Strength, Durability, and Application of Grouted Couplers for Integral Abutments in Accelerated Bridge Construction

Final Report
October 2016

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The Accelerated Bridge Construction University Transportation Center (ABC-UTC) is a Tier 1 UTC sponsored by the U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology (USDOT/OST-R). The mission of ABC-UTC is to reduce the societal costs of bridge construction by reducing the duration of work zones, focusing special attention on preservation, service life, construction costs, education of the profession, and development of a next-generation workforce fully equipped with ABC knowledge.

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The mission of the Bridge Engineering Center (BEC), which is part of the Institute for Transportation (InTrans) at Iowa State University, is to conduct research on bridge technologies to help bridge designers/owners design, build, and maintain long-lasting bridges. The mission of InTrans is to develop and implement innovative methods, materials, and technologies for improving transportation efficiency, safety, reliability, and sustainability while improving the learning environment of students, faculty, and staff in transportation-related fields.

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16. Abstract

As accelerated bridge construction (ABC) has gained the attention of the bridge community, certain bridge types, such as integral abutment bridges, have seen limited use. Integral abutments eliminate the expansion joint from the bridge superstructure by rigidly connecting the superstructure and foundation. The integral abutment is therefore often large and heavily reinforced, which presents challenges for ABC projects.

This research investigated integral abutment details for use in ABC projects through mechanical splicing of the integral diaphragm and the pile cap. Two ABC details, the grouted reinforcing bar coupler detail and the pile coupler detail, were evaluated in the laboratory for constructability, strength, and durability. A typical cast-in-place detail was also constructed and tested as a baseline.

For the grouted reinforcing bar coupler detail, a plywood template was used to "match cast" the pile cap and the integral diaphragm. The template was simple to construct and resulted in the successful alignment of 17 spliced steel bars and grouted couplers over an 8 foot specimen. Though the grouting of two couplers was obstructed, more than adequate strength was created by the connection, and the crack width at the precast joint was comparable to that of the cast-in-place specimen.

The pile coupler reduced the number of spliced connections between the pile cap and integral diaphragm sufficiently to facilitate adequate construction tolerances. The splicing system worked well during construction, but the detail's strength and durability was less than ideal. Several lessons were learned from these tests that could improve the structural performance of the pile coupler detail.

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STRENGTH, DURABILITY, AND APPLICATION OF GROUTED COUPLERS FOR INTEGRAL ABUTMENTS IN ACCELERATED BRIDGE CONSTRUCTION

Final Report
October 2016

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EXECUTIVE SUMMARY

In areas of high traffic, long-term bridge construction can have significant impacts on the traveling public and surrounding communities. To minimize this impact, engineers and contractors prefabricate bridge elements and utilize technologies that facilitate rapid bridge assembly. This strategy is known as accelerated bridge construction (ABC) and has gained the attention of the bridge community, as information on and the benefits of ABC projects have been shared.

The potential in this movement has not been tapped, as advantages of certain bridge types, such as integral abutment bridges, have seen limited use. Integral abutment bridges were developed as a means of eliminating the expansion joint from the bridge superstructure, because expansion joints present long-term maintenance concerns.

To eliminate the joint, integral abutments rigidly connect the superstructure and foundation so that the entire structure experiences thermal expansion and contraction as one. For this reason, the integral abutment is often large and heavily reinforced, which presents challenges for use in ABC projects. The size of the abutment presents weight issues, and mechanical splicing of the abutment to the deep foundation presents tight construction tolerances.

This research investigated integral abutment details for use in ABC projects through mechanical splicing of the integral diaphragm and the pile cap. To complete this work, two ABC details were evaluated in the laboratory based on constructability, strength, and durability. The construction process used to fabricate and erect the specimens was documented and is presented in this report, as this criterion often governs the design of ABC details.

The specimens were tested for strength and durability by simulating thermal loads and live loads. Strain gauges placed on the concrete and reinforcing steel captured the strain developed in the testing to evaluate strength. Displacement transducers placed across the precast joint measured the crack width that developed under loading to assess durability.

The ABC details investigated were the grouted reinforcing bar coupler detail and the pile coupler detail. To establish baseline performances for an integral abutment, a typical cast-in-place detail was also constructed and tested.

In the grouted reinforcing bar coupler detail, a plywood template was used to "match cast" the pile cap and the integral diaphragm. The template marked the locations of the spliced reinforcing steel and served as the base for the formwork in the integral diaphragm, holding the grouted couplers in position. The template proved to be simple to construct and resulted in the successful alignment of 17 spliced steel bars and grouted couplers over the length of an 8 foot specimen.

A grout bed was pumped into the precast joint on the specimen. Unfortunately, grout leaked past two of the grouted coupler seals and obstructed the grouting of two couplers. Even with the two un-grouted reinforcing bar couplers, more than adequate strength was created by the connection,

and the crack width that developed at the precast joint was comparable to that of the cast-in-place specimen.

The pile coupler detail was developed to facilitate the use of a slide-in bridge with integral abutments. The pile coupler reduced the number of spliced connections between the pile cap and integral diaphragm significantly to facilitate adequate construction tolerances. The splicing system worked well during construction; however, the detail's performance in terms of strength and durability was less than ideal.

If there is a demand for the benefits of the pile coupler detail in terms of constructability, the detail should be further investigated, as several lessons were learned from these tests that could improve the structural performance of the detail.

CHAPTER 1. INTRODUCTION

1.1 Background

In accelerated bridge construction (ABC) projects, bridge components or entire superstructures are prefabricated and then lifted or slid into place. Engineers and contractors work to design and build bridges in this manner so that the majority of construction can occur outside of the right-of-way, reducing road closure times and impact to the traveling public. Using ABC techniques, road closure times due to bridge construction have been reduced anywhere from months to weeks and sometimes even to days.

These ABC techniques are relatively new to most agencies and currently require significant increases in cost and planning, as ABC bridges do not follow typical designs nor construction methods. The benefits of ABC projects are economically realized when factors such as traffic disruption, environmental impacts, and improved highway work-zone safety are given monetary values.

As ABC has gained popularity in the bridge community, knowledge has been gained, expanded, and shared, significantly increasing the quality of the ABC product and the acceptance of this method of bridge construction. Since ABC is still relatively new, there are types and aspects of bridges whose benefits have not yet been or are rarely utilized in the ABC movement.

The integral abutment bridge has seen limited use in ABC practice today but has distinct characteristics and advantages that can benefit the long-term viability of ABC. The integral abutment was originally developed to eliminate or move the expansion joint off of the bridge superstructure.

Expansion joints are fragile and, if not designed, constructed, and maintained properly, will allow chlorides and debris to penetrate the deck joint and cause corrosion to critical substructure elements. This elimination of the expansion joint has seen widespread use, as it often leads to reduced maintenance costs. The so-called jointless bridge is also faster and less expensive to construct because the integral abutment is simple in geometry, has only one row of foundation piling, and eliminates the use of beam bearings.

While there are many benefits to the integral abutment bridge, there are also some drawbacks to its use, which typically stem from the complex soil-structure interaction. Since there is no expansion joint, the entire bridge expands and contracts as one, and thus the maximum length and skew are typically limited on integral abutment bridges.

Integral abutments are often large and heavily reinforced to transfer and distribute load between the superstructure and substructure, which makes it difficult to use this bridge type in ABC projects. This typically results from two reasons: mechanical splicing of the abutment is difficult due to construction tolerances and transportation of the abutment as a whole is difficult due to weight issues.

To overcome these two design complications, the integral abutment bridges that have been constructed in ABC practice have relied on cast-in-place closure pours to create part of or the entire integral diaphragm. These closure pours alleviate construction tolerances and create an ABC integral abutment detail that is contractor-friendly. However, the downside to cast-in-place closure pours is in the high-performance concrete (HPC) or ultra-high-performance concrete (UHPC) used in the pour. These materials add significant cost to the project, as the material must achieve a high early strength so the bridge may be quickly opened to the traveling public.

1.2 Research Scope, Objectives, and Tasks

The goal of this research is to provide information that will aid in the planning, design, and construction for ABC projects utilizing integral abutment designs. Engineers with the Bridge Engineering Center (BEC) at Iowa State University (ISU) and the technical advisory committee (TAC) discussed many possible details for integral abutments in the ABC application, of which the most promising were selected for full-scale laboratory investigation. The laboratory specimens were evaluated on three criteria: constructability, strength, and durability.

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

1. Conduct a literature review examining ABC projects and integral abutments.
2. Develop and design details for an integral abutment using ABC methods.
3. Fabricate the most promising designs for testing in the laboratory and document the construction and erection process.
4. Test the designs 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 future use of integral abutment bridges with accelerated bridge construction.

CHAPTER 2. LITERATURE REVIEW

2.1 Connection Details for Prefabricated Bridge Elements and Systems (2009)

The integral abutment bridges previously built using ABC techniques commonly utilize precast pile caps and girders and rely on cast-in-place closure pours to form the integral connection (Figure 1) (Culmo 2011).
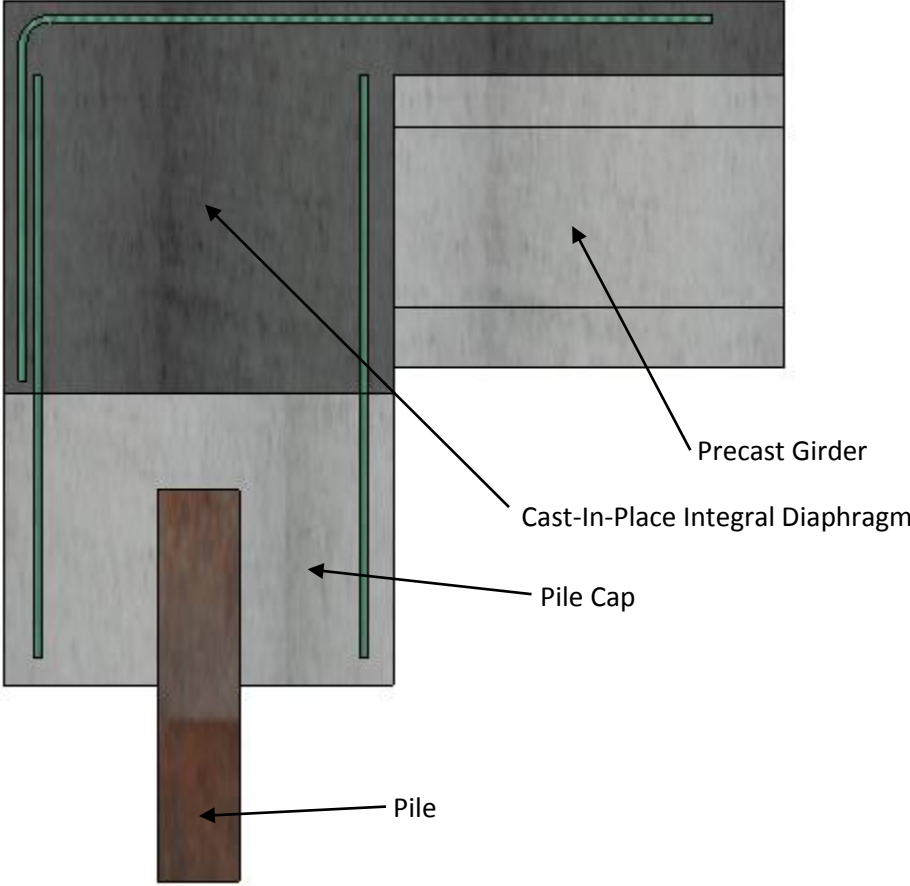
Figure 1. Integral abutment with closure pour

The disadvantage to cast-in-place closure pours is that they use rapid curing high performance concretes, which add significant cost to the project. One means of eliminating the closure pour is through the use of grouted reinforcing bar splice couplers (Figure 2).
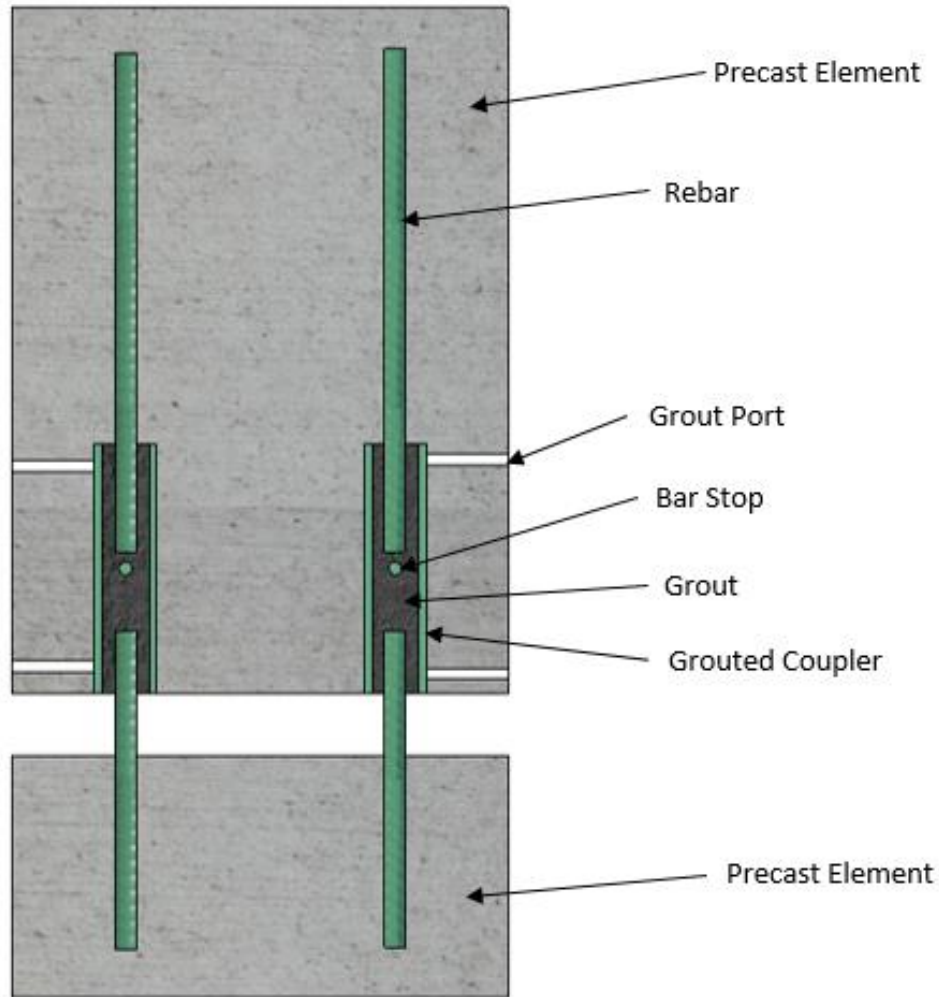
Figure 2. Grouted coupler conceptual drawing

Grouted reinforcing bar couplers function by inserting steel reinforcing bars into a sleeve, which is then grouted shut. The splice is capable of developing the full strength of the steel reinforcing over a short distance and has been around for several decades. Grouted reinforcing bar couplers often create tight construction tolerances when large amounts of splices are present; therefore, integral abutments have seen rare used with the technology.

