and Measurements

Field observations regarding the bridge's cracked concrete parapets were recorded during various site visits. Observations relevant to the location, severity, and potential causes of the cracked parapets are discussed below.

3.3.5.1 Qualitative Observations

In general, the vertical cracks in the inner barrier walls between the sidewalks and the roadway appear to be more severe than the cracks in the outer parapet wall. Nearly all of the cracks in the inner barrier wall are located approximately midway between control joints. Some of the cracks in the outer parapet wall are continuous through the sidewalk, inner barrier wall, and bridge deck. Many cracks are clearly visible but not wide enough to effectively measure crack width. Crack widths were also difficult to measure due to an outer paint layer on the parapets. Crack measurements were recorded for the outer parapet wall, not the inner barrier wall.

Most of the cracks in the outer parapet walls are located below the VPF base plates. However, the north parapet wall also exhibits some vertical cracks that are midway between the control joints. Cracking in the north parapet wall is noticeably worse than in the south parapet wall. Some horizontal cracks are present on the inner face of the north parapet wall. Many of the cracks below the VPF base plates on the north wall show significant flaking of the concrete around the cracks. Nearly all the cracks in the south wall are located below the VPF base plates, with virtually no cracking near the midsections between control joints.

Significant amounts of map cracking are present on the sidewalks throughout much of the length of the bridge. Sidewalk cracks are also noticeably more numerous near the center of the bridge and at either end of the bridge.

3.3.5.2 Parapet Dimensions

The outer parapet height measured in the field was 28 inches (711 mm) for both outer parapets, which matches the design height. The measured parapet width for both outer parapets was approximately 13 inches (330 mm), which is slightly greater than the design width of 12 inches (305 mm). Spacing between the control joints varied slightly throughout the bridge, but as mentioned above, the outer ends of the bridge typically contained control joints spaced at 192 inches (4.9 m), while the middle section of the bridge contained control joints spaced at 90 inches (2.3 m).

3.4 Wagar Road over Interstate-90

3.4.1 Overview

The Wagar Road Bridge is an overpass of Interstate-90 in Rocky River, Ohio. It was originally built in 1977. In 2001 the bridge deck and superstructure underwent major rehabilitation.

3.4.1.1 Inventory Number and Structural File Number

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

Bridge Inventory Number: CUY-90-0621
Structural File Number: 1807757

3.4.1.2 Functional Classification

The ODOT functional classification of the bridge is Minor Arterial – Urban.

3.4.1.3 Structure Type

The bridge structure consists of a reinforced concrete deck slab on continuous steel beams on a reinforced concrete substructure.

3.4.1.4 Major Repairs

In 2001 the bridge underwent a major rehabilitation of the bridge deck and superstructure.

3.4.1.5 Traffic Information

The bridge carries four lanes of traffic, consisting of two lanes in either direction. The traffic data taken in 2001, which was used for the design of the rehabilitation, is as follows:

Current ADT: 15,500

Design Year ADT (2021): 22,100

Design Year ADTT: 440

Traffic data taken in 2002, which is listed in the ODOT bridge inventory, is as follows:

ADT: 22,233

ADTT: 778

3.4.2 Designer and Contractor Information

3.4.2.1 Original Construction

The designer of the original construction was Shaffer, Parrett and Associates. Design of the bridge was completed in October 1973. The contractor for the original construction of the bridge was National Engineering. Construction was completed in July 1977.

3.4.2.2 Deck and Superstructure Rehabilitation

The designer of the rehabilitation work was Burgess and Niple. Design of the rehabilitation work was completed in November 2000. Construction of the major rehabilitation work was completed in December 2001.

3.4.3 Designed Bridge Dimensions

3.4.3.1 Length

Total length of the bridge is 124.50 feet (37.9 m). It consists of two equal spans lengths of 62'-3" (19.0 m). The bridge profile is shown in Figure 7.

3.4.3.2 Width

The total section width of the bridge is 78 feet (23.8 m), with a roadway width of 64 feet (19.5 m).

3.4.3.3 Parapet Dimensions

The height of each parapet is 28 inches (711 mm). The width of each parapet is 12 inches (305 mm). The bridge parapet detail is shown in Figure 8.

Figure 7: Wagar Road Construction Plans, Profile

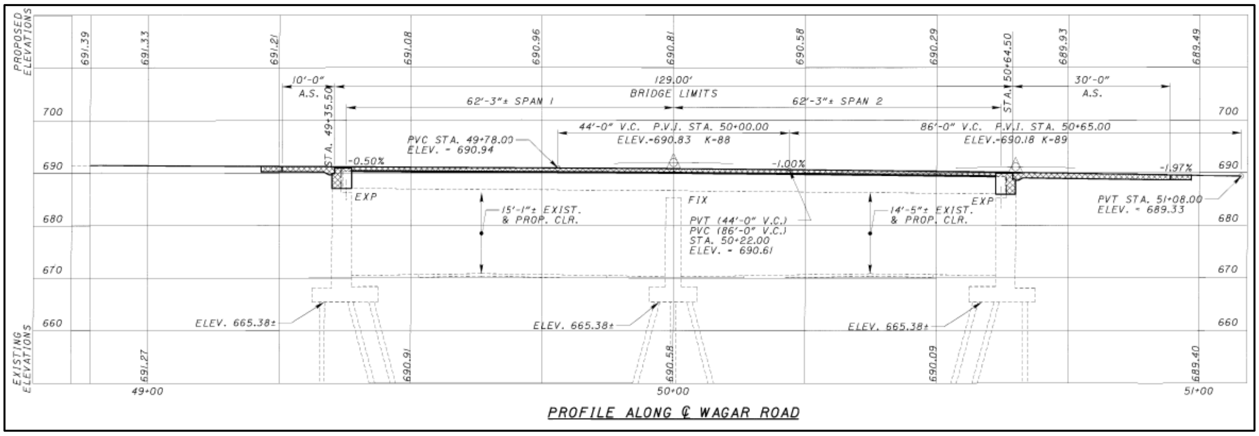
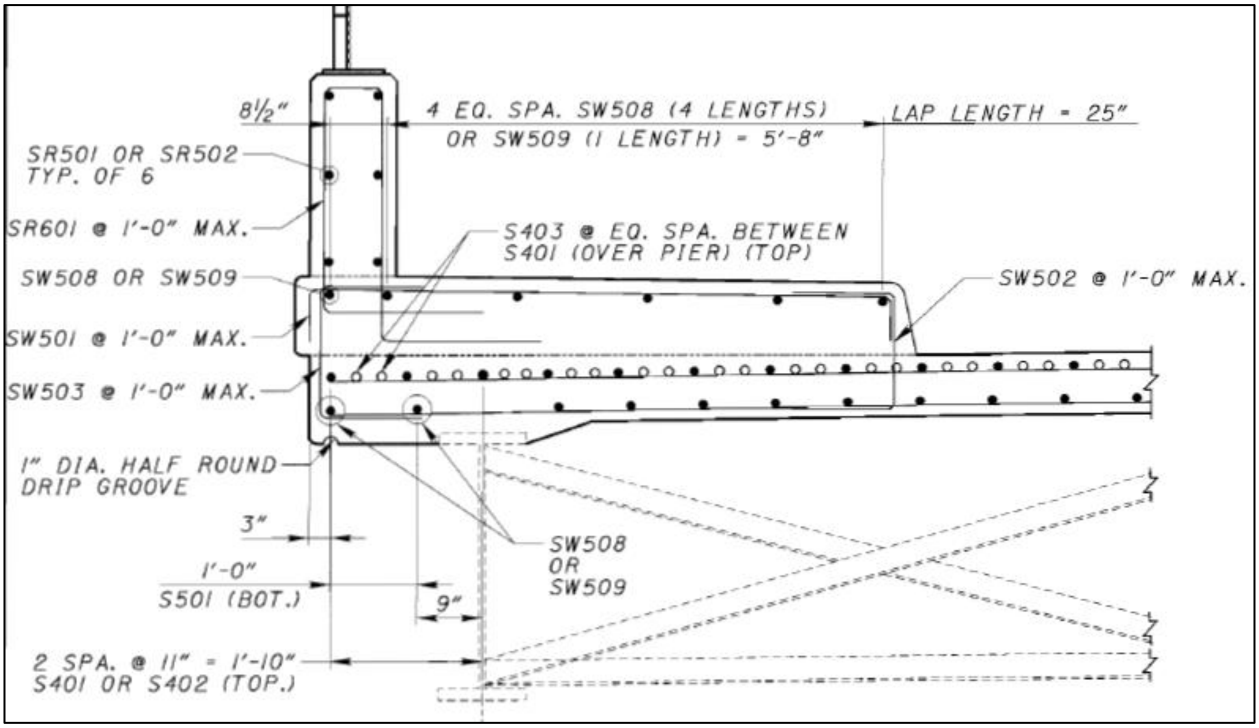


Figure 8: Wagar Road Construction Plans, Parapet Cross Section



3.4.4 Analysis of Available Records

3.4.4.1 Inspection Records

Routine annual inspection records are available beginning in 1985. All inspection records since the 2002 rehabilitation specify a condition rating of “1” for the deck railings. According to the ODOT of Manual of Bridge Inspection, this rating indicates deficiencies ranging from “new” to “some minor problems, minor impact damage.”

3.4.4.2 Maintenance Records

Repair projects performed over the bridge’s lifetime include painting of structural steel and a deck overlay.

3.4.5 Field Observations and Measurements

Field observations regarding the bridge’s cracked concrete parapets were recorded during various site visits. Observations relevant to the location, severity, and potential causes of the cracked parapets are discussed below.

3.4.5.1 Qualitative Observations

Many vertical cracks appeared to be located approximately halfway between the sawcut control joints. In addition, most of the control joints contained a crack that was continuous through the sidewalk. Some cracks split into two cracks, or were redirected toward control joints or other cracks. This seems to indicate that the control joints were active but provided an insufficient level of crack control for the given section of concrete. In general, most cracks that occur through the full height of the parapet appear to be slightly wider at the top of the parapet. Many cracks are clearly visible, but are not wide enough to effectively measure crack width.

Another common location of vertical parapet cracks was below or near the base plates of the VPF posts. This may indicate that the connection details of the base plates have reduced the durability of the concrete parapet directly below them. In addition, many of the base plates are anchored into the parapets directly above, or within a relatively short distance, of the sawcut control joints, which may also contribute to the reduced durability of the concrete at these locations.

The parapets do not appear to have a layer of paint on the outside, where the other bridges in this study do. A few cracks appear to have been covered with a type of patching material. A few other cracks appear to have been filled with an epoxy sealant. In some cases, the sealant makes the cracks appear worse than they actually are.

One construction joint near the north end of the bridge is continuous through the bridge deck, sidewalks, and inner half of the parapet, but not the outer half of the parapet. Another construction joint near the south end of the bridge is continuous through the bridge deck and sidewalks but not the parapets.

3.4.5.2 Parapet Dimensions

The parapet height measured in the field was 28 inches (711 mm) for both parapets, which matches the design height. The measured width for both parapets was approximately 13 inches (330 mm), which is slightly greater than the design width of 12 inches (305 mm). Spacing between control joints varied slightly throughout the bridge, but the typical control joint spacing was 96 inches (2.4 m).

CHAPTER IV

HYPOTHESES

There are many possible factors that can contribute to uncontrolled cracking of concrete bridge parapets. This section outlines those factors and briefly summarizes the theory associated with each hypothesis as it applies to the case study bridges. These hypotheses are organized into four categories: design, materials, construction, and service/maintenance.

4.1 Design

Design factors refer to joints, details, reinforcement, member dimensions, and structural actions. These factors may influence cracking regardless of field conditions and construction quality.

4.1.1 Control Joints

The design details for parapet control joints are possibly one of the most significant factors involved with crack control, yet are sometimes overlooked in the design process. Design factors associated with parapet control joints that may contribute to cracking include the following: dimensional properties like the depth of the joint and the spacing between joints, location of the joints relative to other structural components, and the amount of continuity within the concrete as well as the steel reinforcement.

