Integral Abutment Connection Details for Accelerated Bridge Construction

Final Report
January 2019

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16. Abstract

The use of precast elements and prefabricated bridge segments along with accelerated construction techniques, known as accelerated bridge construction (ABC), has allowed for increased efficiency of construction, reduced safety concerns, and converted month-, or even year-, long closures into a matter of weeks, or at times, days. This tactic is growing in popularity within the bridge community, and research projects have been initiated to investigate how the construction of bridge elements can be expedited.

One such element being investigated is the integral abutment. This structural connection for bridges was introduced to eliminate the need for expansion joints between the substructure and superstructure, where the presence of water and other deteriorating chemicals caused long-term and frequent maintenance issues. Due to this area needing to be heavily reinforced, congestion issues arise when attempting to apply ABC methods. In addition to the reinforcing congestion, the construction tolerances and weight of the integral abutments cause some problems for ABC projects.

These issues are the basis for this project, which was intended to investigate the use of mechanical couplers to splice the foundation elements to the superstructure elements of bridges while applying ABC techniques. Since this was a Phase II project, the methodologies and laboratory setup for evaluating the ABC connection details were the same as that of Phase I. From the results of Phase I, three connection details were developed for investigation in Phase II. Of which, two were a revised design of the two mechanical coupler connection details tested in Phase I, and the third was a new connection detail designed through the Iowa Department of Transportation (DOT) to be used on an upcoming bridge project.

With this project completed, further investigations about integral abutment connection details for ABC applications should be conducted to provide more literature on the subject. Such investigations would be further revisions to the designs of the connection details and field monitoring of real-world applications of the connections.

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INTEGRAL ABUTMENT CONNECTION DETAILS FOR ACCELERATED BRIDGE CONSTRUCTION

Final Report
January 2019

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ACKNOWLEDGMENTS

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EXECUTIVE SUMMARY

Often, during bridge construction projects, lane and road closures can have significant impacts on the public. To alleviate this impact, the use of precast elements and prefabricated bridge segments along with accelerated construction techniques, known as accelerated bridge construction (ABC), has allowed for increased efficiency of construction, reduced safety concerns, and converted month-, or even year-, long closures into a matter of weeks, or at times, days. This tactic is growing in popularity within the bridge community, and research projects have been initiated to investigate how the construction of bridge elements can be expedited.

One such element being investigated is the integral abutment. This structural connection for bridges was introduced to eliminate the need for expansion joints between the substructure and superstructure, where the presence of water and other deteriorating chemicals caused long-term and frequent maintenance issues. The integral abutment alleviates the need for the expansion joint by having the superstructure rigidly connected to the foundation resulting in the two elements acting together in response to traffic loads as well as thermal expansions and contractions. Due to this area needing to be heavily reinforced, congestion issues arise when attempting to apply ABC methods. In addition to the reinforcing congestion, the construction tolerances and weight of the integral abutments cause some problems for ABC projects.

These issues are the basis for this project, which was intended to investigate the use of mechanical couplers to splice the foundation elements to the superstructure elements of bridges while applying ABC techniques. Since this was a Phase II project, the methodologies and laboratory setup for evaluating the ABC connection details were the same as that of Phase I. The Phase I investigation consisted of a cast-in-place integral abutment connection, which was the control specimen, and two ABC connections utilizing mechanical couplers. From the results of Phase I, three connection details were developed for investigation in Phase II. Of which, two were a revised design of the two mechanical coupler connection details tested in Phase I, and the third was a new Ultra-High Performance Concrete (UHPC) connection detail designed through the Iowa Department of Transportation (DOT) to be used on an upcoming bridge project.

The strength and durability of the connection details was evaluated through full-scale laboratory testing that applied simulated thermal loads and live loads. Strain gauges were used to capture the development and strength of the specimen and connecting materials, and displacement transducers monitored the propagation and magnitude of precast joint openings between the integral diaphragm and pile cap to evaluate the durability and serviceability of the connection details. The results of these tests were compared to the control specimen tested in Phase I.

The UHPC connection detail utilized a “notched” cross section formed into the integral diaphragm, protruding reinforcing bars from integral diaphragm and pile cap, and filling the void between the two precast elements with UHPC. The construction of the precast elements was not difficult and should be achievable for experienced fabricators. The results from the testing suggest this connection detail is a viable option for creating a strong, durable and constructible integral abutment bridge in an advanced bridge construction setting.

With this project completed, further investigations about integral abutment connection details for ABC applications should be conducted to provide more literature on the subject. Such investigations would be further revisions to the designs of the connection details and field monitoring of real-world applications of the connections.

CHAPTER 1. INTRODUCTION

1.1 Background

Accelerated bridge construction (ABC) has become a useful bridge construction procedure utilized by many bridge engineering agencies around the world, and in the United States. ABC is being analyzed and formalized to replace conventional bridge construction in more and more projects due to the significant decrease in construction time and traffic impact, as well as the increase in bridge element quality and worker and public safety. ABC can allow for replacement of an existing bridge in a matter of weeks, or even days, utilizing prefabricated bridge element and systems (PBES); compare this to conventional bridge construction, which can have construction times of months and result in detours that greatly affect the flow of traffic, as well as the safety of the public and construction workers.

ABC differs from conventional bridge construction by utilizing PBES and other technologies to lift, slide, and rotate parts of a bridge, or at times the entire bridge, into position. Once in position, connections are made to join the precast elements into one cohesive bridge system. These connections have been, and still are being, researched and tested for many locations within a bridge to improve their durability, constructability, and efficiency.

One detail still being researched and tested is the integral abutment. An integral abutment is a connection composed of combined shear and moment connections between the bridge superstructure and substructure. This connection is appealing to bridge designers since it results in the elimination of the expansion joint, which typically is the common location of structural deterioration.

In conventional bridge construction, the superstructure and substructure are connected by an expansion joint. This detail often allows infiltration of water, debris, and deicing chemicals when not designed properly. As a result, these infiltrations can cause structural deterioration and corrode elements of the abutment connection, which may compromise the integrity of the bridge. These issues create the need for the integral abutment connection, which can reduce the cost of maintaining the bridge since there are no joints to allow infiltration.

Since the integral abutment reinforcement can be highly congested to resist the different forces acting on both the substructure and superstructure, the issue of transporting and installing these elements govern the design in ABC applications. The issue of transporting comes from the weight of the specimen, and the installation issues are the result of the splices that will need to be connected after the lift, slide, etc., have been completed.

To alleviate these issues, the method of cast-in-place integral abutments has been the common procedure for this ABC connection. This procedure eases the tolerances of the connection during construction by creating a simpler integral connection, which is done by placing the prefabricated pile cap on the driven piles, setting the prefabricated girder, and then placing a closure pour over the connection to create the integral connectivity. A significant downside to this connection detail is the closure pour material which typically consists of a large mass of high-performance concrete (HPC) or regular concrete which require several days to a week to form, prepare and cast the diaphragm plus curing time which may take several days to a week as well. This creates delays in opening the structure to traffic.

1.2 Research Scope, Objectives, and Tasks

The scope of this research is to provide information for the construction of the ultra-high performance concrete (UHPC) joint connection detail, specifically any issues encountered, and laboratory test results to aid in the planning, design, and construction of the integral abutment connection detail when used in ABC projects. Engineers with the Bridge Engineering Center (BEC) at Iowa State University (ISU) discussed the design for the UHPC joint integral abutment connection detail for ABC with the Iowa Department of Transportation (DOT), and how to prepare it for a full-scale laboratory investigation. The laboratory specimen was evaluated on three criteria: constructability, strength, and durability.

The following five tasks were completed to meet the objectives of the project:

1. Conduct a detailed review of the results from Phase I, as well as a literature review of ABC procedures with respect to integral abutments.
2. Develop and design connection details for an integral abutment using ABC methods, as well as results of Phase I.
3. Investigate and evaluate the constructability aspects of the connection details and adjust designs accordingly. Also, test the flowability of UHPC through the designed cross-section of the UHPC joint connection detail.
4. Construct and test the full-scale specimen of the connection detail in the laboratory, measuring performance of the detail in terms of durability and strength.
5. Present the results of this study in a final report discussing the findings of the research for the future use of integral abutments in ABC applications.

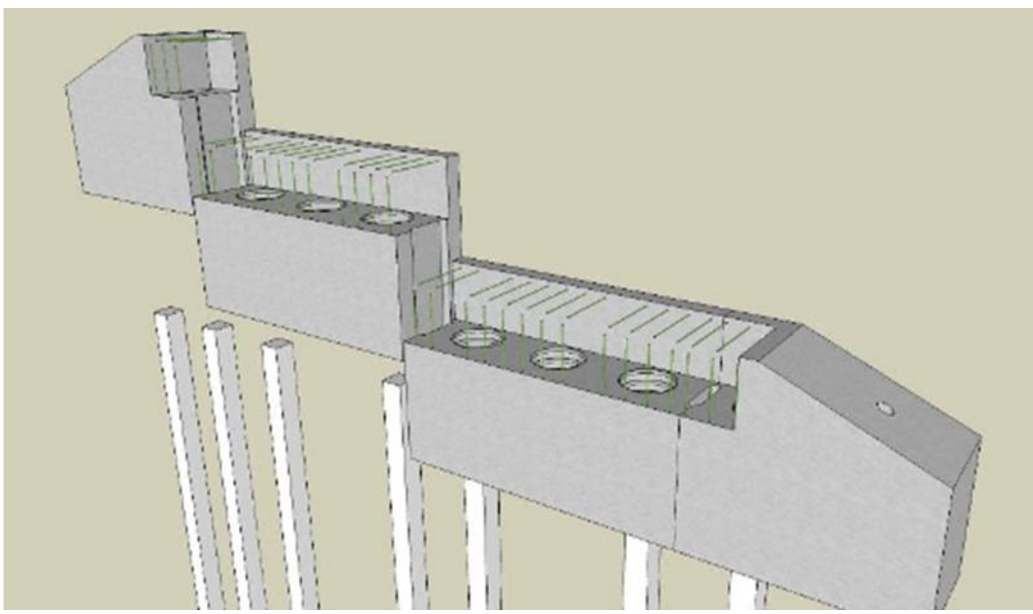
CHAPTER 2. LITERATURE REVIEW

2.1 Accelerated Bridge Construction (ABC) Manual (2011)

The ABC Manual (Culmo 2011) defines an integral abutment as:

"A bridge abutment type that is made integral with the bridge superstructure through a combined shear and moment connection. They are often constructed with a single row of piles that allow for thermal movement and girder rotation. Soil forces behind the abutments are resisted through the strut action of the superstructure."

The implementation of a cast-in-place concrete closure pour is typically the method used in ABC to create the integral abutment connection (Figure 1).



Utah DOT

Figure 1. Prefabricated integral abutment, prior to closure pour

While this connection has been the normal procedure, other connections such as mechanical and grouted couplers are a favorable alternative. These couplers would be ideal when compared to a cast-in-place connection for the ease of construction, as well as the decrease in time to complete the connections. The factor limiting the benefits of couplers is the tighter tolerances when installing the bridge elements to be constructed, as well as the smaller construction spaces in which to install the connections themselves.

This manual covers a multitude of construction aspects regarding ABC projects, such as contracting and decision-making procedures, but one important construction aspect outlined was the differences in placement methods. A few methods outlined were: self-propelled modular transporters (SPMTs), longitudinal launching, horizontal skidding/sliding, and conventional cranes. Of these options, the horizontal skidding/sliding option became the method of focus for the connection details to be designed and investigated on the basis that if the connection details were acceptable for horizontal sliding, then they would be acceptable for the other technologies as well since horizontal sliding could pose issues with some protruding elements of the connections. This method typically involves erecting the new bridge parallel to the existing bridge, or final location of the bridge, and then sliding the new bridge into location after the old bridge is demolished, or the substructure is complete. The slide can be done via numerous methods, but typically hydraulics and rollers or Teflon pads allow for the lateral movement of the bridge elements.

2.2 Innovative Bridge Designs for Rapid Renewal – ABC Toolkit (2013)

The integral abutments defined in the ABC Toolkit are based on a pile driving tolerance of 3 in. in all directions of the specified locations. Precast pile caps are fabricated with voids created from corrugated metal pipe (CMP), which are designed to fit around the driven piles and then filled with self-consolidating concrete (SCC) providing the connection between the abutment and piles.

