NEW ENGLAND TRANSPORATION CONSORTIUM

CURVED INTEGRAL ABUTMENT BRIDGE RESEARCH - LITERATURE REVIEW

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1 LITERATURE REVIEW

1.1 INTRODUCTION

The development of integral abutment bridges (IAB) for relatively short structures (50 feet – 100 feet) began in the 1930's in the United States, New Zealand and Australia. The experimental nature of these developments and the lack of rational design guidelines meant that increases in allowable length for future structures would be based empirically on the bridge owner's experience with successful in-service prototypes. As a result, each highway agency developed unique limitations and guidelines for integral abutment bridges [1].

In the early 1960's, a study of nationwide bridge maintenance requirements determined that joints and bearings are a major source of bridge maintenance problems, and bridge engineers observed that bridges constructed without expansion joints were in service longer and required less maintenance than bridges constructed with expansion joints. (See Figure 1.1) [2]. While many of the jointless bridges had cracking in their abutments, these cracks were not detrimental to serviceability. In general, jointless bridges did not experience the same level of maintenance distress as did jointed bridges [3]. The movement previously accommodated with deck end expansion joints is shifted to a flexible pile supported substructure in an IAB system. Integral abutment structures gained popularity for straight crossings as the need to extend the service life and reduce life cycle costs became priorities for state Departments and Agencies of Transportation. Many states now provide simplified design methods or significant guidelines for design of these structures.

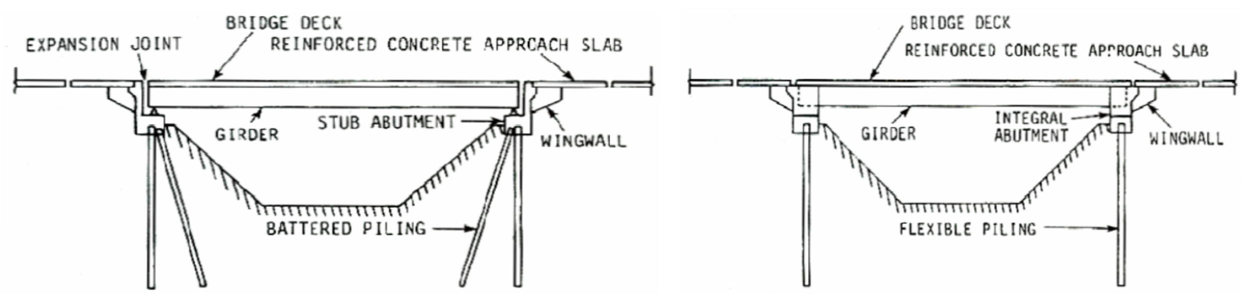

Figure 1.1 - Schematic of a Jointed Bridge (Left) and an Integral Abutment Bridge (Right) [2]

Bridge locations were historically determined by the most convenient crossing site with little regard to the general alignment of the roadway, with the highway designer or surveyor laying out the highway to match the chosen crossing. As costs and concerns associated with right of way acquisitions, earthwork, and permitting increased, the need to design the bridge to fit the most economical roadway alignment became apparent, often resulting in crossings located on a curved alignment.

While standards and guidelines for straight integral abutments have developed substantially, less guidance is available for curved integral structures. Some research has been done to further understand the in-service behaviors of curved integral abutment bridges and how designers can best predict and account for these behaviors during design, which will be discussed within this literature review. [1] [4] [5] [6] [7] [8]

This research effort is focused on the development of guidance for simplified design procedures for horizontally curved steel girder integral abutment bridges. A set of three-dimensional finite element models will be used to perform a parametric study to investigate the effect of various design parameters on the structural behavior of these structures. Parameters that are included in this study are: span length, radius of curvature, abutment skew angle, pile length and orientation, and wingwall orientation. The set of analysis models will consider the complete bridge including the superstructure, substructure and soil-structure interaction on the abutment backwall.

The purpose of this literature review is to document previous work in the design of curved girder integral abutment bridges to inform the practices, parameters, and key results of this finite element model study. Current New England Transportation Consortium (NETC) state and federal guidelines for curved steel I-girder bridges and straight integral abutment bridges were the primary sources to develop the basis for this study. Relevant published research relating to curved integral abutment bridge design and behavior, as detailed below, was then used to refine and confirm the modeling practices, study parameters, and key model outputs that will be included in this research.

1.2 STATE AND FEDERAL GUIDANCE

As individual states recognized the benefits of jointless structures, they developed their own guidelines and standards for IAB's. This often resulted in highly variable requirements from state to state, including assumptions related to pile behavior and guidelines for estimating and designing for the passive pressure developed in the abutment backfill due to longitudinal effects. The American Association of State and Highway Transportation Officials (AASHTO) Load and Resistance Factor Design (LRFD) Bridge Design Specifications outline design requirements for curved superstructures, but guidance associated with integral abutments (whether curved or straight) is still limited. Therefore, design engineers use state design codes as the primary source of information and design standards for these structures.

New England Transportation Consortium states encourage the use of integral abutments for new bridges to decrease the maintenance burden of the bridge inventory. For example, article 2.4.1 of the Vermont Agency of Transportation (VTrans) Structures Design Manual [9] states that "the Agency considers the integral abutment as the primary choice for bridges in the state". The following sections present readily available recommendations from NETC state design guidelines and federal agencies regarding the design of straight integral abutment bridges and traditional curved steel beam bridges. Information and guidance from states outside of New England are not specifically included in this review. The results of a nationwide survey will be addressed in the Task 3 submission, and any applicable design guidance resulting from the survey will be addressed at that time.

1.2.1 DESIGN GUIDELINES FOR STRAIGHT IAB'S

State requirements for the design, analysis, and detailing of integral abutment bridges are generally provided in their respective Bridge Design Manuals, however Vermont has issued an Integral Abutment Bridge Design Guideline document that is to be used in conjunction with their Structures Manual. Table 1.1 provides a summary of relevant design requirements and limitations for straight integral abutment bridges from NETC member states. In the cases of Massachusetts [10], Vermont [11], and New Hampshire [12], a simplified design method for integral abutment bridges is available with the necessary criteria reflected in Table 1.1. When requirements for simplified approaches are not met, a detailed analysis is required. Maine [13], Connecticut [14], and Rhode Island [15] do not specify separate design guidance for simplified or refined procedures. Further discussion of simplified methods will be provided in the final report.

SUPERSTRUCTURE DESIGN

The common approach for the design of the superstructure in an IAB is to design the girders assuming two unique sets of support conditions. For positive moment regions, the girders are considered simply supported, where no rotational restraint is present at the abutments. This process accounts for the uncertain rotational fixity present at the abutments and results in a conservative design for positive moment in the superstructure. For negative moment regions, frame action is recommended for determining the demand on the girders due to composite loads. Frame action is also considered when determining strength and serviceability requirements for reinforcement at deck ends to limit cracking due to the tensile stresses resulting from negative flexure. The FHWA Steel Bridge Design Handbook notes that neglecting the development of negative moments at deck ends may result in deck cracking and / or overstress of girder flanges [16].

Approach slabs are required for use with integral abutment bridges in all NETC states to remove live load surcharge from the abutment and reduce settlement of the pavement structure [9] [10] [12] [13] [14] [15]. The details of the approach slab and pavement joint details vary significantly with the states. All member states except for Maine and Massachusetts generally require at grade approach slabs. Maine prefers the use of below grade approach slabs seated on the lower abutment stem, however, it does allow for at grade slabs with sleeper slabs, particularly for long span integral abutment bridges. The thickness varies from 8" for MaineDOT to 15" for NHDOT, CTDOT and VTrans, with VTrans using 16" slabs when 25' lengths are required at high skews. States such as New Hampshire and Rhode Island routinely utilize sleeper slabs at the far end, which allow for more substantial joint structures to be implemented where needed. Several states use poly sheeting below the slabs to accommodate movement. Massachusetts requires that the approach slabs are keyed into the backfill and remain motionless, with thermal movement of the bridge accommodated by the slab sliding on a shelf on the back of the abutment stem. Even though the detailing varies, the states agree that approach slabs should be used and therefore it is recommended that the finite element study include provisions for the approach slabs and no live load surcharge demand.