4.1.1.1 Spacing

The designed spacing between crack control joints in concrete parapets may be too large to provide a sufficient level of crack control. Among the four case study bridges, the most common specification calls for control joints spaced between 6 feet and 10 feet (1.8 m and 3.0 m) throughout the length of the parapet. A concrete mass has a natural tendency to crack from various causes such as shrinkage and temperature effects. If the control joints spacing is too large, these joints may not be sufficient in number to restrict the transverse concrete cracks to these areas, creating additional visible cracks between control joints.

4.1.1.2 Depth of Sawing

The designed depth of sawing of the parapet control joints may not be enough in proportion to the total section of the concrete to provide a sufficient level of crack control. The common specification used for the four case study bridges, as well as many others, calls for a 1 ¼ inch (32 mm) deep sawcut control joints. This specification may not be enough to initiate naturally occurring cracks within the concrete at these areas. Transverse cracks may then initiate through a section of concrete between control joints if the joint itself does not provide a weak enough section to attract the cracks. This sawcut depth is about 10 % of the typical thickness of a parapet. In contrast, concrete pavements typically require sawcut depths of ¼ to 1/3 of the pavement thickness to ensure a properly functioning control joint.

4.1.1.3 Location

The location of the control joints along the parapet may contribute to the initiation of concrete cracks. Control joints located near the base plates of the VPF posts may attract cracks created by the base plate anchorages. This could subsequently reduce the ability of the control joint to initiate shrinkage cracks within the concrete mass, causing additional cracks to initiate elsewhere, particularly between control joints. In addition, concrete in negative moment regions may be more susceptible to cracking due to composite structural action. Parapets may require a closer spacing of control joints in negative moment regions in order to adequately control cracking caused by these effects.

4.1.1.4 Continuity

The construction of control joints helps to reduce to the continuity of the concrete within the length of a concrete parapet. Sections of concrete parapet that are continuous over larger lengths of bridge deck are more likely to develop transverse cracks due to shrinkage and other effects. This also applies to the longitudinal reinforcement within the concrete parapet. Smaller degrees of continuity, of both the longitudinal reinforcement as well as the concrete used for the parapets, may be required in order to provide a sufficient level of crack control.

4.1.2 Reinforcement Details

Designed details of the steel reinforcement of the concrete parapet may contribute to or interfere with the ability of the parapets to control cracking. Though reinforcing steel provides the resistance to tensile forces within a concrete structure, improper dimensional specifications for the reinforcement within a cross section may actually have adverse effects on the concrete’s ability to resist cracking.

4.1.2.1 Percentage of Steel in Cross Section

The percentage of steel within the cross section of concrete can have an impact on the concrete's tendency to crack. A high percentage of steel may not allow for adequate consolidation of the concrete after it is placed. Conversely, a low percentage of steel may not provide adequate tensile resistance to the loads on the concrete structure. The percentage of steel appears to be within reasonably accepted limits for the concrete parapets in this study, so this may not be an important factor in this instance.

4.1.2.2 Concrete Cover

The amount of concrete cover of steel reinforcement has a large, yet sometimes overlooked, influence on a concrete section's ability to resist cracking. In the case of concrete parapets, if the amount of vertical cover over longitudinal reinforcement is too small, the concrete at the top of the section may not be adequately consolidated around the top layer of reinforcement. The concrete around the top reinforcement layer then becomes more susceptible to cracking, as is often the case for horizontal cracks in parapets. Insufficient cover on any face of a concrete parapet may also increase the rate of water and chemical ingress through the concrete, thus accelerating the corrosion of the reinforcement in these areas (Dilek, 2009).

4.1.3 Composite Structural Action

Presently, concrete parapets are typically designed to withstand the forces of vehicle impacts, and are assumed not to carry any of the structural loads. While this practice adds a level of conservatism to the design of the primary structural members, it may not be wholly realistic for designing the required strength of the parapets. It is likely that the parapets do in fact carry some portion of the live loads on the bridge. The tensile stresses developed in the parapets due to these loads may be large enough to develop cracks in parapets, despite the fact that they have not been considered to contribute to the overall structural stiffness of the bridge (ACI 224.1R, 2007).

4.1.3.1 Negative Moment Effects

Since parapets are located above the bridge deck and main structural elements, they will be more likely to develop large tensile stresses in the negative moment regions of the structure's span. Generally, this would correspond to the areas of the span over the pier supports. Therefore, parapets that act compositely with the structure would be more likely to exhibit cracking in these areas, as opposed to lengths of the bridge span that lie within positive moment regions. This hypothesis may be evaluated by comparing the extent of cracking in positive and negative moment regions of continuous bridges.

4.1.3.2 Stiffness of Primary Structural Elements

The structural stiffness of concrete parapets relative to the overall stiffness of the structure is a crucial factor in determining to what degree the parapet will act compositely with the bridge deck and primary structural elements. The stiffer a parapet is the more live load stresses it will attract. This is especially true of loads located nearer to the outside of the bridge deck, as the parapets are more likely to absorb live load stresses when the loads are applied nearer to them. As noted in the literature review, various research studies have shown that the contribution of parapets can increase the overall stiffness of the structure by as much as 25%, which implies that ignoring these forces in the design of the parapets may not be reasonable (Brenner, 2005).

4.1.4 Vandal Protection Fence

Many bridges are designed with a vandal protection fence mounted to the top of the concrete parapets over the majority of the length of the bridge span. Several factors associated with the presence of these fences may be contributing to the development of cracks in the concrete parapets that they are mounted to, including: effects of temperature changes, design details for the base plate anchorages, and the spacing of the fence posts.

4.1.4.1 Temperature Effects

Changes in ambient temperatures may create tensile stresses in concrete parapets due to the differences in thermal movements of the VPF posts and the concrete parapets. The steel used to construct the fence may have a higher coefficient of thermal expansion than that of the concrete parapets, and there are significant differences in thermal mass between the VPF and the parapets. As a result, when ambient temperatures change drastically, the steel fence may expand or contract longitudinally at a faster rate than the parapet itself. The fence post could develop a “pulling” force on the concrete that creates tensile stresses large enough to initiate cracking of the parapet (Corley, 2007). Verifying this mechanism would probably require an extensive finite element analysis, which is beyond the scope of this study.

4.1.4.2 Anchorage Details

The anchorage system used for the VPF posts on the bridges in this study includes attachment of the post to a steel base plate, which is mounted to the top of the concrete parapet with four steel bolts. The bolts may either be cast in place as the concrete for the parapet is placed, or drilled into the concrete after it has cured. In either case, the presence of the bolts may cause weak zones or stress concentrations in the concrete section that lead to the development of cracks in the parapet at these locations. In the case of drilled bolt holes, it is conceivable that the drilling operation itself causes enough damage to the cured concrete to cause it to crack.

4.1.4.3 Post Spacing

The length of spacing between VPF posts may have a noticeable effect on the tendency of the concrete parapets to develop cracks. As the spacing between fence posts becomes larger, the amount of dead load and wind load forces carried by each individual post also becomes greater. At a certain point, the loads carried by each post may create stresses that exceed the tensile strength of the concrete in the parapets, causing it to crack. Therefore, the farther apart the fence posts are spaced, the more likely it may be that the concrete parapets develop cracks at these locations. In addition, fence posts may create additional weak zones of the concrete parapet if the base plates are located too close to a control joint. For this reason, fence post base plates are usually specified to be located a minimum distance away from the control joints.

4.2 Materials

The type and properties of various materials used in the construction and maintenance of concrete bridge parapets can have an impact on the frequency and severity of parapet cracks. These materials include the concrete used for the parapet, coating materials used on the steel reinforcement, and materials used for sealing or patching of concrete surfaces.

4.2.1 Concrete Mixture

The various materials that go into any concrete mixture can have a tremendous influence on the overall quality and behavior of the finished concrete product. Yet the degree of influence of these materials in any particular batch of concrete is often not entirely predictable. Some of the properties of the concrete mixture which may have an impact on the tendency of a concrete parapet to develop cracks are discussed below.

4.2.1.1 Absorptivity of Aggregates

Variations in the absorptivity levels of the aggregates used in a concrete mixture may impact the overall quality of the concrete. As noted in the literature review, another DOT has noticed a higher tendency toward cracking in concrete mixtures containing aggregates of high absorptivity levels. However, this tendency may be due to an overall poor quality of the aggregates used in that particular study, rather than the absorptivity levels. In contrast, ODOT has recently implemented the use of concrete mixtures intentionally designed to have higher absorptivity levels for the purpose of increasing durability. This practice has shown good results thus far (Delatte et al., 2007).

4.2.1.2 Strength and Stiffness

The superstructure concrete specified in the plans of the case study bridges is high strength concrete, typically having a minimum compressive strength of around 5,000 psi (34.5 MPa). This is often the same type of concrete used to construct the bridge deck. Depending on various field conditions, the in place strength of the concrete for the parapets could be significantly higher than the design strength of 5,000 psi (34.5 MPa). It is conceivable that concrete strength and corresponding stiffness may be unnecessarily high for parapets, and could actually be contributing to the tendency of the parapets to crack in various ways. In general, higher strength concrete tends to be more prone to shrinkage cracks than lower strength concrete. Also, the stiffer the concrete in a parapet is, the more likely it is to attract additional composite structural stresses due to its increased stiffness and brittleness.

4.2.1.3 Slump

Slump is a measure of the consistency of a concrete mixture and is often used to establish a certain level of workability for placing the concrete. A concrete mix with a low level of slump may be difficult inside the formwork. Conversely, concrete with a high level of slump could translate into problems associated with other properties of the concrete such as water content or strength, and may be more prone to bleeding or segregation.

4.2.1.4 Water Content

The water content in a concrete mixture has a large impact on other important properties including the strength of the concrete, the consistency and workability of the concrete, and its susceptibility to shrinkage from drying and temperature effects. These properties are also affected by the water to cementitious materials ratio. Proper specification of this ratio in the design of a concrete mixture is often one of the most important factors in achieving the optimal mix design for a particular application. Adequate attention to this factor should be considered in designing concrete mixtures for parapets (Kosmatka, 2003).

4.2.1.5 Shrinkage

Excessive shrinkage of concrete is one of the most common causes of crack initiation. Susceptibility to shrinkage is a difficult to predict and often overlooked factor in design of a concrete mixture. Concrete can be vulnerable to excessive shrinkage due to many of the various factors discussed in previous sections. In the construction of concrete parapets, shrinkage effects need to be adequately considered in design, and closely monitored during construction, in order to minimize shrinkage cracking. Excess water and cement content, and thus excess paste content, contribute to higher shrinkage of concrete (ACI 224.1R, 2007).

4.2.1.6 Temperature Effects

Temperature can be related to crack initiation and propagation in concrete parapet in several ways. During the curing process, the concrete develops high internal temperatures created by the hydration process. As with other factors, the stresses caused by the heat of hydration are difficult to predict accurately. Temperature can also be related to stress development in concrete parapets caused by changes in ambient temperatures. As the temperature of the concrete changes, expansion or contraction of the parapet can cause cracks to develop if adequate crack control measures have not been implemented (ACI 224.1R, 2007).

4.2.2 Reinforcement Coating

Another material which could be related to the development of cracks in concrete parapets is the coating material used on the steel reinforcement. Coating materials, generally epoxy, are used to prevent moisture and other chemicals from contacting the steel. Moisture and chemicals lead to corrosion and accelerate deterioration of the reinforcement and the concrete structures as a whole. Reinforcement coating materials can sometimes limit the ability of the reinforcement to bond to the concrete. This subsequently reduces its capacity to transfer the tensile stresses in the concrete to the reinforcing steel. While reinforcement coatings can greatly increase the durability of concrete structures, care should be taken to ensure that the reinforcement develops a sufficient bond to the concrete. ODOT uses epoxy coated reinforcement for bridge decks and parapets.

4.2.3 Concrete Sealant

Concrete parapet construction often includes the application of sealant materials to and/or painting of the concrete surfaces. This helps to prevent the corrosive effects of moisture and chemical ingress into the concrete. Many parapets are also specified to have sealing materials applied in the control joints for purposes similar to those previously stated. However, these materials are sometimes ineffective or improperly applied and thus fail to provide an adequate seal.