Integral abutments are most advantageous to ABC when connections between the elements of the integral connection can be made efficiently, as well as effectively. The integral connection, otherwise called “jointless construction,” enhances the longevity of the bridge due to the exposure of structurally deteriorating materials being eliminated. This connection between the integral diaphragm and pile cap is typically completed through a cast-in-place concrete closure pour, which requires minimal formwork to provide adequate support for the placement of the closure pour. Therefore, contractors normally pursue this type of connection, but the time to let the concrete reach the specified strength introduces the need for different connections.

To mitigate the issue of concrete cure time, the concept of installing prefabricated integral abutment elements arises. By having all elements being installed efficiently, and joined with advanced connection technology, construction time can be minimized. One such connection technology brought up in the toolkit is the grouted splice coupler. During fabrication, a template should be created for each element to contain a part of the coupler to ensure the minimal tolerances will be met during placement of the elements. Also, the toolkit recommends a “dry-fit” be completed with the connection prior to the elements’ shipment to the project site, as to alleviate probable construction issues in the field (HNTB Corporation et al. 2013).

2.3 Iowa Accelerated Bridge Construction History (2014)

Since 2006, ABC has been utilized for bridge construction in Iowa. This paper described five key ABC projects that have advanced the understanding and application of ABC to the Iowa DOT. The five projects, along with their major impact for furthering ABC, and some lessons learned after completion of the project are listed (Nelson 2014):

Mackey Bridge

- Pile pocket connection verified
- Consider prestressing precast substructure elements for dynamic impact loads experienced during transportation

Madison Bridge

- A pile driving tolerance of 3 in. was implemented for the Pile Pocket Connection, and well executed by the contractor
- Use of a flowable mortar to fill void under abutment footing made by temporary blocking used to set the element to the correct elevation

24th Street Bridge over I-29/I-80 in Council Bluffs

- Sand blasting was used to roughen precast concrete surfaces for adequate bonding to cast-in-place concrete

Keg Creek Bridge

- When grouted couplers are to be used in connecting prefabricated elements, a template should be used to alleviate minimal tolerances in the field
- Grouted splice couplers are a very efficient and effective technology for connecting prefabricated elements
- The semi-integral detail with an overhanging backwall posed a forming issue to properly prevent leakage of the UHPC placed to complete the integral connection

Massena Lateral Bridge Slide

- From a project bid standpoint, design alternatives of a precast and a cast-in-place concrete abutment to allow the contractors to choose which alternative would best suit their capabilities
- In cases where either more or larger piles are required, design alternatives that implement different piling alternatives as well as precast and cast-in-place concrete abutments

2.4 Precast Concrete Elements for ABC: Volume 1-1: Laboratory Testing of Precast Substructure Components, Boone County Bridge (2009)

One of the objectives was to find the actual strength of the connection between the precast abutment cap and the piles, as well as to document the construction process, particularly any problems or difficulties that occurred.

The setup of the specimens was representative of the conditions that would be applied to the element in the field. A single-pile (Figure 2) and double-pile (Figure 3) cap abutment was set up and tested similarly by applying loads onto the inverted pile cap setup.

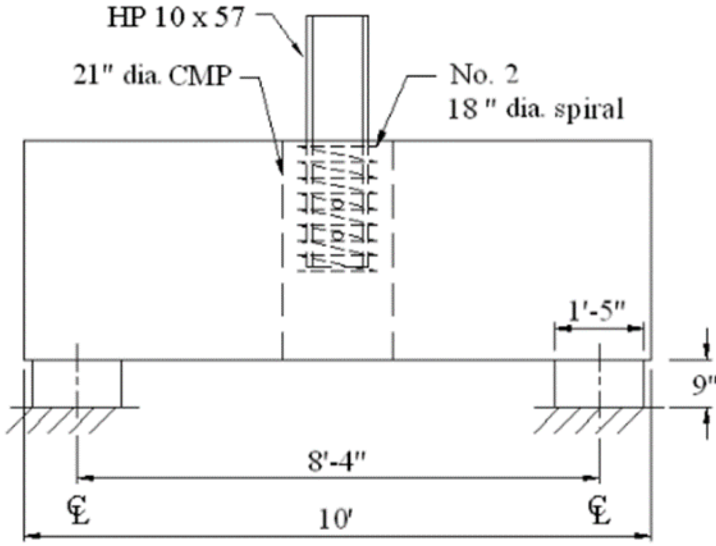


Figure 2. Single-pile abutment test support details

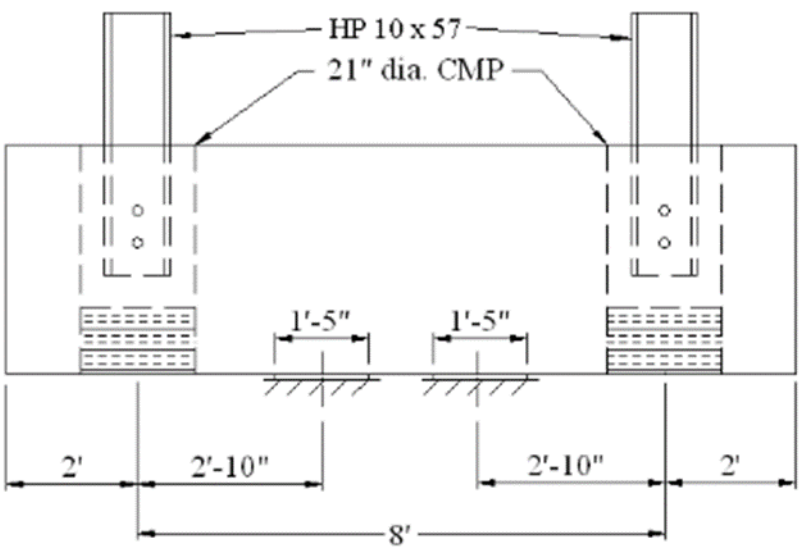


Figure 3. Double-pile abutment test support details

The single-pile cap abutment was designed to represent a negative moment applied in the field, and the double-pile cap abutment was to represent a positive applied moment in field conditions. Also, since the double-pile cap had yet to fail after moment testing, a shear test was conducted to see if the connection would fail through "punching" through the precast section.

After testing both pile abutment specimens, it was reported "that there is no concern for a shear failure between the H-pile and the concrete, or between the precast concrete in the CMP." The failure recorded for both specimens was a flexural-shear failure when loaded to a minimum of 4.5 times the unfactored design load for the single-pile abutment and loaded to approximately two times the unfactored design load for the double-pile abutment. Note the orientation of the double-pile abutment resulted in loading that was more severe than the loading of the element in the field.

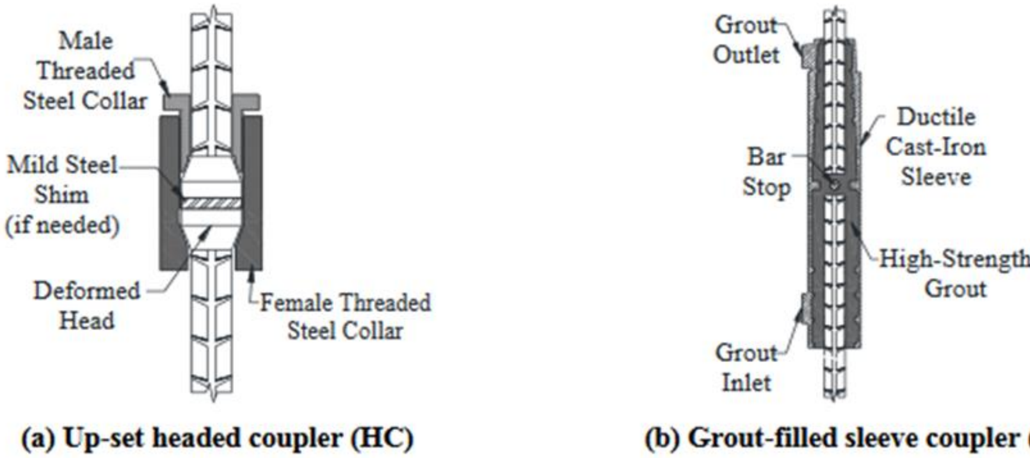
The construction of the pile cap abutments was reported to have gone smoothly with the only waiting time being on the arrival of the delivery truck. There were no clearance issues recorded between the CMP and the H-piles, and the installation of the abutments took approximately 15 minutes (Figure 4) (Wipf et al. 2009).

Courtesy of James Nelson, Iowa DOT

Figure 4. Abutment being lowered into place

2.5 Precast Column-Footing Connections for ABC in Seismic Zones (2013)

ABC connections between elements in moderate or high seismic zones have not been used extensively due to the uncertainty of the seismic performance of the connections. To advance the documentation and knowledge of ABC connections in seismic regions, the California Department of Transportation (Caltrans) studied two types of mechanical bar splices, up-set headed coupler (HC) and grouted-filled sleeve coupler (GC) (Figure 5), by testing against a cast-in-place column-footing connection, specifically focusing on detailing of the connection for seismic regions.



Caltrans

Figure 5. Mechanical splices used for this investigation

To study these connections for strength, durability, and seismic design tolerances, three experimental studies were performed on the connections. These studies were:

- Half-Scale Column Models
  - Five half-scale reinforced concrete bridge column models based on the Caltrans' seismic design criteria (SDC) for a displacement ductility design made to achieve large inelastic deformations before the specimen failed. The precast elements of the column-footing had geometry and reinforcement details commonly used in California with modern seismic detailing.
- Testing of Individually Mechanically-Spliced Bars
  - Uniaxial tests on individual HC and GC devices, static and dynamic, were performed to aid in the analytical testing of the half-scale specimens.
- Analytical Studies
  - Models of both the individual components of the mechanical splices and the half-scale columns were made into OpenSEES using plasticity frame-elements with uniaxial fiber-sections. These models were compared to the results of the half-scale column models, as well as the testing of the individual mechanical splices, to validate the modeling methods.

Through analysis of the results of the three studies, the following conclusions were made about mechanical bar splices for ABC applications in seismic zones (Haber et al. 2013):

- Mechanical bar splices are a practical option to replace cast-in-place connections for ABC
- Caltrans and American Association of State Highway and Transportation Officials (AASHTO) restrictions on couplers should be lifted, or at least revised
- HC and cast-in-place connections for the half-scale columns had similar behavior for seismic behavior
- GC had a lower drift capacity than the cast-in-place and HC, but the seismic performance was still acceptable

- The analytical models' calculated results were well correlated with the measured results of the half-scale column models
- All couplers failed due to bar fracture, away from the coupler, for the tension tests to individual couplers