Table 1.1 – Summary of State Requirements for Straight Integral Abutment Bridges

		MaineDOT	NHDOT	VTrans	MassDOT	CTDOT	RIDOT
Application to:		*General*	*Simplified Method*	*Simplified Method*	*Simplified Method*	*General*	*General*
Pile Type		Steel HP	Steel HP	Steel HP	Steel HP	-	Steel HP
Pile Head		Fixed	Fixed	Fixed	Fixed	Pinned	Fixed
Pile End		Fixed	Fixed	-	Fixed	-	
Pile Orientation		Weak Axis Preferred	Either	-	Weak Axis Required	Weak Axis	Weak Axis Required
Minimum Pile Length		10ft	-	16ft	Must extend 5' past point of fixity**	-	10ft
Concrete Abutment Height Limit		12ft	13ft	13ft	15ft	8ft	-
Skew Limit		20 deg	20 deg	20 deg	30 deg	-	30 deg
Max. Total Length	**Steel**	300ft *	300ft	395ft	140ft	-	350ft
	Concrete	500ft *	600ft	695ft	200ft	-	600ft
Max. Single Span		-	150ft	145ft	-	-	-
Curvature Limit		Straight Beams	Straight Beams	Straight Beams	Straight Beams	-	Straight
Approach Slabs		Required for steel spans > 80ft and concrete spans > 140ft	Required with Sleeper Slabs	-	Required	Required	Required
Wing Orientation		In Line Preferred	In Line Preferred	U-back preferred	U-back Required	U-back Required	U-back - separate from abutment
Wingwall Length		10ft	10ft	10ft	10ft	-	N/A - Joint

All fields left blank for criteria not explicitly addressed

** Steel bridges between 200ft and 300ft and concrete bridges between 330ft and 500ft are considered long span IAB's, and require multiple additional requirements. Currently long span IAB's in Maine are required to be straight.*

*** Regions of high bedrock explicitly disallowed*

MaineDOT Bridge Design Guide [13] - *https://www.maine.gov/mdot/bdg/*
NHDOT Bridge Design Manual [12] - *https://www.nh.gov/dot/org/projectdevelopment/bridgedesign/manual.htm*
VTrans Integral Abutment Bridge Design Guideline [11] - *https://vtrans.vermont.gov/docs*
MassDOT LRFD Bridge Manual [10] - *https://www.mass.gov/manual/lrfd-bridge-manual-2013-edition*
CTDOT Bridge Design Manual [14] - *https://portal.ct.gov/DOT/State-Bridge-Design/State-Bride-Publications*
Rhode Island LRFD Bridge Design Manual [15] - *http://www.dot.ri.gov/business/contractorsandconsultants.php*

SUBSTRUCTURE DESIGN

Foundations for integral abutment bridges typically incorporate a singular line of steel H-piles along the centerline of bearing which provide vertical load capacity and flexibility to accommodate longitudinal bridge movements. A minimum of one pile per girder is required by most NETC states with the option to include more if required for strength. The majority of NETC states prefer that H-piles be oriented for weak axis bending, where the web is oriented parallel to the abutment wall and perpendicular to the girder centerlines. This orientation provides greater flexibility in the frame system. Alternative pile types, such as micropiles, have been utilized for straight integral abutment bridges, such as the Bunker Creek Bridge in Durham, New Hampshire, however steel piles remain the primary method of support.

In the case of skewed abutments, there are variations in the guidance provided by the NETC states regarding the orientation of the pile. MassDOT [10], VTrans [11], and CTDOT [14] all state that the web should be oriented parallel to abutment face for skews meeting design requirements. RIDOT [15], NHDOT [12], and MaineDOT [13] state that the pile webs should be oriented perpendicular to the girder centerlines regardless of skew. In the case of extreme skews exceeding the simplified design requirements, VTrans [11] states that pile webs should be oriented perpendicular to girder centerlines. The common skew limitation from NETC states range from 20 or 30 degrees. This is generally a limiting factor for the simplified design criteria for states with simplified design methods available. Skew limitations for straight integral abutment bridges are typically incorporated to reduce rotational effects and tension in the acute bridge corners.

Abutment height is a primary concern due to the need to minimize earth pressures acting on the structure, with limitations in NETC states ranging from 8’ in Connecticut to 15’ in Massachusetts, (see Table 1.1 for more details). Abutment heights are dictated by the required superstructure depth, inspection requirements, and embedment. Both end abutments are typically required to be the same height to provide similar stiffnesses on each end of the structure. Wingwalls for integral abutments are generally cast integrally with the abutment stem and do not usually incorporate piles for support. U-back style wing walls are preferred by Vermont, Massachusetts, Rhode Island and Connecticut and the In-line style is preferred by Maine and New Hampshire. Wall lengths are often limited to 10', with vertical joints utilized for separation when longer walls are required.

The Federal Highway Administration (FHWA) Manual for Refined Analysis in Bridge Design and Evaluation [17] recommends that soil-structure interaction (SSI) be included in analysis for integral abutment bridges. Use of soil springs on the abutment backwalls and piles is generally required for bridges with seismic applications. For non-seismic conditions, the equivalent cantilever method with compression only backfill springs on the abutment faces is the most common approach. This method uses either empirical tables and equations or design programs such as COM624P or L-Pile to determine the effective length of piles based on site specific soil conditions. A finite element model incorporating SSI in this way should include the piles as beam-columns with fixed boundary conditions at the base and no supports along the length. Spring stiffnesses are dependent on the p-y curves for the soil conditions and the tributary area accounting for each spring. The determination of spring stiffnesses to be used in this study will be discussed in detail in the final report. MassDOT [10] specifies equivalent pile lengths to be used in 3-D models of IAB's based on pile size, soil conditions, and skew, with nonlinear springs oriented perpendicular to the abutment face at 1/3 the height.

ADDITIONAL DATA COLLECTION

Several states outside of New England, such as California, Kansas, Ohio, Tennessee and Missouri, are identified as being early users of integral abutment bridge structures [18]. Tennessee has been noted specifically for pushing the limits of integral abutment bridges, constructing structures such as an 8-span, 1175’ integral abutment bridge on a 14000’ radius curve [19]. Missouri has incorporated a simplified pile design procedure for straight and curved integral abutment bridges, which only accounts for axial load in design [20]. Consideration of the lessons learned from the experiences of states outside of New England would benefit the development of design, construction, and maintenance guidance for this bridge type.

To draw from nationwide experiences, a list of survey questions for bridge engineers across the United States has been generated. This survey (Appendix A) will focus on usage, design, and maintenance of integral abutment bridges. The results of this survey will be presented in the Task 3 submission of this project, and used to develop guidance for future usage, design, and maintenance of curved integral abutment bridges.

1.2.2 DESIGN GUIDELINES FOR CURVED STEEL I-GIRDER BRIDGES

The AASHTO Guide Specification for Horizontally Curved Steel Highway Bridges is applicable to steel spans up to 300 feet in length with a radius of 100 feet or larger. AASHTO [21] states that effects of curvature on steel I-girder bridges with an arc span length to radius ratio of less than 0.06 radians are considered negligible, and these structures may be modeled as straight bridges with a span length equal to the length of the curved bridge. There are simplified analysis procedures available for curved steel I-girder bridges such as the V-Load method, but NETC state design guides [9] [10] [12] [13] [14] [15], AASHTO [21], and FHWA [16] all recommend refined analysis be completed for structures with significant skew or curvature. These guidelines do not explicitly address integral behavior for curved structures.

Refined analysis methods are discussed in depth in the FHWA Steel Bridge Design Handbook and FHWA Manual for Refined Analysis in Bridge Design and Evaluation [17]. A two-dimensional (2-D) grillage analysis method is the most basic level of refined analysis, where the section and material properties of the bridge deck, girders, and substructure are represented by a series of beam elements. A 2-D model is well suited to analyze global force effects on the structure; however, a 3-D analysis is more appropriate for analyzing local force effects in the deck, girder webs and flanges, diaphragms, abutments, piles, and soil-structure interaction. Information on how these modeling procedure recommendations informed this study is discussed in section 1.4.

1.2.3 REVIEW OF EXISTING STRUCTURES

This section will highlight some examples of curved integral abutment bridges in service in NETC states. While the guidance of curved integral abutment bridges is still limited, these bridges show a willingness of Agencies to extend integral abutment usage to curved structures. Table 1.2 details the characteristics of the four bridges highlighted in this section. This list is not exhaustive of all curved integral abutment structures in NETC states. Only two span bridges are presented in this section as a result of the information available to the research group. Though single spans were not included in these studies, single span bridges are included in the subsequent finite element study (Task 2) and design guidance (Task 3).