4.3 Construction

The quality of the construction of concrete parapets is an important factor in their durability. Many common construction procedures, if not given adequate attention, can be linked to premature cracking in concrete parapets. Ensuring that high quality construction practices are adhered to is the last critical step before the bridge goes into service. Some of the construction factors that can have an impact on the control of cracking in the finished parapets are discussed below.

4.3.1 Concrete Curing Conditions

Concrete parapet quality is greatly influenced by curing conditions. All construction plans should have detailed specifications for procedures that should be followed in order to ensure proper curing. Some of these conditions that are relevant to concrete parapet construction include moisture, ambient temperatures, formwork materials, and formwork removal.

4.3.1.1 Moisture Conditions

Moisture conditions should be closely monitored throughout the curing process. A commonly used practice for curing concrete parapets is to cover the top of the parapet, as well as any other concrete surface that is not covered by formwork, with a layer of wet burlap that is continually moistened by a hose, sprinkler, or some other source. If a concrete surface becomes exposed to open air or is not kept properly hydrated for an extended period of time, the concrete can dry out and develop cracks even before the formwork is removed. Lack of attention to this condition could conceivably initiate cracking in concrete parapets (ACI 224R, 2008).

4.3.1.2 Ambient Temperatures

The strength gain of concrete is often directly related to the ambient temperatures during the curing process. Typically concrete must be poured during a period where the ambient temperatures are expected to be within a specific range necessary to ensure adequate strength gain of the concrete. Recently, techniques for cold weather concreting have been developed that involve various technologies and quality control procedures. In cases where construction time is critical, cold weather procedures may be ignored or not properly adjusted for, in which case premature deterioration of the parapets is nearly certain. High temperatures may contribute to excessive concrete shrinkage, particularly if combined with low humidity and wind (Dobrowolski, 1998).

4.3.1.3 Formwork Materials

Poor curing conditions for concrete parapets may occur through the use of different formwork materials on either side of the parapet. This is not common practice but has been noticed in a few instances in other studies, as noted in the literature review.

This situation would create temperature gradients within the concrete, leading to potentially problematic thermal effects or eventual crack development. It can be reasonably assumed that this scenario is not likely the cause of cracking for most District 12 parapets, but warrants consideration in terms of the overall quality control process (Cusson, 2000).

4.3.1.4 Formwork Removal

Premature removal of formwork could potentially cause cracking of concrete parapets. If the parapet has not gained sufficient strength, the concrete within the parapet could shift slightly leading to a poorly bonded concrete matrix. In addition, removing formwork too early could exacerbate the negative effects of other, previously discussed curing conditions and lead to higher shrinkage. This is another scenario that becomes more likely in cases of tighter construction schedules.

4.3.2 Concrete Consolidation

Poorly consolidated concrete is almost certain to exhibit signs of premature deterioration. This could be due to the presence of weak zones within the concrete section, severe susceptibility to the damage of freeze thaw cycles, or other various factors. This is the most obvious explanation for the horizontal cracks that are commonly located at the top layer of longitudinal reinforcement in concrete parapets. There is often not enough concrete above this reinforcement layer to provide for adequate consolidation below and between the two parallel bars. The voids that are created in the concrete in these areas become prone to freeze-thaw cycles and subsequently deteriorate at highly accelerated rates.

4.3.2.1 Slipform Construction Method

As discussed in the literature review, many organizations have reported prematurely cracked parapets constructed using the slipform method. For this reason, ODOT, as well as many other Transportation Departments, have made a point to avoid the slipform method in recent years. Thus, this method does not apply to many of the District 12 bridges. However, some of the consolidation-related lessons learned from the slipforming process should also be applied to parapets constructed using traditional formwork.

4.3.2.2 Vibrator Placement and Operation

Some agencies have cited improper vibrator handling and operation during the concrete placement as a cause of poorly consolidated concrete parapets. This applies to both slipformed and traditionally formed parapets. Workers should be educated in proper vibrator operation prior to the concrete placement in order to prevent this problem (Clausen, 2006).

4.3.3 Control Joints

Proper construction of control joints is one of the most effective means of minimizing premature cracking in concrete parapets. If control joints are not constructed correctly, they may not be effective in controlling the severity of parapet cracks, regardless of the quality of their design. Some of the most important factors in control joint construction that can have a significant effect on their ability to effectively control cracks include spacing, timing of sawcut operations, sawcut depth, and sealing and drainage (ACI 224.3R, 2008).

4.3.3.1 Joint Spacing

Control joints may occasionally be installed with a spacing distance greater than that specified in the plans. Control joints are intended to restrict the naturally occurring cracks within the parapet to the plane of the sawcut joint. Sometimes the difference between effective and non-effective control joints may come down to a few inches if the as-built spacing of the joints exceeds some critical distance at which cracks will develop at locations between control joints. A more conservative approach in establishing the spacing for control joints may be necessary in order to maximize their effectiveness.

4.3.3.2 Timing of Sawcut Operations

The precise timing of sawcut operations in control joints construction is a potentially critical factor in their ability to control cracks. Sawcutting should be performed after the concrete has gained enough strength to avoid damage, but before the concrete has hardened and cured enough to crack naturally. This presents a relatively small window for installing effective sawcut joints. If this detail goes overlooked, the control joints may be virtually useless because the cracks will have already formed. Greater care should be taken to ensure that sawcutting is performed during in the appropriate timeframe.

4.3.3.3 Sawcut Depth

Sawcut depth is another critical factor is determining the effectiveness of a control joint. Common specifications call for a 1 ¼ inch (32 mm) deep cut, but the as-built depth of these joints is often significantly less than this. Contractors sometimes install shallow sawcuts as a precaution against potentially making contact with the reinforcement and causing significant damage. However, if constructed correctly, the reinforcement should contain adequate concrete cover to eliminate the possibility of this problem. If the sawcut is not deep enough, it could become ineffective in providing a plane of weakness within the parapet by which to attract and limit cracks.

4.3.3.4 Sealing and Drainage

Control joints in parapets could deteriorate if they are not properly sealed. A common specification calls for some kind of caulk or epoxy material to be applied in the openings of the control joints while leaving an approximately 1 inch (25 mm) gap at the base of the parapet. This allows adequate movement of the joint, while limiting moisture from entering the opening and allowing any moisture which may enter the joint to drain out. If the joint is not properly sealed, moisture could become trapped in the joint and cause severe damage as freezing and thawing cycles occur (ACI 201.1R, 2008).

4.3.4 Uniformity of Concrete Properties

Measures should be taken to ensure that the properties of the concrete used throughout the length of a parapet are as uniform as possible. If the properties of the concrete vary considerably between different areas of the parapet, certain sections could become more susceptible to premature deterioration. These differences could be due to small variations in the batches of concrete delivered by separate trucks or significant interruptions in concrete delivery.

4.3.5 Restraint of Parapets

Concrete parapets that are constructed with a high degree of restraint are more likely to develop premature cracks. If the concrete cannot move freely as it undergoes shrinkage, contraction or expansion, the objects causing the restraint will create tension in the concrete, leading to the development of tensile stresses and cracks. Items in parapets that could add restraint to the concrete include the reinforcement, formwork, dowel rods, or the sidewalk (ACI 224.1R, 2007).

4.3.5.1 Placement Sequence

Another construction factor that could create additional restraint of concrete parapets is the sequence in which the concrete is placed. Placing parapets in alternating, discontinuous sections along the length of the bridge is one method that has been shown to be effective in reducing the concrete restraint in parapets. It is, of course, more time consuming and difficult to place the parapets this way. Conversely, the typical current practice of constructing parapets in one continuous placement may add enough restraint to initiate cracking in the parapets.

4.4 Service/Maintenance

Various factors that come into play after a bridge has entered service could have an impact on the initiation and propagation of cracks in the parapets. Some of the possible factors of this type include fatigue effects, impact effects, propagation of cracks from the bridge deck or sidewalk into the parapet, effects of prior crack repairs, and the effects of corrosion.

4.4.1 Fatigue Effects

Fatigue is generally considered to have little effect on concrete structures. However, steel components of a bridge may be susceptible to fatigue, and damage of the steel components due to fatigue may translate to eventual damage of the concrete components.

4.4.2 Impact Effects

Concrete parapets could be damaged by vehicle impact forces. Though concrete parapets are designed to be able to resist the forces from vehicle impacts, a collision could still cause noticeable damage to the parapet, including severe cracking. This does not appear to be a factor in the bridge parapets in this study due to the similar and widespread nature of the crack patterns. However, the rare instances of vehicle impacts still warrant consideration in damaged parapets.

4.4.3 Crack Propagation from Deck and Sidewalk

Many bridges exhibit patterns of transverse cracking through the bridge deck and sidewalk that closely match those found in the parapets. It is possible these transverse cracks originated in the bridge deck or sidewalk due to any number of various factors, and then spread to the parapets through composite action. Typically, the bridge deck, sidewalk, and parapets are all constructed separately. However, the dowel rod connections used to integrate each phase of the construction may be rigid enough to transfer transverse cracks to the adjoining components. Crack propagation from the deck into the parapet would be very difficult to prevent.

4.4.4 Prior Crack Repairs

Some of the bridge parapets in this study have already undergone some type of maintenance procedure on the parapet cracks, generally involving covering the visible cracks with a patching material. In some cases, the cracks have reappeared through the patching material, often causing the cracks to look worse than they actually are. Reevaluating the procedures for patching these cracks may help reduce the likelihood of these cracks becoming an eyesore to bridge users (Issa, 2009).

4.4.5 Traffic Demand

The actual level of traffic demand on a bridge may also be related to premature deterioration of parapets. This is similar to the phenomenon of fatigue discussed earlier. It is worth noting that the case study bridges currently have a significantly greater traffic demand than that predicted in design. In some cases, a bridge could be carrying nearly twice the amount of traffic projected for its twenty year design life, only a few years after its construction.

4.4.5.1 Traffic Vibrations

As discussed in the literature review, some agencies have reported that parapet cracking may be initiated when a bridge with recently constructed parapets is opened to traffic. Since the parapets usually are one of the final steps in the construction or renovation of a bridge deck, it is possible that a bridge may be opened to traffic before the parapets have gained sufficient strength to resist the vibrations caused by traffic flow. This may also introduce weak areas in the parapets that develop cracks later into the bridge’s service life (Cusson, 2000).

4.4.6 Corrosion Effects

Corrosion can affect concrete parapets in many different ways and from a variety of sources. The sooner that a corrosive agent begins to attack a concrete component, the faster the rate of deterioration becomes. In the case of concrete parapets, if the parapet is not properly sealed against moisture and harmful chemicals, severe damage to the concrete such as cracking and spalling is sure to occur once these agents begin to corrode the reinforcement (Kovler, 2009).

CHAPTER V

FIELD OBSERVATIONS AND ANALYSIS

This section summarizes the field work and physical analyses performed for this study. The results of the field work include the following information: field observations, crack measurements and statistics, crack mapping of the Sheldon Road parapets, and various non destructive tests performed on the Sheldon Road parapets. A tabular summary comparing the applicability of some of the most common factors associated with cracked parapets is also provided.

5.1 Field Observations

Specific field observations for each bridge are provided in the case studies section. There are also several general observations that are common among several or all of the case study bridges, as well as many additional bridges within District 12. Some of these observations have been identified as having potentially significant implications with regard to the causes of parapet cracking.

The first major observation is the commonality of crack locations among the studied bridge parapets. These common locations include the following: horizontal cracks located a few inches below the top of the parapets, vertical cracks located approximately midway between control joints, and vertical cracks located near or directly below the vandal protection fence post base plates. The widespread nature of these crack types implies that there may be an inherent flaw in the design and/or construction specifications of certain aspects which contributes to premature cracking of the parapet at these locations. Examples of cracks are shown in Figures 9 through 15.

