A Case Study on Curved Fully Integral Abutment Bridge Thermal Deformation: I-390 over I-490

AMANDA BAO, PhD, PE, Rochester Institute of Technology, Rochester, NY; CHRISTOPHER SICHAK, PE, AND SAM ANTHONY, PE, Erdman Anthony, Rochester, NY.

IBC 23-67

KEYWORDS: Integral abutment bridge, Thermal deformation, Horizontal curve

ABSTRACT: The awarding-winning I-390 southbound bridge over I-490 eastbound is a 525-feet long and 43-feet wide curved fully integral abutment bridge, which is the longest fully integral abutment bridge in New York State by the project completion time in 2021. In this paper, the thermal deformations in the curved bridge are simulated by 3D finite element modeling. The soil-pile-structure interaction mechanism is investigated to understand the behavior of the curved fully integral abutment bridge subjected to thermal expansion and shrinkage. According to the results, design recommendations for curved fully integral abutment bridges will be proposed to facilitate further adoption of the cost-effective and low-maintenance integral abutment construction in horizontally curved bridge practices.

Introduction:

Integral abutment bridges remove the joint and the bearings to eliminate the gaps between the girder ends and the abutment walls and reduce the leakage through the joints. The advantages of simplifying the construction process, lowering maintenance costs and increasing bridge service life make integral abutment bridges the excellent alternative to conventional bridges. While integral abutment bridges have been widely implemented in the United States, some states still do not use them due to the uncertainties and concerns about subsoil conditions, structural behaviors of substructures and climates. In this study, the state-of-the-art and design practices of integral abutment bridges in the United States are summarized. The key factors identified in integral abutment bridges design and construction include geographical location, span number, span length, total bridge length, skew angle, curvature of bridges, girder type, backfill soil condition, subsoil condition and foundation type.

There are growing needs in understanding the behaviors of curved integral abutment bridges to facilitate further use of the cost-effective integral abutment construction method in horizontally curved bridges. In this paper, a case study on a curved integral abutment bridge is analyzed. The bridge deformation due to thermal expansion and shrinkage is investigated and the service limit state is evaluated. Radial displacements are unique for curved bridges subjected to thermal loads and are of particular interest. The longitudinal and radial displacements will be analyzed for the curved integral abutment bridge. The analysis results will shed a light on fully integral abutment adoption in curved bridges. Design recommendations for curved integral abutment bridges will be proposed according to the analyses.

Integral Abutment Bridge:

Conventional bridges have expansion joints located at the end of bridge deck with the girders on bearings to allow for movement of the bridge

superstructure due to temperature changes year around. However, bridge deterioration is mainly caused by moisture exposure and water leakage through deck joints, which increases maintenance costs and decreases the lifespan of the bridge. [1, 2, and 3]

In integral abutment bridges, the girder ends are embedded into the concrete diaphragms so that the bridge superstructure and substructure are integrated into one continuous structure. The removal of the gaps between the superstructure and substructure of the bridge eliminates the water leakage problem through deck joints, reduces the cost of maintenance and construction, simplifies the construction process, increases the bridge service life as well as smooths the riding surface. [4, 5, and 6]

The comparison of the integral abutment bridge with the conventional bridge is illustrated in Figure 1.

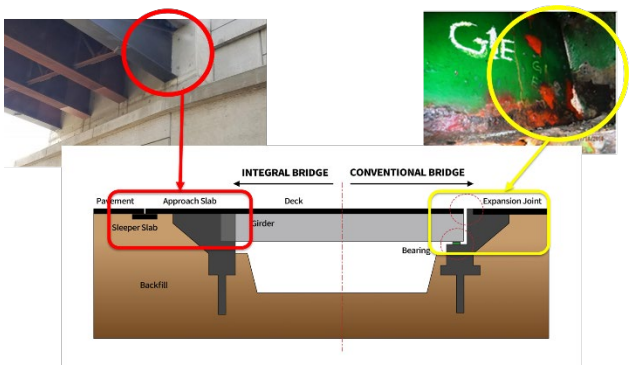

Figure 1: Integral Abutment Bridge versus Conventional Bridge (Pictures courtesy of Short Span Steel Bridge Alliance, Association for Bridge Construction and Design-Western New York Chapter and Midas Bridge)