Table 1.2 – Summary of Selected In-Service Curved Integral Abutment Bridges in New England

Component	Stimson Bridge	River Road Bridge	Pine Hill Road Bridge	Stockbridge Bridge
State	Maine	Vermont	Massachusetts	Vermont
Length (ft)	168	164	228	222
Spans (ft)	2 (84,84)	2 (81,81)	2 (114,114)	2 (111,111)
Curvature (ft)	1011	730	1100	1130
Abutment 1 Skew Angle (deg)	27.5	0	27.5	11.25
Abutment 2 Skew Angle (deg)	27.5	0	15.5	0
No. Girders	5	4	5	5
No. Piles per Abutment	5	4	5	5
Pile Orientation	Weak Axis	Weak Axis	Weak Axis	Weak Axis
Pile Size	HP 14x89	HP 14x102	HP 10x57	HP 14x117

Figure 1.2 - Stimson Bridge, Waterboro and Limerick, Maine (holyetanner.com)

The Stimson Bridge over the Little Ossipee River between Waterboro and Limerick, Maine was designed in 2016 by Hoyle, Tanner & Associates (See Figure 1.2). This bridge is a 2 span, 168' (84' – 84') crossing on a 1011' radius. The bridge cross section consists of 5 welded plate girders at 7-foot on center spacing with a composite concrete deck on a 5% superelevation. The integral abutments are skewed approximately 27.5 degrees from radial and were 3'–8" wide by approximately 12'–6" tall. Five HP 14x89 piles oriented for weak axis bending perpendicular to girder longitudinal axis are located at each abutment and are embedded 2' in the abutment wall. Standard MaineDOT below grade approach slabs were utilized and placed at the abutment stem and diaphragm joint.

A grillage model in Midas Civil® was used to model, analyze, design, and code check the superstructure of the Stimson Bridge. For design of the substructure, the simple supports were removed and the abutments and piles were included in the model. Plate elements were used to model the abutments in order to calculate the force distribution to the piles; however, the actual abutment design was completed using traditional approximate methods. Beam elements were used to model the piles in order to use the Midas Civil design and code check features. Soil-substructure interaction along the piles was modeled with the Midas Civil integral abutment pile soil spring wizard. The at rest earth pressure acting on the abutments was calculated separately and applied as a load across the backwall of the abutment. Connectivity between the girder beam elements and the abutment plate elements was modeled using a rigid link connecting the girder nodes to the abutment nodes. The approach slab was not included in the model, and was accounted for using eccentric loads applied to the piles.

The River Road Bridge over the New Haven River in New Haven, Vermont, shown on the cover on this report, was designed in 2015 by WSP. This bridge is a 2 span, 164' (82' – 82') crossing on a 730' radius. The bridge cross section consists of 4 welded plate girders at 9' on center spacing with a composite concrete deck on a 4% superelevation. The integral abutments are aligned radially and were 4' wide by approximately 11'–6" tall. Five HP 14x102 piles oriented for weak axis bending and are embedded 2' into the abutment wall. At grade approach slabs are utilized on each end.

The River Road Bridge was designed using a 3-D model with beam elements representing all components except for the deck, which were modeled with plate elements. The model included construction stage loading with simply supported conditions until deck cure, and frame action for superimposed dead loads and transient loads. An influence surface was developed to optimize the application of live loads. Additionally, the superstructure was checked under simply supported conditions for all loads in order to envelope the expected demands. Passive pressure acting on the abutment backwall was modeled as compression only soil springs with stiffness calculated using the Caltrans Seismic Design Criteria Version 1.7. The piles were modeled using the equivalent cantilever method to account for the pile-soil interaction. All other components of the structure were designed in accordance with standard VTrans procedures.

Figure 1.3 - Pine Hill Road Bridge, Newburyport, MA

(https://commons.m.wikimedia.org/wiki/File:New_Pine_Hill_Road_Ferry_Road_Bridge_in_Newburyport_(19098796804).jpg)

The Pine Hill Road Bridge over I-95 in Newburyport, Massachusetts was designed in 2014 by HNTB (See Figure 1.3). This bridge is a 2 span, 228’ (114’ – 114’) crossing on a 1100’ radius. The bridge cross section consists of 6 welded plate girders at 8’ – 6” on center spacing with a composite concrete deck on a 4% superelevation. The integral abutments are skewed approximately 27.5 degrees from radial at abutment 1 and 15.5 degrees from radial at abutment 2 and are 4’ wide by 11’ tall. Six HP 10x57 piles are oriented for weak axis bending aligned with the longitudinal axis of the abutment (skewed to the girder) and are embedded 2 feet. Below grade approach slabs are utilized and placed on a corbel near mid-girder height on the back face of the abutment.

A 3D model in CSI Bridge® was used to design the Pine Hill Road Bridge. Beam elements were used to model girder flanges, piles, cross-frames, and the pier. Thick shell elements were used to model the abutment walls and thin shell elements were used to model the girder webs and concrete slab. The superstructure was modeled as simply supported for the design of positive moment regions and modeled as integral with soil-structure interaction for the design of negative moment regions at the abutment. This structure did not meet the requirements for simplified design procedures. Compression-only springs were applied to the abutment and multi-linear plastic springs were applied to the full height of the piles in the longitudinal and transverse directions with unbraced lengths assumed to be zero. CSI Bridge® automatically generated spring stiffnesses. Pile design included centrifugal force effects calculated by hand and included in the load combinations.

The Stockbridge Bridge over the White River in Stockbridge, Vermont is a two span, 222’ (111’ – 111’) bridge crossing on a 1130’ radius. The bridge cross section consists of five welded plate girders at 7'-8" on center spacing with a composite deck on a 6% superelevation. The integral abutments are aligned radially and are approximately 3' wide by approximately 20'-6"inches tall. Five HP 14x117 steel piles are oriented for weak axis bending perpendicular to the girder’s longitudinal axis are located at each abutment and are embedded 2’ in the abutment wall. There is a geofoam material applied to the backwall of each abutment prior to backfilling. Approach slabs are utilized at this bridge. This bridge was included in the 2014 University of Massachusetts, Amherst project, as detailed in section 1.3.1.

It is not surprising that the first uses of curved integral structures are seen on two-span continuous structures, as the pier absorbs a portion of the substructure demand and maximum force effects in the girders are reduced. A key portion of this research effort will be to consider the effects of a single span structure compared to a two-span arrangement.

1.3 APPLICABLE STUDIES

A literature review completed by Wiss, Janney, Elstner Associates, Inc. for VTrans in 2002 [22] synthesized the technical information available about jointless bridge construction at the time. Since then, considerable research efforts on the topic of curved integral abutment bridges have been completed. This section focuses on four recent research efforts specifically related to this project and is non-exhaustive on the topic of curved or straight integral abutment bridges.

Curved integral abutment bridges are complex structures whose behavior is affected by many different parameters. It is unrealistic, however, to include every variable in a bridge design as a parameter in this finite element study. The processes and conclusions from the following research efforts have been used to guide this project towards the practices and parameters with the highest significance in curved integral abutment bridge behavior. This way, the finite element study may be targeted toward those parameters most influential on responses of interest.

The results of each study are noted herein and are further synthesized in section 1.4 of this report.

1.3.1 UNIVERSITY OF MASSACHUSETTS

The University of Massachusetts (UMass) Transportation Center at UMass Amherst has made a significant effort in researching the behaviors of curved and straight integral abutment bridges. A multi-year study was completed in 2014 for the Vermont Agency of Transportation to monitor the performance of three in-service jointless bridges. VTrans initiated an instrumentation program of these three integral abutment bridges of varying complexity in the state in order to evaluate their performance. Researchers from UMass have since published literature related to structural instrumentation, live load testing, construction analysis, long term responses, and finite element modeling procedures for these structures [5] [6] [7].

The three bridges studied are The Middlesex Bridge, the East Montpelier Bridge, and the Stockbridge Bridge. The Middlesex Bridge is a single span integral abutment bridge located on VT12 in Middlesex, VT. The East Montpelier Bridge is a skewed single span integral abutment bridge located on US2 in East Montpelier, VT. The Stockbridge Bridge is a two-span curved integral abutment bridge located on VT Route 100 in Stockbridge, VT. Table 1.2 provides a summary of the basic bridge characteristics. The Stockbridge Bridge is the only curved structure included in the study. It is also important to note that the Stockbridge location included a geofoam material applied to the abutment backwall prior to backfilling, which is uncommon, and impacts the development and magnitude of passive pressures on the abutments.

Table 1.3 – Summary of Bridges Studied by UMass Transportation Center [4]

Component	Middlesex	East Montpelier	Stockbridge
Length (ft)	141.1	121.4	222
Spans (ft)	1	1	2 (111,111)
Width (ft)	33.5	46.6	37.1
Curvature (deg)	0	0	11.25
Skew Angle (deg)	0	15	0
Abutment Type	Integral	Integral	Integral
Wing Wall	Integral U-back	Integral U-back	Integral U-back
# Girders	5	5	5
# Piles	5	5	5
Pile Orientation	Weak Axis	Weak Axis	Weak Axis
Pile Size	HP 12x84	HP 12x84	HP 14x117

All three bridges in this study were instrumented with structural sensors on the piles, abutments and superstructures during construction. A controlled pseudo-static load test was conducted for each bridge and the collected data was used to calibrate finite element models of each bridge completed in SAP2000®. The 3-D structural finite element models incorporated all components of the bridge superstructure, substructure, and soil-structure interaction. Concrete components, including deck and abutments, were modeled as four node shell elements with six degrees of freedom at each node along with cracked section properties. Piles, diaphragms, and flanges of the steel girders were modeled using two node 3-D frame elements. Rigid links were used between girder and deck elements to simulate composite behavior, between the top and bottom flange of the girders to simulate the web depth, and at the superstructure-abutment connection in order to transfer moment to the substructure. Preliminary models included the full depth of each pile, but it was shown that pile moment was negligible below a depth of 20'. Therefore, the pile depth on each bridge was ultimately modeled to 20 feet below the bottom of the abutment and considered fixed at the base. Spring elements were used to simulate the soil-structure interaction and were applied at discrete nodes along the piles, abutment, and wingwalls. Though the piles were not modeled for their full depth and fixed at the point of negligible moment, this is not considered a traditional equivalent cantilever model due to the inclusion of pile-soil interaction along the length of the piles at 1' increments. See Figure 1.4 for a schematic of the elements used to represent the Stockbridge Bridge in the finite element model created by UMass [5].