Although not widely utilized, grouted couplers are gaining in popularity and have been successfully used in ABC projects like the Mill Street Bridge in Epping, New Hampshire (Culmo 2011). This bridge is unique in the fact it was constructed entirely from modular precast elements, which utilized grouted couplers to make all of the precast connections. The dimensional tolerances in precast elements when using grouted couplers are a major concern for contractors. Techniques like match casting and measuring couplers and reinforcing locations from a single point are used to minimize construction errors and ensure field alignment. To increase constructability for the precast elements in the Epping Bridge, the design team oversized the grouted reinforcing splice couplers by two sizes, which is acceptable for some types/brands

of reinforcing bar couplers. Utilizing these strategies, the Mill Street Bridge was successfully erected in eight days.

2.2 Accelerated Bridge Construction Manual (2011)

ABC projects that use an integral abutment design typically utilize a cast-in-place closure pour to form the integral connection between the superstructure and the substructure (Dahlberg and Phares 2015) (Figure 3).
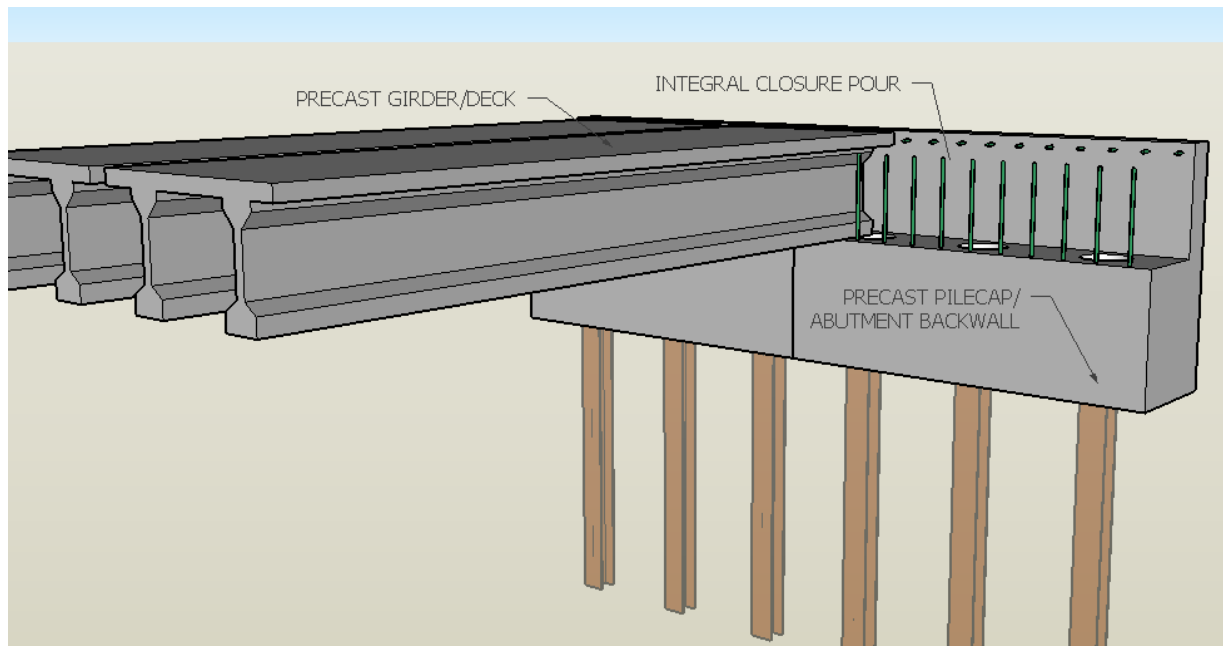
Figure 3. Three-dimensional drawing of integral abutment with closure pour

The abutments are often prefabricated and post-tensioned transversely or are connected using grouted shear keys. To reduce the size of the integral diaphragm closure pour, the option of a prefabricated backwall can be used. The alternative to cast-in-place closure pours is mechanical splice connections such as grouted reinforcing bar couplers. Couplers are attractive because the mechanical connection is fast and strength is achieved rapidly. The limiting factor when using grouted couplers is the dimensional tolerances associated with aligning the steel reinforcing and grouted couplers.

2.3 Innovative Bridge Designs for Rapid Renewal ABC Toolkit (2014)

The substructure designs for ABC projects described in this toolkit are based on the assumption that pile driving will occur within +/- 3 inches of the specified plan locations (HNTB Corporation et al. 2013). Integral abutments are desirable for use in ABC projects because they offer a variety of benefits, including faster initial construction speed, enhanced service life, and lower lifetime maintenance costs. Integral abutments typically have a single row of abutment piling, which saves construction time and material costs. The long-term durability is improved

because there is no expansion joint or beam bearings that require maintenance and/or replacement. The use of the integral abutment bridge is also advantageous for use in seismic areas, where a common problem is the unseating of beams after an extreme event.

The elimination of beam bearings in an integral abutment bridge also improves the tolerance issues associated with erecting precast beam elements if a cast-in-place integral diaphragm is used. The cast-in-place integral diaphragm is easy and fast for contractors because there is limited formwork required to place this concrete. On the other hand, the use of fully precast elements is desirable to maximize erection speed. In Figure 4, a full precast integral abutment system is shown where the pile cap and integral abutment are connected using steel dowels and grouted voids to allow for generous construction tolerances.
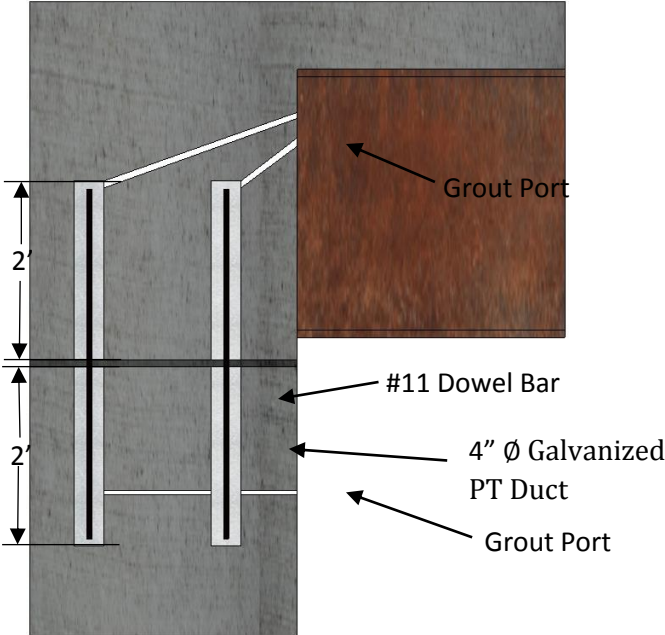
Figure 4. Integral abutment with bar dowels

In scenarios when the precast elements are too heavy, such as in a heavy abutment system, voids should be placed inside of the elements. Once the elements are in place, the voids are to be filled with self-consolidating concrete to complete the element.

The report also recommends two specifications for the contract documents to facilitate the use of grouted reinforcing bar couplers. The first specification is the requirement of a template to place the grouted reinforcing bar couplers and steel reinforcing bars in the field. The second specification is that the precast elements should be "dry fit" to check for proper alignment before leaving the fabrication yard. These two practices will ensure that the elements are fabricated properly and facilitate erection of the bridge. An additional recommendation for the design of elements using grouted reinforcing bar couplers is that they be placed on the bottom side of the precast elements so debris will not fall into the couplers. The reinforcing bars located on the top

of the precast elements also facilitate the storage and transportation because the bars are less likely to be bent out of position.

2.4 Laboratory and Field Testing of and Accelerated Bridge Construction Demonstration (2013)

The Keg Creek Bridge, near Massena, Iowa, was built entirely using modular precast elements (Rouse and Phares 2013). The Keg Creek Bridge is a three-span, two-lane, semi-integral abutment bridge, which is a common layout that could serve as a template for thousands of future ABC projects. The substructure of the Keg Creek Bridge utilized grouted reinforcing bar couplers, which spliced the reinforcing bars between the precast footings, columns, and pier caps. The use of grouted reinforcing bar couplers and precast elements allowed the substructure to be erected in a few days, where months of work would have been required to create similar cast-in-place components. The downside to using grouted reinforcing bar couplers is that construction tolerances are often tight between precast elements. In order to ensure alignment between precast elements, a template was used to tie the reinforcing bar cage and to hold the grouted couplers. The template was seen as critical to the success of the system and is promising for use in future projects (Nelson 2014).

The erection of the superstructure was accelerated through the use of modular elements comprised of steel beams, a precast concrete deck, and precast semi-integral abutments with an overhanging backwall. The longitudinal and transverse deck joints, along with semi-integral abutments, allowed for adequate construction tolerances when placing the superstructure. The modular deck elements had reinforcing that protruded into the longitudinal and transverse deck joints, which were filled with UHPC to create moment resisting connections. During a post-construction bridge inspection, it was noticed that efflorescence appeared on the underside of the longitudinal joints, indicating that chlorides had penetrated the deck joint from the top of the bridge deck. The use of joints in ABC is critical, and information regarding long-term performance should be monitored. Overall, the Keg Creek Bridge demonstrated that the use of precast elements can be successfully used to erect a three-span bridge in two weeks.

2.5 Plastic Energy Absorption Capacities of #18 Reinforcing Bar Splices under Monotonic Loading (1994)

In the American Association of State and Highway Transportation Organizations (AASHTO) code, reinforcing steel bar splices are required to develop a minimum of 125% F_y of the reinforcing bar. The only splice allowed in plastic hinge zones is the full penetration weld, which is undesirable from a constructability standpoint (Rouse and Phares 2013). In order to investigate the use of other bar splices, the research team investigated the ductility of the full penetration weld, grouted reinforcing bar coupler, and other splicing technologies. In some scenarios, the splice may not develop the minimum yield strain of 0.00207 before the connected bars fail. A need exists to establish a requirement for ductility of splices that will allow for the dissipation of energy in a seismic event. In all but one of the grouted NMB Splice Sleeves tested in this study, the bar fractured outside of the coupler in monotonic loading after the bar yielded. One coupler violently ruptured after the minimum yield strain was developed; it was later determined that the

coupler failed due to a manufacturing defect. Further investigations should examine the rotational capacity of the hinge created by the yielding reinforcing bars when spliced with grouted reinforcing bar couplers in full structural concrete members.

2.6 Evaluation of Grout-Filled Mechanical Splices for Precast Concrete Construction (2008)

The Michigan Department of Transportation (DOT) performed laboratory testing on the NMB Splice Sleeve and the Lenton Interlok grouted reinforcing bar couplers (Jansson 2008). These couplers are capable of simulating traditional cast-in-place construction by providing continuity between the reinforcing steel bars in precast elements. The need for the rapid erection of bridges has led to an increased demand and use of the grouted coupling technology. The prefabrication of integral abutments is desirable for use with grouted couplers because of the fast field connections. This combination has been previously used with success on Route 9N over Sucker Creek, in Hague, New York, in 1992. This bridge used grouted reinforcing bar couplers to connect precast deck elements to the precast abutment wall stem (Figure 5).
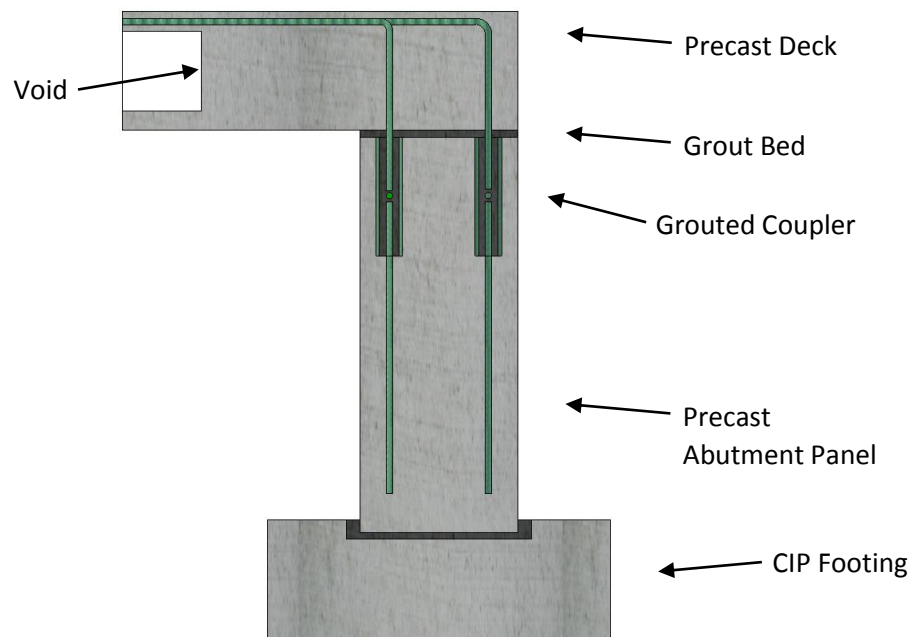
Figure 5. Grouted reinforcing bar coupler joining precast deck and abutment

The use of integral abutments is desirable for rapid replacement projects because the need for expansion joint and beam bearings is eliminated.