2.6 Plastic Energy Absorption Capacity of #18 Reinforcing Bar Splices under Monotonic Loading (1996)

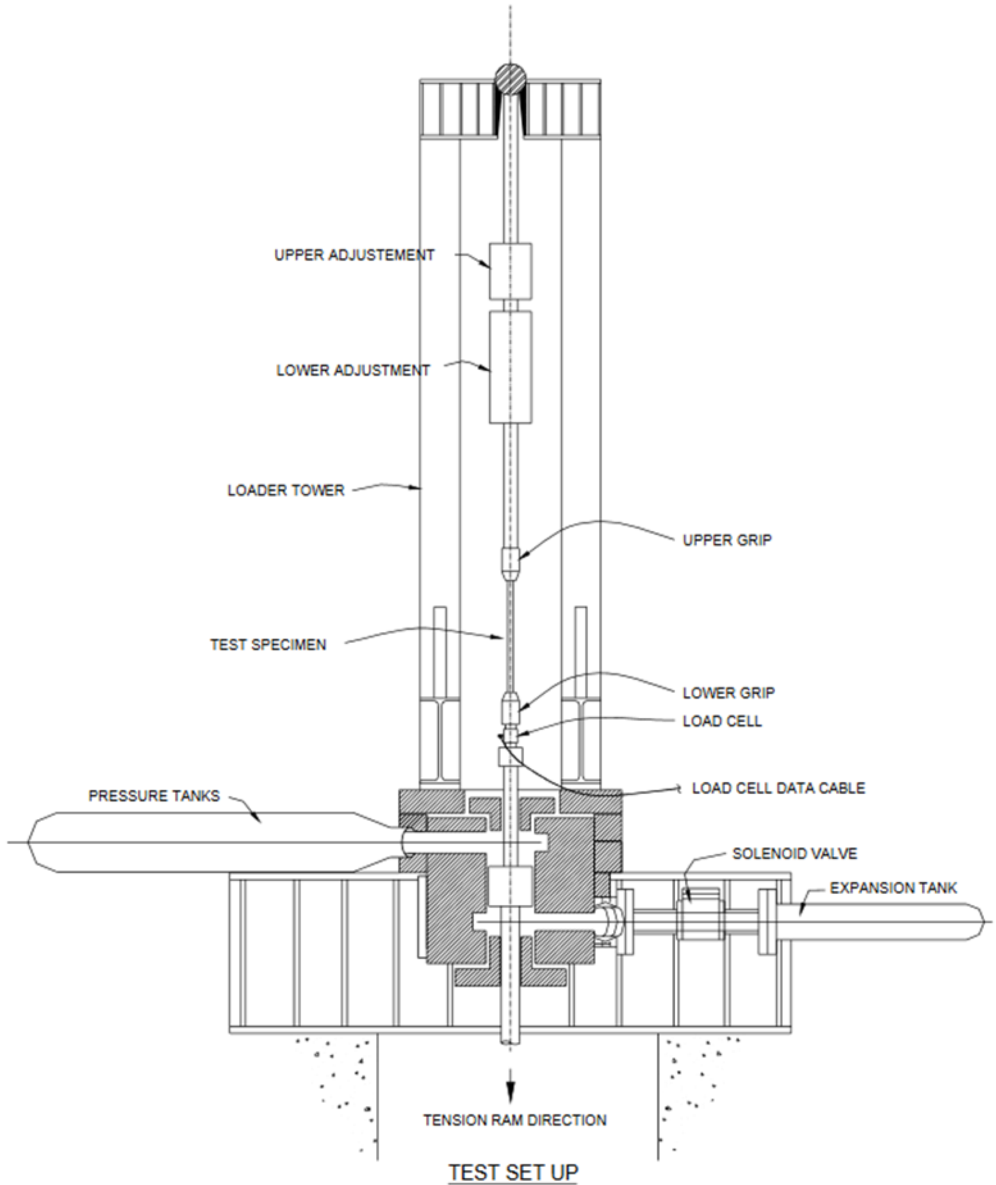
Strain criteria for reinforcing steel bar splices was to be established and included with the strength criteria for rebar splices for Caltrans, which is 125% F_y. This additional criterion was sought after to have mechanical bar splices potentially replace welded splices in the plastic hinge region. To do this, a study was created to test six #18 bar mechanical splicing systems, which were prequalified by Caltrans, under monotonic loading of the spliced samples in tension to fracture.

This study concluded some welded reinforcement connections may be replaced by mechanical bar splices in the plastic hinge zone due to the coupler's performance in dissipating strain energy throughout the connection. Also, a strain minimum needs to be further studied and set by design standards due to the result of some splices potentially failing before the yield strain is developed in the reinforcing bars, which was seen in the threaded mechanical bar splices in the study by some of the reinforcing bars simply slipping out of the threaded connection prior to yielding (Noureddine 1996).

2.7 Performance of Reinforcement Bar Mechanical Couplers at Low, Medium, and High Strain-Rates (2015)

In the design of structures subjected to blast effects, a large quantity of reinforcement is used in concrete slabs, beams, and at corners of a structure. This results in high congestion and difficulty of placing reinforcement, as well as increasing construction costs. To alleviate these issues, mechanical splices are being introduced into detailing of blast-resistant structures. Previous literature allows this application but has been updated to now require certain results in strain testing the connection to allow the development of ultimate dynamic tensile strength of the reinforcing bar while allowing ductility of the steel to remain present. The driving parameter set by literature for the results of strain testing the mechanical connection is that "…all tests shall demonstrate the development of a minimum 3% strain in the rebar…"

This design standard set the objective for this study to test the performance of mechanical couplers when subjected to high-strain rate stressing. This study would either validate available couplers or provide a guide for further testing and validation of mechanical couplers in blast-resisting structures. To do this, control specimens were tested in tension as were the specimens of both reinforcing bar and a mechanical coupler (Figure 6).



US Army Corps of Engineers

Figure 6. Test setup

Five mechanical couplers were to be tested:

- Up-set-head and coupling sleeve with straight threads
- Grout-filled coupling sleeve
- Shear-screw coupling sleeve
- Taper-thread system
- Thread-like deformed reinforcement bar coupler system

The results of the testing were that only one of the five coupler products passed the updated criteria without requiring further testing, which was the grout-filled coupling sleeve. The shear-screw coupling sleeve and taper thread coupler specimens both failed the new criteria, while the last two require further testing to validate them under the new criteria and be applied to blast-resistant structures (Rowell 2015).

2.8 Laboratory and Field Testing of an ABC Demonstration Bridge: US Highway 6 Bridge over Keg Creek (2013)

With the application of ABC, advanced material closure-pours and quick-to-install construction details are required, in addition to the prefabricated elements. This study focused on the performance of the bond between the concrete deck made of HPC and the closure pour consisting of UHPC, through both laboratory and field measurements.

The bond testing in the laboratory measured the strength of the bond through two test types: Direct Tension Testing and Simulated Modulus of Rupture (MOR) Testing. The direct tension testing consisted of 4 in. diameter cylinders cast in half with a threaded steel rod, one half precast HPC that cured 28 days, and then the other half was UHPC match casted onto the half-cylinder. The interface preparation of the specimens varied, to see how it affected results, between: 1,500 psi pressure wash, 3,000 psi pressure wash, plywood (untreated), sandblasted, groove cut, and epoxy bonding agent (Figure 7).

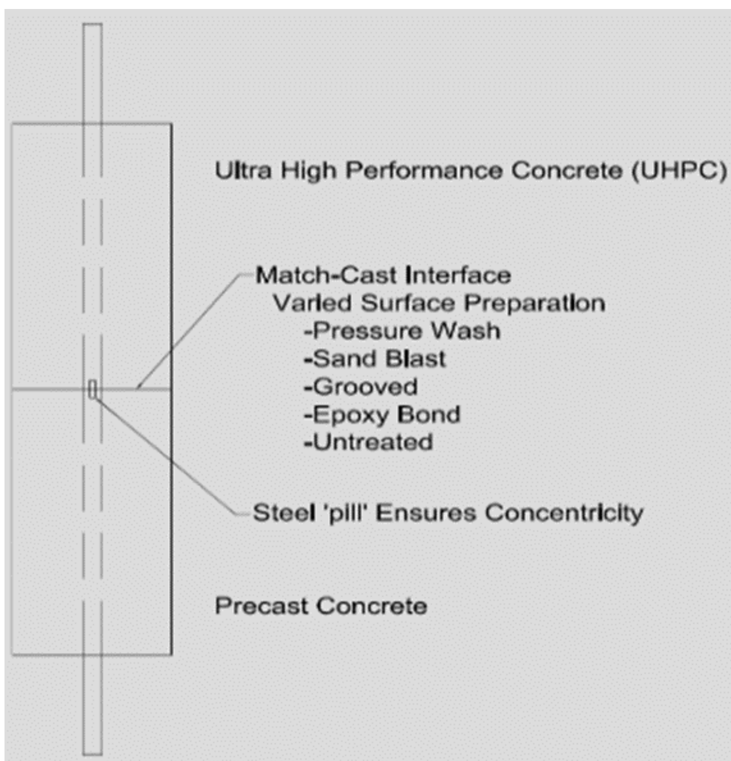


Figure 7. Direct tension test specimen

The simulated MOR testing had beams that were cast similarly to the cylinders for the direct tension test, with one half being precast HPC and the other half being match casted UHPC (Figure 8).

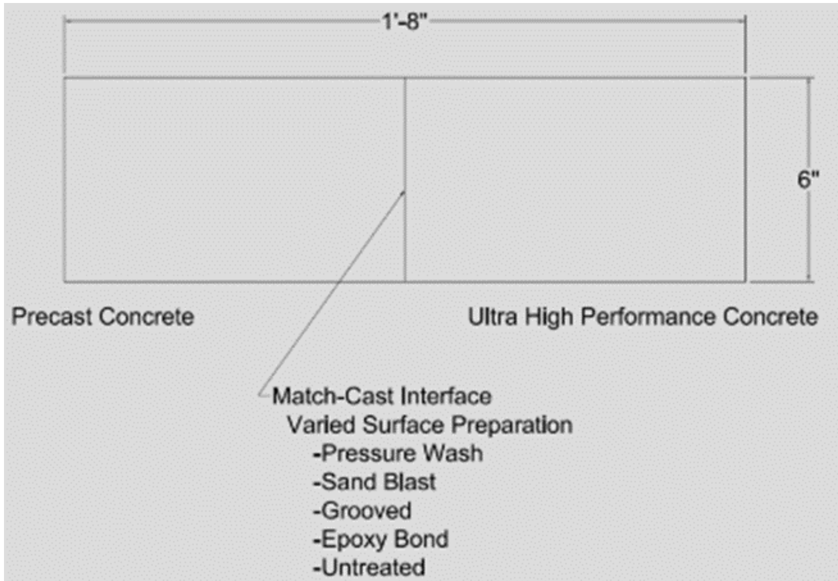


Figure 8. Simulated MOR test specimen

The bond was then tested by computing stresses in the beam under three-point bending.

The bond testing in the field was measured through instrumenting the HPC/UHPC bonds on the bridge deck and applying a live-load via slowly driving a truck over the bridge at different locations on the deck.

The results of the study concluded the following about the HPC/UHPC bond (Phares et al. 2013):

- When no surface preparation is performed, there is essentially no bond between precast HPC and UHPC.
- Under the conditions implemented on the test specimens, the surface preparation resulting in the best results was the 3,000 psi pressure wash.
- The MOR average results for the bond were less than the MOR of the 5,000 psi compressive strength HPC, which implies the cracking will be at the UHPC and HPC interface.
- Large variations in bond strength from sample to sample leads to the conclusion of variations in the development of the HPC/UHPC bond, no matter the surface preparation.
- UHPC maturity was apparent due to the 7-day UHPC having the maximum bond strength, and then the strength decreasing over the 14- and 28-day UHPC. This implies the bond deterioration over time.
- Strains recorded in the field measurements were less than the cracking strain for both the HPC and UHPC, which indicates cracking is doubtful at service load conditions.

- Maximum field recorded strains across the HPC/UHPC interface were not consistent, which verifies bond inconsistencies.
- The field recorded strains between the 2011 test and 2012 test were significantly different, with the latter being higher, which verifies the laboratory conclusion of bond deterioration over time.

2.9 Strength, Durability, and Application of Grouted Couplers for Integral Abutments in ABC (2015)

This report was Phase I for the project of focus, hence the project had the same research objectives. Three specimens were tested to determine the strength, durability, and constructability of two proposed connections compared to a cast-in-place control specimen. The two proposed connections were: grouted reinforcing bar coupler (Figure 9) and pile couplers (Figure 10).