Current Practices of Integral Abutment Bridges in the United States:

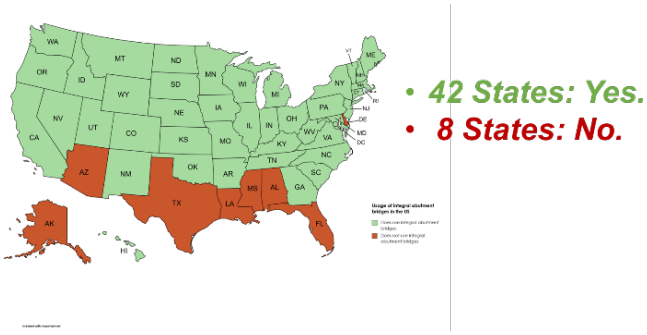

Figure 2: Integral Abutment Bridge Usage in the United States

Currently, forty-two states use integral abutment bridges in the United States as shown in Figure 2. Each State Department of Transportation specifies the design parameters and limitations of integral abutment bridges in Bridge Design Manuals and Specifications. There are growing needs in understanding the behaviors of curved integral abutment bridges to facilitate further use of the cost-effective integral abutment construction method in horizontally curved bridges. The success practices in the existing structures are important for developing the design guidelines of curved integral abutment bridges. [7, and 8]

For the eight States that currently do not use integral abutment bridges, the main reasons are summarized in Table 1. The responses in Table 1 were collected through literatures, phone interviews and email surveys.

Table 1: Reasons Not Using Integral Abutment Bridges

State	Reasons
Alabama	The predominant soil type in Alabama is high-volume expansive clay. Expansion joints are critical to accommodate the shrinkage and swelling of the soil.
Alaska	Extremely cold weather with freezing temperatures. Frozen soil restraints the movement of the fully integral abutment.
Arizona	Costly repairs due to the longitudinal movements caused in approach slabs.
Delaware	Never used with no information.
Florida	The elimination of joints between the superstructure and the back wall is important for using deicing salts. In Florida, where road salts are not used, there is no need for a joint-less system.
Louisiana	Poor soft soil conditions.
Mississippi	The predominant soil type is expansive clay, and expansion joints are critical to accommodate the shrinkage and swelling of the soil.
Texas	Concrete piles are used for soft soil conditions in Texas. Concrete piles are too stiff to move and large pile movements will cause cracking. Integral abutment bridges are not economical to build or repair due to the poor soil conditions.

The current practices indicate that integral abutment bridges are not suitable in the regions where the thermal expansion/shrinkage can exceed 2 inches, and not suitable in the zones where expansive clay exists and/or poor subsoil conditions are concerning. [9, and 10]

The maximum number of spans specified in the State DOT Bridge Design Manuals are summarized in Table 2. There are 11 States explicitly allow integral abutment bridges for single span and multi-span bridges, Maine specifies maximum two spans for integral abutment bridges and Michigan allows a maximum of six spans for integral abutment bridges. Other States don't explicitly specify the maximum number of spans.

Table 2: Maximum Number of Spans for Integral Abutment Bridges

Maximum Number of Spans	>=1	2	6
State	Arkansas, Colorado, Massachusetts, New Jersey, New York, Ohio, Oklahoma, Pennsylvania, Rhode Island, South Dakota, Wisconsin	Maine	Michigan

The maximum bridge lengths specified in the State Bridge Design Manuals are listed in Table 3. Some States set the maximum bridge lengths for steel girder bridge and concrete girder bridge separately due to the different temperature ranges for two materials.

Table 3: Maximum Bridge Length for Integral Abutment Bridges

Max Bridge Length	State
<=200 feet	Massachusetts
<=300 feet	Arkansas
<=400 feet	California, Illinois, Kansas, New York, North Carolina, North Dakota, Ohio, Oklahoma
<=500 feet	Maine, New Jersey, Virginia
<=600 feet	Indiana, Iowa, Pennsylvania, Rhode Island
650-1000 feet	Colorado, Idaho, Kentucky, South Dakota, Tennessee

The maximum span length is ranging from 130 feet to 200 feet in most States.