Prior to using this technology in departmental projects, the Michigan DOT desired a better understanding of how these couplers perform in terms of strength, fatigue, slip, and creep with respect to the AASHTO Load and Resistance Factor Design (LRFD) requirements. After testing, the couplers met the requirements in pre- and post-fatigue slip testing, having less than 0.010 inches of displacement. The couplers met the requirement that 125% of F_y must be developed in

the steel reinforcing bars prior to failure of the system. Creep testing demonstrated that the splices were not vulnerable to displacement under a sustained load at a magnitude of 40% F_y of the steel reinforcing. Lastly, none of the systems failed after one million cycles in a fatigue test where stress ranged between 6 ksi and 26 ksi. Subsequently, the research team recommended that the grouted reinforcing bar couplers be approved for use in Michigan DOT projects. Further research is suggested by the research team in the investigation of the effects of misalignment in the bar splices. This effect is desirable to understand because perfect alignment may not be the case in construction projects.

2.7 High Strain-Rate Testing of Mechanical Couplers (2009)

Due to the often congested areas in concrete construction encountered when lapping steel reinforcing bars, mechanical splices have become popular to alleviate the congestion (Rowell 2009). Mechanical splices have been studied and have proven to be an effective and simple means to splice steel reinforcing; however, there have been few studies that investigated the performance of these splices under high strain-rates such in as blast loading. One type of splice investigated that relates to this research is the grouted reinforcing bar coupler, where two bar ends are grouted into the coupler. Six grouted couplers were tested in pure tension, two in each of the following categories: slow, intermediate, and high strain-rates. The dynamic tensile strength of these spliced connections showed good performance in all three strain-rates. The ductility of the bars achieved in this loading condition was poor in comparison to the control bars tested. The author recommended that additional tests be performed in order to evaluate the performance of the grouted reinforcing bar couplers when used in structural concrete.

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

The use of grouted couplers has increased as the need and demand for ABC projects has increased (Haber 2013). The ability of grouted couplers to splice reinforcing bars between precast elements to simulate cast-in-place construction has made them a popular choice for bridge designers. Currently, the use of grouted couplers with ABC in seismic zones has been limited because of the performance uncertainties relating to the new technology. Concern exists for the use of grouted couplers between column and footing connections, where energy must be dissipated in seismic events through nonlinear deformations. The goal of the research was to investigate the use of grouted couplers and headed couplers for ABC connections in moderate to high seismic zones. The researchers constructed five half-scale column-to-foot connections that included a cast-in-place typical detail and two headed coupler and two grouted reinforcing bar coupler details. Performances of the headed coupler and grouted coupler details were similar to that of the cast-in-place detail with regards to energy dissipation, force-displacement ratios, and damage progression. After testing, the headed reinforcement coupler connections and grouted reinforcing bar couplers were removed and inspected for damage. Consistent through all models, the splicing was undamaged while the longitudinal bars experienced failure. The headed reinforcement connections had a marginally better performance with respect to the cast-in-place model; however, this method of splicing featured tighter construction tolerances and was more time consuming to connect. Due to the performances of the analytical and experimental models

created in this research project, the researchers suggested the removal of the restrictions placed on grouted reinforcing bar couplers by AASHTO in seismic zones.

2.9 Laboratory Connection Details for Grouted Coupler Connection Details for ABC Projects (2015)

With the increase in demand for precast bridge elements, new technologies have often been used before major advancements in empirical and theoretical relationships exist (Hosteng 2015). The grouted reinforcing bar coupler that is often used to connect precast elements falls into this category. The majority of research on this technology has focused on a direct tension test that may not accurately represent conditions met in the field. In order to investigate the grouted reinforcing bar coupler in a realistic application, a precast element system was fabricated for testing in the laboratory (Figure 6).
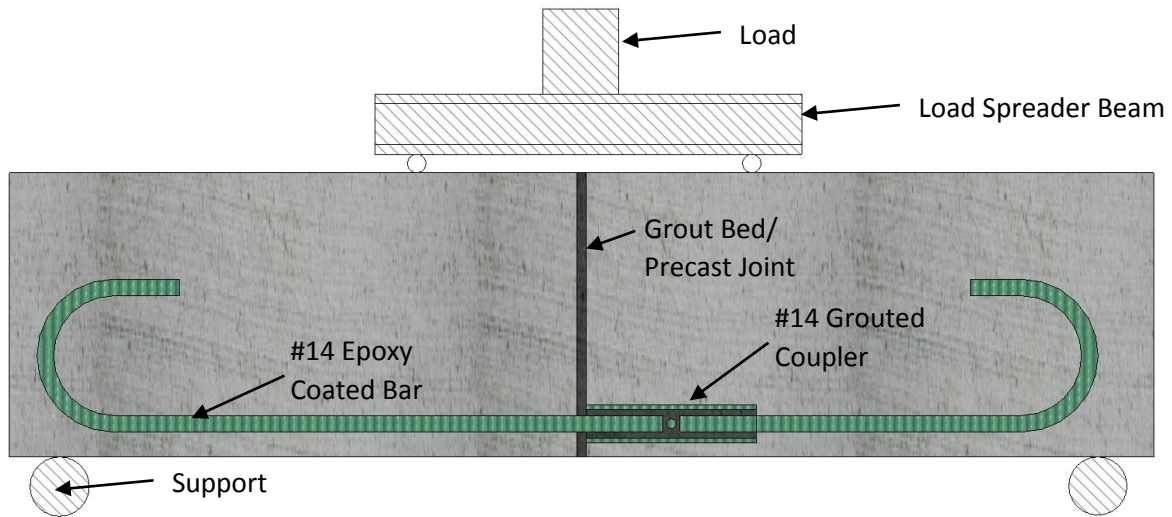
Figure 6. Grouted reinforcing bar coupler precast laboratory specimen

The system tested #14 epoxy-coated reinforcing bars that are spliced by epoxy-coated grouted reinforcing bar couplers manufactured by Dayton Superior. The precast joint for the first five specimens utilized W. R. Meadows 588-10k grout for the bedding material. The ability of the grouted reinforcing bar coupler to develop flexural capacity between elements was investigated in three loading cases. The loading cases for the specimen were pure bending, axial load plus bending, and a cyclical test of the system in pure bending. Overall, the static testing demonstrated that the empirical calculations utilized in the design of the specimen were accurate.

The crack located at the precast joint in this case opened almost immediately under load, and the application of axial load to the specimen had little effect. The last specimen fabricated was unique in the fact it used a UHPC grout bed, which marginally increased the load required to crack the joint. For the specimen subjected to one million cycles of fatigue stress, the reinforcing splice was placed at 18 ksi of stress in accordance with the AASHTO LRFD design

specification. The total deflection observed in this test remained constant through the million cycles, and the crack width at the precast joint did not exceed 0.02 inches.

Additional specimens were created to measure the susceptibility of the spliced connection to chlorides, which is of concern to bridges where de-icing salts are present. These specimens consisted of #14 epoxy-coated steel bars spliced with a grouted coupler and placed in the center of an 8 inch diameter concrete cylinder. The joint at the specimen was uncracked, and this specimen was soaked in a 3% chloride solution for six months. Periodic readings were taken, and no evidence of corrosion was seen.

CHAPTER 3. ABC INTEGRAL ABUTMENT DETAILS

The primary objective of this research was to investigate integral abutment details for ABC through laboratory testing. Since integral abutments with integral diaphragm closure pours have already been used successfully in the ABC community, this research focused on eliminating the closure pour through the use of a precast pile cap and integral diaphragm. The following sections discuss the design philosophy for integral abutments, the development of ABC details chosen for this investigation, and potential applications of the ABC details.

Each detail was evaluated on constructability, ensuring that contractor friendly practices can be used to construct and connect the precast pile cap and integral diaphragm successfully in the field. In addition to this, it was desired that the connection be comparable in strength and durability to a cast-in-place integral abutment, giving agencies confidence in the use of the new technology. To test the details, loads were simulated through the use of actuators, load frames, and a reaction floor to evaluate the strength and durability of the precast connection between the pile cap and integral diaphragm. The strength criteria were used to evaluate the shear and flexural capacity of the precast connection, while the durability criteria were used to examine the crack width that developed at the precast and/or cold joint, in addition to monitoring additional cracking that may develop at other locations. Crack widths were measured in order to provide information on the design's vulnerability to water and chlorides that could infiltrate the construction/precast joint and corrode the reinforcing.

3.1 Cast-in-Place

In order to evaluate the new ABC details in this investigation, the research team constructed a traditional cast-in-place integral abutment to establish baseline performances in constructability, strength, and durability. In general, an integral abutment is designed so that the superstructure and the substructure are rigidly connected, creating continuity and a jointless bridge. During thermal expansion and contraction of the superstructure, translation with small rotations of the pile cap is desired by engineers. To achieve this, engineers design the foundation piling below the pile cap to be relatively flexible, allowing the entire abutment to translate and rotate without inducing extreme forces in the foundation and superstructure. To design the connection between the integral diaphragm and the pile cap, vertical reinforcing steel is placed across the cold joint so that the connection is capable of developing the sum of all the plastic moment capacities of the foundation piles (INDOT 2015). Engineers also turn this vertical reinforcing steel along the back face of the diaphragm into the deck, providing additional flexural strength for the negative moment region that exists in the girder and deck at this location.

The standard integral abutment detail from the Iowa DOT was chosen to serve as the cast-in-place specimen in this laboratory investigation. The detail is shown in plan view in Figure 7 and again in a section view taken through the girder in Figure 8.
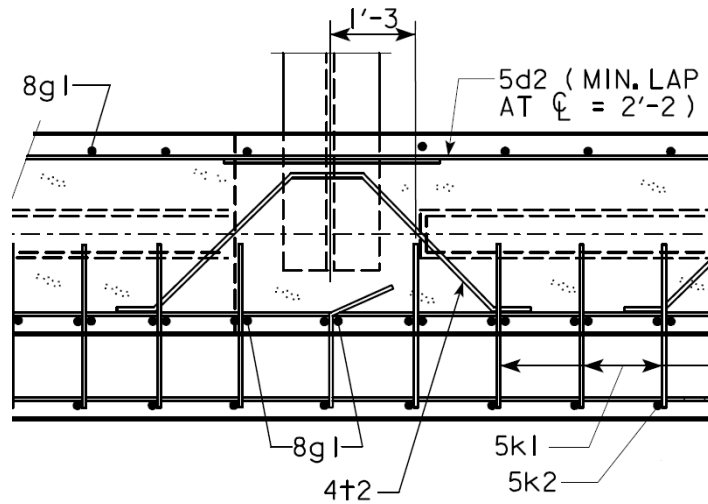
Figure 7. Integral abutment plan view from Iowa DOT
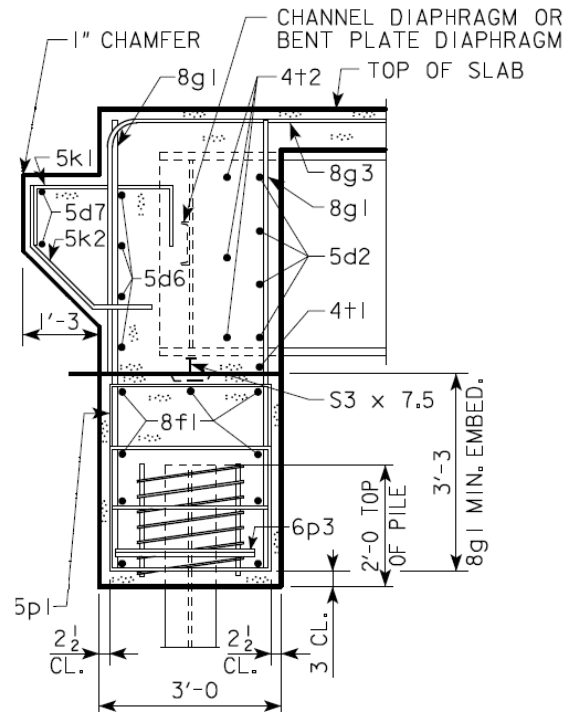
Figure 8. Integral abutment section view from Iowa DOT

This standard detail is similar in design to those used by other agencies and involves a cold joint with compression and tensile reinforcement to rigidly connect the pile cap and integral diaphragm. To provide better carry over and correlation with the study of the ABC details developed for this research, the width of the Iowa standard abutment was increased from 3 to 4 feet for the laboratory investigation. This change was made so that the cast-in-place specimen would share the same width as the ABC details investigated in order to make valid comparisons