For each bridge, construction stage comparisons were completed to evaluate measured stresses against model predictions. Long term studies were then completed for each structure. Additionally, two sensitivity studies were completed to evaluate the effect seasonal thermal responses, one for variations in curvature and the other for effects of skew and pile orientation.

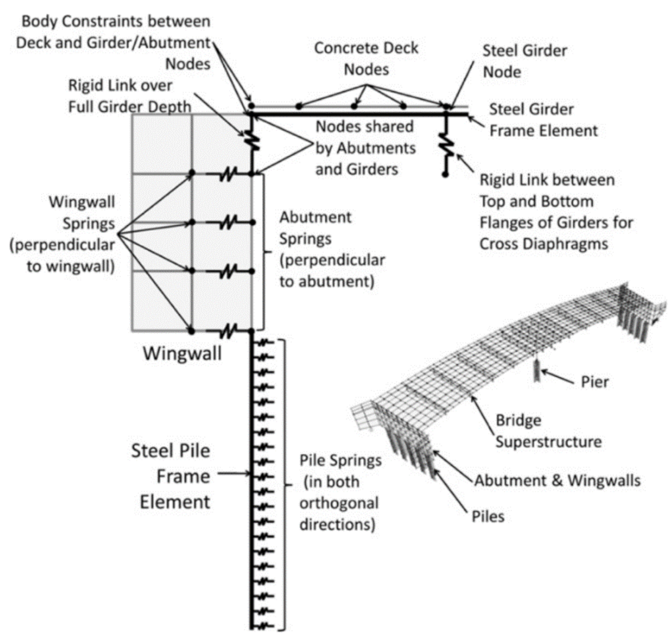

Figure 1.4 - Structural Component Mesh and Connectivity of the Stockbridge Bridge [5]

LONG TERM RESPONSES

Responses of the three bridges due to thermal effects were monitored over the course of four years [4] [6]. The data collected was compared to the calibrated finite element models for each bridge. The curved integral abutment bridge in Stockbridge had the most consistent substructure displacement year to year which is attributed to the geofoam material effectively minimizing the potential for ratcheting effects due to soil wedge generation during seasonal thermal fluctuations.

The skewed East Montpelier Bridge exhibited seasonal rotation in plan with the majority of the displacements recorded at the acute corners of the abutments. The maximum earth pressure recorded behind the abutments of any of the three bridges also occurred at the East Montpelier bridge behind the obtuse abutment corners. This resulted in the East Montpelier Bridge also experiencing the highest strong axis pile bending moment (46.7 kip-ft) compared to the non-skewed Stockbridge Bridge (17.6

kip-ft) and the Middlesex Bridge (15.4 kip-ft). The pile weak axis bending stresses were similar at all three bridge locations. This indicates the passive pressure generation behind the abutments is impacted by the tendency for rotation to occur in a skewed bridge structure about its longitudinal axis. The abutments at all three bridges experienced a net shift toward the backfill over the monitoring period, which the researchers attributed to changing backfill soil properties. It was noted that the monitoring time period included extreme weather event Hurricane Irene, after which the Middlesex bridge experienced asymmetric abutment displacements.

PARAMETRIC STUDY OF CURVATURE

A parametric study on the seasonal thermal load response of curved integral abutment bridges was conducted using the models and data from the project for VTrans [5]. In this study, the calibrated model for the Stockbridge Bridge was used as the base model. The model iterations were performed on a 100' long bridge with radius iterations of straight, 191', 286', and 573', and soil iterations of dense and loose sand. Two thermal load ranges of 55.6 degrees Celsius were considered for this study, with the midpoint of the first range based on the high construction temperature (21 degrees) and the second based on the low construction temperature (-6.8 degrees) recorded during construction of the Stockbridge Bridge.

This study concluded that changes in curvature had a significant impact on the structural response to thermal fluctuations. It was observed that increasing curvature (smaller radii) resulted in a decrease in longitudinal abutment displacements, earth pressure, and weak axis bending of the piles for degrees of curvature greater than 20 degrees. For larger radii (fegree of curvature between 0 and 20), the response was not substantially impacted. This reduction was as large as 38% from the straight bridge to the 191' radius bridge (degree of curvature of 30 degrees), indicating a measurable shedding of response in the transverse direction. Lateral displacement increases were seen at degrees of curvature as low as ten degrees, with the majority of the response being taken by the piles. This is further evident in the magnitude of pile moments, where the weak axis moments steadily decreased, and the strong axis moment increased as the degree of curvature increased.

The use of integral U-back wingwalls resulted in a reduction in the strong axis bending moments of the piles (piles were oriented for weak axis bending about the centerline of bearing). Soil pressures acting on the wingwalls of the abutment reduced the lateral demand on the system. The strong axis bending moments in the piles increased by 25% for the 191' radius bridge and 15% in the 573' radius bridge when the wingwalls were separated from the abutments, which effectively removed the passive earth pressure resistance on one of the wings.

Additional observations included:

- Rotation about the centerline of bearing was shown to be the dominant mode of displacement in the abutments.
- Loose sand backfill reduced the backfill pressure at higher thermal loads, allowing a larger abutment rotation and reducing top of pile moments.

PARAMETRIC STUDY OF SKEW, LENGTH, AND PILE ORIENTATION

A parametric study on the effect of pile orientation, span length, and skew due to changes in thermal load was also completed [6]. The models used for this study were based on the techniques utilized to model the original three bridges (Middlesex, East Montpelier, and Stockbridge), however geometry and section properties were modified. The effect of piles oriented with the web parallel (weak axis) and perpendicular (strong axis) to the abutment centerline were modeled on bridges with lengths of 50', 100' and 150' and skews of 0 degrees, 15 degrees, 30 degrees, and 45 degrees. This study was completed on only single span bridge models and it is stated that the results are not transferrable to two span bridges.

System performance was shown to be impacted by skew angle. The acute corner of the abutment maintains a nearly constant longitudinal displacement while the obtuse corner longitudinal displacement decreases due to thermal expansion with increasing skews. This is attributed to the increase in transverse displacement and plan rotation caused by an increase of skew angle. The impact of skew was shown to increase as the bridge length increased.

It was found that thermal transverse pile bending moments increased with skew and surpassed the longitudinal bending moments for skews of 15 degrees or higher. This is attributed to the transverse displacements that occur from plan rotation on the skewed structures and this trend was not impacted by pile orientation. It was also observed that pile orientation had little effect on the overall longitudinal bridge displacements, and ultimately it was concluded that there is not one optimal pile orientation for the entire range of skews considered.

1.3.2 IOWA STATE UNIVERISTY

The Bridge Engineering Center at Iowa State University completed a long-term bridge monitoring and research project for the Federal Highway Administration, Ohio DOT, Pennsylvania DOT, Wisconsin DOT, and Iowa DOT (lead state) in 2014. This study was completed with the objective of investigating the behavior of curved integral and semi-integral abutment bridges, specifically with interest in thermal responses. In order to complete this objective, several bridges were monitored during live load testing and during seasonal thermal events. Finite element models were created and calibrated to the field results, from which analytical and sensitivity studies were completed for the bridges in Table 1.3 [7].

The six bridges studied by Iowa State University are located on the interchange of I-80, I-35, and I-235 in Des Moines, Iowa. These bridges are all one-lane highway bridges of varying lengths, curvatures, and substructure systems. A summary of the bridges in the study is provided in Table 1.3. Bridge 2408 was not monitored because bridge 109 shares the same geometry.