Figure 9: Vertical crack midway between control joints, Canterbury Road

Figure 10: Crack below VPF base plate, Canterbury Road

Figure 11: Crack below VPF base plate, Sheldon Road

Figure 12: Vertical cracks on inner parapet midway between control joints, Spring Road

Figure 13: Cracking and flaking below VPF base plate, Spring Road

Figure 14: Vertical crack midway between control joints, Wagar Road

Figure 15: Crack below VPF base plate, Wagar Road

Another major observation is that many of the control joints in the parapets are improperly or poorly constructed. Specifications typically call for a ¼ inch (6 mm) wide, 1 ¼ inch (32 mm) deep sawcut joint, spaced in the range of six to ten feet (1.8 to 3.0 m). The sawcut should extend through the full height of the parapet on both sides and is to be filled with a sealant material all the way around the sawcut, except for the bottom two inches at the base of the parapet to allow moisture to drain out. However, the majority of control joints observed in the field contained at least one and sometimes several of the following discrepancies: sawcuts less than 1 ¼ inches (32 mm) deep (often measured to be around ½ inch (13 mm)), poor quality application or complete absence of the joint sealant, joints that are completely sealed to the bottom and do not allow for moisture drainage, sawcuts that terminate several inches above the base of the parapet, and joints located too close to a VPF base plate. These are shown in Figures 16 through 19.

Figure 16: Completely sealed control joint, Canterbury Road

Figure 17: Unsealed control joints with incomplete sawcuts, Sheldon Road

Figure 18: Completely sealed control joint, Spring Road

Figure 19: Completely sealed joint located directly below VPF base plate, Wagar Road

Another major observation is that many of the vertical parapet cracks continue through the sidewalks and bridge deck. These are visible as a completely continuous transverse crack through the concrete deck and superstructure. This phenomenon implies that a high degree of continuity is present between the bridge deck and sidewalk and between the sidewalk and parapets,. High continuity between components subsequently creates a higher degree of composite structural action, as tensile stresses are shared among the components. These are shown in Figures 20 through 22.

Figure 20: Continuous crack through sidewalk, Canterbury Road

Figure 21: Continuous crack through sidewalk, Sheldon Road

Figure 22: Continuous crack through sidewalk, Wagar Road

5.2 Crack Measurements and Statistics

Field work for collecting crack measurements was performed on two separate occasions during the project. The first set of data was collected in September 2011, and the second set of data was collected in February 2012. The purpose of this was to compare the measurements taken during cold weather and warm weather, to determine the effect of seasonal temperatures on the width and severity of cracks in the parapets. Theoretically, the addition thermal contraction created by lower seasonal temperatures could cause the cracks to be wider during the winter months than during the summer months. The data was collected by measuring the distance between visible cracks, the distance between control joints, and the distance between VPF posts on each parapet. The crack measurements also included a measurement of the width and type (either full, top-down, or bottom-up) for each crack.

The data recorded during these measurements was then compiled, and various statistics calculated for each parapet. These statistics are not intended to be used to draw any specific conclusions regarding the causes of parapet cracking. However, comparison of the values between the different bridges as well as the two different sides of each bridge does provide a general qualitative reference for the overall condition of each parapet. As noted previously in the Case Studies Section, many of the cracks observed during these measurements were clearly visible, yet were not wide enough to effectively measure the width of the crack. These cracks were recorded as having a width of 0.005 inches (0.13 mm), the width shown on the crack comparator used for these measurements. In an effort to account for this consideration, some of the statistics calculated were calculated once using all of the recorded cracks, and again excluding the cracks recorded as having the minimum width of 0.005 inches (0.13 mm).

A summary of the resulting crack data and calculated statistics can be seen in the tables below. Table II shows the September 2011 statistics. Table III shows the February 2012 statistics. Table IV shows the differences in each statistical value between the two data sets, where a positive number represents a larger value for the February (cold weather) data set. Similarly in Table 4, a negative value represents a larger value for the September (warm weather) data set. The calculated values shown in these tables should be used simply as a relative comparison between the overall cracking condition and severity of each parapet.

Upon completion of the second set of measurements in February 2012, it was apparent that the parapet cracks had not undergone any significant widening during the period of colder ambient temperatures. This implies that the thermal expansion and contraction caused by changes is seasonal ambient temperatures was not a significant factor in the severity of the parapet cracks. There are some minor differences between the two data sets. However, these differences can be reasonably assumed to be a direct result of the human subjectivity and variability involved in the data collection process. For example, cracks that were marginally visible may have been recorded in one data set but not the other. Some subjectivity was also involved in the measurement of each crack width due to the coarse precision level of the crack comparator.

Table II: Tabular summary of crack data statistics, September 2011

Bridge	Canterbury		Sheldon		Spring		Wagar		
Statistics (September 2011)	East	West	North	South	North	South	East	West	Units
Total number of cracks	49	54	78	63	25	20	34	26	cracks
Total number of cracks (excluding 0.005")	45	18	62	46	5	0	29	20	cracks
Total number of control joints	36	36	27	27	23	23	20	17	joints
Total number of VPF posts	32	32	36	35	38	39	18	15	posts
Total parapet length within VPF extents	274.5	277.2	243.6	238.0	253.9	253.6	152.5	140.0	ft
Total number of cracks per total parapet length	0.18	0.19	0.32	0.26	0.10	0.08	0.22	0.19	cracks/ft
Total number of cracks per total parapet length (excluding 0.005")	0.16	0.06	0.25	0.19	0.02	0.00	0.19	0.14	cracks/ft
Average distance between cracks	5.40	5.07	2.96	3.85	9.95	12.62	4.31	5.17	ft
Average distance between cracks (excluding 0.005")	5.76	14.92	3.68	5.19	49.77	0.00	4.90	6.47	ft
Total number of cracks per total number of control joints	1.36	1.50	2.89	2.33	1.09	0.87	1.70	1.53	cracks/joint
Total number of cracks per total number of control joints (excluding 0.005	1.25	0.50	2.30	1.70	0.22	0.00	1.45	1.18	cracks/joint
Total number of cracks per total number of VPF posts	1.53	1.69	2.17	1.80	0.66	0.51	1.89	1.73	cracks/post
Total number of cracks per total number of VPF posts (excluding 0.005")	1.41	0.56	1.72	1.31	0.13	0.00	1.61	1.33	cracks/post
Average crack width	0.012	0.009	0.008	0.010	0.006	0.005	0.008	0.010	in
Average crack width (excluding 0.005")	0.012	0.018	0.009	0.011	0.008	0.000	0.009	0.012	in
Sum of crack widths	0.567	0.510	0.625	0.609	0.141	0.100	0.288	0.272	in
Sum of crack widths (excluding 0.005")	0.547	0.330	0.545	0.524	0.041	0.000	0.263	0.242	in
Sum of crack widths per foot of parapet length	0.002	0.002	0.003	0.003	0.001	0.000	0.002	0.002	in/ft
Sum of crack widths per foot of parapet length (excluding 0.005")	0.00199	0.00119	0.00224	0.00220	0.00016	0.00000	0.00172	0.00173	in/ft
Sum of crack widths per total number of control joints	0.01575	0.01417	0.02315	0.02256	0.00613	0.00435	0.01440	0.01600	in/joint
Sum of crack widths per total number of control joints (excluding 0.005")	0.01519	0.00917	0.02019	0.01941	0.00178	0.00000	0.01315	0.01424	in/joint
Sum of crack widths per total number of VPF posts	0.01772	0.01594	0.01736	0.01740	0.00371	0.00256	0.01600	0.01813	in/post
Sum of crack widths per total number of VPF posts (excluding 0.005")	0.01709	0.01031	0.01514	0.01497	0.00108	0.00000	0.01461	0.01613	in/post
Number of full cracks	34	34	64	57	7	4	31	21	cracks
Ratio of full cracks to total	0.69	0.63	0.82	0.90	0.28	0.20	0.91	0.81	
Number of top down cracks	7	4	13	2	17	6	3	1	cracks
Ratio of top down cracks to total	0.14	0.07	0.17	0.03	0.68	0.30	0.09	0.04	
Number of bottom up cracks	8	16	1	4	1	10	0	4	cracks
Ratio of bottom up cracks to total	0.16	0.30	0.01	0.06	0.04	0.50	0.00	0.15	
Number of cracks with adjacent sidewalk cracks	34	47	46	57	7	4	24	21	cracks
Ratio of cracks with adjacent sidewalk cracks	0.69	0.87	0.59	0.90	0.28	0.20	0.71	0.81	
Number of cracks with adjacent bridge deck cracks	30	40	15	42	9	5	9	9	cracks
Ratio of cracks with adjacent bridge deck cracks	0.61	0.74	0.19	0.67	0.36	0.25	0.26	0.35	

Table III: Tabular summary of crack data statistics, February 2012

Bridge	Canterbury		Sheldon		Spring		Wagar		
Statistics (February 2012)	East	West	North	South	North	South	East	West	Units
Total number of cracks	54	49	64	53	25	16	31	22	cracks
Total number of cracks (excluding 0.005")	22	22	24	40	4	0	26	22	cracks
Total number of control joints	36	36	27	27	23	23	20	17	joints
Total number of VPF posts	32	32	36	35	38	39	18	15	posts
Total parapet length within VPF extents	274.5	277.2	243.6	238.0	253.9	253.6	152.5	140.0	ft
Total number of cracks per total parapet length	0.20	0.18	0.26	0.22	0.10	0.06	0.20	0.16	cracks/ft
Total number of cracks per total parapet length (excluding 0.005")	0.08	0.08	0.10	0.17	0.02	0.00	0.17	0.16	cracks/ft
Average distance between cracks	5.00	5.62	3.62	4.31	10.28	16.09	4.65	5.85	ft
Average distance between cracks (excluding 0.005")	12.05	12.27	9.49	5.60	61.71	0.00	5.37	5.59	ft
Total number of cracks per total number of control joints	1.50	1.36	2.37	1.96	1.09	0.70	1.55	1.29	cracks/joint
Total number of cracks per total number of control joints (excluding 0.00	0.61	0.61	0.89	1.48	0.17	0.00	1.30	1.29	cracks/joint
Total number of cracks per total number of VPF posts	1.69	1.53	1.78	1.51	0.66	0.41	1.72	1.47	cracks/post
Total number of cracks per total number of VPF posts (excluding 0.005")	0.69	0.69	0.67	1.14	0.11	0.00	1.44	1.47	cracks/post
Average crack width	0.007	0.007	0.006	0.009	0.005	0.005	0.008	0.011	in
Average crack width (excluding 0.005")	0.010	0.010	0.008	0.010	0.008	0.000	0.009	0.011	in
Sum of crack widths	0.382	0.347	0.395	0.451	0.135	0.080	0.262	0.236	in
Sum of crack widths (excluding 0.005")	0.222	0.212	0.195	0.386	0.030	0.000	0.237	0.236	in
Sum of crack widths per foot of parapet length	0.00139	0.00125	0.00162	0.00189	0.00053	0.00032	0.00172	0.00169	in/ft
Sum of crack widths per foot of parapet length (excluding 0.005")	0.00081	0.00076	0.00080	0.00162	0.00012	0.00000	0.00155	0.00169	in/ft
Sum of crack widths per total number of control joints	0.01061	0.00964	0.01463	0.01670	0.00587	0.00348	0.01310	0.01388	in/joint
Sum of crack widths per total number of control joints (excluding 0.005")	0.00617	0.00589	0.00722	0.01430	0.00130	0.00000	0.01185	0.01388	in/joint
Sum of crack widths per total number of VPF posts	0.01194	0.01084	0.01097	0.01289	0.00355	0.00205	0.01456	0.01573	in/post
Sum of crack widths per total number of VPF posts (excluding 0.005")	0.00694	0.00663	0.00542	0.01103	0.00079	0.00000	0.01317	0.01573	in/post
Number of full cracks	48	41	64	53	19	7	30	22	cracks
Ratio of full cracks to total	0.89	0.84	1.00	1.00	0.76	0.44	0.97	1.00	
Number of top down cracks	0	4	0	0	6	1	1	0	cracks
Ratio of top down cracks to total	0.00	0.08	0.00	0.00	0.24	0.06	0.03	0.00	
Number of bottom up cracks	6	4	0	0	0	8	0	0	cracks
Ratio of bottom up cracks to total	0.11	0.08	0.00	0.00	0.00	0.50	0.00	0.00	
Number of cracks with adjacent sidewalk cracks	47	41	49	47	11	3	27	21	cracks
Ratio of cracks with adjacent sidewalk cracks	0.87	0.84	0.77	0.89	0.44	0.19	0.87	0.95	
Number of cracks with adjacent bridge deck cracks	35	28	4	3	9	4	22	17	cracks
Ratio of cracks with adjacent bridge deck cracks	0.65	0.57	0.06	0.06	0.36	0.25	0.71	0.77	