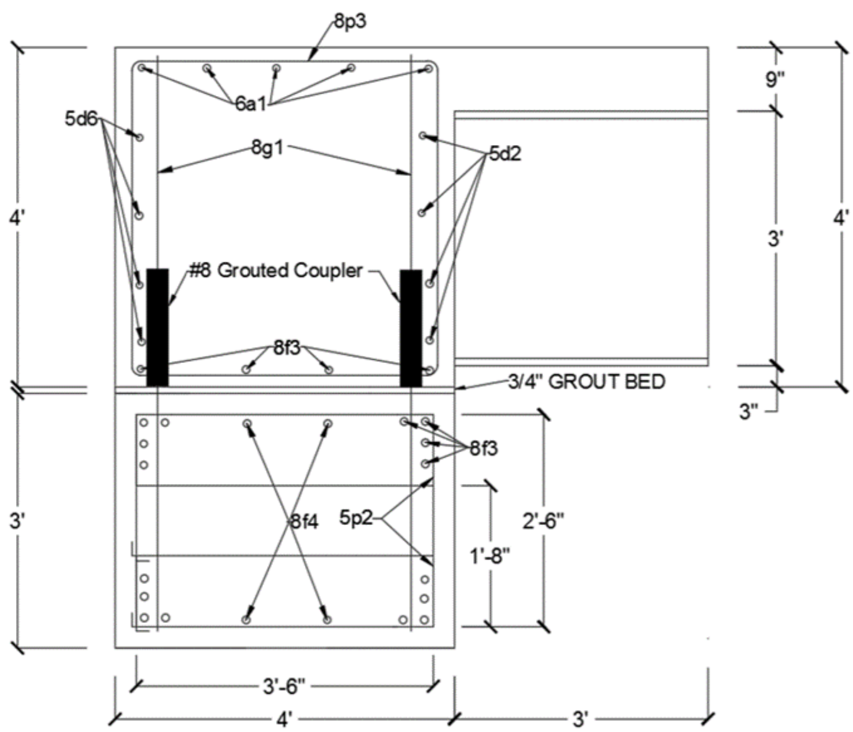


Figure 9. Grouted reinforcing bar coupler

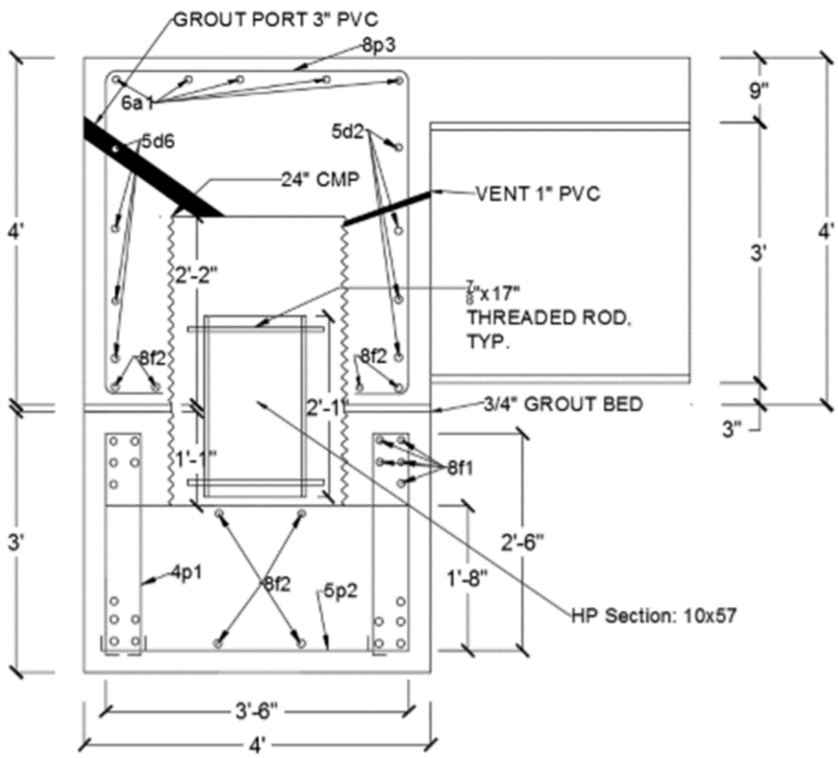


Figure 10. Pile coupler

The design philosophy behind the two connections was:

- Grouted Reinforcing Bar Coupler
    - Due to previous success with the connection, the need for a closure pour over the integral connection could be eliminated with the presence of the grout-filled mechanical couplers providing the integral connection through protruding reinforcing bars from one element being inserted into sleeves on the other element to be connected, and then filling the sleeve with a grouting material. The ABC application for this connection would likely be suspending the element via crane and placing it in the final location.
- Pile Coupler
    - The basis of this design was the previous use of HP-sections being cast in grout within CMP voids in a precast pile cap. The HP-section would be suspended within a CMP void in a precast element and slid into place onto a precast pile cap with matching CMP void locations to receive half of the suspended HP-section. This void would then be filled with a grouting material just as the previously used precast pile cap/pile connection. This connection allows for the ABC application of "slide-in" construction and alleviates small tolerances that are present in the grouted reinforcing bar coupler connection.

Construction of the three specimens did not pose any significant challenges. The cast-in-place control specimen was erected by forming the steel reinforcement cage (Figure 11), and then simply pouring concrete.

Figure 11. Cast-in-place specimen reinforcing cage

The grouted reinforcing bar coupler specimen had the pile cap cast with protruding reinforcing bars (Figure 12), utilized a match-casting procedure (Figure 13) to cast the sleeves for the connection in the integral diaphragm element, the integral diaphragm was placed on top of the pile cap via crane (Figure 14), and finally the sleeves were filled with grout to complete the connection.

Figure 12. Grouted reinforcing bar coupler pile cap

Figure 13. Grouted reinforcing bar coupler template used for match-casting

Figure 14. Grouted reinforcing bar coupler connection placement

The pile coupler was constructed like the grouting reinforcing bar coupler, by having two elements cast with a part of the connection, but instead of protruding reinforcing bars and sleeves, each element had CMP voids. The integral diaphragm had a longer CMP void with the HP-section being suspended within the void (Figure 15 and Figure 16), while the pile cap had CMP voids half the length of the HP-section (Figure 17).

Figure 15. Integral diaphragm CMP void for pile coupler

Figure 16. Suspended HP-section for pile coupler

Figure 17. Pile cap CMP void for pile coupler

The elements were cast with the CMP voids and then placed together; then, the HP-section was lowered into place via a pulley system, and finally the CMP void was filled with grout to complete the connection.

To test the strength and durability of the connections, the specimens were tested in the structural laboratory with the setup shown in Figure 18.

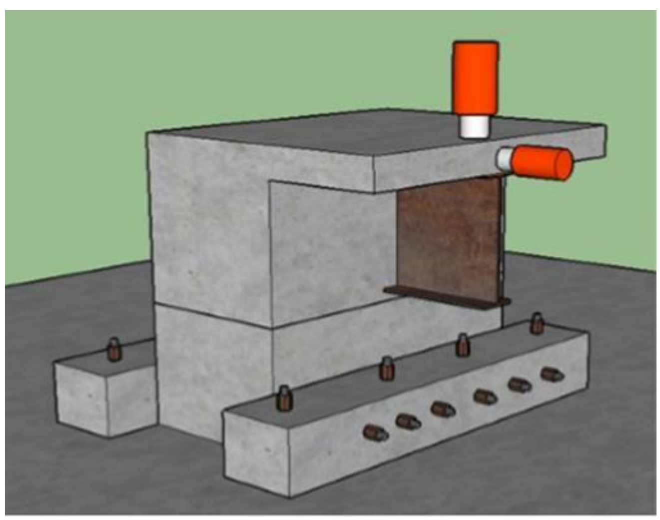


Figure 18. Laboratory setup for integral abutment specimens

The actuators were placed on the specimen to resemble live and thermal loads typically induced on a bridge abutment. The horizontal actuator was set to apply a load of 100 kips onto the face of the steel beam to relate to loading seen from thermal contraction of the bridge superstructure, while the vertical actuator was designed to apply a load of 400 kips to simulate both live loading on the abutment, as well as loading from thermal expansion.

The results of this study led to the following conclusions (Hosteng et al. 2016):

- Tight tolerances typically seen with grouted reinforcing bar couplers were alleviated through a match-casting procedure
- Strength and durability of the grouted reinforcing bar coupler specimen was similar to the cast-in-place control specimen. The crack width of the back face of the integral abutment was measured at the precast joint to be 0.035 in. for the grouted reinforcing bar coupler, and 0.019 in. for the cast-in-place control specimen, which means the grouting reinforcing bar coupler's resulting crack width was about 1.8 times greater than the control specimen
- Strength and durability of the pile coupler was less favorable than the grouted reinforcing bar coupler, with a crack width measured to be approximately 1.75 in., or about 92 times greater than the control specimen
- The constructability of the pile coupler was more ideal than the grouted reinforcing bar coupler simply due to the ability of the pile coupler allowing for the slide-in application of ABC, while the grouted reinforcing bar coupler would have to be suspended via crane and lowered into place
- Improvements to the pile coupler would be:
  - Increasing the length of the HP-section
  - Increasing the amount of threaded rods/shear studs on the steel section
  - Increasing/revising the amount of reinforcing steel in the abutment
  - Using two HP-sections to act as a force couple

CHAPTER 3. ABC INTEGRAL ABUTMENT DESIGN

The basis of the design in this section is based on the concept of ABC, as well as the results from Phase I testing of the connections (Hosteng et al. 2016).

A new connection was developed by the Iowa DOT and finalized through meetings and discussions between the Iowa DOT and the Bridge Engineering Center. The connection was created based on ABC methods and the desire to eliminate a closure-pour to achieve a "jointless" bridge. Contractor friendly construction methods and materials were a major driving force behind the design, as were the strength and durability of the connection.

3.1 UHPC Joint

The Iowa DOT developed this integral abutment connection to facilitate the combined use of the ABC method of "slide-in construction," and UHPC. UHPC was chosen in lieu of concrete or a grouting material due to the increased flowability, impermeability, and high strength characteristics of UHPC. The placement of reinforcement throughout the specimen was based on the reinforcement of the grouted reinforcing bar coupler specimen from Phase I, except for the connection bars which were 17 #7 reinforcing bars (Figure 19).

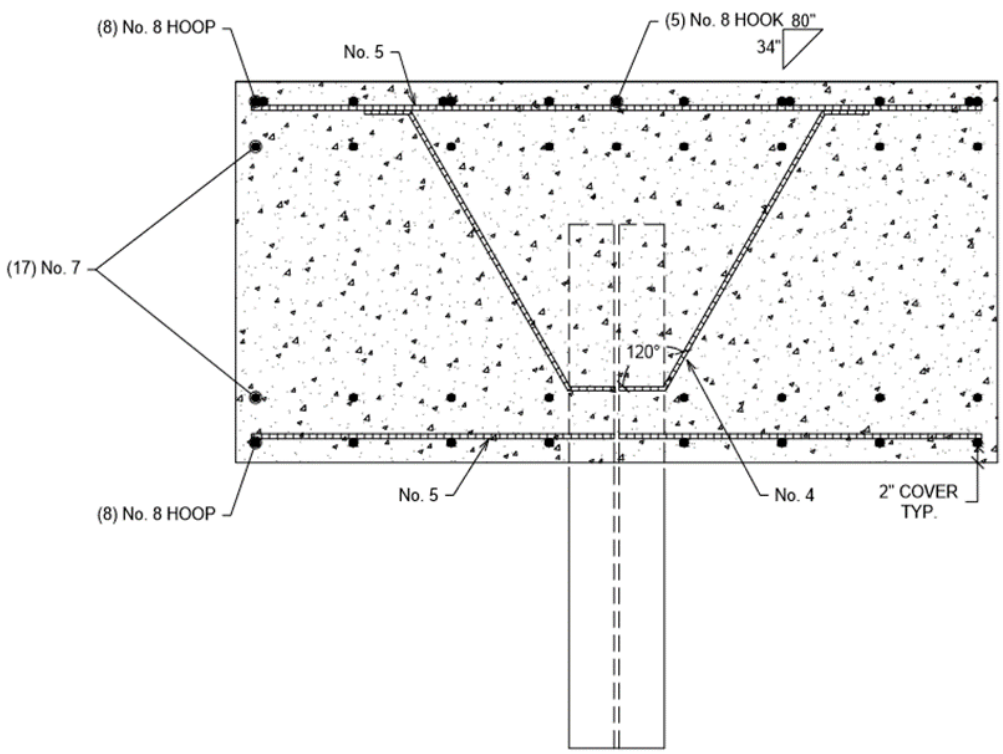


Figure 19. Plan view of UHPC joint specimen showing locations of connection bars

One of the initial design notes for this specimen was the eight #7 reinforcing connection bars on the front face of the pile cap of the specimen would need to utilize a mechanical coupler to eliminate the issue of the protruding bars from the pile cap interfering with the steel beam during the slide. These mechanical couplers were designed to be Dayton Superior D310 Taper-Lock Standard Couplers, which were chosen over other couplers due to ease of installation in the tight space while maintaining acceptable strength and durability. Another design note was to create two 7 in. wide "chimneys" along the rear face of the integral diaphragm to create a pressure head to aid the flowability of the UHPC (Figure 20).