Table 1.4 – Iowa State University Bridge Engineering Center Report Bridge Summary [7]

Component	Bridge 109	Bridge 209	Bridge 309	Bridge 2208	Bridge 2308	Bridge 2408
Length (ft)	304	332	319	330	302	304
Spans (ft)	3 (80,144,80)	3 (90,152,90)	3 (85,149,85)	3 (90,150,90)	3 (80,142,80)	3 (80,144,80)
Width (ft)	26	26	26	26	26	26
Radius (ft)	0	1340	950	1340	950	0
Skew Angle (deg)	15	35	15	35	15	15
Abutment Type	Integral	Semi-integral	Integral	Integral	Semi-Integral	Integral
# Girders	4	4	4	4	4	4
# Piles	-	-	8	-	-	-
Pile Orientation	-	-	Weak Axis	-	-	-
N. Pier Support	Fixed	Fixed	Fixed	Fixed	Fixed	Expansion
S. Pier Support	Expansion	Expansion	Fixed	Expansion	Fixed	Fixed

RESULTS OF FIELD MEASURED RESPONSES

Five of the six bridges in Table 1.3 were live load tested for static and dynamic loads. Two locations on the superstructure were specifically instrumented for live load effects. Section 1 (S1) was located at the midpoint of the unbraced length between two diaphragms and section 2 (S2) was located at an adjacent diaphragm, as shown in Figure 1.5 [7]. These instrumentation locations were in the center of an end span on the bridges.

It was noted that the most moments occurred at section 1 in the exterior girder for the bridges with the most severe curvature (Bridge 309 and Bridge 2308). This is likely due to the increased arc span length associated with tighter radii. Lateral bottom flange bending moments were more severe on the curved girder bridges than the straight bridge, which is an expected behavior. The diaphragms of the curved bridges were observed to experience both flexure and axial tension, which supports the requirement to design diaphragms as primary members on curved structures. This was attributed to the outermost girder expanding radially more than the innermost girder. No conclusions were drawn about curvature or skew angles.

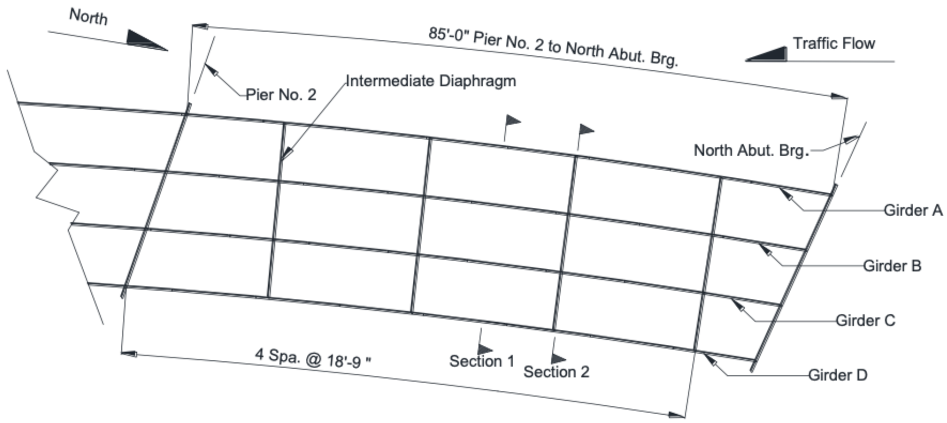

Figure 1.5 - Plan View of Bridge 309 Instrumentation Sections [7]

ANALYTICAL STUDY

Bridge 309 has the most similar characteristics to the parameters included in this NETC Curved Integral Abutment research project. This bridge was the most heavily instrumented and investigated bridge in the Iowa project, and the only structure to include instrumentation of the substructure. It was chosen for the primary finite element model because it has the greatest restraint at the supports, the smallest radius, and the broadest set of structural response data collected from both load tests and seasonal observations. This model was calibrated based on results of field measured responses. The resulting modeling methods and techniques were then utilized for the models developed for the parametric study and analytical study.

The Bridge 309 abutment is supported by 8 steel HP 10x57 piles set in predrilled holes filled with bentonite with webs oriented parallel with abutment centerline (weak axis). Six of the piles supported the abutment wall and each U-back wingwall was supported by a single pile.

The finite element model was built in ANSYS® and includes all major components of the bridge superstructure, substructure, and soil-structure interaction. The model considered the following components to be insignificant and therefore were not included in the model: superelevations, differential changes, concrete haunches, field splices, and plate stiffeners. 3-D elastic shell elements with bending and membrane capabilities were used to model the bridge abutments, deck and webs of the steel plate girders. These elements have four nodes with six degrees of freedom at each node. Beam elements with tension, compression, bending, and torsion capabilities were used to model the abutment piles, pier caps and columns, and flanges of the steel plate girders. These elements have two nodes with six degrees of freedom at each node. Rigid links were used to simulate composite behavior between the girders and the deck and were used to connect the piers to the girder. Girder ends were directly connected to the abutments using shared nodes between the girder and abutment elements. The equivalent cantilever method was used to model the stiffness of the piles which were modeled as 18' long with fixed boundary conditions at the pile ends. See Figure 1.6 for a visual of element mesh and connectivity used in this study [7]. The report does not discuss the use of soil springs to model abutment wall soil pressures, though girder and diaphragm response was the primary focus of the analytical study.

The results of the finite element model of Bridge 309 were compared to the collected structural response from the load test data and the long-term thermal data. AASHTO design load cases were used as structural demands for the Bridge 309 model, including thermal loads.

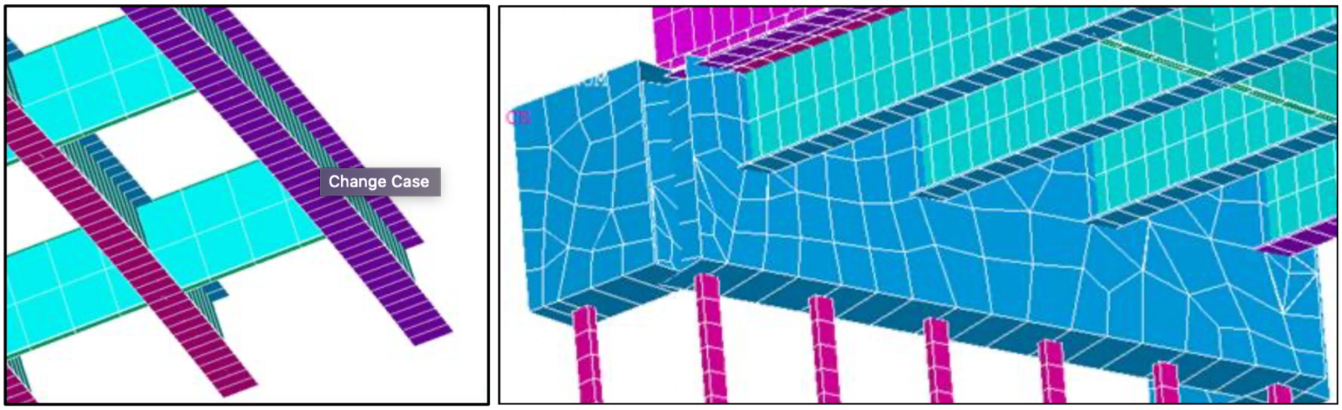

Figure 1.6 - ANSYS® Model of Bridge 309, Illustration of Structural Component Mesh and Connectivity [7]

It was noted in this study that the equivalent cantilever model did not accurately predict the relationship between pile strain and pile head displacement measures that were recorded from field testing. This was attributed to the high error in displacement surveys or variances in planned and actual pile bore depths. However, if the model did not include abutment soil springs than this discrepancy is not unexpected.

The recorded pile axial response strains did not yield usable conclusions, as strains recorded at various pile locations along the abutment were erratic and inconsistent.

Additional conclusions from the analytical study of the Bridge 309 finite element model include [7]:

- Lateral bottom flange bending moments were nearly 10 times greater at the fixed pier when including temperature effects.
- The finite element model predicted 12-22% larger strains than results from live load testing and 18% larger axial strains in the exterior girder compared to long term thermal data.
- Transverse pile strain increases were greater at the innermost piles than outermost piles (radially). Conversely, longitudinal pile strains were greater at the outmost piles, with the exterior pile on the north abutment of Bridge 309 (acute corner) experiencing the highest weak axis bending strain.

SENSITIVITY STUDY

The calibrated model of Bridge 309 was used to perform a sensitivity study for skew and radius of curvature utilizing 12 different bridge models. Parameters of the study included skew iterations of 0, 15, and 30 degrees and radius iterations of 350', 550', 950', and 20950' (used to represent a straight bridge). The key locations of results were in the maximum positive and negative bending regions at each span. Important conclusions made about the effects of skew and curvature include [7]:

- Positive Moment Region: Mid-span critical stress in the center span of the bridge increased at the exterior girder and decreased at the interior girder as curvature increased, regardless of skew. The largest critical stress occurred in the outer girder. The lateral bending stress at the same location increased with curvature for all skews. This is an expected result and supports the inclusion of lateral bending effects in curved girder bridge designs.
- Negative Moment Region: At the north pier section, critical stresses at the exterior and interior girders increased with curvature. The largest lateral bending stress occurs at in the inner girder at the piers and increased with curvature for all skews.
- A bridge with a 10 degree skew and 0.06 arc span length to radius ratio can be designed as a straight bridge if a 10% stress increase over the expected straight girder demand is acceptable.