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of constructability, strength, and durability. The resulting cast-in-place laboratory specimen is shown in plan view in Figure 9 and again in a section view through the girder in Figure 10.
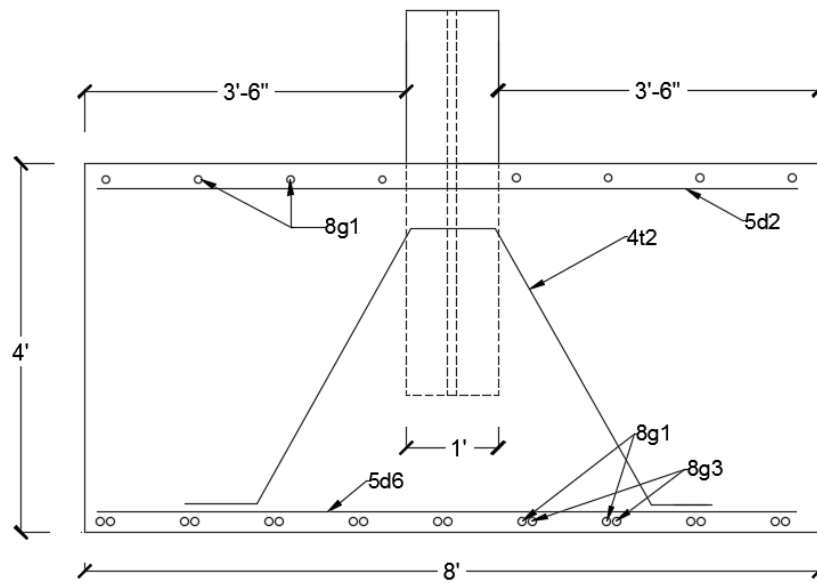
Figure 9. Cast-in-place specimen plan view
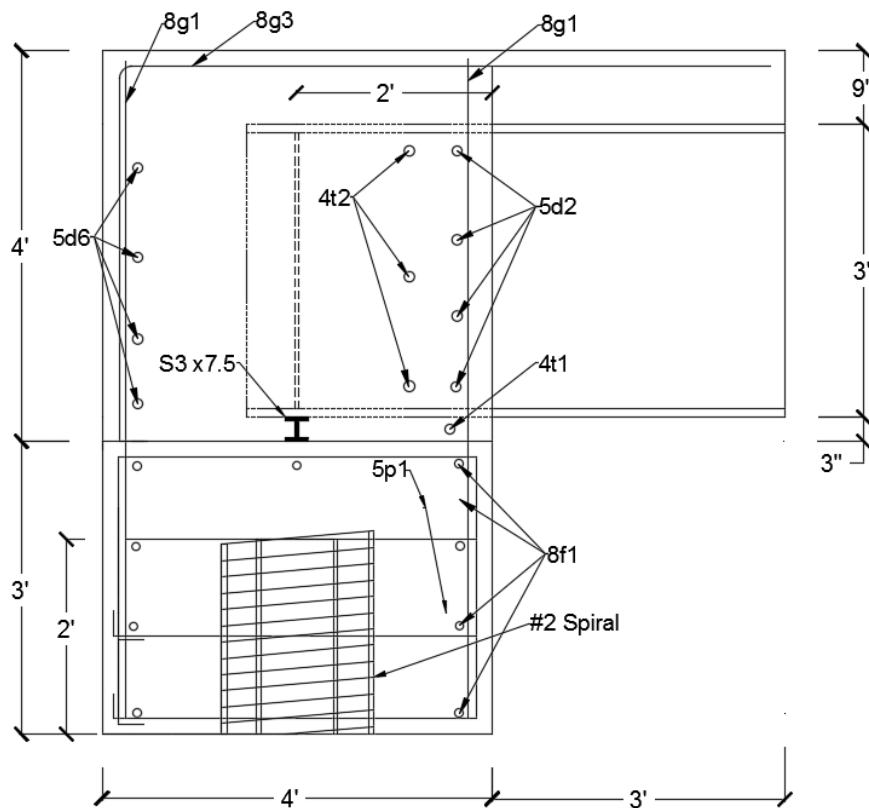
Figure 10. Cast-in-place specimen section view

Note that the laboratory detail was constructed without the foundation pile in the pile cap. This was left out to simplify the test configuration.

3.2 Grouted Reinforcing Bar Coupler

The first ABC integral abutment detail selected for laboratory investigation was one that splices the pile cap and the integral diaphragm using grouted reinforcing bar splice couplers and is referred to here as the grouted reinforcing bar coupler detail. The detail conceptually applies itself well to a precast element system such as the one shown in Figure 11.
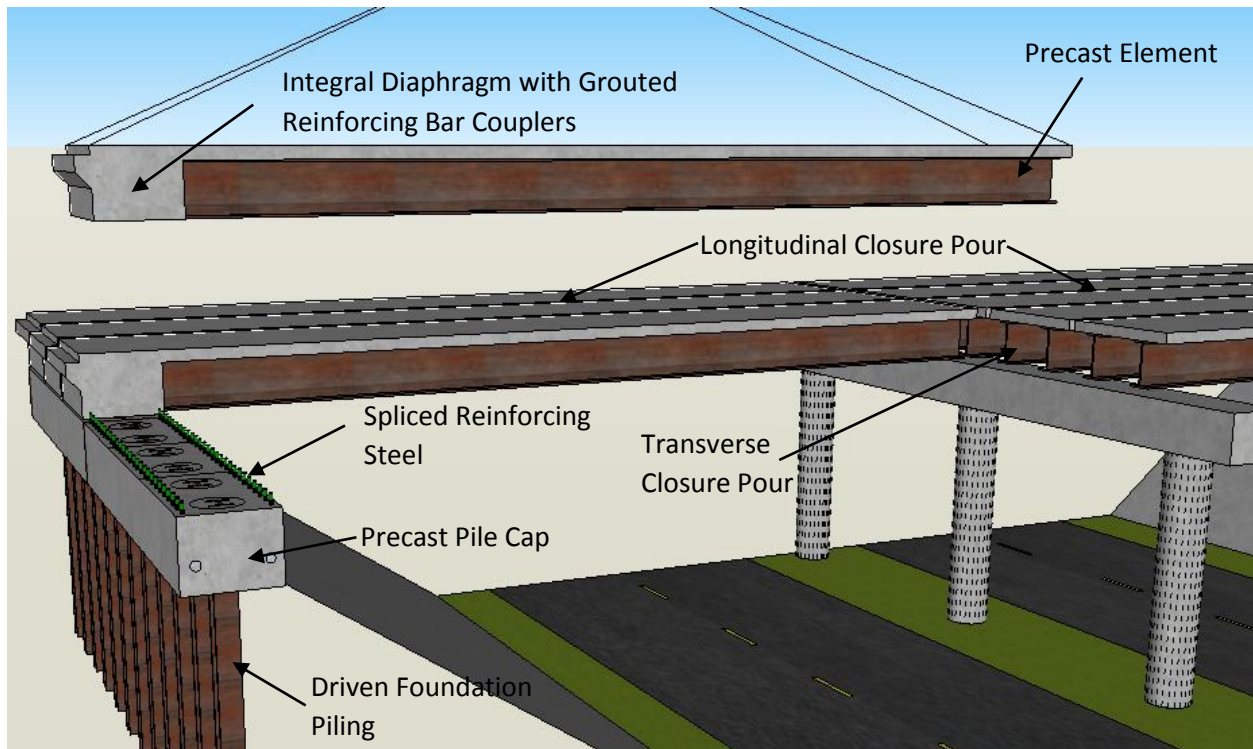
Figure 11. Prefabricated bridge elements and systems (PBES) using integral abutment with grouted reinforcing bar couplers

The chances of success for the grouted reinforcing bar coupler detail are maximized in this scenario, when a longitudinal (along the length of the bridge) and a transverse (across the length of the bridge) closure pour are utilized. These closure pours minimize the number of grouted couplers that require alignment per precast element connection and eliminate a precast element that requires alignment at both ends. The reinforcing steel bars protruding from the pile cap add complications to the constructability aspect of the bridge if slide-in bridge construction is attempted using this detail. For a slide-in bridge, the superstructure would require jacking, sliding in an elevated state, and the simultaneous lowering and alignment of a large quantity of grouted couplers.

As previously mentioned, the width of the standard cast-in-place Iowa pile cap was increased from 3 to 4 feet to suit the ABC application. This modification in width allows for a precast pile cap, shown conceptually in Figure 12, to be cast with corrugated metal pipe (CMP) pocket voids that fit over the top of the driven foundation piling.
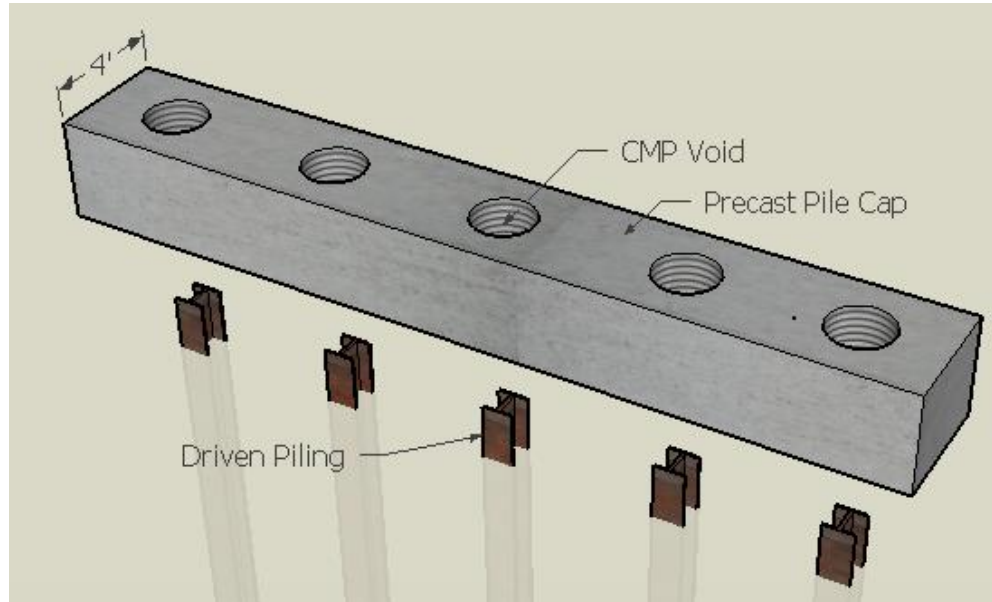
Figure 12. Precast pile cap

The pile cap is then connected to the foundation piles by filling the CMP voids with a specially designed concrete chip mix, which provides a strong pile-to-pile cap connection (Culmo 2009).

To test an integral abutment detail that utilizes grouted couplers, the standard Iowa cast-in-place abutment detail was modified to include the use of Dayton Superior's sleeve-lock grouted reinforcing bar splicing system. To modify the design of this detail, the typical cold joint was replaced with a precast joint, and the reinforcing steel across the cold joint was spliced using grouted couplers. In plan view, the specimen looks the same as the cast-in-place specimen, which is 8 feet in width, and requires splicing and coupling of 17 reinforcing bars spaced at 1 foot intervals. The width of the laboratory specimen was similar in width to a precast element that might be used in the field because 8 1/2 feet is the maximum transportation width. Since these two are relatively the same size, information on constructability from the laboratory would apply well to an element system created at a precasting plant. Should the elements be precast on site, however, these dimensions can/will change depending on the contractors and their equipment's capabilities.