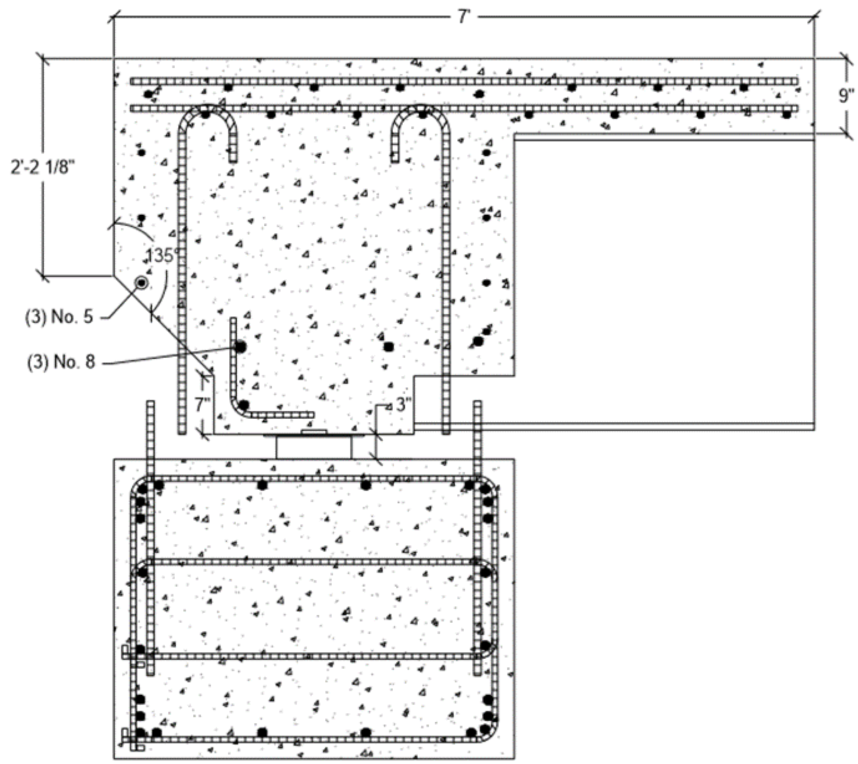


Figure 20. UHPC joint specimen section through "chimney"

Dimensionally, this specimen was identical to the other specimens tested for the project, with the exception of the "grout-bed" which was 3 in. instead of the ¾ in. grout bed seen in the other two specimens. Therefore, to maintain the overall height of the specimen, the height of the integral diaphragm was decreased (Figure 21 and Figure 22), and is governed by the concrete cover of the steel bearing plate and beam.

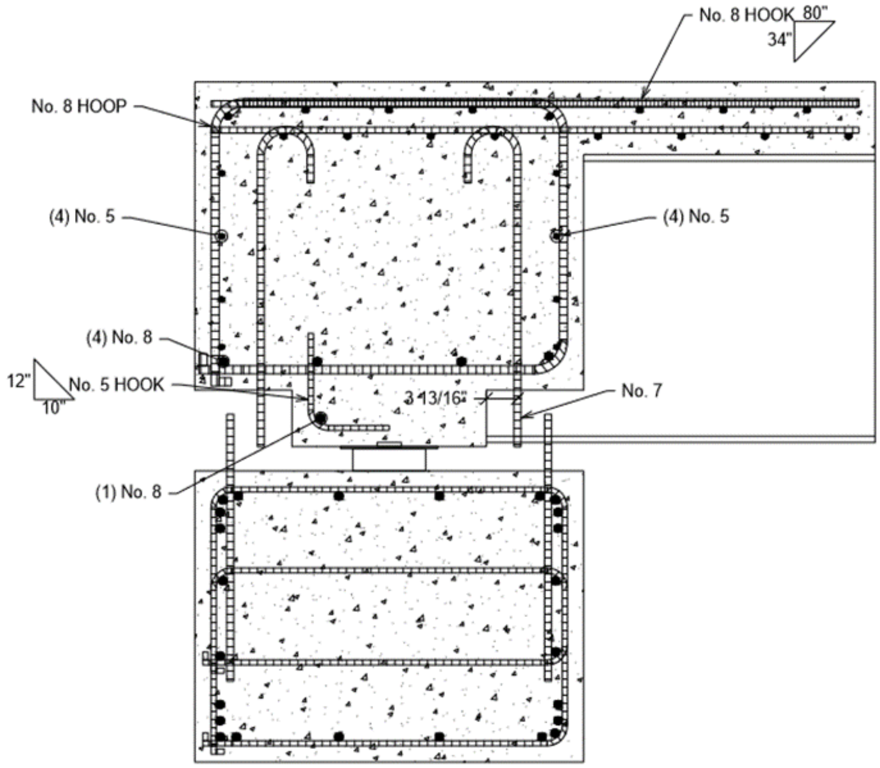


Figure 21. UHPC joint specimen section view

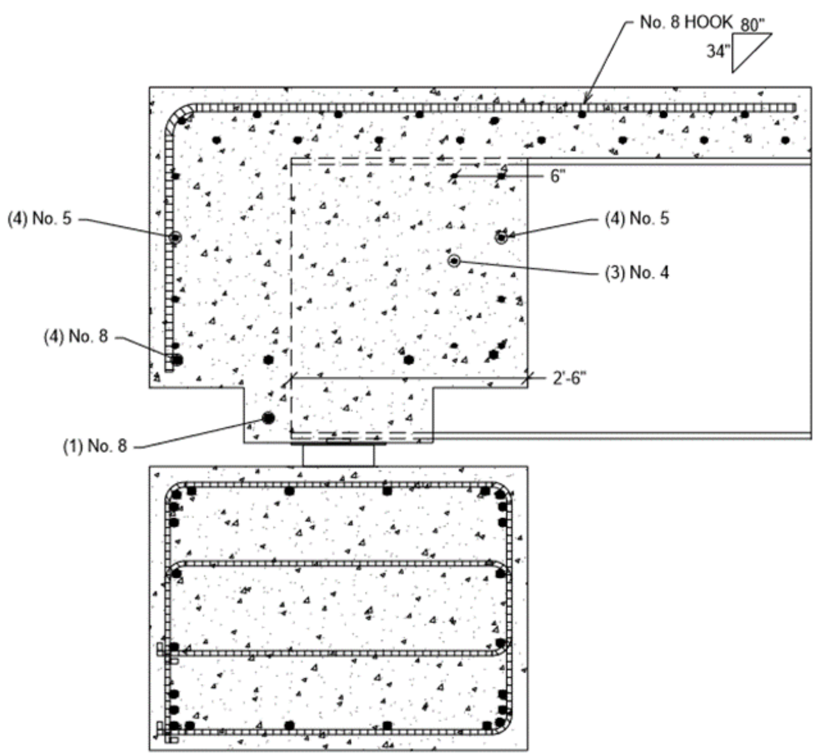


Figure 22. UHPC joint specimen section view through beam

Note the steel bearing plate under the beam, the steel sliding shoe under the bearing plate, and the neoprene pads under the sliding shoe.

The UHPC joint specimen was to utilize the ABC application of “slide-in construction,” using laminated neoprene pads with Teflon and stainless-steel sliding “shoes” (Figure 23).

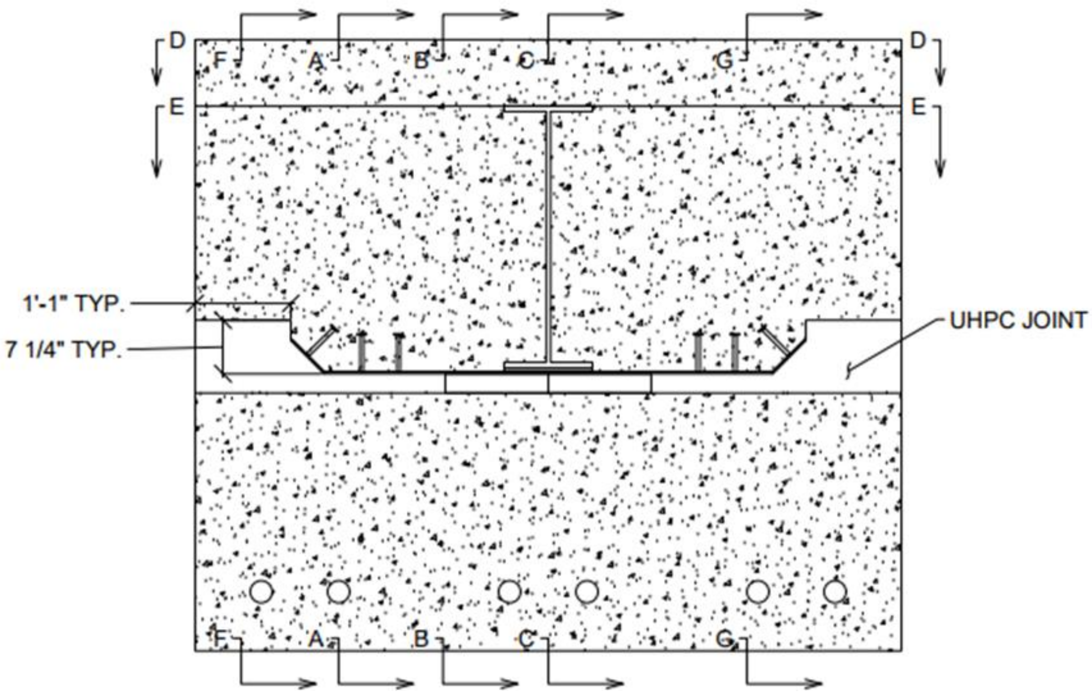


Figure 23. UHPC joint specimen front view showing “sliding shoes” and pads

After sliding the diaphragm section into its final position, the eight #7 mechanical couplers would be installed per manufacturer’s instructions into the pile cap at the designed locations. Form work will then be set for the installation of the UHPC to fill the joint and allowed to cure for the specified design time. After the design strength of the UHPC is achieved, formwork shall be removed, and this integral abutment connection is complete.

One initial concern from the design team for this connection was the ability for the UHPC to fill the entire joint without leaving voids, specifically on the front face interior corner of the joint. This issue was to be tested through a UHPC-flowability test, which was designed to simulate the proposed joint cross-section (Figure 24), as well as a modified version (Figure 25), and UHPC installation procedure.

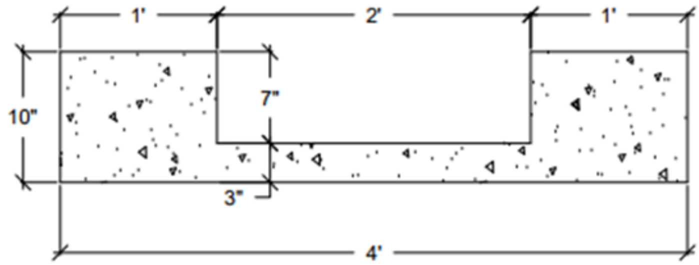


Figure 24. UHPC-flowability test design proposed cross-section

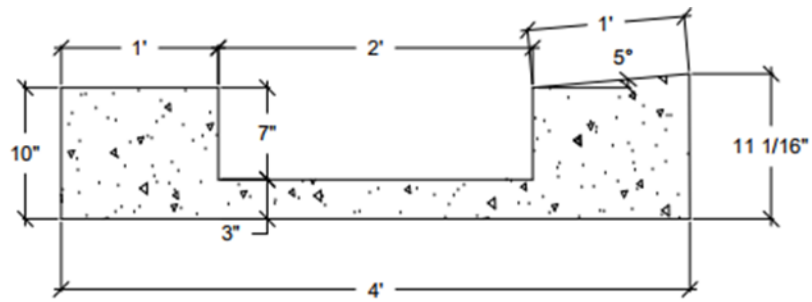


Figure 25. UHPC-flowability test design modified cross-section

The modified cross-section was to investigate the result of adding a 5° rise to aid in the removal of air. The section was designed to be 2 ft wide with the 7 in. "chimney," and be constructed out of metal and wood to provide proper formwork and support for the UHPC (Figure 26).

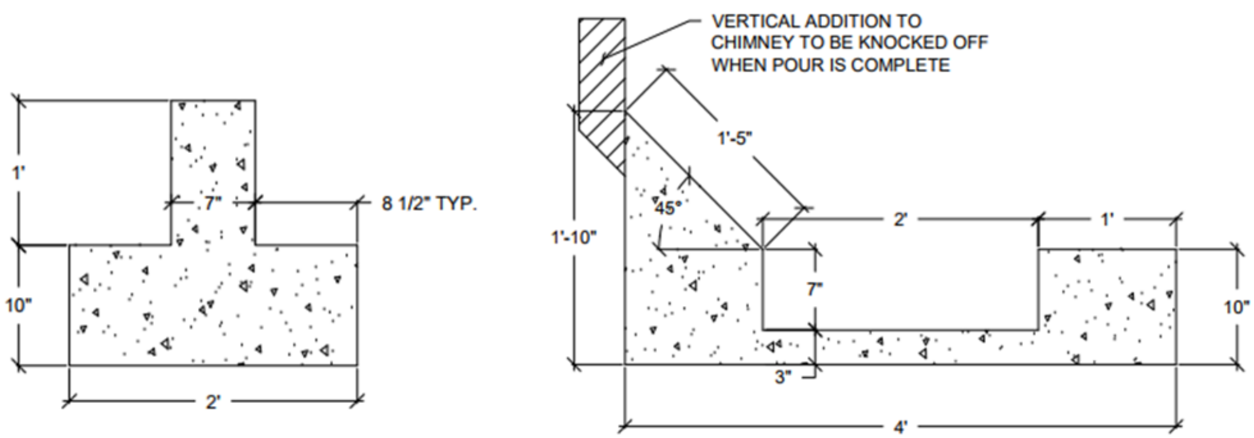


Figure 26. UHPC-flowability test setup design "chimney" cross-section

After the UHPC had cured, the form was to be removed and observations of the final cross-section were to be made to investigate how well the UHPC had filled the form.