The curved integral abutment bridge adoption in the United States is listed in Table 4. Some States do not explicitly specify yes or no for the curved integral abutment bridge use.

Table 4: Curved Integral Abutment Bridge Adoption in the United States

Curved Bridge Allowed?	State
Yes	Arkansas, California, Colorado, Idaho, Iowa, Kansas, Kentucky, Massachusetts, Maine, Minnesota, Nevada, New Hampshire, New Jersey, New York, North Carolina, Oregon, Pennsylvania, South Dakota, Virginia, West Virginia, Wisconsin
No	Illinois, Indiana, Michigan, Ohio, Rhode Island, Vermont

From Table 4, we notice that curved integral abutment bridges have been widely used in the United States.

Table 5 lists the limitations of the curved integral abutment bridge adoption, such as maximum curvature, minimum curve radius and girder geometry.

Table 5: Curved Integral Abutment Bridge Limitation

Limitation	State
Max Curvature = 2°	West Virginia
Max Curvature = 5°	Arkansas, Colorado, Massachusetts
Max Curvature = 10°	Nevada
Max Curvature = 20°	California
Min Curve Radius	Iowa (900 feet), Oregon (1200 feet)
Straight and Parallel Girders should be in Curved Bridges with integral abutment	New Hampshire, New Jersey, Pennsylvania

Typical foundation types used in integral abutment bridges are steel H-driven piles, steel pipes, precast concrete piles and drilled shafts. Steel H-driven piles are the most common foundation type in integral abutment bridges in the United States, but the orientations of the H piles are not consistent among States. [11, 12, and 13] Some States specify the

steel H pile should be oriented with strong axis parallel to the bridge longitudinal direction, while other States require the H pile strong axis parallel to the bridge transverse direction. There is no consensus about the H pile orientation in integral abutment bridges. According to the research findings [11, 12 and 13], it is more economical to orient the H pile web parallel to the bridge transverse direction in seismic force governing zones, while in the non-seismic governing design, it is more economical to orient the H pile web parallel to the bridge longitudinal direction.

Case Study on I-390 Bridge over I-490

The awarding-winning I-390 southbound bridge over I-490 eastbound is 525 feet long and 43 feet wide. The bridge has the maximum span to radius ratio of 0.0925. The bridge is the longest fully integral abutment bridge in New York State by the project completion time in 2021 as shown in Figure 3.

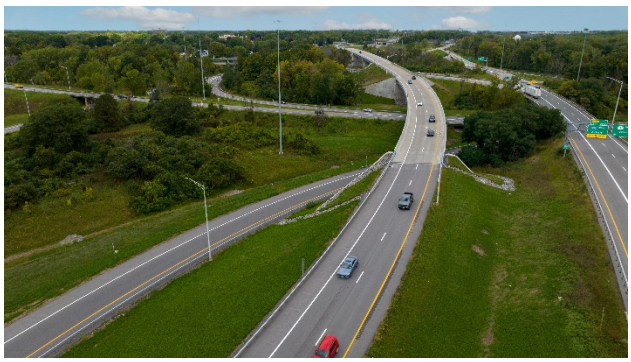

Figure 3: I-390 Southbound Bridge over I-490 Eastbound (Photos courtesy of Erdman Anthony)

Figure 4 shows the bridge superstructure that consists of three continuous span multi-steel I-plate girders on a horizontal curve with a 2000 feet radius, and the span lengths are 185 feet, 155 feet and 185 feet, respectively. The girder spacing is 9.25 feet and the deck overhang is 3 feet on each side. The bridge width out-to-out is 43 feet with the clear roadway width of 40 feet. The fully integral abutments are supported by steel H-driven piles with the pile web orientation parallel to the bridge longitudinal direction as demonstrated in Figure 5.