1.3.3 UNIVERSITY OF NEBRASKA

A dissertation completed by Saeed Eghtedar Doust [8] for the University of Nebraska in 2011 examined previous conclusions about curved integral abutment bridges and the effects of curvature and different load combinations on concrete and steel integral abutment bridges [8]. The models used in this dissertation were not calibrated to performance from an existing structure; therefore, results from this study are theoretical.

The I-480 Bridge in Omaha, NE is used as the base bridge modeled in the study of effects on a steel bridge. It is composed of a 60' – 8" wide bridge with seven steel welded plate girders spaced at 9' on center, 6% superelevation and an 8" deck. The 3'–6" wide abutments are integrally connected with the superstructure and vary in height between 9'–4" and 13'. The abutment is supported by seventeen 70' long HP 12x53 steel piles spaced at 3'–6" on center. Wingwalls are not integral with the abutment wall and are not included in the model.

The finite element model created in SAP2000® used two-node beam elements to model cross bracing, pier columns, cap beams, and piles for the abutments and the pier. These elements model axial deformations, biaxial bending, torsion, and biaxial shear. Shell elements were used to model the deck slab, parapets, flanges and webs of the girders, stiffeners, abutment walls, and pile caps. The shell element uses three or four nodes and combines membrane and plate behaviors, as shown in Figure 1.7 [8]. Nonlinear link elements were used for the connections between the piers and superstructure. Nonlinear support elements were used to model the effect of soils on the abutment walls and piles and are based on p-y curves.

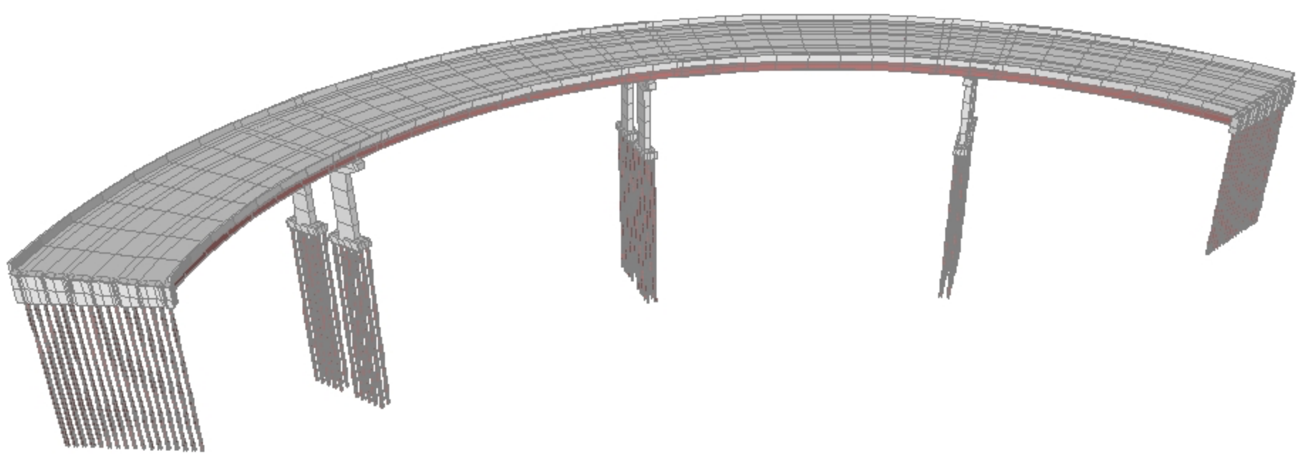

Figure 1.7 - SAP2000® Finite Element Model of the I-480 Bridge in Nebraska [8]

Parameters for the study include:

- Bridge length / number of spans: End span lengths were all 154' and interior span lengths were all 193', resulting in length iterations of 308', 501', 694', and 887'
- Curvature: Straight bridge and curved with radius iterated for 300', 538', 1000'
- Strong and weak pile orientation

HP 12x53 piles were utilized at the abutments and HP14x89 piles were utilized at the piers. Primary outputs considered in this study were shear and bending forces in the piles and movement of the abutments. Effects of each load case were considered and ranked on a numeric scale based on their significance in bridge response. These are not direct measurements of force or demand, but rather rank the importance of the force effect on the response of the structure.

Bridge contraction had the highest normalized weight factor of importance of any load effect (rated 31), more than double the weight factor of expansion (rated 14) or live load (rated 12) for pile bending moment. The following conclusions were drawn for system response to thermal contraction:

- Contraction moments in abutment piles increased with bridge length for straight bridges, which was also observed for bridges with large radii (1000'). This is an expected behavior.
- For the 300' and 538' radius structures, moments increased from the 2-span to the 3-span structure, however, a decrease in pile moments due to contraction were observed in the 4 and 5 span arrangements.
- Contraction resulted in higher pile moments than expansion at the abutments.
- Internal forces in the piles due to contraction of curved girder bridges were always smaller than straight bridges.

Bridge expansion was noted to have the second greatest weight factor. The following conclusions were drawn regarding system response to thermal expansion:

- Pile bending moments in straight bridges consistently increased with increasing total bridge length.
- In curved bridges, the pile moments increased with total bridge length for the 2-span to the 3-span structures, however, a decrease in pile moments were observed in the 4 and 5 span arrangements. This is a similar observation to the contraction case.
- Pile moments in shorter curved bridges were greater than in straight bridges due to expansion

These results highlight the need to include a range of bridge lengths and curvatures within a parametric study.

Additionally, it was noted that abutment forces due to earth pressure depend on curvature. Bridges with a smaller radius lose a balance of earth pressures and results in large global lateral displacement of the bridge and large pile stresses. As the curve radius tightens, the abutments move further away from parallel with respect to each other. These trends should be considered during this CIAB finite element study.

1.3.4 UNIVERSITY OF MARYLAND

A dissertation completed by Narong Thanasattayawibul [1] for the University of Maryland in 2006 focused on horizontally curved I-girder bridges with integral abutments. Parameters of the study include: bridge length (50’ – 1200’), span length (50’ or 100’), radius (straight, 400’, 600’, 800’, 1200’, and 2400’), temperature, soil profile, and pile type [1]. Total bridge lengths were achieved using multiple spans of either 50' or 100'. The models used in this dissertation were not calibrated to performance from an existing structure; therefore, results from this study are theoretical.

The finite element models made in ANSYS® include the superstructure, substructure, and soil-structure interaction. Shell elements with four nodes and six degrees of freedom at each node were used for concrete slabs, flanges and webs of girders, and flanges and webs of piles. Beam elements with two nodes and six degrees of freedom at each node were used for the cross bracing. Solid elements with eight nodes and three degrees of freedom at each node were used for the abutments. Piles were modeled across their entire length supported by soil springs tuned to match different soil conditions of interest, as shown in Figure 1.8 [1]. Pile length was changed based on the soil conditions.

The model bridge used six steel W30x132 girders spaced at 6’ on center and a 7” deck for all iterations. The abutments were 3’ wide and 7’–7“ tall. Eleven HP 10x 42 steel piles oriented with webs perpendicular to girder centerlines (weak axis) were used to support the abutments.

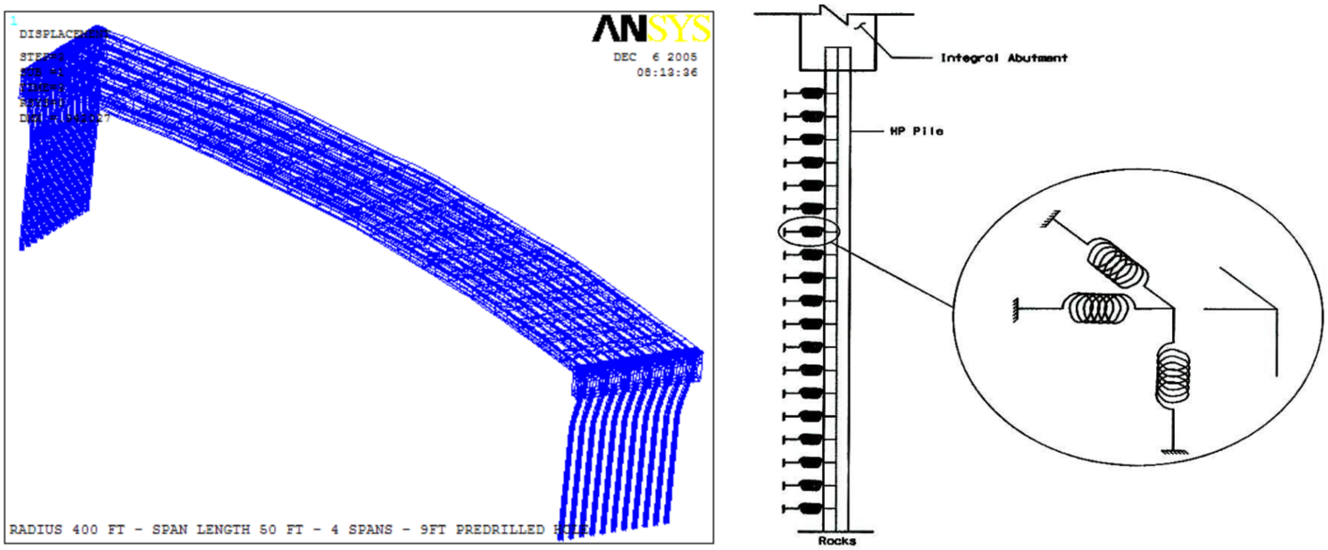

Figure 1.8 - ANSYS® Model and Pile Support Representation for Integral Abutment Bridge Model [1]