Table IV: Value difference between September 2011 and February 2012 crack statistics

Bridge	Canterbury		Sheldon		Spring		Wagar		
Statistics (Differences from Sept 2011 - Feb 2012)	East	West	North	South	North	South	East	West	Units
Total number of cracks	5	-5	-14	-10	0	-4	-3	-4	cracks
Total number of cracks (excluding 0.005")	-23	4	-38	-6	-1	0	-3	2	cracks
Total number of control joints	0	0	0	0	0	0	0	0	joints
Total number of VPF posts	0	0	0	0	0	0	0	0	posts
Total parapet length within VPF extents	0	0	0	0	0	0	0	0	ft
Total number of cracks per total parapet length	0.02	-0.02	-0.06	-0.04	0.00	-0.02	-0.02	-0.03	cracks/ft
Total number of cracks per total parapet length (excluding 0.005")	-0.08	0.01	-0.16	-0.03	0.00	0.00	-0.02	0.01	cracks/ft
Average distance between cracks	-0.40	0.56	0.65	0.46	0.33	3.48	0.34	0.68	ft
Average distance between cracks (excluding 0.005")	6.29	-2.65	5.81	0.42	11.94	0.00	0.47	-0.88	ft
Total number of cracks per total number of control joints	0.14	-0.14	-0.52	-0.37	0.00	-0.17	-0.15	-0.24	cracks/joint
Total number of cracks per total number of control joints (excluding 0.005	-0.64	0.11	-1.41	-0.22	-0.04	0.00	-0.15	0.12	cracks/joint
Total number of cracks per total number of VPF posts	0.16	-0.16	-0.39	-0.29	0.00	-0.10	-0.17	-0.27	cracks/post
Total number of cracks per total number of VPF posts (excluding 0.005")	-0.72	0.13	-1.06	-0.17	-0.03	0.00	-0.17	0.13	cracks/post
Average crack width	-0.004	-0.002	-0.002	-0.001	0.000	0.000	0.000	0.000	in
Average crack width (excluding 0.005")	-0.002	-0.009	-0.001	-0.002	-0.001	0.000	0.000	-0.001	in
Sum of crack widths	-0.185	-0.163	-0.230	-0.158	-0.006	-0.020	-0.026	-0.036	in
Sum of crack widths (excluding 0.005")	-0.325	-0.118	-0.350	-0.138	-0.011	0.000	-0.026	-0.006	in
Sum of crack widths per foot of parapet length	-0.001	-0.001	-0.001	-0.001	0.000	0.000	0.000	0.000	in/ft
Sum of crack widths per foot of parapet length (excluding 0.005")	-0.00118	-0.00043	-0.00144	-0.00058	-0.00004	0.00000	-0.00017	-0.00004	in/ft
Sum of crack widths per total number of control joints	-0.00514	-0.00453	-0.00852	-0.00585	-0.00026	-0.00087	-0.00130	-0.00212	in/joint
Sum of crack widths per total number of control joints (excluding 0.005")	-0.00903	-0.00328	-0.01296	-0.00511	-0.00048	0.00000	-0.00130	-0.00035	in/joint
Sum of crack widths per total number of VPF posts	-0.00578	-0.00509	-0.00639	-0.00451	-0.00016	-0.00051	-0.00144	-0.00240	in/post
Sum of crack widths per total number of VPF posts (excluding 0.005")	-0.01016	-0.00369	-0.00972	-0.00394	-0.00029	0.00000	-0.00144	-0.00040	in/post
Number of full cracks	14	7	0	-4	12	3	-1	1	cracks
Ratio of full cracks to total	0.20	0.21	0.18	0.10	0.48	0.24	0.06	0.19	
Number of top down cracks	-7	0	-13	-2	-11	-5	-2	-1	cracks
Ratio of top down cracks to total	-0.14	0.01	-0.17	-0.03	-0.44	-0.24	-0.06	-0.04	
Number of bottom up cracks	-2	-12	-1	-4	-1	-2	0	-4	cracks
Ratio of bottom up cracks to total	-0.05	-0.21	-0.01	-0.06	-0.04	0.00	0.00	-0.15	
Number of cracks with adjacent sidewalk cracks	13	-6	3	-10	4	-1	3	0	cracks
Ratio of cracks with adjacent sidewalk cracks	0.18	-0.03	0.18	-0.02	0.16	-0.01	0.17	0.15	
Number of cracks with adjacent bridge deck cracks	5	-12	-11	-39	0	-1	13	8	cracks
Ratio of cracks with adjacent bridge deck cracks	0.04	-0.17	-0.13	-0.61	0.00	0.00	0.44	0.43	

5.3 Sheldon Road Crack Mapping

Crack maps were developed for the Sheldon Road bridge parapets by photographing the entire length of the parapet in ten foot wide sections. Lengths of ten feet were measured and marked on the parapet with white colored chalk, beginning at ending at the construction joint on either end of the bridge. For both the north and south parapets, measurements began at the west construction joint. Hence, the numbers shown on the north parapet photographs increase from left to right, while on the south parapet photographs they increase from right to left. Major cracks were highlighted with another color of chalk for better visibility in the photographs. A photo of each ten foot section was taken, creating a detailed view over the entire length of the parapet of all the major cracks and their location along the bridge length. Crack map photos for the north parapet can be found in Appendix A. Crack map photos for the south parapet can be found in Appendix B.

5.4 Sheldon Road Non Destructive Evaluations

In conjunction with the crack mapping, several non destructive evaluation methods were used on the Sheldon Road parapets to get a better understanding of the actual condition of the parapets. A rebound hammer was used to compare relative values of the surface hardness of the concrete at various points throughout the parapets. A cover meter was used to determine the location and size of the vertical reinforcing bars at various points throughout the parapets. The cover meter was also used with its “scan map” function to determine spacing between vertical bars along the lengths of the parapets.

The rebound hammer tests were intended to be used to identify any locations along the parapet where the resulting rebound number was significantly different from the rebound numbers recorded at other locations along the parapet. A large difference in the rebound number at a particular location would indicate a difference in the properties of the concrete in the corresponding section of parapet. However, after several trials were conducted with the rebound hammer at multiple locations, it became apparent that the resulting rebound numbers were highly sensitive to many uncontrollable factors. It was determined that the rebound hammer was not able to produce consistent enough results to provide useful information under these conditions. These tests were abandoned since no reasonable conclusions would be offered regarding the consistency of the concrete properties throughout the parapets.

The cover meter was used to determine the location and size of the horizontal reinforcing bars at various points along the parapet length. This information could not be recorded due to the sensitivity required in operating the cover meter. However real-time readings were used by the operators to draw conclusions. Though measurements for both the amount of cover and relative height within the parapet displayed minor variations among different trials and locations, the results appeared to be fairly consistent throughout the parapets. This indicates that, in general, the horizontal reinforcement in the parapets was constructed properly and showed no obvious discrepancies from the construction plans.

The cover meter's "scan map" function was used to determine the spacing between the vertical bars for the entire length of each parapet. This function works by taking continuous cover readings along a specified length, from which the locations of the bars can be determined by identifying the low values points in the graph generated from this data. The device was set to record data in intervals of 48 feet (14.6 m), however this process was repeated for every 40 foot (12.2 m) section of the parapet in order to make to it easier to identify the location where each scan map begins. Hence, each parapet required six separate scan maps of 48 feet (14.6 m) – where the final eight feet of each map is repeated in the first eight feet (2.4 m) of the next map – to cover the full distance of 226 feet (68.9 m) between the construction joints on either end of the bridge. These maps show a typical spacing of approximately 12 inches (305 mm). This again indicates that, in general, the parapet reinforcement was constructed properly. The scan maps for the north parapet can be found in Appendix C. The scan maps for the south parapet can be found in Appendix D.

5.5 Summary of Key Evidence

In the preliminary stages of the project, several hypotheses were presented which summarize the key points of the investigation. Throughout the research, information has been collected which either supports or refutes certain hypotheses. These key hypotheses, and the available evidence used to evaluate each of them, are summarized below in Table V.

Table V: Summary of Key Evidence

Hypothesis	Supporting Evidence	Refuting Evidence
Concrete mixture used in parapets	Concrete mixture used for parapets has a much higher strength and stiffness than necessary, which may be vulnerable to excessive shrinkage.	Recent changes in the concrete mixture typically used for parapets have shown a lower cracking tendency.
Parapet construction techniques	The types of cracks found on the investigated bridge parapets show a high degree of similarity.	ODOT has historically avoided the slipform method for parapet construction. This method has been shown in other states to greatly reduce the durability of concrete parapets.
Structural effects on parapets	Studies have shown that parapets can still absorb a significant portion of the live load stresses when constructed compositely with the bridge deck.	Parapet cracks did not appear to be more frequent in the negative moment regions of the investigated bridges, as would be expected from the high tensile stresses in these locations.
Parapet joint details	Older parapet specifications showed a lower tendency toward premature cracking than the new specifications used on the case study bridges.	Parapet cracks appear in other locations besides those influenced by the effectiveness of the control joints.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Scope of Parapet Cracking On District 12 Bridges

The problem of prematurely cracked concrete bridge parapets can be seen on bridges throughout District 12 and other districts throughout the state of Ohio. The literature review found that this problem has been recognized by several other agencies throughout North America. However, the type of deterioration reported in other instances appears to be slightly different than the cracks seen on District 12 parapets. While other agencies identified problems such as slipform construction and joint sealant materials, the cracks seen on ODOT District 12 bridges show a high frequency of cracking between control joints and near the vandal protection fence posts. The four case study bridges all displayed nearly identical patterns of parapets cracks and were all constructed within about a six year time frame. Similar types of parapet deterioration can commonly be seen on many other District 12 bridges that were built during the same time period and are of similar structural design. Therefore, the factors which have been identified as the probable causes of cracking for the case study bridges are most likely applicable to many other bridges throughout District 12 as well as the state of Ohio.

6.2 Factors Most Likely Causing Parapet Cracking

Section 4 discussed all of the relevant hypotheses that were considered potential causes of parapet cracking for the purposes of this study. Analysis of the available information has led to the identification of the following factors as the most likely causes on parapet cracking on District 12 bridges.

6.2.1 Ineffective Control Joints

The majority of the sawcut control joints observed appeared to be inadequate in controlling vertical cracks in the concrete parapets. Vertical cracks were most frequently found approximately halfway between the sawcut joints. The inability of these joints to attract and limit cracking to these areas is probably a factor of both the design and construction of these joints.

6.2.1.1 Construction

Many of the observed control joints displayed obvious deficiencies that did not conform to the construction plans. Sawcut depths were commonly much shallower than the 1 ¼ inch (32 mm) depth specified. Many joints contained incomplete sawcuts that terminated several inches above the base of the parapet. When control joints are constructed in this manner, it seems apparent that these joints may not control the severity of cracks, and may not be any more likely to initiate cracks at all, as opposed to other cross sections. Some joints were also either completely sealed or completely unsealed, instead of being sealed with a one inch (25 mm) gap at the bottom of the parapet as per the specifications. This allows water to become trapped in the joint, and potentially causes serious deterioration with freezing and thawing temperatures.

In addition, it seems probable that the typical specification for constructing these control joints is not sufficient to effectively control cracks. In order to effectively control early age cracking, the joints must be cut during a very narrow window of time during the curing process. It is conceivable that the sawcut operations commonly occur too late, after shrinkage cracks have already begun to develop. However, the contractor is also limited by the removal of the formwork before the sawcut operations can be performed. In this way, the construction method itself seems to present obvious deficiencies as an effective method of crack control.

6.2.1.2 Design

The design of the sawcut control joints also appears to be insufficient. These parapets are usually constructed in one continuous placement of concrete, with single continuous lengths of reinforcement over the entire bridge length. Concrete structures constructed in a continuous manner should necessitate the use of a high quality and reliable method of crack control, which is clearly not present in this method of constructing concrete parapets. These joints need to be designed to be more effective than they are at present. Possible alternative designs that would be more effective could include shorter spacing between joints, forming joints by placing inserts within the formwork instead of sawcutting afterwards, and/or designing the system of reinforcement to be discontinuous at the control joints.