Figure 4: Superstructure of I-390 Southbound Bridge over I-490 Eastbound (Photos courtesy of Erdman Anthony)

Figure 5: Steel H Pile Foundation of I-390 Southbound over I-490 Eastbound (Photo courtesy of Erdman Anthony)

The refined analysis method is required for the bridge based on the curvature exceeding 0.06 and the total bridge length exceeding 400-feet according to the limits specified in AASHTO and NYSDOT bridge design criteria.

New York State specifies the maximum span length for integral abutment bridge is 150 feet, and the 185 feet span for the I-390 southbound bridge over I-490 eastbound exceeds this limit. In order to accommodate the thermal displacement and alleviate horizontal earth pressure on the cantilever surround walls, the steel H piles are sleeved as demonstrated in Figure 6.

Figure 6: Steel Pile Sleeves (Photos courtesy of Erdman Anthony)

Figure 7 shows the integral abutment is under construction with the end wall and wingwalls being completed. The cast-in-place concrete deck pour, the approach slab and the sleeper slab construction are shown in Figure 8. The expansion joint is located at the end of the approach slab and on the sleeper slab.

Figure 7: Integral Abutment Under Construction (Photo courtesy of Erdman Anthony)

Figure 8: Concrete Deck Pour and Approach Slab (Photos courtesy of Erdman Anthony)

The location of the expansion joint and the details of the expansion joint are illustrated in Figure 9. The expansion joint uses 4-inch joint seal to accommodate thermal deformations. The design construction temperature is 68°F.

The design temperature range for steel girders in Rochester, New York is from -30°F to 120°F. The expansion joint design should accommodate both longitudinal and radial displacement during temperature change.

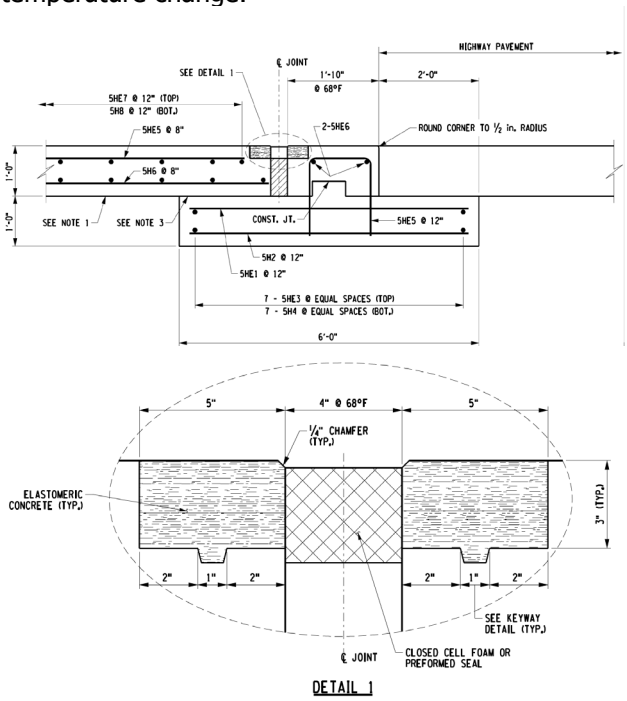

Figure 9: Sleeper Slab and Expansion Joint Details

Structural Modeling and Results:

The I-390 over I-490 bridge integral abutments are designed using a refined analysis as defined in NYSDOT Bridge Manual Section 11.2.1.[14] The refined analysis requires a three-dimensional finite element model to determine the maximum loads acting on the piles, abutment stem, backwall, and superstructure. The model includes the effects of skew, curvature, soil-structure interaction, thermal movements, dead and live loads, and roadway grade.

The 3D finite element models are built to analyze the bridge loads and deformations as shown in Figure 10. The temperature range in the analysis is from -30°F to 120°F.

In this study, the finite element model was built in CSI Bridge, and L-Pile was used together with CSI Bridge to account for the effects of lateral loads due to thermal movements and soil-structure interaction. A series of L-Pile analyses were used to calibrate and determine the non-linear spring parameters used in the CSI Bridge model.