The parametric study observed the maximum stress intensity of the piles and lateral displacement of the abutments to form conclusions about the effects of the parameters on bridge structural response. Important conclusions that relate to this study include [1]:

- For multi span bridges up to 300 feet, those with a larger radius have a lower stress intensity of the piles than smaller radius bridges.
- For multi span bridges up to 300 feet, those with a larger radius have smaller lateral displacements than smaller radius bridges.

For temperature rise, the following observations were drawn:

- Curved bridges with 50’ spans have a greater pile stress intensity increase than 100’ spans.
- Curved bridges with 50’ spans have a greater abutment lateral displacement increase than 100’ spans.
- For bridges with 50’ spans, pile stress intensity increases more in bridges with smaller radii.
- For bridges with 100’ spans, pile stress intensity increases less for bridges with smaller radii.

Minimal discussion was included as to what may be causing these observations. They are noted here to support the need to look for trends not only within a given span length for a range of radii, but also between variable span length or each set of radii.

1.4 SYNTHESIS OF LITERATURE

This section will discuss the important study parameters, modeling procedure, and behaviors of interest suggested for the NETC CIAB research project. The state and federal guidance, as well as the applicable studies presented earlier in this report, will inform decisions made about each of these topics and should be used in determining the modeling protocol for use in this research effort.

This literature review indicated that bridge length, radius, skew, pile geometry, and abutment geometry are all parameters of interest. These parameters were shown to have significant effects on key response parameters such as abutment displacements and stresses in the piles. Input from NETC Technical Committee members has also shaped the type and range of the structural parameters considered for this study.

The discussion herein is not intendent to be exhaustive, but rather to note the important aspects of these parameters as they relate to the literature review. Further discussion of the range and scope of each of these parameters will be provided in the final report.

1.4.1 BRIDGE LENGTH

The outcomes of this study must be applicable to a range of potential bridge locations, and therefore bridge length must be a parameter of this study. Bridge length has also been shown to directly affect response parameters such as pile stresses and abutment displacements and has a relationship to other parameters such as skew angle and curvature. Bridge length has a relationship with skew angle, with skew effects increasing as length increases. This is to be expected as bridge length effects the magnitude of expansion and contraction of the structure. Logical upper bounds should be set to those noted for existing straight integral abutment guidelines.

1.4.2 RADIUS

Bridge radius is a critical parameter included in this study. The UMass, Iowa, and Nebraska studies note that as curvature increases, lateral displacements of the abutments and pile stresses increase when subjected to thermal loads. The Iowa study also reported increases in girder mid-span stresses and flange lateral bending effects as curvature increased. Though girder designs are not included in the scope of this project, trends in flange lateral bending effects may warrant further study.

Logical bounds for radius were discussed in the previous section on design of curved bridges. An arc span length to radius ratio of 0.06 radians is the criteria for a curved bridge to be considered straight for design purposes and is a logical upper bound for radii to be included. While the AASHTO guide for design of curved structures is applicable radii as small as 100 feet, a lower bound of 340 feet is recommended based on the anticipated applications of bridge models in this study.

1.4.3 SKEW

Skew angle has been shown to have a significant effect on integral abutment bridge responses. Monitoring of the skewed East Montpelier Bridge showed significant in-plan rotation due to seasonal thermal effects compared to the two non-skewed bridges studied in this project [4]. Additionally, the Iowa study indicated variations in earth pressure responses of the structure at the acute and obtuse corners due to varying skews. While the pile responses for Bridge 309 were reported as erratic, the geometry of that bridge is significantly different from the bridges proposed in this study, and the results of Iowa's parametric test show that simplified design may be applicable to low skew curved integral abutment bridges.

These studies confirm that skew is an important parameter to be considered when evaluating bridge response. Therefore, it is recommended that skew angle be investigated for 0 to 20 degrees for this study, which is the limit set by VTrans for simplified design of a straight integral abutment bridges.

1.4.4 PILES

There has not been a clear consensus on pile orientation across the state and federal guidelines and the applicable published research reports. Most agree that piles should be oriented for weak axis bending, though in some cases strong axis may be preferable. In the case of skewed bridges, there are more options for orientation including alignment with the abutment centerline or alignment with the girder centerline. Weak and strong axis orientation does not appear to affect longitudinal displacements. Regardless of orientation, the weak axis bending moment was always critical, as noted in the UMass study.

Furthermore, inconsistencies are noted for in place structures in pile alignment. The Stimson River Bridge in Limerick, Maine incorporates piles oriented for weak axis bending with webs perpendicular to the girder lines. The Pine Hill Road Bridge in Newburyport, MA has piles oriented for weak axis with webs parallel to the abutment centerline.

Following conversations with NETC Technical Committee members, piles will be primarily oriented for weak axis bending with webs perpendicular to the girder centerlines. Strong axis orientation will also be investigated for each of the 50-foot and 100-foot span iterations for in-line wingwalls only for comparison with weak axis orientations of the same parameter set.

1.4.5 ABUTMENTS AND WINGWALLS

It is recommended that the finite element study primarily investigate in-line wingwalls due to the higher passive earth pressure acting on the system. The UMass study observed that U-back style wingwalls integral with the abutment are able to decrease transverse moments in foundation piles, highlighting the need to design U-back wings for passive pressures, and the need to consider inline wings in a study intended to encompass a range of bridge conditions to ensure maximum pile responses are captured.

Following discussions with NETC Technical Committee members, U-back wingwalls will be included in the finite element study for the 50ft and 100ft span iterations with piles oriented for weak axis bending only.

Abutment height is dictated by the length of each bridge due to the required depth of the girders with requirements for adequate inspection shelves and embedment. Changes in abutment height effect soil-structure interaction which is vital to incorporate in the modeling portion of this study. Abutment heights will not be iterated for this study and will be set to an appropriate depth for each span length investigated.

1.4.6 FINITE ELEMENT MODEL AND KEY RESULTS

Finite element models are required to adequately capture the behaviors of curved integral abutment bridges, and all components of the deck, superstructure, substructure, and soil-structure interaction should be included in the model.

The bridge deck should be modeled using plate elements with four nodes and six degrees of freedom at each node. This was the common practice between each study investigated in this literature review. The use of thin plate elements is appropriate for components with thickness much smaller than other dimensions and where membrane forces are present such as load distribution from live load conditions.

Cross frames should be modeled using beam elements. Beam elements use two nodes with six degrees of freedom at each node and can model axial, shear, bending, and torsional stresses. This element choice is adequate for cross frame elements, is recommended by the FHWA [16], and is commonly used in previous studies for this purpose.

Welded plate girders should be modeled using plate elements for webs and beam elements for flanges at a minimum. The studies mentioned in this literature review used a mixture of beam and surface elements for the girders. FHWA recommends modeling girders with plates for webs and beams for flanges with the benefit of simpler modeling procedures with minimal loss of information about torsional and warping behavior associated with curved structures as compared to an all plate modeling approach. Rigid links should be used to simulate composite behavior between the girder elements and the deck elements.

Integral abutments should be modeled using thick plate elements. The interaction between the girders and foundation piles framing into the concrete is complex and is well captured by plate elements. Soil pressures acting on the abutments and wingwalls should be included as non-linear spring boundary conditions connected to each element node and tuned based on assumed p-y curves for typical soil in New England. This method is recommended by FHWA and is also used commonly by the studies mentioned previously in this report.

Modeling of the abutment piles can be complex, and several different approaches have been used by the studies mentioned previously in this report. The UMass, Nebraska, and Maryland studies incorporated soil-pile interaction by including spring boundary conditions representing the soil pressure and friction along the length of the pile. This process would normally require information about the soil conditions at a site or large assumptions about possible conditions, which is not practical for a regional general study. Therefore, the equivalent cantilever method (depth-to-fixity) with abutment springs is recommended for modeling pile behavior and soil-structure interaction. This method assumes that beyond a certain soil depth, the pile is effectively restrained and can be represented by a fixed boundary condition. The length of the pile should be modeled as a beam element for simplicity of the model and rigidly connected to the abutment. The depth to fixity is a function of site soil conditions, so the equivalent pile length should be included as a changing parameter in order to envelope typical site specific soil conditions, with the understanding that severe soil conditions such as very soft clays would fall outside of the realm of any simplified method proposed as a result of this study.