6.2.2 VPF Post Base Plates

Another common type of parapet vertical crack extended downward from the vandal protection fence post base plates. This may be due to excessive wind forces on the fence, which are then transferred to the parapet via the posts and base plates. The stresses on each post could be reduced by shortening the spacing between posts. This would reduce the concentration of stresses at each post anchorage, possibly enough to prevent the formation of cracks. These types of cracks may also be due to the development of a plane of weakness at these locations from the base plate anchorage details. Damage may also be caused during the installation process. Redesign of the post anchorage details or installations method may be necessary to prevent cracking.

6.2.3 Excessive Drying Shrinkage

Concrete bridge parapets may be prone to premature cracking due to excessive drying shrinkage of the concrete during curing. Drying shrinkage can be caused by multiple factors such as ambient temperature and moisture conditions, and internal temperatures created by the hydration process, and the internal moisture content of the concrete. Ensuring the use high quality curing procedures – like providing a constant source of moisture and monitoring ambient temperatures for the concrete to gain adequate strength – is a necessity. It is also worth noting that the strength of the concrete specified for these parapets (4,500 psi or 31 MPa) seems unnecessarily high for parapet applications. High strength concrete is typically more prone to drying shrinkage, due to its relatively low water-cementitious materials ratio. The use of a lower strength concrete may reduce the concrete’s susceptibility to drying shrinkage cracks.

6.2.4 Composite Structural Action

Concrete bridge parapets are typically designed assuming that the parapet does not act compositely with the bridge deck. However, observation of the current construction methods would indicate that at least a small portion of structural load gets shared with the sidewalk and bridge deck. As discussed in the literature review, one study showed that concrete parapets may contribute up to 25% of the total stiffness of the structure. This implies that the current method of designing parapets to ignore live load stresses may not be conservative. In addition, construction methods may need to be reevaluated in order to reduce between the parapet, sidewalk, and bridge deck.

6.2.5 Poorly Consolidated Concrete (Horizontal Cracks)

Another common type of parapet cracking is horizontal cracks located a few inches below the top of the parapet, along the top layer of horizontal reinforcement. This type of deterioration is obvious on many District 12 bridges, often with the top layer of concrete spalling off completely. Poor consolidation of the concrete below this top layer of reinforcement has been recognized as the possible cause of this problem. ODOT seems to have already taken measures to remedy this problem in recent years by using one #6 bar (19 mm) at the top of the parapet instead of two #5 bars(16 mm). This change allows better consolidation of the concrete around the single bar and recent observations indicate that the adjustment has been effective thus far.

6.3 Recommendations

Several general recommendations can be made regarding the problem of prematurely cracked concrete bridges parapets, which are discussed below. Details for the implementation of these recommendations are discussed in Section 7.

6.3.1 Recommendations for Remediation

At this time, the current techniques of patching and sealing cracks, and repainting parapets, seem to be the only realistic methods of repairing cracked parapets. This does not truly repair the cracks since they will most likely eventually reopen from the same displacements that initially caused them. In addition, some of the crack repairs appeared to make the cracks look worse than they would otherwise. However, sealing cracks will increase the parapet's durability by preventing moisture any other deleterious substances from entering the crack, preventing accelerated deterioration of the parapet. Alternative sealing materials or repair techniques should be investigated.

6.3.2 Recommendations for Future Prevention

Several possible measures are available for attempting to prevent the issue of prematurely cracked parapets on future bridges. These measures include making appropriate adjustments to design specifications such as the following: VPF post spacing, VPF post base plate anchorage details, control joint spacing, concrete and reinforcement continuity of parapets, and methods of construction control joints. It is also important to make designers and contractors more aware of this problem so as to demand more of their attention as well as to promote better, more reliable quality control procedures during construction.

6.3.3 Recommendations for Future Research

Future research into this problem could be valuable. Monitoring of parapet conditions on newly constructed bridges would provide more insight into the time at which parapet cracks initiate and the rate at which they further deteriorate. Also, if adjustments to design specifications are considered, monitoring of the effects of these changes through field test sections can give designers and contractors a better idea what the most effective and cost efficient solutions might be. Some specific objectives that could possibly be pursued in future research include the following:

- Discussions and interviews with personnel from other DOTs regarding various parapet details used. This would include assembling DOT parapet details from many locations, along with their performance history.
- Finite Element Modeling of shrinkage and temperature effects.
- Discuss possible case studies with other ODOT districts.
- Revise details for vandal protection fence.
- Develop improved curing procedures for concrete parapets, possibly through the use of internal curing or shrinkage compensating concrete.
- Use of polymer fibers in the concrete mix to reduce cracking and provide resilience after impact.

CHAPTER VII

IMPLEMENTATION PLAN

7.1 Recommendations for Implementation

Specific recommendations for implementing the findings of this research are discussed below.

7.1.1 Industry Awareness

The first step in the implementation process should be to spread awareness among industry professionals of the problems associated with premature cracking of concrete bridge parapets. This group should include designers, contractors, and inspectors. Designers who are informed about the causes of parapet cracking should give this greater consideration during the design of the parapets by adopting more conservative crack control methods, thereby increasing the durability of the parapets. Contractors can use this information to adhere to stricter quality control procedures during construction, ensuring durability of the built structure. In addition, inspectors should use this knowledge as a means of providing better quality control and to encourage earlier detection of these types of problems.

7.1.2 Parapet Condition Evaluations

For in-service bridges that already exhibit signs of premature parapet cracking, it is suggested that a more detailed procedure for evaluating the structural and aesthetic condition of the parapets should be developed. This could allow a threshold level for parapet deterioration to be specified, beyond which replacement is deemed necessary. Some of the crack data statistics discussed in Section 5 could be a possible means for establishing this quantitative threshold for parapet deterioration.

7.1.3 Changes to Design Specifications

As discussed in Section 6, the most effective way of preventing premature cracking of bridge parapets in the future would be to adopt new design or construction specifications for any of the factors suspected of causing these cracks. It is strongly suggested that any or all of the following adjustments be considered:

1. Use a smaller spacing between parapet control joints.
2. Use a smaller spacing between vandal protection fence posts.
3. Form control joints by placing inserts in the formwork prior to pouring the concrete.
4. Use discontinuous lengths of reinforcement, with a gap at each control joint.

7.2 Expected Benefits of Implementation

The expected benefits of these implementation steps are that the frequency of uncontrolled premature cracking in concrete bridge parapets be significantly reduced in future construction, and hopefully eliminated altogether.

7.3 Potential Risks and Obstacles to Implementation

The only potential obstacles to this implementation process are the receptiveness to this information of the involved parties and their willingness to adopt the necessary changes. This applies to both designer and contractors alike.

7.4 Potential Users and Other Relevant Organizations

The potential users of this implementation are expected to be bridge designers, contractors, inspectors and various ODOT Construction and Engineering personnel.

7.5 Estimated Costs

The estimated costs of this implementation are not expected to be significant. Potential costs include those needed to make the appropriate changes to design or construction specifications and the costs of disseminating information to the appropriate personnel. It can be expected that construction costs would increase slightly if a more labor-intensive specification is adopted.