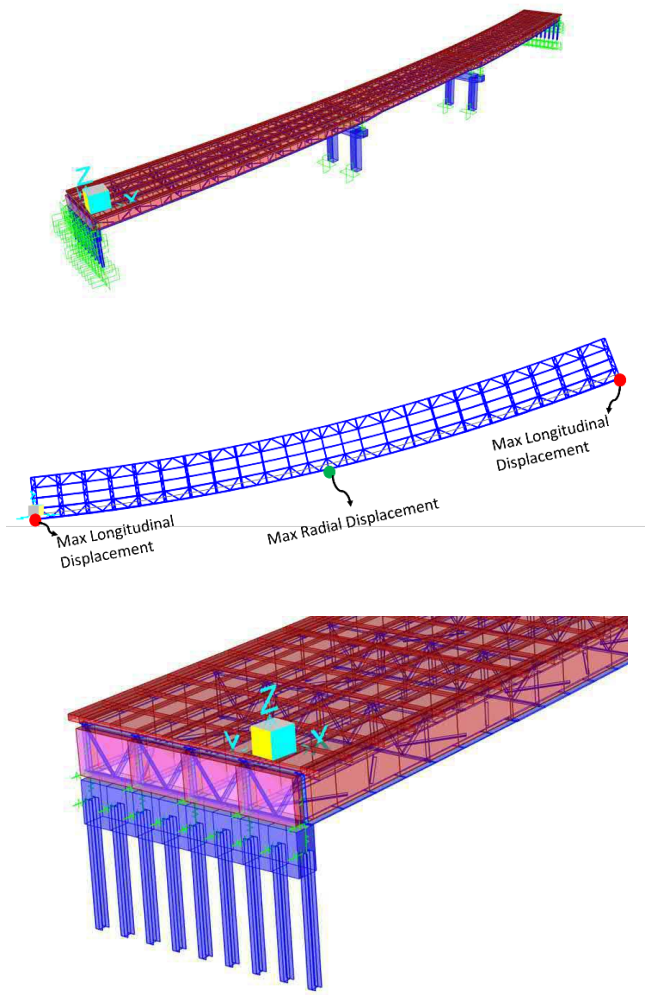

Figure 10: 3-D Finite Element Model for I-390 Southbound Bridge over I-490 Eastbound

In this study, the thermal deformations at the integral abutments are of interest. The longitudinal and radial displacements during temperature change are analyzed. The coefficient of thermal expansion used in the analysis is 6.5×10^{-6} inch/inch/°F.

The maximum longitudinal displacement at the abutment is 3.1 inches for the temperature range of 150°F, and the maximum radial displacement 1.1 inches. The locations of the max longitudinal displacement and the max radial displacement are shown in Figure 10. Minor horizontal rotation at the abutment wall due to the thermal movement is also detected in the analysis in the curved bridge.

Discussions:

Since the completion of the I-390 Southbound Bridge over I-490 Eastbound in 2021, the bridge has performed very well to carry everyday traffic and accommodate the year-around temperature

expansion and shrinkage. The fully integral abutments have functioned as designed, and no issues have been reported. No cracks or excessive deformations have been observed in either bridge longitudinal or transverse direction so far.

Conclusions:

This study summarizes the current practices in integral abutment bridges in the United States. A case study on a horizontally curved integral abutment bridge I-390 over I-490 is conducted to evaluate the fully integral abutment adoption in curved bridges. According to the study, the following conclusions can be drawn:

- Due to lower construction and maintenance costs and longer service life, integral abutment bridges are the excellent alternative to conventional bridges.
- Geographical location plays an important role in integral abutment bridge adoption due to weather and soil conditions.
- Integral abutment bridges are not suitable for the regions with poor subsoil conditions. Some States do not use integral abutment bridges because of the uncertainties about expansive soil conditions and pile structural behaviors.
- Better understanding of curved bridges will facilitate further use of integral abutment bridges.
- The radial displacement is important for curved integral bridges under thermal loads. The bridge expansion joints should be designed to accommodate both the longitudinal and the radial displacement as well as the possible horizontal rotation of the abutment end wall.
- The real-world success of the 525-feet long curved integral abutment bridge sheds a light on further adoption of the cost-effective and low-maintenance integral abutment construction in horizontally curved bridge practices.