The resulting laboratory detail utilizing grouted reinforcing bar couplers is shown in a section view taken through the grouted reinforcing bar couplers in Figure 13 and again in a section view taken through the girder in Figure 14.
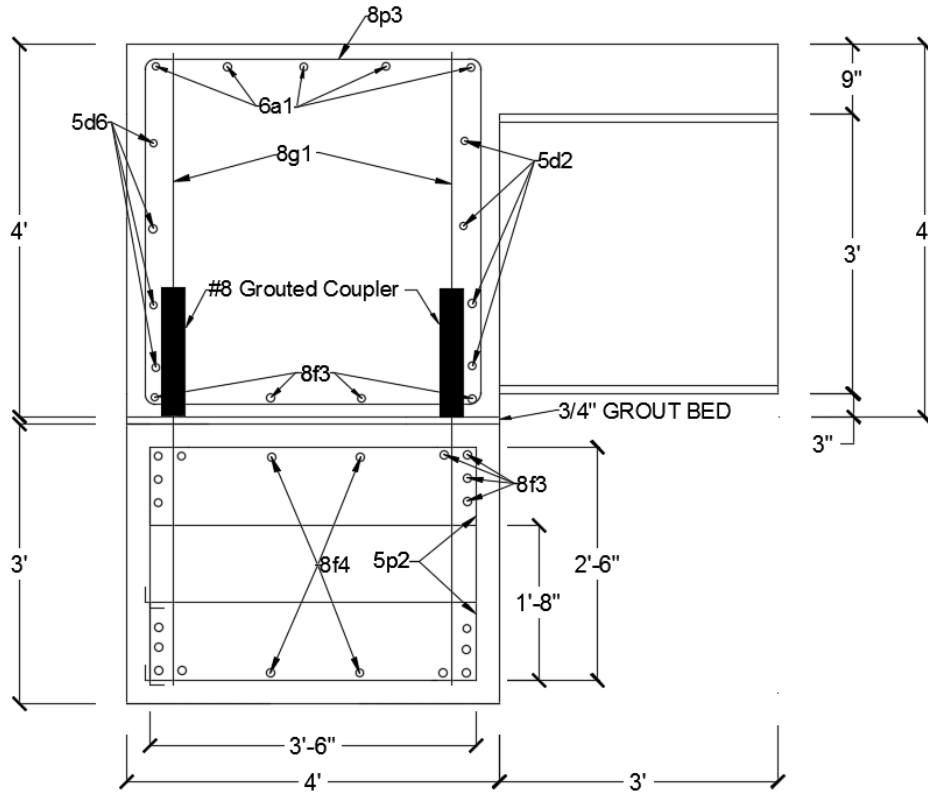
Figure 13. Grouted coupler section view through couplers
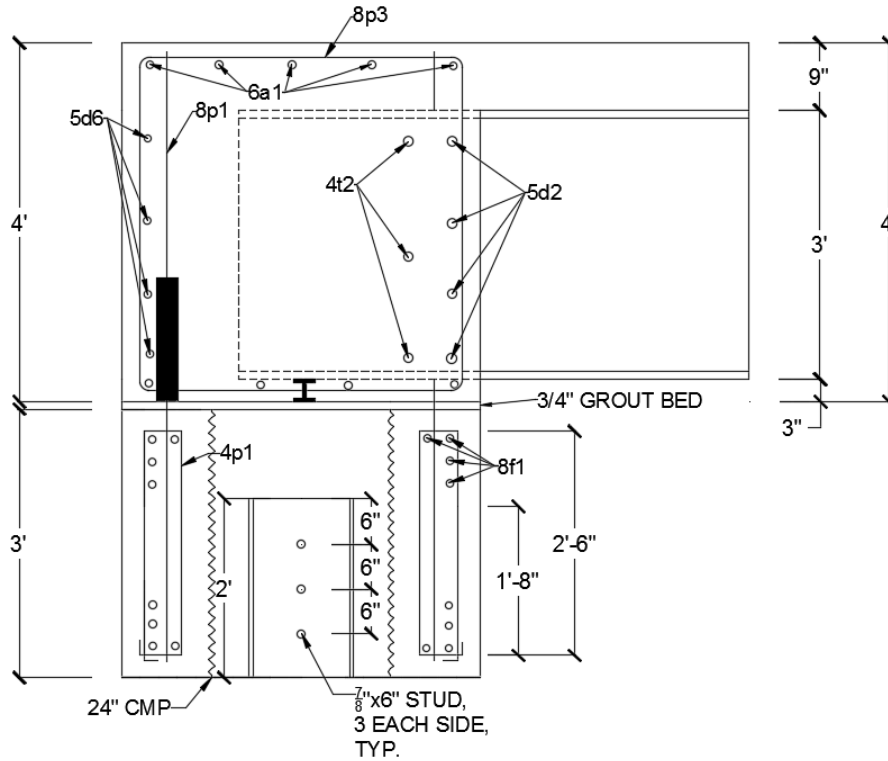
Figure 14. Grouted coupler section view through girder

Note that the laboratory specimen was constructed as it appears in the two section views, except that the foundation pile and CMP were not included to simplify the test setup. To create a flat surface for the precast elements, a 3/4 inch grout bed was detailed at the precast joint. The vertical bars passing through the joint, marked 8g1 in Figures 13 and 14, were spliced using grouted couplers. Since the grouted couplers were larger in diameter than the reinforcing steel, additional concrete cover was provided by moving the vertical bars closer to the center of the section. This design modification slightly reduced the moment arm between the effective internal tension and compression force couple that resists moment within the section. Since the precast elements are lifted and moved into position, additional reinforcing was provided to resist flexure and shear forces that develop in the elements. These bars consist of the longitudinal bars marked 8f3 as well as the stirrups marked 8p3, 5p2, and 4p1, shown in Figures 13 and 14.

3.3 Pile Coupler

The pile coupler detail was developed and designed to facilitate the use of integral abutments with a slide-in bridge application, and is shown conceptually in Figure 15.

18
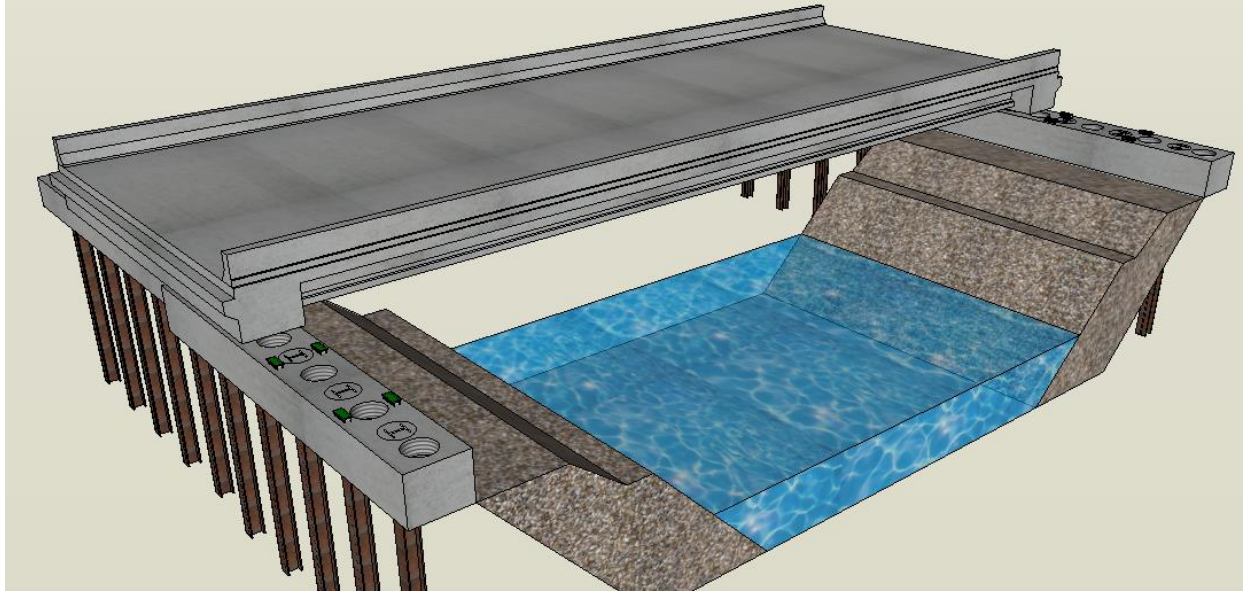
Figure 15. Slide-in bridge using pile couplers

The pile coupler design aims to minimize the number of mechanical connections between the integral diaphragm and pile cap to facilitate the use of slide-in-bridge construction. The pile coupler design uses a 2 foot length of H-pile (HP) section and a 24 inch diameter CMP to essentially create a large grouted coupler that splices the integral diaphragm and pile cap. The resulting detail and dimensions of the laboratory specimen are illustrated in plan view in Figure 16 and in subsequent section views in Figures 17, 18 and 19.
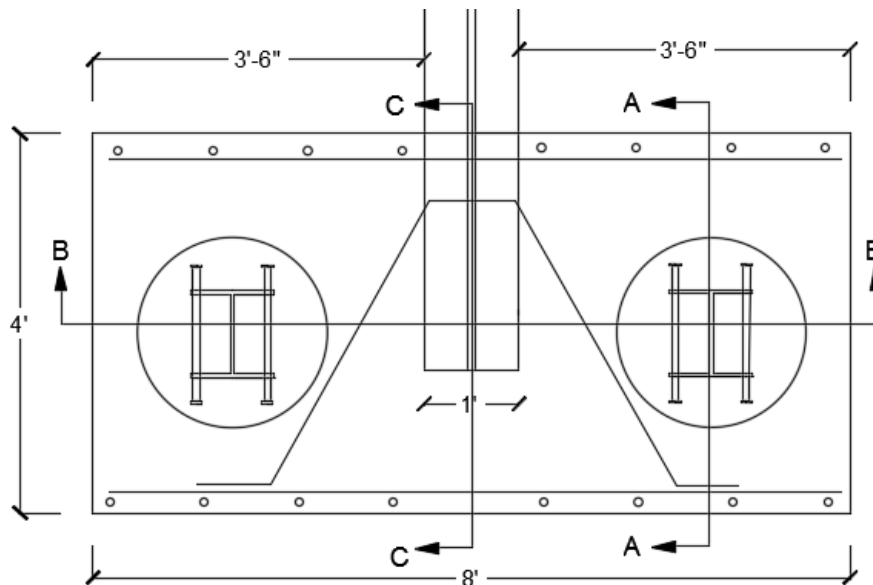
Figure 16. Plan view pile coupler
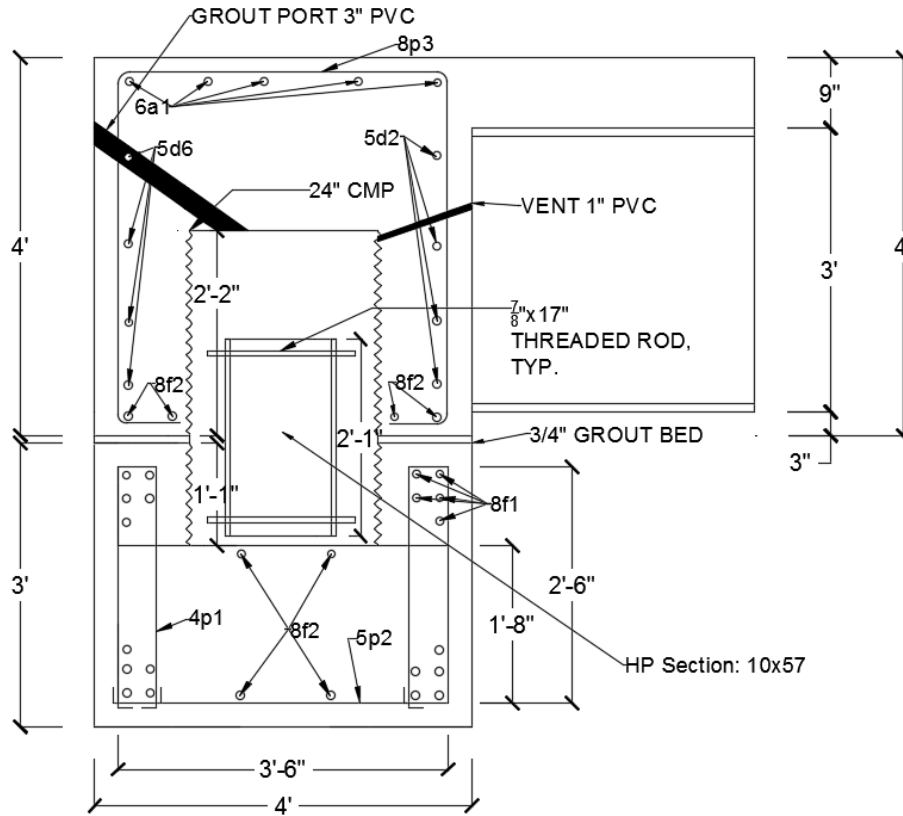
Figure 17. Section view A - pile coupler
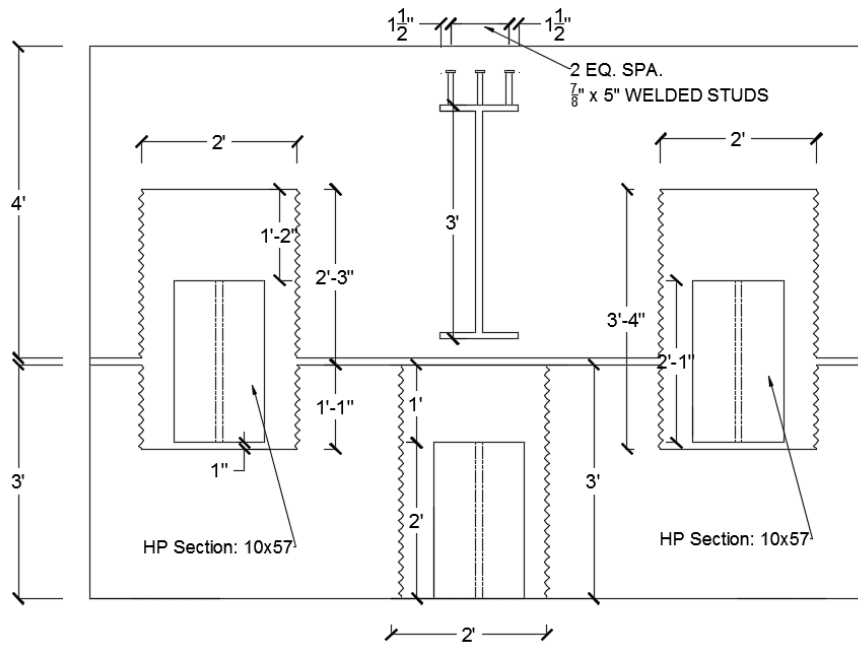
Figure 18. Section view B - pile coupler