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APPENDICES

Appendix A: Sheldon Road, North Parapet, Crack Map Photographs

Figure 23: 0-10 feet

Figure 24: 10-20 feet

Figure 25: 20-30 feet

Figure 26: 30-40 feet

Figure 27: 40-50 feet

Figure 28: 50-60 feet

Figure 29: 60-70 feet

Figure 30: 70-80 feet

Figure 31: 80-90 feet

Figure 32: 90-100 feet

Figure 33: 100-110 feet

Figure 34: 110-120 feet

Figure 35: 120-130 feet

Figure 36: 130-140 feet

Figure 37: 140-150 feet

Figure 38: 150-160 feet

Figure 39: 160-170 feet

Figure 40: 170-180 feet

Figure 41: 180-190 feet

Figure 42: 190-200 feet

Figure 43: 200-210 feet

Figure 44: 210-220 feet

Figure 45: 220-226 feet

Appendix B: Sheldon Road, South Parapet, Crack Map Photographs

Figure 46: 0-10 feet

Figure 47: 10-20 feet

Figure 48: 20-30 feet

Figure 49: 30-40 feet

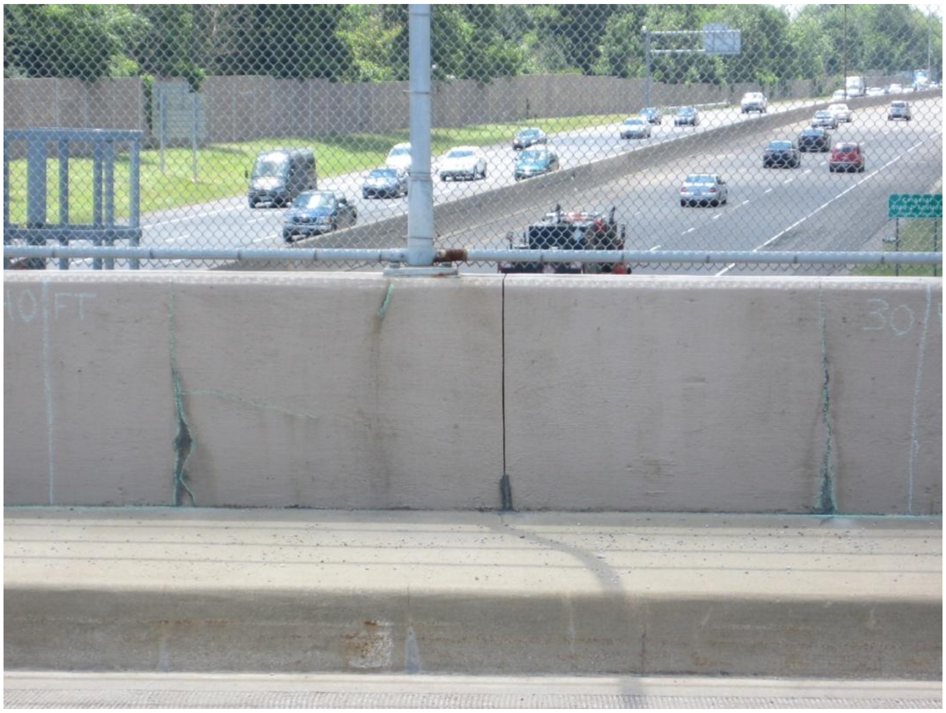


Figure 50: 40-50 feet

Figure 51: 50-60 feet

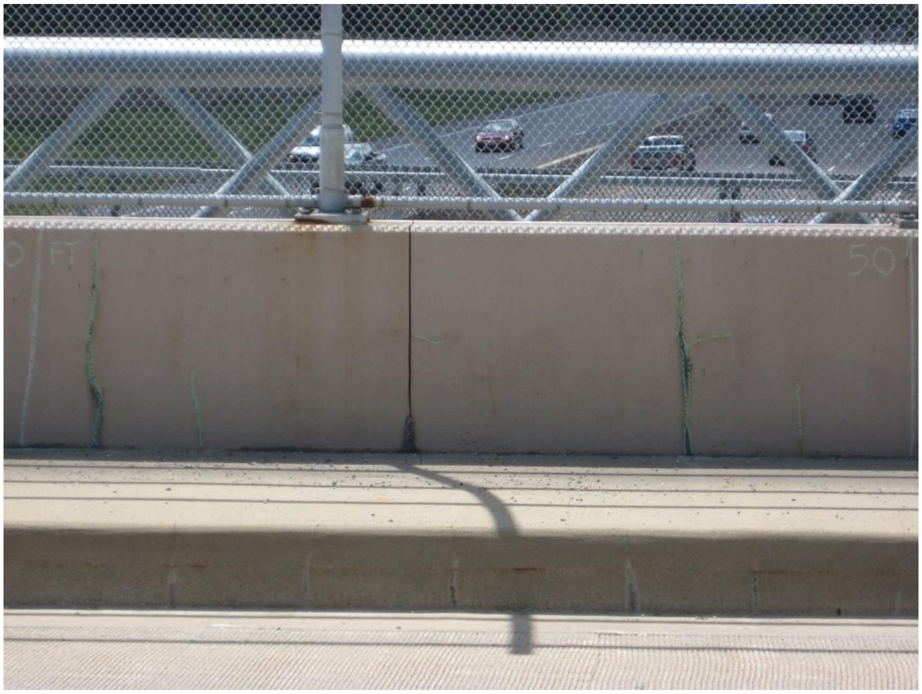


Figure 52: 60-70 feet

Figure 53: 70-80 feet

Figure 54: 80-90 feet

Figure 55: 90-100 feet

Figure 56: 100-110 feet

Figure 57: 110-120 feet

Figure 58: 120-130 feet

Figure 59: 130-140 feet

Figure 60: 140-150 feet

Figure 61: 150-160 feet

Figure 62: 160-170 feet

Figure 63: 170-180 feet

Figure 64: 180-190 feet

Figure 65: 190-200 feet

Figure 66: 200-210 feet

Figure 67: 210-220 feet

Figure 68: 220-226 feet

Appendix C: Sheldon Road, North Parapet, Scan Maps of Vertical Reinforcing Bars

Figure 69: 0-48 feet

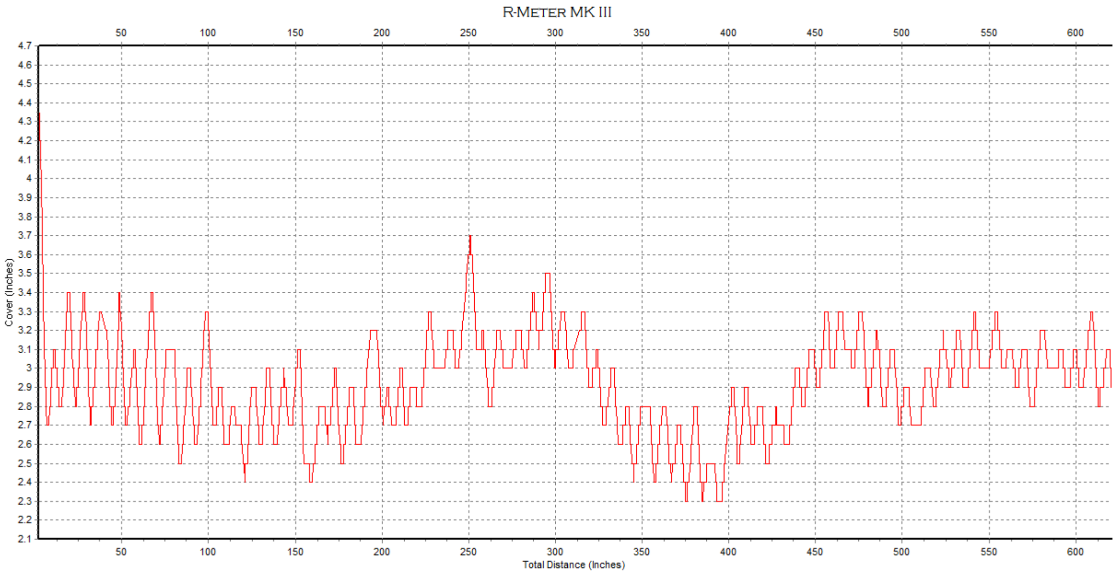


Figure 70: 40-88 feet

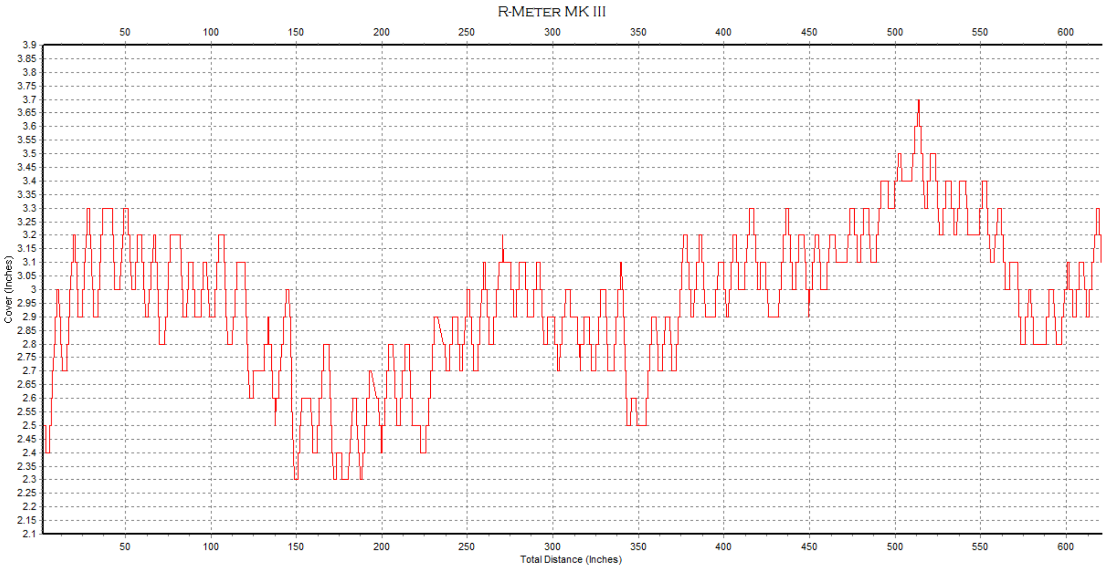


Figure 71: 80-128 feet

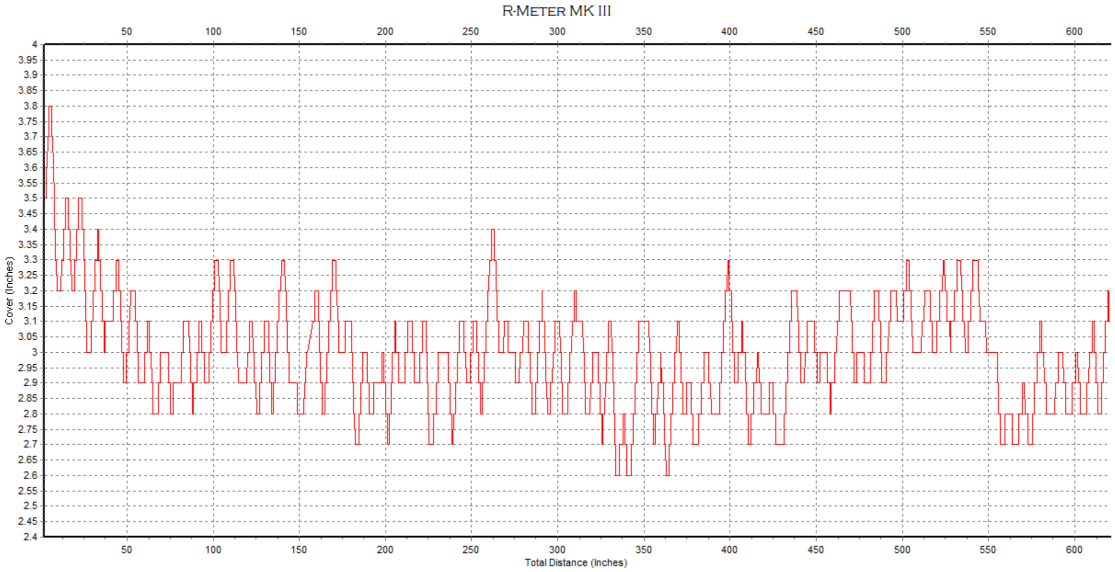


Figure 72: 120-168 feet

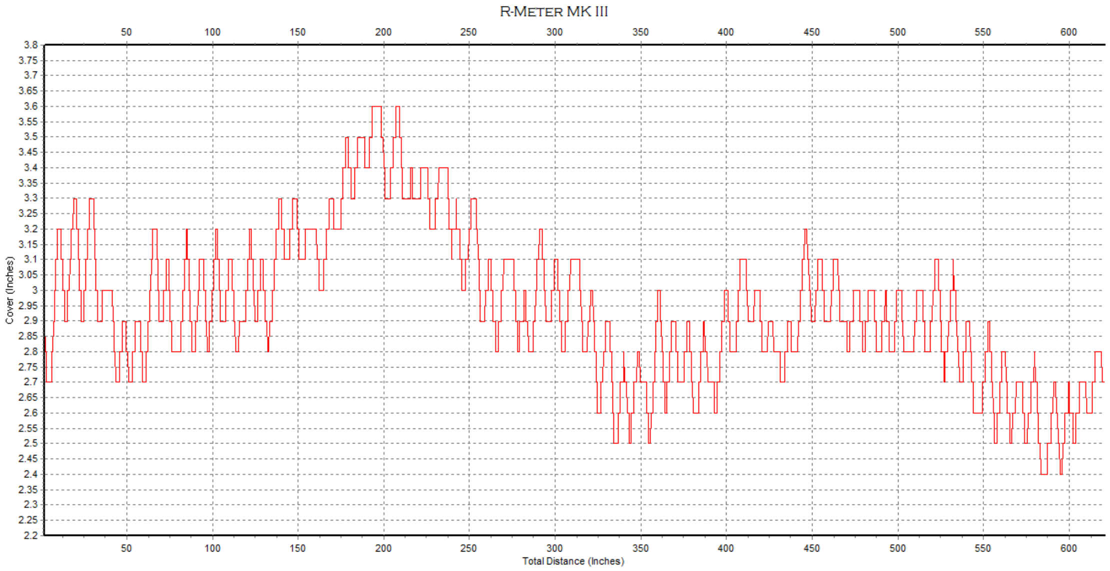


Figure 73: 160-208 feet

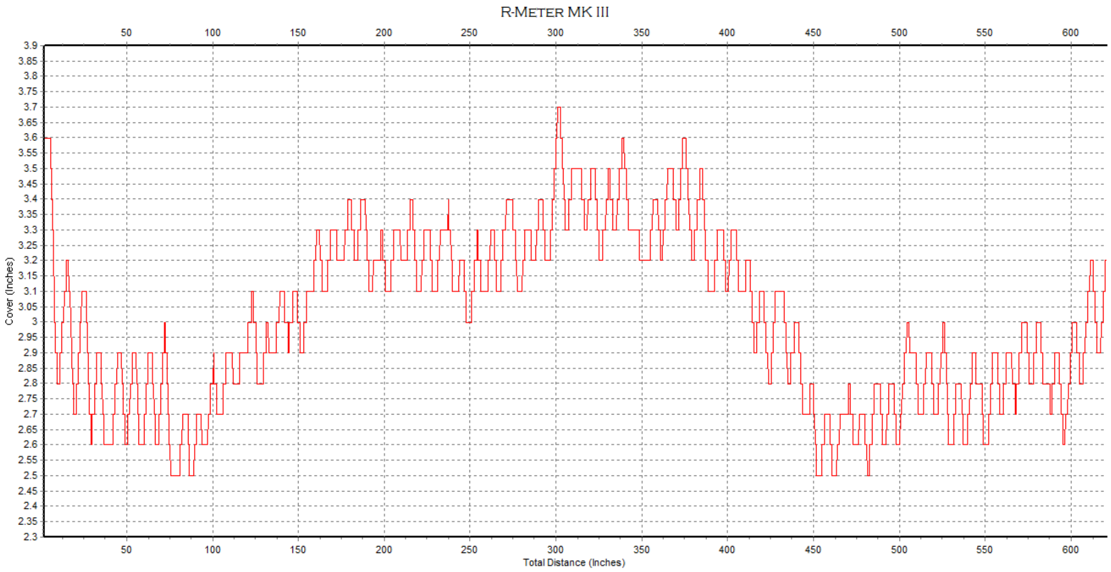
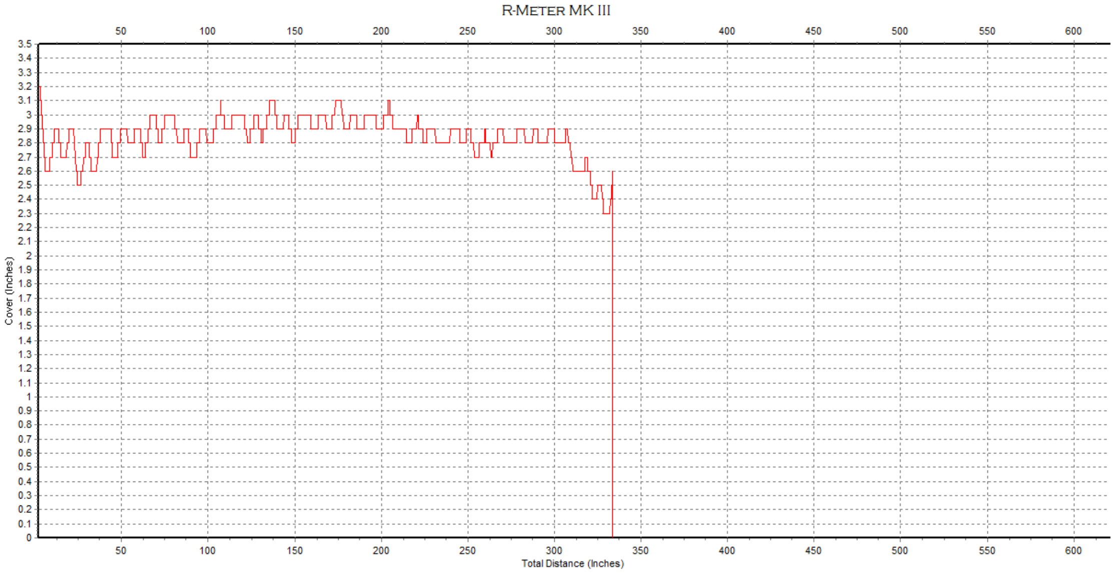