Acknowledgements:

The authors would like to acknowledge Rochester Institute of Technology and Association for Bridge Construction and Design – Western New York chapter for the research grants to support the study, and acknowledge Erdman Anthony for the technical collaboration on this study. Special thanks go to Martin Sosa, Nate Bedard, Madison Bowman, Dennis Kirby, Aaron Khan, Monse Villarreal-Rios, Nick Templeton, Maddy Bullis, and Jordan Parris from Rochester Institute of Technology for their help with the literature review and data collection.

References:

[1] Bao, A., Guillaume, C., Satter, C., Moraes, A., Williams, P., Kelly, T. and Guo, Y., "Testing and Evaluation of Web Bearing Capacity of Corroded Steel Bridge Girders", Engineering Structures, Vol 238, July 2021, 112276, ISSN 0141-0296. https://doi.org/10.1016/j.engstruct.2021.112276
[2] Bao, A., Guillaume, C. and Moraes, A., "Shear Strength of Deteriorated Steel Girders in Multi-Girder Bridges", Proceedings of the 10th International Structural Engineering and Construction Conference - Interdependence between Structural Engineering and Construction Management, ISBN: 978-0-9960437-6-2, Chicago, IL, USA, May 20-25, 2019.
[3] Bao, A., Gulasey, M., Guillaume, C., Levitova, N., Moraes, A. and Satter, C., "Structural Capacity Analysis of Corroded Steel Girder Bridges", Proceedings of the 3rd International Conference on Civil, Structural and Transportation Engineering, Niagara Falls, Canada, June 10-12, 2018.
[4] Kalayci, E., Civjan, S.A., Breña, S.F. "Parametric study on the thermal response of curved integral abutment bridges" Engineering Structures, v 43, 129-138, October 2012.
[5] Civjan, S. A., Kalayci, E., Quinn, B. H., Breña, S. F. and Allen, C. A. "Observed integral abutment bridge substructure response" Engineering Structures. V 56.: 1177-1191, 2013.
[6] Kim, W., Laman, J.A., "Integral abutment bridge response under thermal loading", Engineering Structures, 32(6):1495–508, 2010.
[7] Fennema J.L., Laman J.A. and Linzell D.G., "Predicted and measured response of an integral abutment bridge", Journal of Bridge Engineering, 10(6):666–77, 2005.
[8] Hoffman J. and Phares B., "Thermal load design philosophies for horizontally curved girder bridges with integral abutments". Journal of Bridge Engineering, 19(5), 2014.
[9] Kunin, J., and Alampalli, S. "Integral Abutment Bridges: Current Practice in the United States and Canada," Special Report 132, Transportation Research and Development Bureau, New York State Department of Transportation, Albany, New York, 1999.
[10] Maruri, R., and Petro, S. "Integral Abutments and Jointless Bridges 2004 Survey Summary." Federal Highway Administration and Constructed Facilities Center at West Virginia University, Morgantown, West Virginia, 2004.
[11] Bao, Y., Lawrence, J., Hopson, V., and Puzio,

M., "Optimization of Bridge Deep Foundation Design in Seismic and Tsunami Zone", Proceedings of 2014 Structures Congress, Boston, MA, April 3-5, 2014.
[12] Bao, Y. and Rietz, A., "Seismic Soil-Structure Interaction in Fully Integral Abutment Bridges with HP Driven Piles", Proceedings of 7th International Structural Engineering and Construction Conference, Honolulu, HI, June 18-23, 2013.
[13] Bao, Y. and Rietz, A., "Numerical Modeling of Dynamic Soil-Structure Interaction in Bridges with HP Driven Piles", Proceedings of DFI 37th Annual Conference on Deep Foundations, Houston, TX, October 16-19, 2012.
[14] New York State Department of Transportation Bridge Manual, 2021.