20
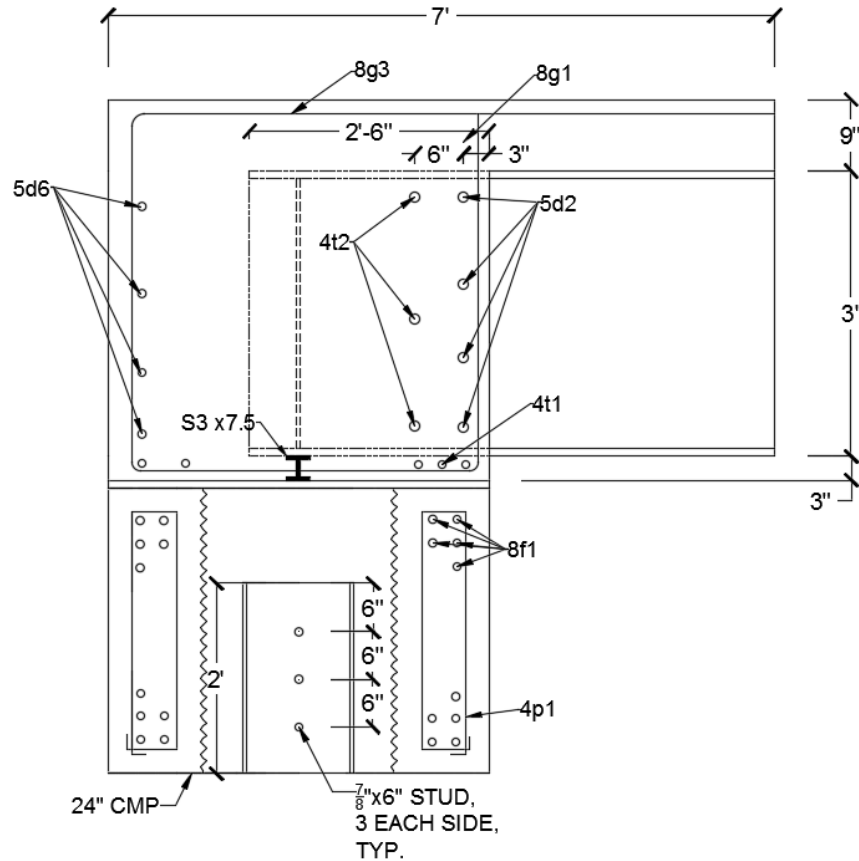
Figure 19. Section view C - pile coupler

The philosophy of this design is that the connection between the pile cap and integral diaphragm is designed to develop the sum of the plastic moment capacities of the foundation piling; thus, the same section used for the foundation piling could also be used to splice and couple the pile cap and integral diaphragm. The key for success lies in the ability of this detail to develop the strength of the relatively short HP section within the grouted connection.

The system facilitates the horizontal sliding of a full superstructure by suspending and containing the entire 2 foot HP section inside of the superstructure until the slide is complete. This eliminates the need to jack the sliding superstructure to pass over protruding reinforcing from the pile cap, such as is required in the grouted coupler detail. Once the superstructure is in position, the HP section is lowered into the CMP void present on the pile cap so that precast joint bisects the final resting position of the 2 foot long HP section (Figure 17). The longest possible HP section is desirable to couple the pile cap to the integral diaphragm so the strength of the HP section can adequately be developed. However, in this case the length of the HP section was limited to 2 feet because the containment within the superstructure was seen as critical to the success of this detail for constructability reasons. To increase connectivity between the grout and the HP section, threaded rods are detailed for use as shown in Figure 17.

Prior to grouting and casting the integral diaphragm, a steel cable is attached to the HP section and strung through a hook on the CMP lid and out of the 1 inch vent. This allows workers to suspend and lower the HP section within the CMP void in the abutment. In order to guide and prevent the HP sections from rotating out of strong axis bending, reinforcing steel is welded to the lid of the CMP and fits in the four corners of the web and flanges of the HP section. In order to grout the CMP void once the HP section is lowered into place, a 3 inch diameter PVC pipe is cast into the diaphragm at an angle so that grout can be gravity fed (Figure 17). A 1 inch PVC pipe is also cast into the diaphragm and doubles as an air vent and as a way to suspend and lower the pile (Figure 17). The vent pipe is tilted upwards slightly so the CMP void fills entirely with grout, pushing out all the air inside, before the grout begins to exit out of the PVC vent. At this time, the vent is plugged and grout is poured until the 3 inch PVC vent is completely filled.

During the design of this detail, there was talk amongst the research team and TAC of extending the CMP void to the top of the concrete deck. This would eliminate the suspension of the HP section and allow for the use of longer HP sections because they could be placed into the voids once the bridge superstructure is slid in place. The subsequent grouting process would also be easier because access to the voids would be from the top of the bridge deck. Despite these advantages, this route was ultimately not chosen in order to avoid the resulting construction joint on the bridge deck, where the use of de-icing salts is heavy during the winter months. The infiltration of chlorides at construction joints on ABC projects has been observed, and the resulting effect on long-term durability is unknown. Subsequently, partial-depth voids within the integral diaphragm and pile cap were selected to avoid a construction joint on the bridge deck, a decision that was seen as critical to the long-term success of this detail.

CHAPTER 4. CONSTRUCTION

4.1 Cast in Place Specimen

Construction for the cast-in-place specimen began with the pile cap. Reinforcing steel was tied, formwork was placed, and the concrete was placed and broom finished to create a good bonding surface to the integral diaphragm (Figure 20).

Figure 20. Cast-in-place pile cap

To construct the integral diaphragm and deck, formwork was attached directly to the pile cap, reinforcing steel was tied (Figure 21), and a W36x150 girder was placed on the pile cap.

Figure 21. Cast-in-place integral diaphragm

Epoxy-coated bars were used for the vertical bars that connect the pile cap to the diaphragm. Black bar was used in the remainder of the abutment because the slip between the concrete and reinforcing steel was not seen as critical to the evaluation and performance of the detail in this study. The diaphragm and 3 feet of deck were cast monolithically, which is consistent with construction practices in the field. Figure 22 shows the completed cast-in-place specimen in addition to the reaction blocks used for rigidly connecting the specimen to the floor.

Figure 22. Cast-in-place integral abutment specimen

4.2 Grouted Reinforcing Bar Coupler Specimen

To construct the grouted reinforcing bar coupler specimen, the pile cap was fabricated very similarly to the cast-in-place specimen, taking extra time to precisely place the vertical bars that connect the pile cap to the diaphragm. Since these bars were being spliced with grouted reinforcing bar couplers, it was important that these bars be plumb and in the correct location, facilitating a proper fit later. However, maintaining exact placement of the vertical bars was impractical because the bars continually shifted while tying the reinforcing steel cage and during the concrete pour (Figure 23).

Figure 23. Pile cap reinforcing bar, formwork, and pour

After casting, all of the vertical reinforcing steel was within 1/2 inch of the planned locations and relatively plumb (Figure 24).

Figure 24. Grouted coupler pile cap

Using a cheater bar, the reinforcing steel bars that had shifted during the pour were bent to the vertical position. To ensure that the couplers would be properly aligned with the protruding reinforcing steel in the pile cap after casting the diaphragm, a template was created to "match

cast" the specimens. The template (Figure 25) was a 4 by 8 foot sheet of plywood that was laid over the top of the pile cap reinforcing steel so that the exact locations could be marked and then drilled into the template.

Figure 25. Grouted coupler template

Form plugs (Figure 26) were then installed into the holes on the template and tightened to hold the grouted coupler tight to the template.

Figure 26. Form plug

With the template complete and the grouted couplers in place, the template served as the base for the formwork, and the remainder of the reinforcing steel was tied and the steel girder was moved into place (Figure 27).
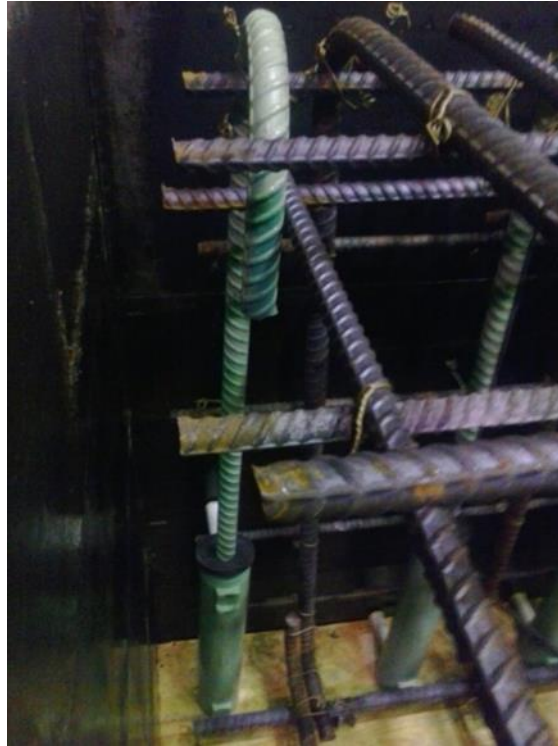
Figure 27. Grouted coupler and reinforcing bar

The remaining formwork was erected, and the integral diaphragm was cast separate from the pile cap (Figure 28).

Figure 28. Integral diaphragm and deck, formwork, and reinforcing bar

With construction of the integral diaphragm complete (Figure 29), a trial fit of the pile cap and diaphragm was made to ensure that the 17 reinforcing steel bars and grouted couplers aligned.

Figure 29. Integral diaphragm

With proper alignment confirmed, 1/2 inch steel shims were placed on the pile cap to support the integral diaphragm during placement of the grout bed. To ensure that the bedding grout did not infiltrate the reinforcing bar couplers, seal plugs were placed on the protruding reinforcing steel bars (Figures 30 and 31).

Figure 30. Seal plug

Figure 31. Neoprene disk, seal plug, and shim

Next, the surfaces of the precast joint were wetted to the saturated surface dry condition (Figure 32), and formwork was installed to cover and seal the precast joint (Figure 33) in preparation for pumping the grout bed.

Figure 32. Integral diaphragm placement

Figure 33. Grout bed formwork

Three holes were cut on the front and back of the grout bed formwork, as well as one hole on either side, so that grout could be pumped into the precast joint from multiple locations. Starting at one corner of the specimen, grout was pumped via a hand pump (Figure 34) until clean grout started coming out of the hole on the opposite side of the specimen.

Figure 34. Grout hand pump

This process was repeated, alternating back and forth from the front to the back side of the specimen, until no more grout could be pumped into any of the holes, with individual holes being plugged as soon as it appeared that the area was adequately filled with grout. Removal of the formwork and inspection of the perimeter of the joint indicated that the grout had adequately filled the bedding joint (Figure 35).

Figure 35. Completed grout bed and coupler grouting

However, without opening up the joint completely it was not possible to know the adequacy of the grout coverage across the entire bedding area. Rough calculations were performed to determine the amount of grout required to fill the joint; this number closely matched the quantity of grout pumped into the joint, giving confidence that the entire joint, or a large amount of the joint, had been filled.

In preparation for grouting the reinforcing bar couplers, air was blown into each grouted coupler to clean the coupler of any dust and check that the top and bottom ports were unobstructed. Two of the grouted couplers did not pass the air test, as grout from the bed seeped past the seal plug and partially filled the couplers, thus blocking fill from the lower port. The grouted couplers labeled 2 and 17 in Figure 36 were blocked.
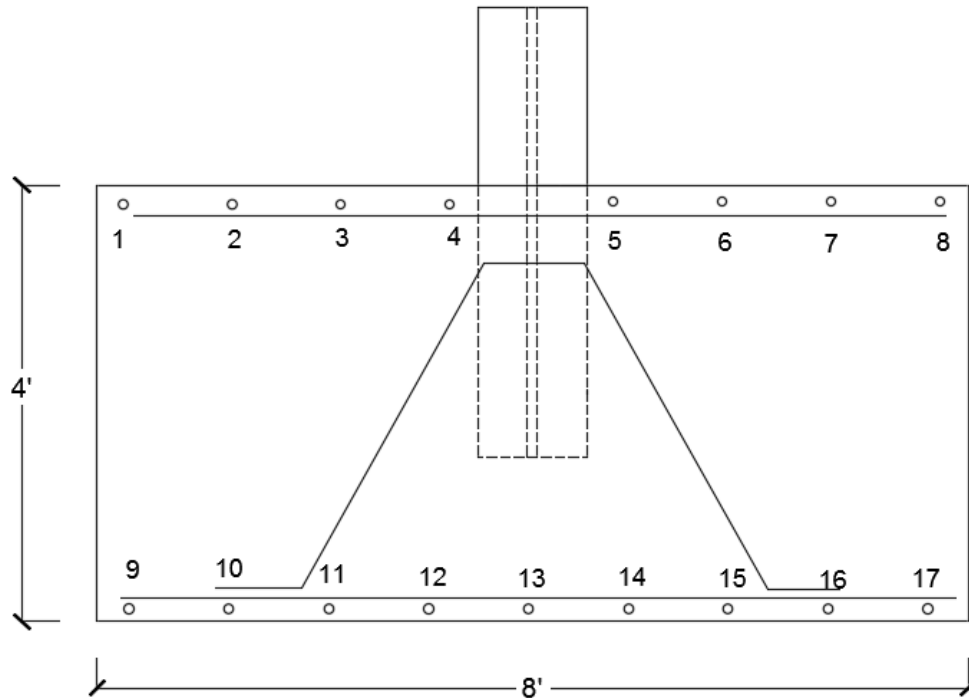
Figure 36. Grouted coupler layout

To grout the functioning couplers, grout was mixed one bag at a time, according to manufacturer recommendations, and poured into the hand pump. The nozzle of the hand pump was then placed into the bottom port of a grouted coupler, and grout was pumped until clean grout flowed out of the top port. The top port was then immediately plugged, and care was taken to quickly remove the nozzle at the bottom port and plug the port as quickly as possible. This is the process outlined and recommended by the reinforcing bar coupler manufacturer.