Figure 74: 200-226 feet



Appendix D: Sheldon Road, South Parapet, Scan Maps of Vertical Reinforcing Bars

Figure 75: 0-48 feet

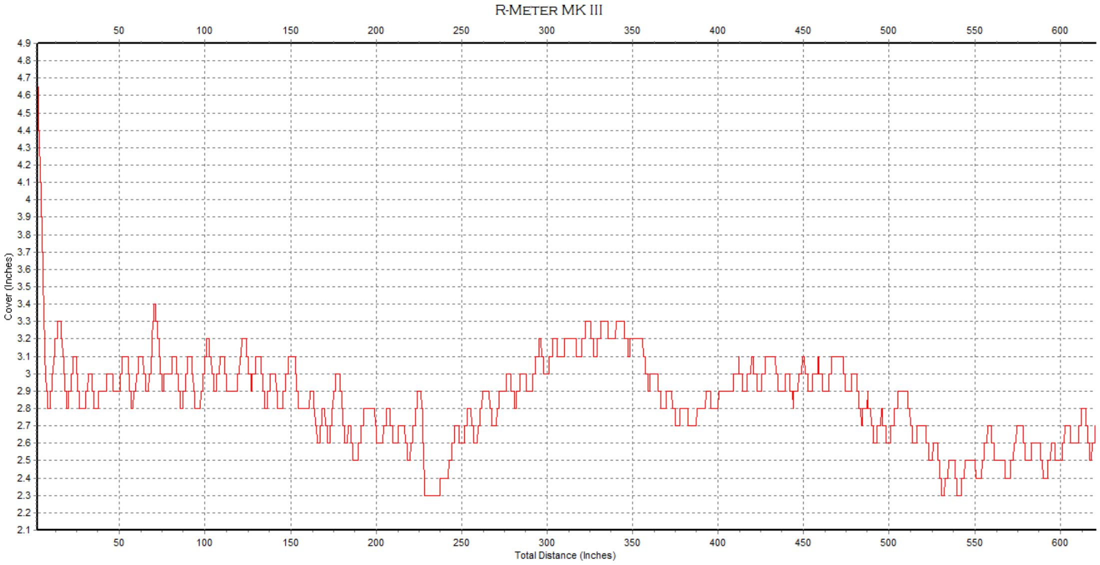


Figure 76: 40-88 feet

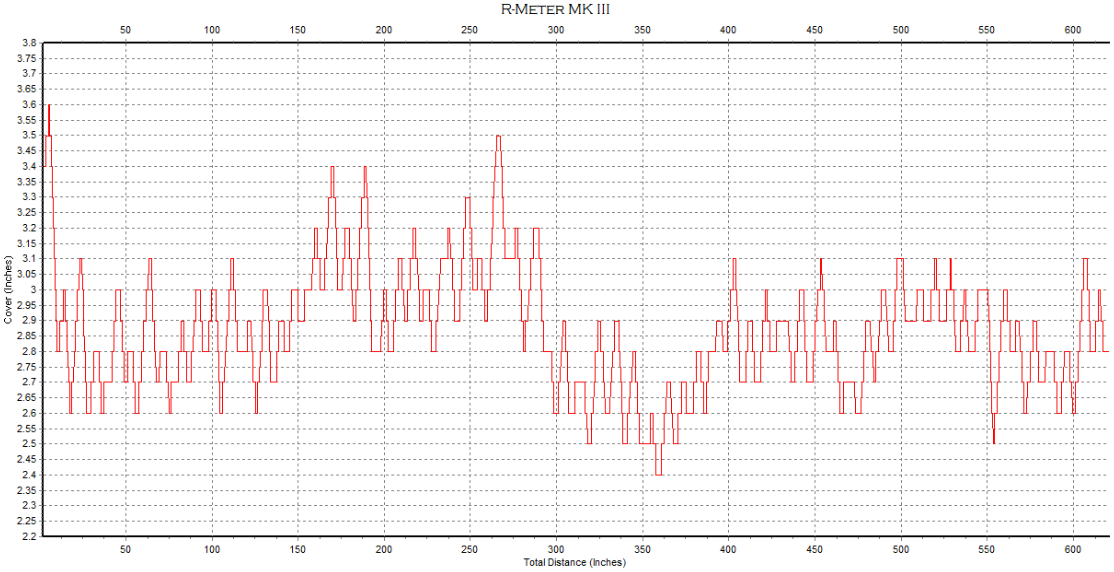


Figure 77: 80-128 feet

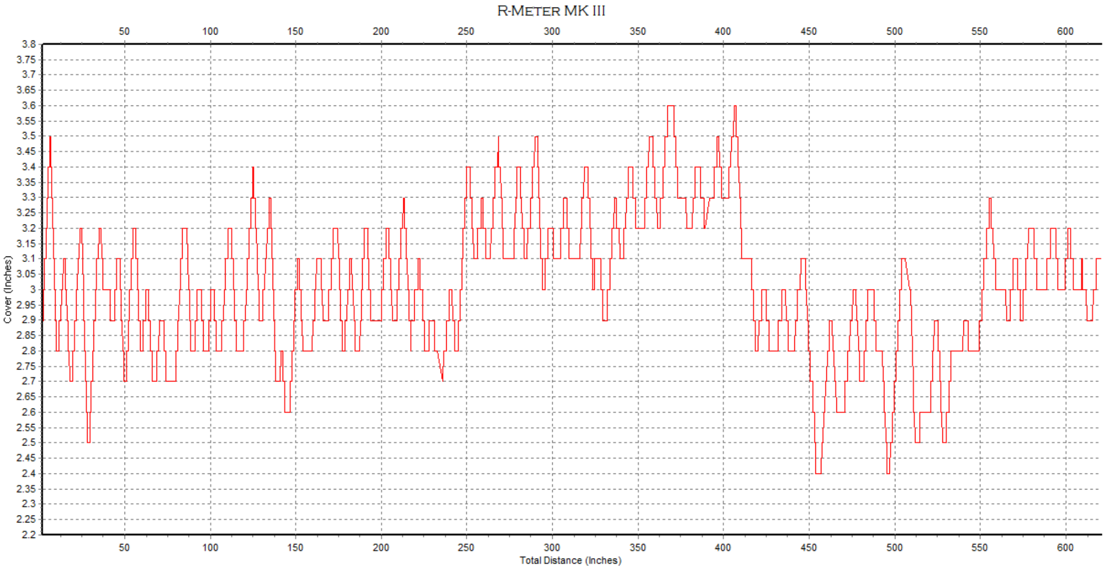


Figure 78: 120-168 feet

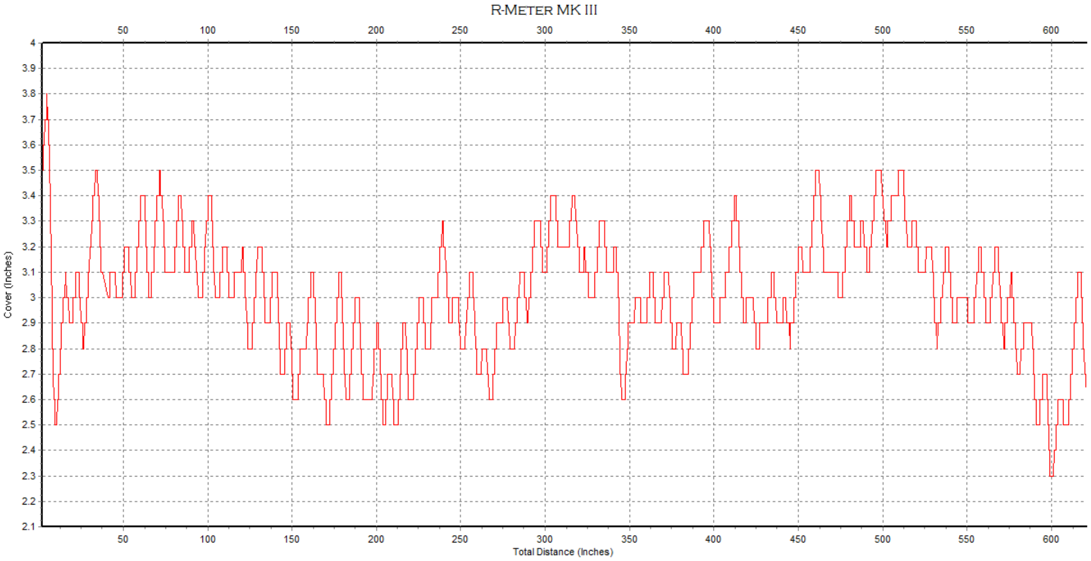


Figure 79: 160-208 feet

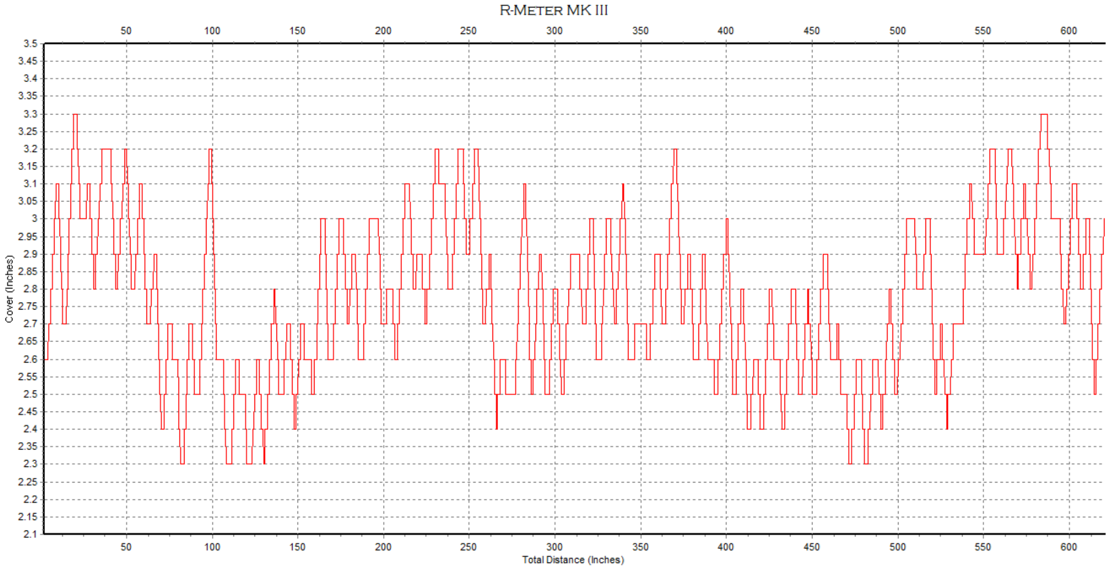


Figure 80: 200-226 feet