CHAPTER 4. CONSTRUCTION

4.1 UHPC Joint

4.1.1 Pile Cap

Construction of the UHPC joint specimen began with the pile cap. A reinforcing cage was erected following the design drawings (Figure 27).

Figure 27. UHPC joint pile cap reinforcing cage

Multiple checks were done to ensure the protruding bars were at their designed locations, specifically in respect to elevation to ensure the 8 in. protrusion required for proper development in the UHPC filled joint. Also, the D310 threaded couplers had to be checked to ensure the tops would be flush with the top of the concrete when complete.

With the cage complete, formwork for the pile cap was erected and the cage was then placed inside (Figure 28).

Figure 28. UHPC joint pile cap formwork

Since a process referred as “match-casting” was to be done to align the polyvinyl chloride (PVC) ducts to the reaction blocks, the blocks were utilized as formwork in addition to the EFCO steel formwork. With the cage set in the forms, checks were done to ensure the 2 in. concrete cover required per design were met, all reinforcement was secured and installed per design, and the formwork was properly secured.

Concrete from a local Ames ready-mix plant was cast in the formwork. Electric concrete vibrators were used to ensure the concrete was filling the form to maximum capacity. The top surface of the pile cap was given a roughened finish to ensure a ¼ in. amplitude, which is required by the Iowa DOT, by roughly brushing with a stiff-bristled broom in multiple directions (Figure 29 and Figure 30).

Figure 29. UHPC joint pile cap cast in concrete

Figure 30. UHPC joint pile cap completed

Also, any concrete covering the tops of the D310 threaded couplers was removed.

Issues/Recommendations

- Not all coupler bars resulted in the required 8 in. protrusion after casting concrete
    - Add more "double-ties" to coupler bars to ensure no movement of coupler bars

4.1.2 Integral Diaphragm

The initial step for constructing the integral diaphragm for the UHPC joint specimen, was to conduct the flowability test of the UHPC in the proposed cross section. A decision was made by the design team to negate the initial cross section, and test only the 5° rise cross section (Figure 31).

Figure 31. UHPC flowability test formwork

The UHPC mix produced by Ductal from Lafarge was used as the UHPC material for this project, and the mix proportions used were that of the Special Provisions document by the Iowa DOT for ultra-high performance concrete (Iowa DOT 2014). The flowabililty quantity of approximately 5.11 ft^3 was calculated to fill the test section along with multiple testing cylinders and account for minor material loss during batching/pouring. The section was filled and left to cure for three days, at which point the formwork was stripped to analyze the adequacy of the flowability of the UHPC (Figure 32).

Figure 32. UHPC flowability test completed

As shown in Figure 32, it is apparent that the UHPC material successfully filled the entirety of the cross section without any issues of voids caused by volume of air. With this knowledge, the formwork for the integral diaphragm could be constructed through multiple ¾ in. plywood diaphragms fastened together, which had the same dimensions used for the flowability test section (Figure 33 through Figure 35).

Figure 33. UHPC integral diaphragm formwork top view of diaphragms

Figure 34. UHPC integral diaphragm bottom formwork completed

Figure 35. UHPC integral diaphragm bottom formwork side view

With the bottom formwork completed, the reinforcement cage was erected. One important note was to ensure the 17 coupling #7 bars would protrude through the bottom plywood formwork by 1 in. to ensure the bars would protrude through the bottom of the section at the required 8 in. (Figure 36 and Figure 37).

Figure 36. UHPC integral diaphragm reinforcement cage

Note the coupler bars passing through the plywood formwork.

Figure 37. UHPC integral diaphragm reinforcement cage completed

Also, the design drawings called for the sliding shoe to protrude from the bottom of the integral diaphragm, but this was not done for the specimen in the laboratory. The purpose of this protrusion is to prevent any concrete catching on the laminated neoprene pads with Teflon during the actual slide of the bridge but no slide would be done in the laboratory; instead, the diaphragm was to be lifted into place by crane. Therefore, to simplify formwork in the laboratory, the sliding shoe was not protruding from the bottom of the diaphragm. To create the best bond surface for the UHPC and precast concrete interface, a form retarder finish needed to be applied to the bottom formwork of the integral diaphragm. To apply the form retarder (Figure 38), it was decided to use a paint roller and brush to ensure the form retarder would be applied to the entirety of the formwork, while not being applied to any reinforcing bars (Figure 39 and Figure 40).

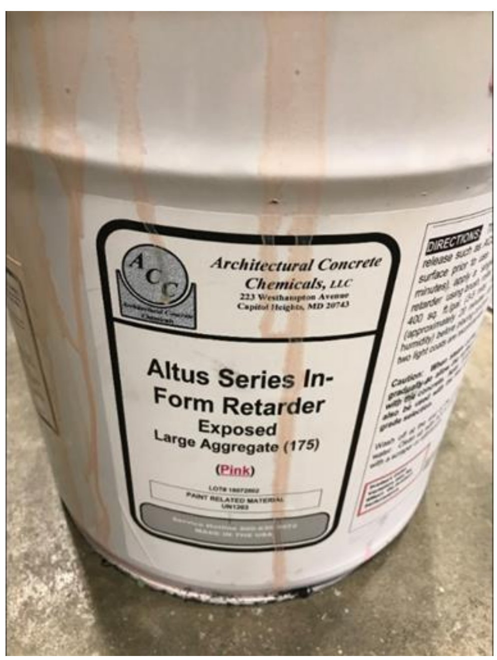


Figure 38. Form retarder to be applied to integral diaphragm formwork

Figure 39. Form retarder being applied to integral diaphragm formwork

Figure 40. Form retarder application completed

With the form retarder applied and final checks done to the formwork, the integral diaphragm was cast in concrete (Figure 41).

Figure 41. UHPC integral diaphragm cast in concrete

The formwork was stripped, and the integral diaphragm was inspected, and it was noted that concrete did not pass underneath the beam as intended, and the coupler bars did not have consistent protruding lengths from the bottom of the section (Figure 42).

Figure 42. UHPC integral diaphragm completed

To finish the required bottom-side finish for the integral diaphragm, a 3,000 psi power wash was used to spray off the form retarder and leave an exposed aggregate finish (Figure 43).

Figure 43. UHPC integral diaphragm exposed aggregate finish

Issues/Recommendations

- Variation of protruding length for coupler bars
  - Add more "double-ties" to coupler bars to ensure no movement of coupler bars, and check protruding length for each bar
- Bottom of beam was not completely cast in concrete
  - Do additional vibrating around beam to allow for movement of concrete
- #5 hooks behind beam to hold #8 longitudinal bar did not stay in place
  - Revise this area of reinforcement, specifically how to tie the #5 hooks to the rest of the cage
- #7 coupler bars were not easily tied to reinforcing cage
  - Revise length of coupler bars, or orientation, to ensure proper areas to tie bars to rest of reinforcing cage

4.1.3 Connection

The integral diaphragm was craned over to the test area where the pile cap was installed and prepared for the connection. Since this connection would utilize the ABC method of "slide-in" construction, a slide had to be simulated to ensure the protruding bars on the back side of the abutment would have proper clearance during the installation process. The integral diaphragm was suspended just over the neoprene pads enough to allow for movement, the slide was simulated, and the clearance of the rear bars was proven to be adequate (Figure 44).

Figure 44. UHPC joint rear connection bars with adequate clearance

After the integral diaphragm was placed in its final location, the threaded bars on the front side of the specimen were installed. One concern was the available space to insert the bar into the threaded coupler in the pile cap and be able to properly tighten the bar, but this was proven to be done without any issues (Figure 45).

Figure 45. Front connection bars

Note the installed threaded bars in pile cap.

With the connection bars properly installed, the joint formwork was erected. This formwork included ports along the side and front faces to allow for air to be pushed out by the UHPC during the install, and a spout and chimney system to allow for a simplified installation of the material into the joint from the mixer (Figure 46 through Figure 48).

Figure 46. Front face joint formwork with air ports

Figure 47. Rear face joint formwork with chimneys

Figure 48. Spout and chimney system for installation of UHPC material

The UHPC material, Ductal by Lafarge, had to be installed in five batches, due to the limited availability of mixing equipment in the structures laboratory, and each batch took approximately 30 minutes to mix and then pour into the joint. This caused issues with the casting of the joint as the previous batch would crust on the surface prior to the next batch being placed into the joint. This resulted in each batch setting up too quickly to allow for the batch being casted to flow into the previous batch, which caused layers of material within the joint instead of one cohesive layer of material (Figure 49).

Figure 49. Completed UHPC joint

Note the multiple layers of material.

Issues/Recommendations

- UHPC layers due to installing material in multiple batches
  - Have construction procedures and equipment available to install the UHPC joint in one large batch instead of multiple batches, which should allow the material to flow as it did in the flowability test

CHAPTER 5. LABORATORY TESTING

5.1 Methodology

The testing of the strength and durability of the three integral abutment connection details outlined in this report was conducting using the same setup and methodology as was used for the three specimens evaluated in Phase I. As stated previously, the results from the three Phase II specimen were compared to the control specimen tested and detailed in the Phase I report. The setup utilized two concrete reaction blocks constructed to attach the specimens to the strong floor of the structural laboratory with post-tensioning, causing the specimens to have a fully-fixed boundary condition (Figure 50 through Figure 52).

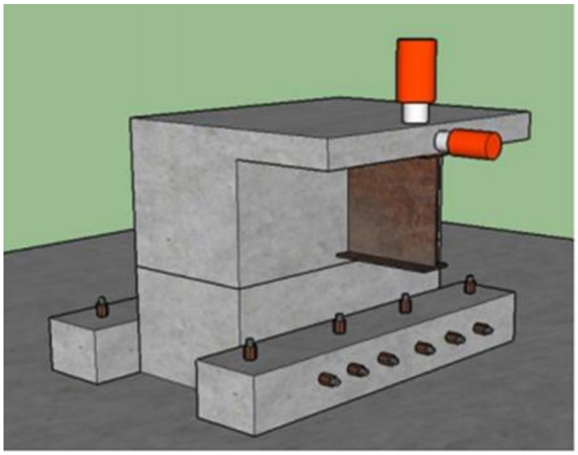


Figure 50. Model of testing setup front view

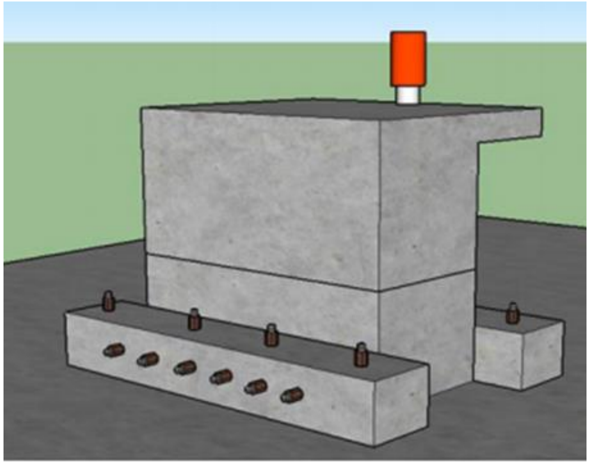


Figure 51. Model of testing setup rear view

Figure 52. Laboratory testing setup

Actuators and load frames were used to apply two loads onto the specimens to simulate thermal loads and live loads, which tested the strength and durability of the three integral abutment connection details, as well as the adequacy of the design of the precast segments of the specimens. The analysis for strength and durability of the connection details would be conducted by only static loading and observing the structural responses of the specimen, specifically the magnitude of the crack widths between the precast segments and the stresses of coupling materials. The values recorded would then be presented and compared to the Phase I results utilizing the same testing procedures.