Overall, the grouted coupler specimen took more time and effort to construct than the traditional cast-in-place specimen. Most of the extra time was in the alignment of the spliced vertical bars in the pile cap. Fortunately, the template for the grouted couplers worked well and facilitated a successful fit for the precast element connection. Even though the precast elements were more challenging to construct, the crucial aspect for ABC projects is the erection time. Placing the precast element and grout bed formwork and grouting the bed and finally the couplers was a fast process and could be replicated in the field, facilitating a quick erection of the bridge. A contractor should pay special attention to sealing the bottom of the grouted couplers during placement of the grout bed so grout does not leak into the couplers and block the grouting operation, as it did in this investigation.

4.3 Pile Coupler Specimen

To construct the pile coupler specimen, the reinforcing steel cage for the pile cap was tied with 3 inch PVC pipes fitted at the bottom of the cage, which were used to post-tension the pile cap to the floor for testing (Figure 37).

36

Figure 37. Pile cap reinforcing steel bar cage

Formwork was erected around the cage, and a CMP was used to create a void in the pile cap for the HP section (Figure 38).

Figure 38. Pile cap reinforcing bar, formwork, and CMP

To seal the bottom of the CMP and create the void, plywood was cut into two half-circles and placed in the bottom of the CMP, which facilitated easy removal of the plywood after concrete placement (Figure 39).

Figure 39. CMP void in pile cap

To create the void in the integral diaphragm, a circular piece of sheet metal, 3/16 inch thick, was fabricated and used as a lid for the CMP. The thickness of the lid was chosen so that minimal deflection, less than 1/2 inch, would occur due to the concrete pressure present on the lid during

the pour. A U-shaped anchor bolt was installed in the center of the CMP lid, which, in combination with a steel cable, functioned as a pulley for suspending and lowering the HP section inside of the integral diaphragm. Holes were drilled in the steel lid and #4 reinforcing steel bars were welded in the holes, creating a guide system for lowering the HP section (Figure 40).

Figure 40. CMP lid with reinforcing bar guides and U-bolt

To attach the lid to the CMP, three holes 1/8 inches in diameter were drilled, and tie wire was used to secure the two together (Figure 41).

Figure 41. CMP with lid

Holes were drilled in the HP section, and threaded rods and nuts were installed in lieu of shear studs (Figure 42).

Figure 42. HP section with threaded rods

Once the integral diaphragm reinforcing steel bars were tied, the CMP voids were placed inside the cage (Figure 43).

Figure 43. Integral diaphragm reinforcing bar cage

A 3 inch PVC duct with a flange was attached to the CMP lid and run to the back side of the abutment formwork. The flange on the 3 inch PVC allowed for the CMP void to be filled all the way to the top before grout started filling the 3 inch PVC pipe. A 1 inch hole was also drilled in the CMP for a 3/4 inch PVC pipe that functioned as a vent and gave access to the pulley system (Figure 44).

Figure 44. Side view of CMP void

A steel cable was attached to the HP section and run through the U-bolt on the CMP lid and through the 3/4 inch PVC pipe, where it remained during the casting of the integral diaphragm, and was retrieved after the formwork was removed. With the HP section and CMP void in place, the integral diaphragm was ready to be cast (Figure 45).

Figure 45. Integral diaphragm deck reinforcing bar

Once the concrete had been placed, finished, and cured, the formwork was removed and the steel cables connected to the HP sections were pulled tight. This suspended the HP sections for transportation of the integral diaphragm (Figures. 46 and 47).

Figure 46. Integral diaphragm with suspended HP sections

Figure 47. Suspended HP sections

Washer plates and clamps were used to hold the cable tight during the transportation and placement of the superstructure.

Prior to placement of the diaphragm on top of the pier cap, 1.5 inch foam backer rod was placed around the CMP on the pile cap (Figure 48) to create a dam around the CMP void.

Figure 48. Pile cap with backer rod seal

This was principally done in order to prevent grout bed material from filling the CMP void. The backer rod also alleviated inaccuracies in placement of the CMP voids, as the top and bottom CMP were not perfectly aligned. The surface of the precast joint was then wetted to the saturated surface dry condition before the diaphragm was lowered onto the pile cap. Once the integral diaphragm was in place, the metal clamps were taken off of the steel cable holding up the HP sections, and the piles were lowered. In the laboratory, several checks were made prior to the final install to ensure and confirm the proper function of the pile lowering system. To place the grout bed, formwork was installed over the precast joint and the grout bed was pumped into place using the technique utilized in the construction of the grouted coupler specimen (Figures 49 and 50).

Figure 49. Grout bed formwork back

Figure 50. Grout bed formwork front

Following completion of the grout bed, grout for the CMP void was transported and poured using a barrel with a closable valve (Figure 51).

Figure 51. Grout funnel system

The system poured grout into a 3 inch PVC 90 degree elbow (Figure 51), which funneled grout into the CMP from the 3 inch PVC tubing cast into the diaphragm.

The CMP was filled with grout until the grout flowed out of the vent on the front side of the abutment, the filling paused temporarily so the vent could be plugged, and the 3 inch PVC pipe was then filled to the top with grout. There was some settling of the grout inside of the PVC pipe; however, the amount was less than 2 inches. Bleed water leaked through the grout bed in several locations, indicating a relatively high porosity in some locations in the grout bed (Figure 52).

Figure 52. Bleed water passing through the grout bed

CHAPTER 5. LABORATORY TESTING

5.1 Methodology

In order to determine the strength and durability of the integral abutment specimens, a reaction block and post-tensioning system was designed to affix the specimen to the laboratory strong floor (Figures 53 through 55).
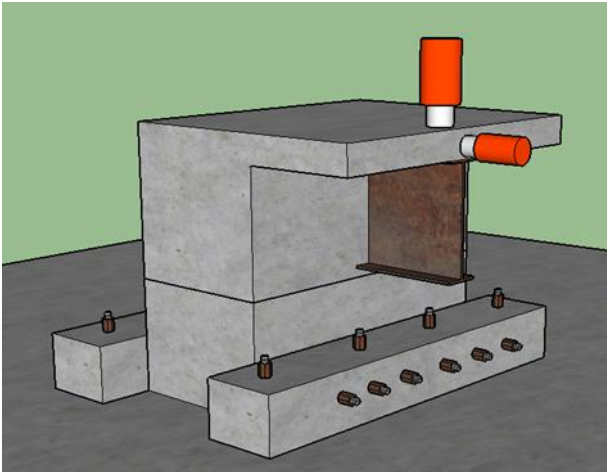
Figure 53. Three-dimensional drawing of laboratory test setup, front
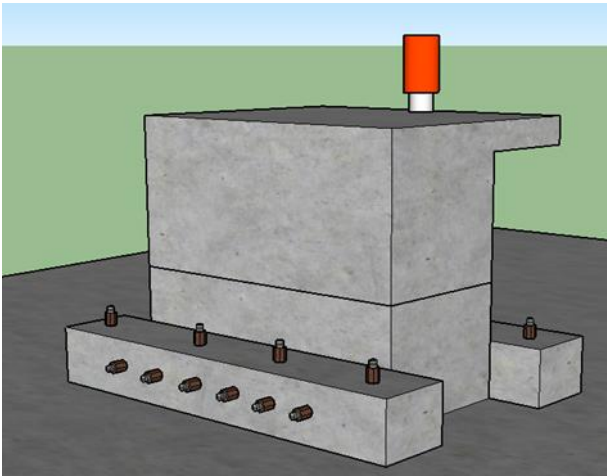
Figure 54. Three-dimensional drawing of laboratory test setup, rear

Figure 55. Laboratory loading and horizontal and vertical actuators

Using the reaction blocks, actuators, and load frames in the laboratory, forces were applied to the specimen simulating live loads and thermal loads. These loads tested the integral abutment laboratory specimen for strength and durability of the cold joint and precast joints, as well as the overall design of the surrounding integral diaphragm, pile cap, and concrete deck. While testing durability by means of cyclical testing was not possible given the available resources in this study, information on durability obtained by means of measuring crack widths present under load can be used to examine the risk of exposing the precast joint to water, chlorides, and debris.

The reaction block and post-tensioning system used in the laboratory makes the abutment react and behave differently than in the field, where translation and rotations of the abutment occur due to the flexibility of the piles and girders. By not including piles, which provide flexibility in an integral abutment bridge, in the laboratory specimen, a worst case loading scenario is possible.

The first load applied in the laboratory was the horizontal load, which developed tensile stresses in the front face of the abutment. This type of loading, according to the free body diagram in Figure 56, simulates stresses that a full integral abutment bridge would experience during thermal contraction.
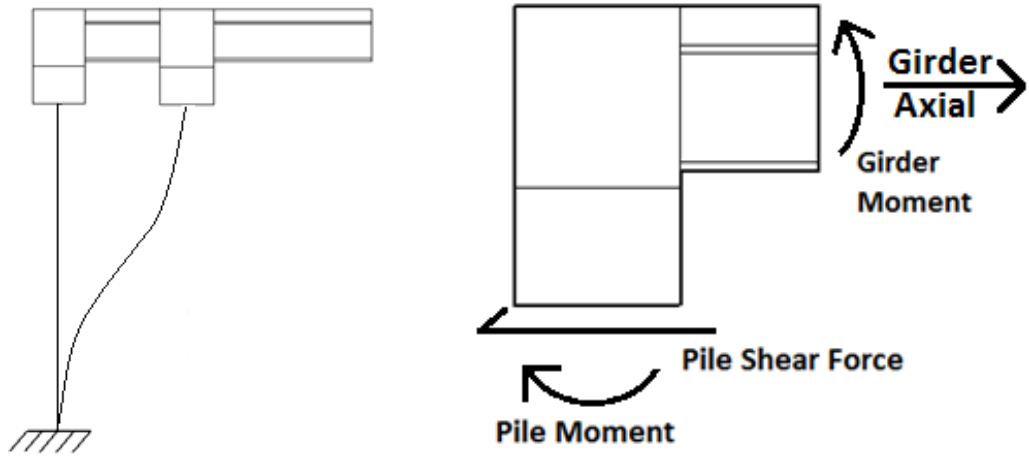
Figure 56. Thermal contraction and free body diagram

The horizontal load chosen to be applied in the laboratory was 100 kips. This load was chosen after examining the thermal forces that could be resisted by the stiffness of the foundation piling and surrounding soil. The intent of the horizontal load is not to fail the specimen, but rather to obtain expectations in performance of the abutment under service loading.

The second load applied in the laboratory was the vertical load. This type of loading developed tension in the back face of the abutment, which, according to the free body diagrams in Figures 57 and 58, is the same type of stress developed in a full integral abutment bridge during live loading and thermal expansion.
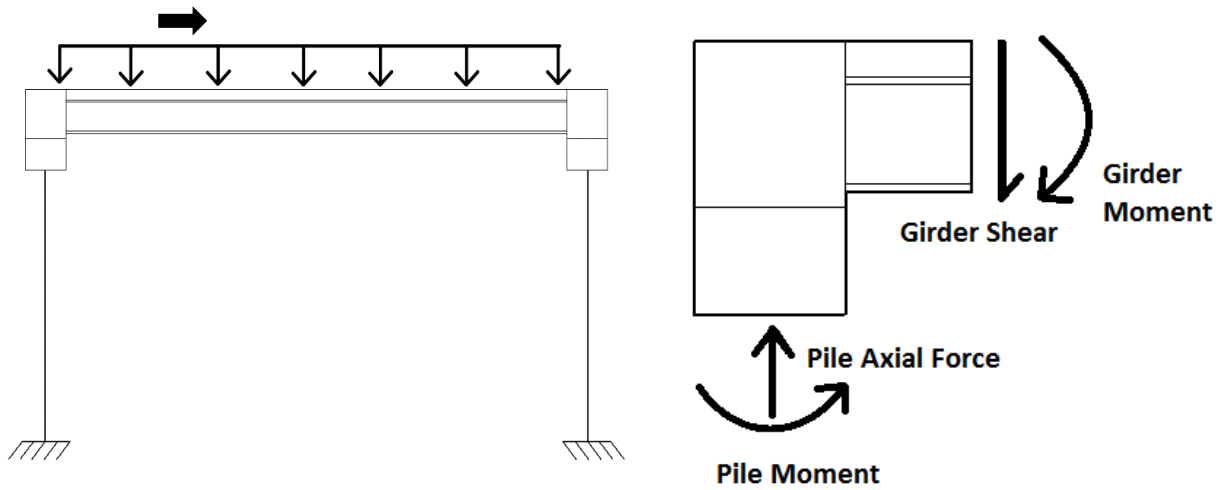

Figure 57. Live load and free body diagram
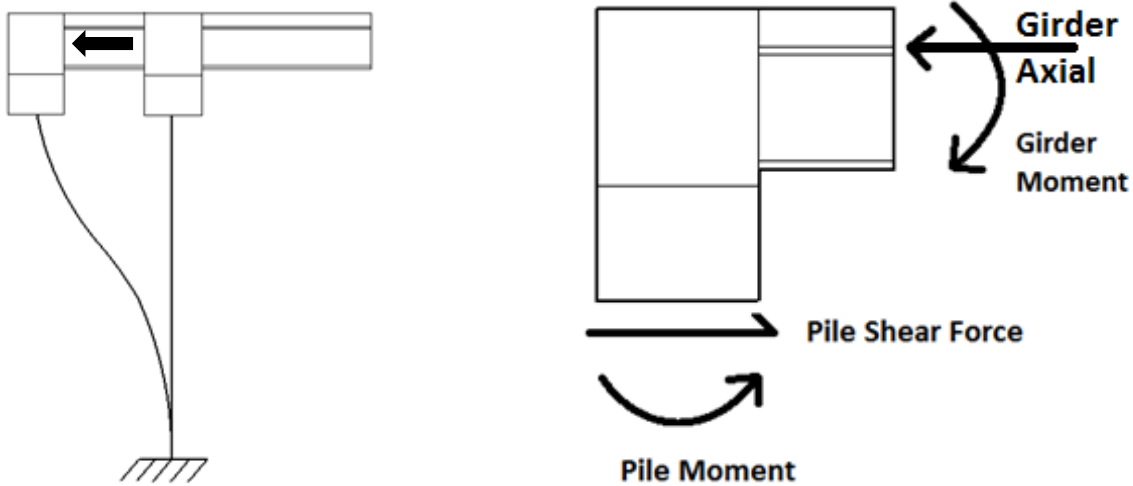
Figure 58. Thermal expansion and free body diagram

The intent of this loading is to first examine the durability of the precast/cold joint through measuring the crack width that develops under the service loading condition. The vertical load in the laboratory was capable of applying a force of 400 kips, which is an applied moment of 2,000 kip-ft, measured from the load to the center of the abutment. This load significantly exceeds the stresses that are expected to be developed in the service loading condition and the maximum possible stresses that can be developed given the relative strength of the foundation piling. In addition, this loading scenario was utilized in the prediction of the failure mechanism of the integral abutment detail. The resulting information can be used to determine an accurate factor of safety in the details, as well as a range in the types of foundation piling that can be used in conjunction with the detail.