There are several response parameters apparent in previous research which should be considered in this project. Abutment rotations and longitudinal and transverse displacements were considered by all of the studies mentioned previously, which suggests that this is a key indicator for curved integral abutment bridge performance. Maximum stresses in the piles due to weak and strong axis bending and shear are also key parameters to include as they have been shown to indicate effects of skew and curvature parameters. UMass and Iowa included girder stresses as part of their studies, particularly axial stresses due to thermal loading. The results of all previously published research were considered in the development of the response metrics suggested to be evaluated in this study, as listed in Section 1.6.

Confidence in results from finite element modeling is increased when the models are calibrated with field data collected during load tests or long-term monitoring. The UMass and Iowa studies both incorporated live load test procedures to refine the model and verify the assumptions made about their models' behavior. It is recommended that a similar approach be incorporated in this study, where instrumentation and data existing at the Stockbridge Bridge and East Montpelier Bridge be compared with results from models used in this study.

1.5 MAINTENANCE ISSUES AND CONCERNS

Long term monitoring of in-service curved integral abutment bridges performed by UMass [4] and Iowa [7] has shown promising performance. The Stockbridge Bridge in Vermont has shown the most consistent movements year to year out of the three bridges included in the study, though this may be attributed to the presence of the geofoam material applied to the abutment backwall. The studies have shown that rotation is the primary mode of displacement in integral abutments, shown by greater magnitudes of top of abutment movement than bottom of abutment movement. The presence of skew does result in rotations in plan of the bridge, but neither long term study reported any alarming results. An inspection report completed in July of 2019 the Stockbridge Bridge available on the VTrans website indicated that the structure is in good condition with no recommendations at that time. Long term assessment of curved integral abutment bridges is not available because this type of bridge is relatively new to the New England region. A report published in 1988 surveyed in-service straight integral abutment bridges and found that they have been performing as intended [2].

The Iowa State University Bridge Engineering Center [7] included a survey of US states regarding the topic of curved integral abutment bridges as part of their research. At the time, prior to 2014, many states choose not to construct curved integral abutment bridges due to lack of familiarity with the design and uncertainty of performance. Other environmental factors such as poor soil conditions and extreme temperature ranges also play a role in the decision not to construct curved integral abutment bridges. New Hampshire and Vermont were the only NETC member states who participated in this survey. New Hampshire and Vermont are both states that use integral abutments, however, they share similar concerns about effects from earth pressure and abutment and pier alignments associated with a curved integral abutment bridges.

1.6 CONCLUSIONS

Integral abutment bridges have become the design of choice for New England states due to the decreased construction and maintenance efforts and associated costs. Curved bridges are also a popular choice in places with restrictive site concerns such as highway alignment, right-of-way, or environmental restrictions. State and federal guidance on the design and construction of curved integral abutment bridges is limited. Simplified design methods are available for straight integral abutment bridges meeting specific criteria in Massachusetts, Vermont and New Hampshire, allowing this style bridge to be used with significantly less effort from the designer. Previous research reports indicate that simplified design methods for straight integral abutment bridges may be extended to curved structures.

The purpose of this literature review was to synthesize the available guidance and research applicable to curved integral abutment bridges and determine appropriate parameters for the study of curved integral abutment bridge behavior. A finite element study following this literature review will investigate how the parameters discussed in section 1.4 affect the response of curved integral abutment bridges. Bridge responses resulting from these parameters (bridge length, skew, radius, pile orientation and depth to fixity, and wingwall orientation) will be analyzed both within a parameter set and across the parameter field.

The past research projects presented above focused on multi-span curved integral abutment bridges. As a result, much of the discussion in this literature review was on multi-span structures. Additionally, information regarding existing curved integral abutment bridges in NETC states was available only for multi-span structures. It is not the intent of the research group to exclude single-span structures from the literature review, and the information learned about multi-span structures may be extended to single-span structures. The finite element study (Task 2) and design guidance (Task 3) will incorporate single-span and two-span structures.

The key bridge responses that are suggested for inclusion in the finite element study include:

- Abutment displacements and rotation
- Pile bending, shear, and axial demands
- Tension in the deck end continuity region
- Torsion in girder ends

The complex interaction between possible characteristics and components of a curved integral abutment bridge means there are many parameters and bridge responses that could be included in the finite element study. In order to maintain a manageable dataset, the parameters and bridge responses noted here are suggested for this study as being the most critical to determine the applicability of a simplified design guidance. These parameters and responses were targeted based on design experience, NETC discussions, review of state and federal guidance, and the literature review of research noted herein. Though not addressed in the literature review, torsion in girder ends is also anticipated to be a potential measure that may determine whether a given combination of design parameters will result in unfavorable conditions. Tension in the deck ends is also included as it poses a serviceability challenge that should be included in any simplified design guidance, particularly for skewed bridges. The application and further discussion of these design and response parameters will be presented in following sections on the finite element study portion of this project report.

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APPENDIX

A

CURVED INTEGRAL ABUTMENT BRIDGE SURVEY OF STATE TRANSPORTATION AGENCIES

APPENDIX A – CURVED INTEGRAL ABUTMENT BRIDGE SURVEY OF STATE TRANSPORTATION AGENCIES

1 Q1 Which State Agency are you representing?

2 Q2 Which region of the United States does your state belong to?

- ◯ Northeast (1)
- ◯ Southeast (2)
- ◯ Midwest (3)
- ◯ Northwest (4)
- ◯ Southwest (5)
- ◯ Other (6) ____

3 Q7 How many straight integral abutment bridges has your agency designed and constructed in the last 5 years?

- ◯ 0 (1)
- ◯ 1-2 (2)
- ◯ 3-4 (3)
- ◯ 5+ (4)

4 How many curved integral abutment bridges has your agency designed and constructed?

- ◯ 0 (1)
- ◯ 1-2 (2)
- ◯ 3-4 (3)
- ◯ 5+ (4)

APPENDIX A – CURVED INTEGRAL ABUTMENT BRIDGE SURVEY OF STATE TRANSPORTATION AGENCIES

5 How many curved integral abutment bridges has your agency designed and constructed in the last 5 years?

- ◯ 0 (1)
- ◯ 1-2 (2)
- ◯ 3-4 (3)
- ◯ 5+ (4)

6 If your agency does not use integral abutment structures, please indicate why (select all that apply):

Lack of natural abutments/geography (1)

Lack of design standards (2)

Lack of performance history (3)

Maintenance concerns (4)

Costs (5)

Seismic performance concerns (6)

Other (7) ____

7 Does your agency have specific design requirements or recommendations for integral abutment bridges?

	Yes (1)	No (2)
Straight Alignment (1)	◯	◯
Curved Alignment (2)	◯	◯

8 Does your agency have specific construction or maintenance requirements for integral abutment bridges that differ from those of non-integral structures, i.e. pile construction tolerances or concrete sealing schedule for abutments?

	Yes (1)	No (2)
Straight Alignment (1)	◯	◯
Curved Alignment (2)	◯	◯

APPENDIX A – CURVED INTEGRAL ABUTMENT BRIDGE SURVEY OF STATE TRANSPORTATION AGENCIES

9 Which methods of analysis are preferred for required for the design of integral abutment bridges in your agency (select all that apply)?

Grillage model (1)

Full 3D model (2)

No model if specific parameters are met (simplified design procedures) (3)

Equivalent cantilever method for piles (4)

Full soil structure interaction model for structural analysis (soil springs for full height of piles) (5)

Other (6) ____

10 Describe any performance issues your agency has encountered related to straight and curved integral abutment bridges (check all that apply):

Approach settlement (1)

Abutment cracking at girder interface (2)

Excessive abutment displacements (3)

Deck cracking at deck ends or reflective cracking in the overlay at deck ends (4)

Deck cracking other than at deck ends (5)

Bridge rail to bridge approach rail connections (6)

Other (7) ____

11 What issues has your agency documented as most concerning related to maintenance or service life of straight and curved integral abutment bridges?

12 What issues are your agency documented as most concerned related to the design of curved integral abutment bridges?

13 Please provide link(s) to your agency's design guides or construction and maintenance requirements that include integral abutments bridges:

14 Please provide reference information or links for any published or unpublished reports that address the performance, monitoring, design, or maintenance of curved integral abutment bridges

15 Would someone from your agency be interested in/available for a follow-up phone interview related to your state’s experience with curved integral abutment bridges?

Yes (1) / No (2)

16 Please provide contact information