The fixed boundary condition applied to the specimens through the reaction blocks and post-tensioning caused the specimens' structural response to be a worst-case scenario for the connection details. This is apparent since in the field application, translations and rotations of the integral abutment would be present due to the flexibility of the driven piles connected to the pile cap as well as the girders connected to the integral diaphragm.

The two static loads applied to the specimens were first a horizontal load meant to cause tension on the front face of the abutment, and the second was a vertical load to cause tension at the rear face of the abutment. The horizontal load was to simulate thermal contraction of the integral abutment bridge, while the vertical load was to simulate thermal expansion of the bridge as well as live loading. Both load cases, and theoretical structure response, are shown in Figure 53 through Figure 55.

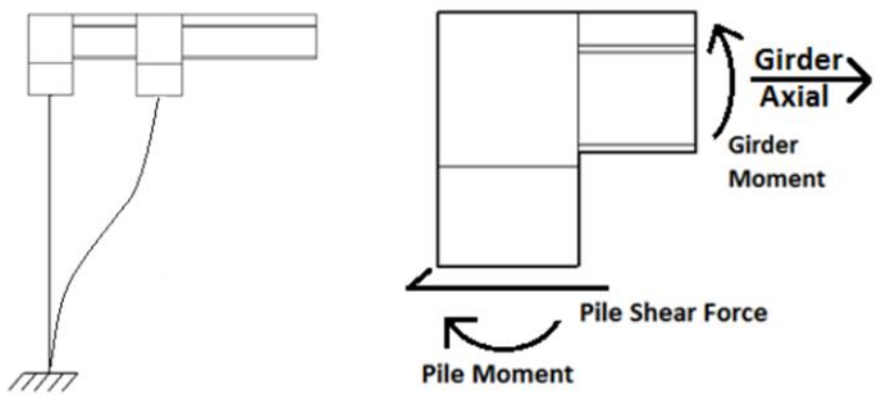


Figure 53. Structural analysis for thermal contraction of bridge

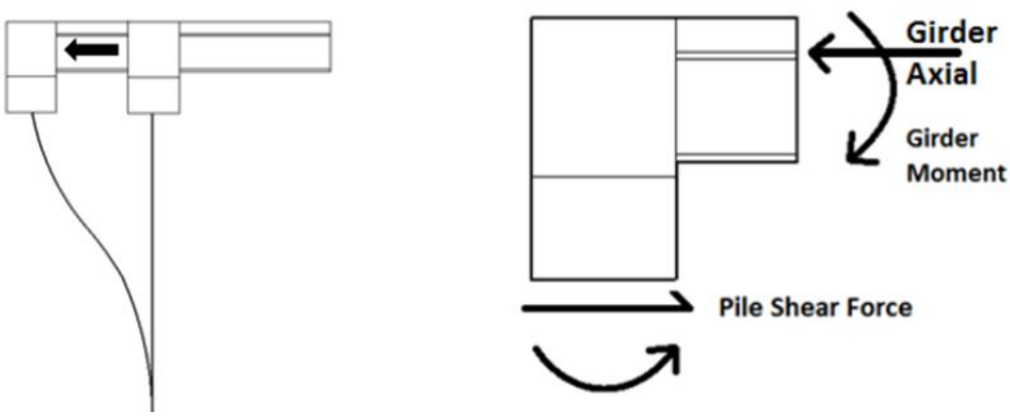


Figure 54. Structural analysis for thermal expansion of bridge

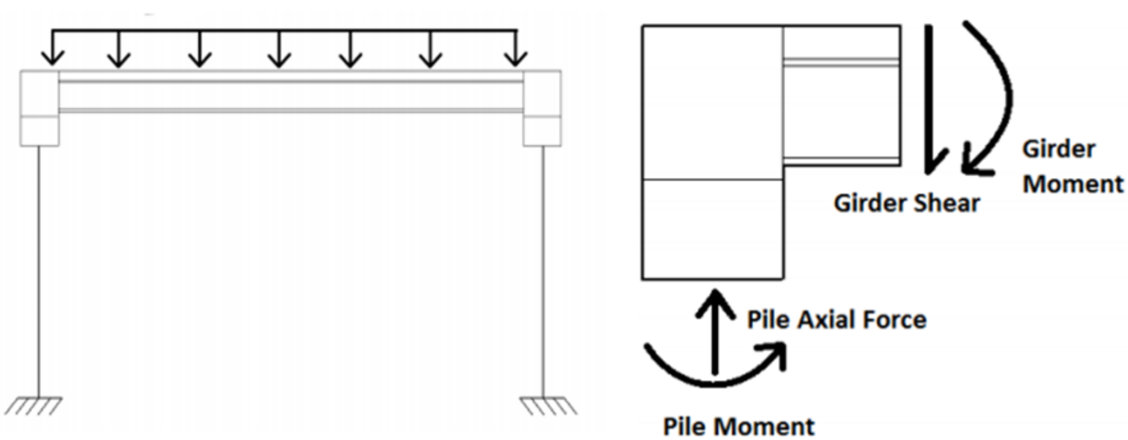


Figure 55. Structural analysis for live loading of bridge

The magnitude of loads to be applied was carried over from Phase I of this project so comparisons could be made with the results. The horizontal loading was set to 100 kips from a study of thermal forces typically resisted by the stiffness of the foundation piles and surrounding soil. This load was not designed to fail the specimen, but to analyze the results at service loading.

The vertical loading was set to 400 kips since it was the largest load that would be able to be applied in the structural laboratory. This vertical load is much greater than the service level loading conditions to the integral abutment and maximum stresses that can be present in the foundation piles but was used to establish the failure mode of the connection details. Utilizing the results of these failure modes will aid in designing an appropriate factor of safety and help with designs using these integral abutment connection details.

5.2 Instrumentation

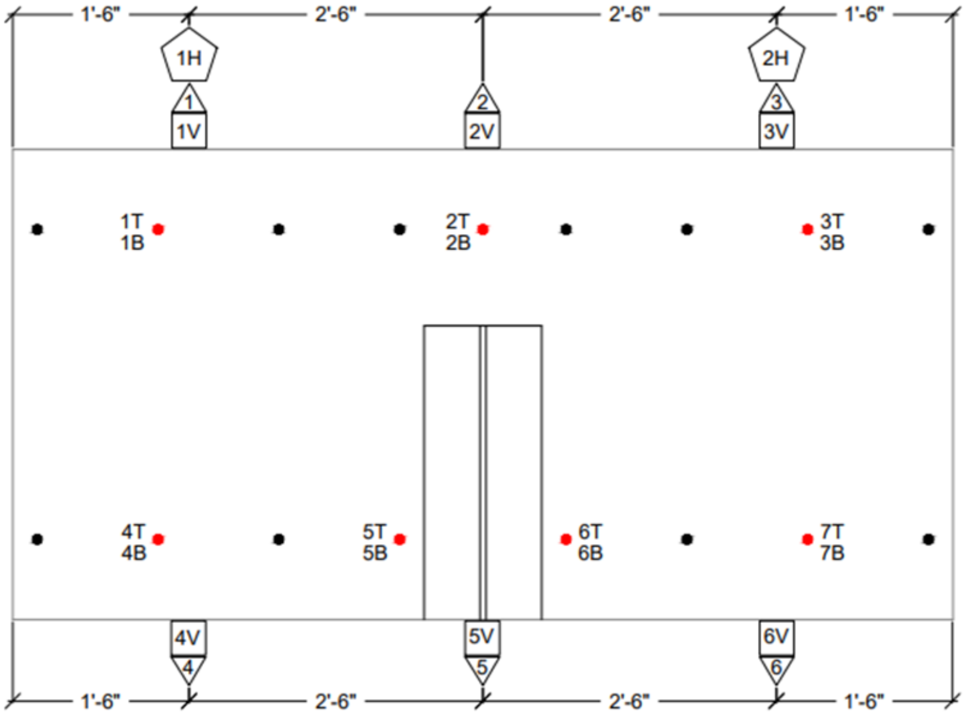
A variety of instruments were installed on the specimens to monitor and analyze the strength and durability of the three integral abutment connection details. First, to record the magnitude of the tension-side crack widths for each loading case, displacement transducers, called DCDTs, were installed at three positions on both the front and rear face of the specimens. These transducers would record the vertical displacements caused by cracking of the cold-joint between the integral diaphragm and pile cap of the integral abutment. The result of these recordings would be compared to those of Phase I and report the severity of the possibility of infiltration of water or other chemicals that could cause structural deterioration of the connection details. Another two displacement transducers were installed at the rear face of the specimen to monitor any horizontal displacement, or slip, between the integral diaphragm and pile cap during horizontal loading.

Second, to record the development of the coupling materials, sacrificial strain gauges were installed on some of the coupling reinforcing steel bars for the UHPC joint. These gauges would monitor the development of strains in the materials, which can be tabulated into stresses to determine the level of strength of the coupling materials during both loading cases.

Third, external strain gauges, called BDIs, were installed at the locations of the vertical displacement transducers to record the overall strength of the integral abutment during both load cases. The recorded values would be compared to values determined by AASHTO to declare which type of failure was present during the test.

Finally, displacement gauges, called string-pots, were installed at four corners of the pile cap to monitor any rotation of the pile cap that would be opposed to the assumed fixed boundary condition. Also, one displacement gauge was installed at the end of the cantilever beam to record the displacement of the beam during both load cases and compare it to the displacement of the joint crack.

The layout of the instrumentation for each specimen are shown in Figure 56 and Figure 57.



Squares represent vertical displacement transducers; pentagons represent horizontal displacement transducers; triangles represent external strain gauges; and red dots represent locations of sacrificial strain gauges

Figure 56. Instrumentation plan for UHPC joint

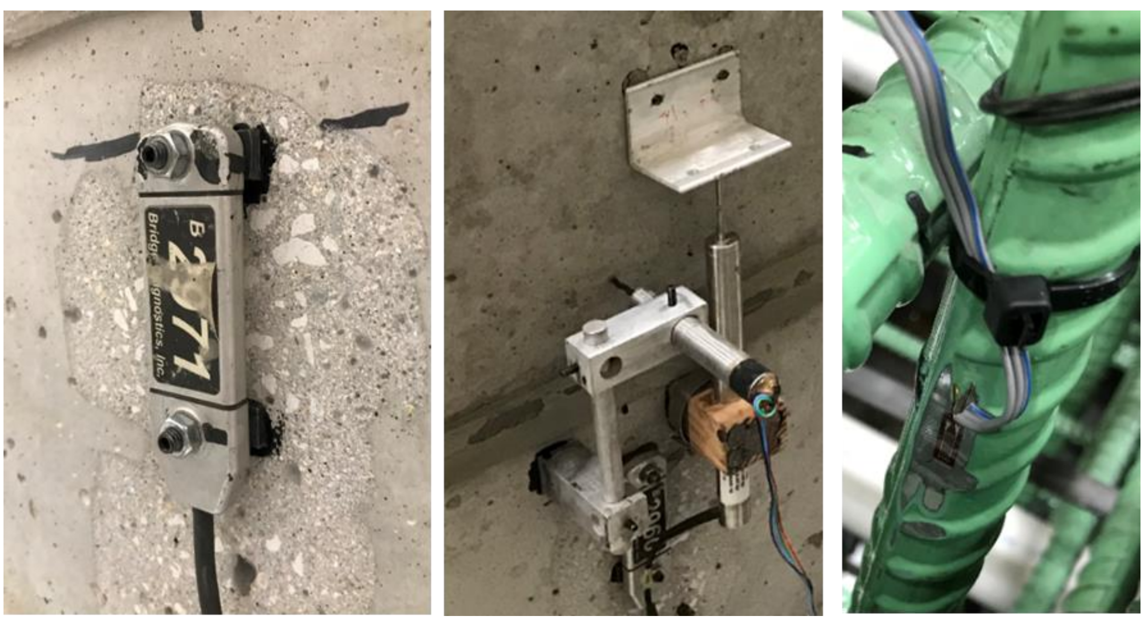


Figure 57. External strain gauge, left; vertical displacement transducer, horizontal displacement transducer, and external strain gauge, center; and sacrificial strain gauge, right

5.3 Results

5.3.1 UHPC Joint

The horizontal loading reached the maximum value of 100 kips, which caused a crack at the front face of the abutment to be 0.018 in. (Figure 58).

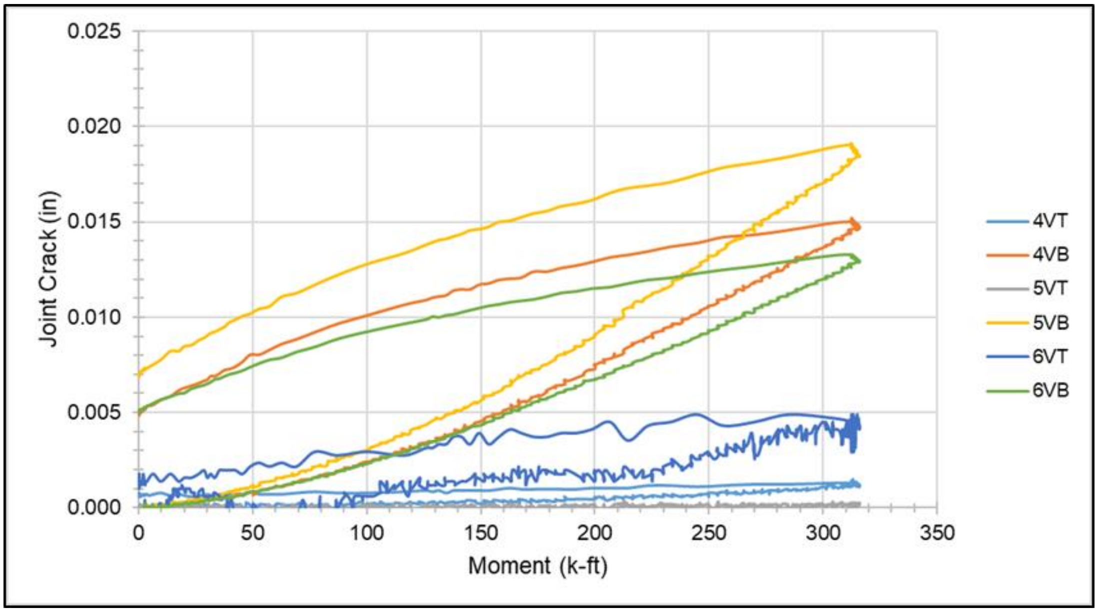


Figure 58. Crack width versus moment due to horizontal load

The control specimen from Phase I had a crack of 0.001 in. for the same loading, therefore the crack seen from the UHPC joint connection was approximately 18 times greater.

Note that for this specimen, two displacement transducers were used to capture the crack propagation of both the integral diaphragm to joint interface (4VT, 5VT, and 6VT) and the joint to pile cap interface (4VB, 5VB, and 6VB), and the larger values of the cracks came from the joint to pile cap interface. This is reasonable since the surface preparation of the pile cap was not as complex as that for the integral diaphragm.

No horizontal slip was recorded for the connection, and the maximum rebar stress for the connection bars was approximately 12 ksi in the connection bars protruding from the pile cap.

The vertical load was then applied up to a value of 397 kips, at which point the beam began to fail due to the buckling of the web (Figure 59).

Figure 59. Beam buckling failure causing end of test

The maximum joint crack recorded at the rear face of the specimen at the maximum load was 0.032 in. (Figure 60).

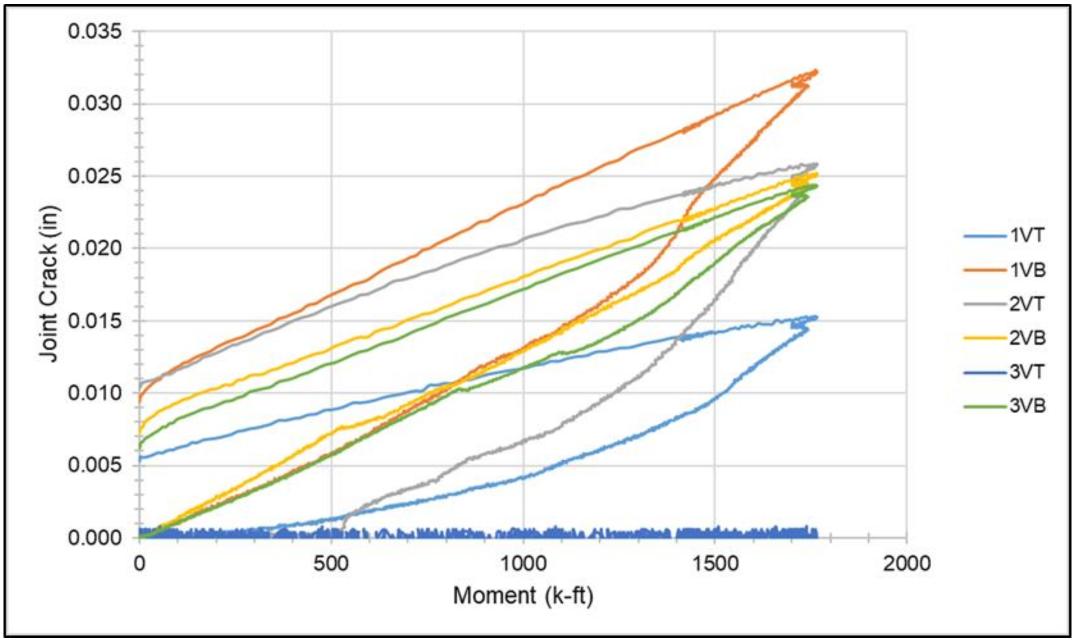


Figure 60. Crack width versus moment due to vertical load

The control specimen from Phase I reached a maximum load of 385 kips and reported a maximum joint crack of 0.025 in. The UHPC joint specimen had a crack of 0.031 in. under a

385-kip load, which is approximately 1.3 times greater than the control specimen. Again, it is shown most of the maximum joint cracks derived from the joint to pile cap interface, but after unloading the cracks closed (Figure 61).

Figure 61. UHPC joint rear face after testing

The maximum rebar stress recorded during the vertical load test was 48.1 ksi at the maximum load of 397 kips, which indicates none of the connection bars yielded (Figure 62).

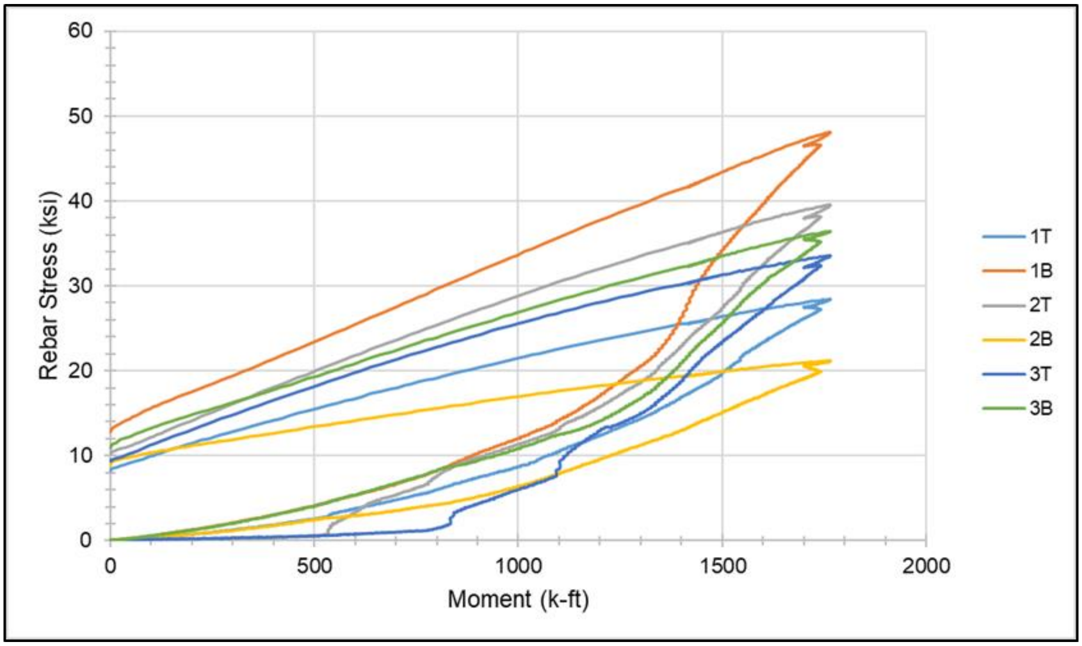


Figure 62. Tension reinforcing bar stress versus moment due to vertical load

Figure 62 shows the connection bars protruding from the integral diaphragm and the pile cap both had adequate, and near even, development, which proves the design allowed for a proper amount of protrusion for the connection bars within the UHPC joint.

CHAPTER 6. SUMMARY

To advance the use of integral abutments with ABC, rather than relying on a closure pour, three connection details were designed to be constructed full-scale and tested in the structures laboratory to monitor overall strength and durability of each connection detail. The design philosophy of the connection detail was to be able to complete adequate structural connections in a matter of a few days while maintaining the structural integrity and response present with the closure pour connection. The UHPC joint connection detail, which is the subject of this Phase II report, was a design created through the Iowa DOT to be used on an upcoming bridge construction project.

The UHPC joint connection utilized a “notched” cross section with protruding rebar from the integral diaphragm and pile cap, which was filled with UHPC. The connection detail was successfully constructed and documented in detail, specifically concerning any issues that arose during the construction process and were evaluated based on not only the constructability but also the strength and durability of the connection.

The construction of the precast elements was not difficult and should be achievable for experienced fabricators. It is important that the fabricator ensure the required protrusions for the reinforcing bars to provide adequate development length within the UHPC joint, which can be accomplished through proper quality control procedures. Prior to casting the joint, UHPC mixing procedures and equipment should be prepared such that the entire joint can be filled with UHPC in one continuous pour to eliminate the possibility of layered sections within the joint.

The laboratory testing of the UHPC joint showed that the connection would be able to resist high-magnitude cold joint cracks, and consequently, prevent infiltration of deteriorating chemicals and water. Since the failure mechanism seen in the laboratory specimen was the web buckling of the beam, it can be assumed the connection detail is most comparable to the closure pour connection detail for integral abutments, since under the same load the UHPC joint specimen had a maximum joint opening of 0.031 in. and the closure pour specimen had a maximum joint opening of 0.025 in.

The magnitude and propagation of cracking is important to know since any cracking of the cold joint will allow for infiltration of water or other chemicals into the structure, which can lead to deterioration of the coupling materials. Furthermore, these cracks are the result of only one static load and would presumably increase in magnitude over cyclic loading and presence of deterioration of the connection materials.

The conclusion of this study can lead to the initiation of another investigation focusing on the following topics:

- Revision of the UHPC joint connection detail with the “notch” of the front face of the integral diaphragm being transferred to the front face of the pile cap (Figure 63)

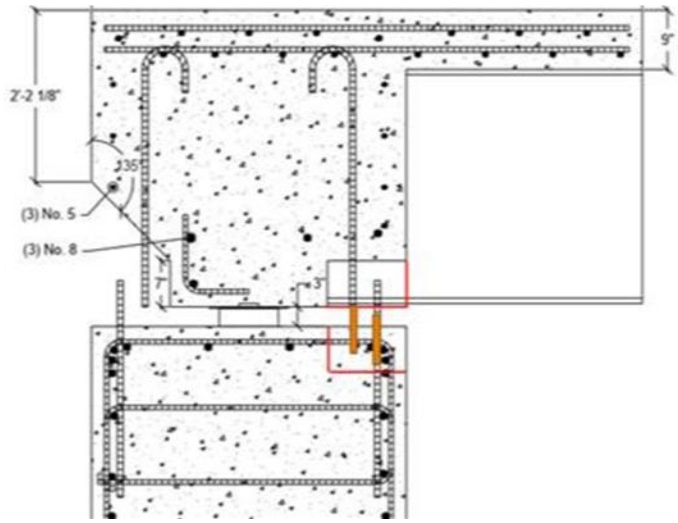


Figure 63. Proposed revision to UHPC joint connection detail

This would allow the protruding coupling bar from the pile cap to be lowered enough to not cause an issue with the beam during slide-in construction, yet have enough length for proper development within the UHPC. By making this revision, formwork for the bottom of the integral diaphragm could be simplified but would require another round of research to verify.

- Cyclic loading of the connection details
- Analysis of real-world applications of the connection details through field monitoring

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