5.2 Instrumentation

To measure the durability of the specimens, the cold/precast joint between the pile cap and integral diaphragm was instrumented with displacement transducers. The displacement transducers were placed on the front side of the abutment during the horizontal loading and on the back face of the abutment during the vertical loading. The transducers measured the width of the crack that developed on the tension face of the abutment in order to compare this information for the various specimens. Additional displacement transducers were placed on the rear side of the abutment during horizontal loading to measure the horizontal slip between the pile cap and integral diaphragm. The locations of the vertical displacement transducers are represented by squares and the horizontal displacement transducers are represented by pentagons in Figures 59, 60, and 61 for the different specimens and loading cases.
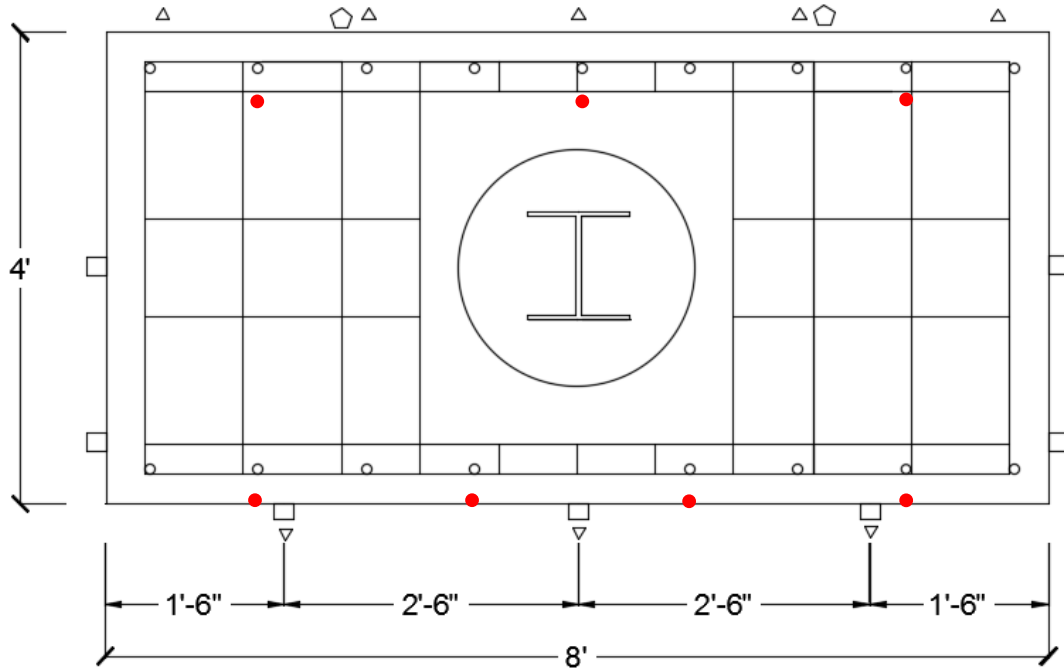
Figure 59. Plan view for horizontal loading, all specimens
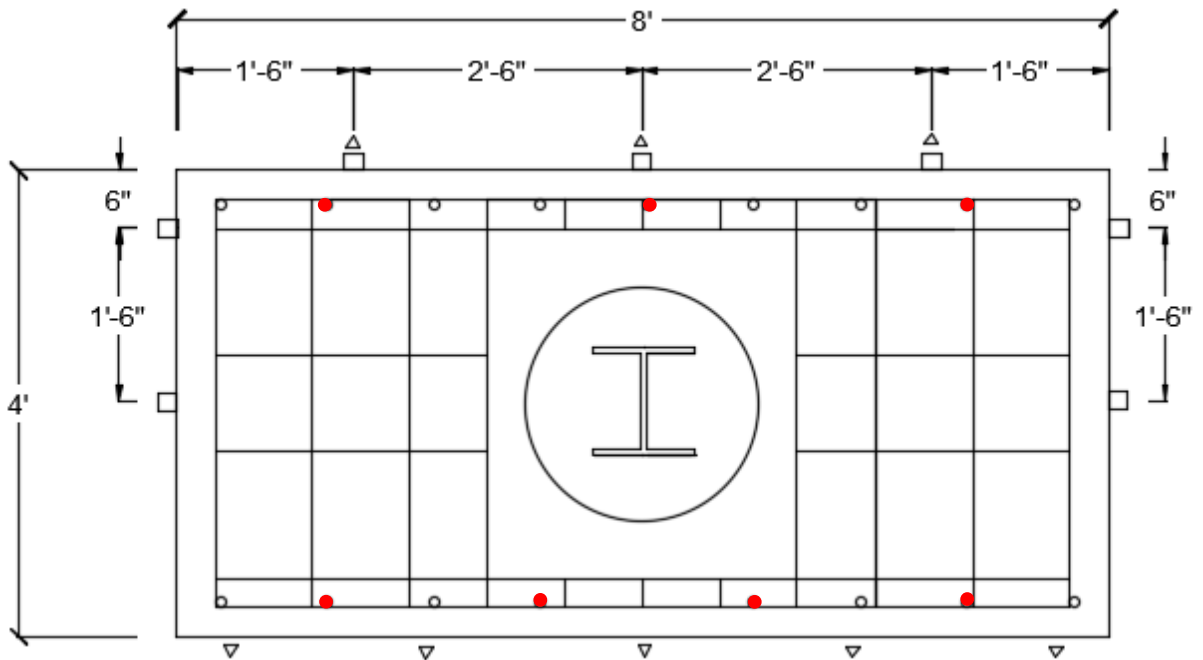
Figure 60. Grouted coupler and cast-in-place instrumentation plan view for vertical loading
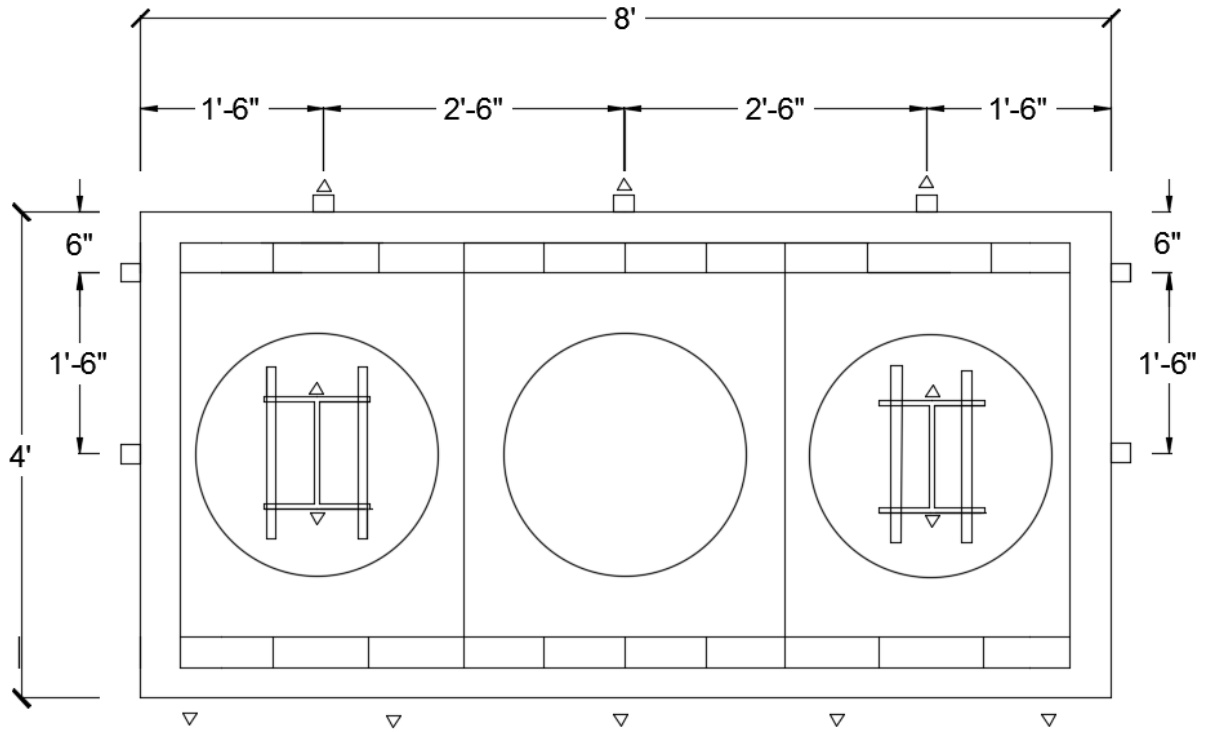
Figure 61. Pile coupler instrumentation plan view for vertical loading

Images of the typical instrumentation setup are shown for the horizontal loading test in Figures 62 and 63.

Figure 62. Front face of the abutment during horizontal loading
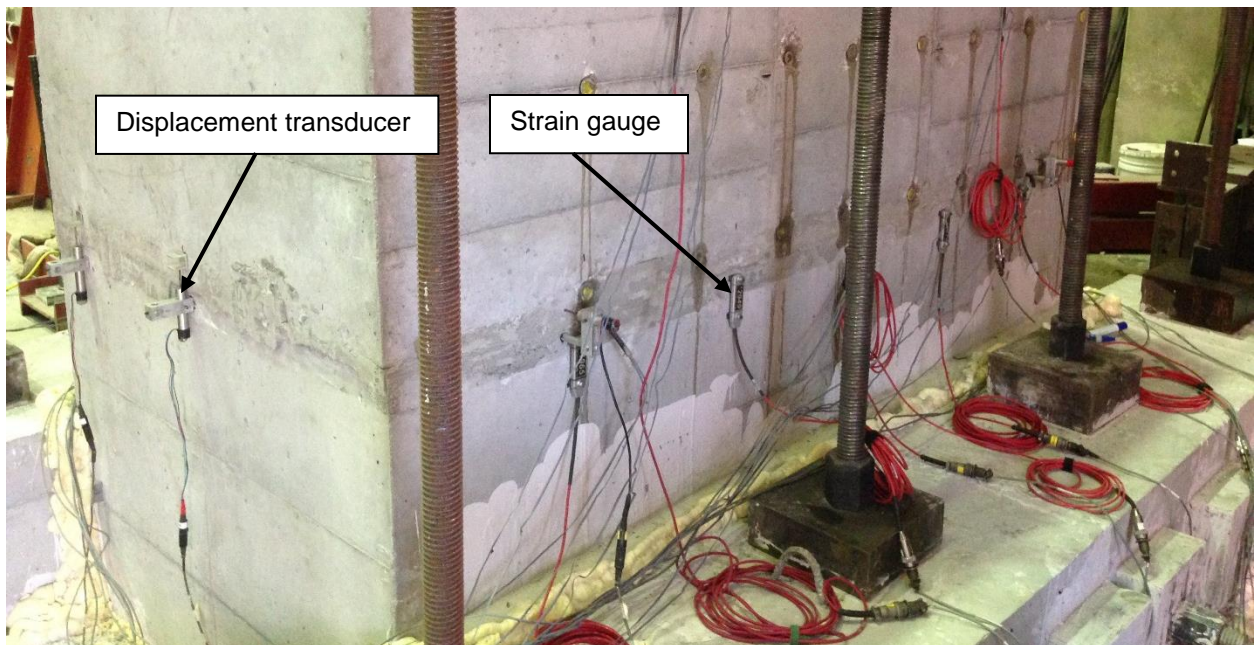
Figure 63. Rear face of abutment for horizontal loading

To measure the strength of the specimens, strain transducers were placed on the tension and compression faces of the abutment 2 inches below the joint. The locations of these gauges on the specimen for the different loading cases are illustrated in Figures 59, 60, and 61. The gauges are also pictured in the horizontal loading test in Figures 62 and 63. On the vertical "8g1" steel

reinforcing bars that connect the pile cap to the integral diaphragm, sacrificial strain gauges were installed on the bars prior to casting the specimen. Two strain gauges were placed on each steel reinforcing bar, one 4 inches below the joint and the second 18 inches above the joint, which was directly above the grouted couplers. To measure the development in strength of the HP section used to splice the pile coupler specimen, three strain gauges were placed on each flange as shown in Figure 64.
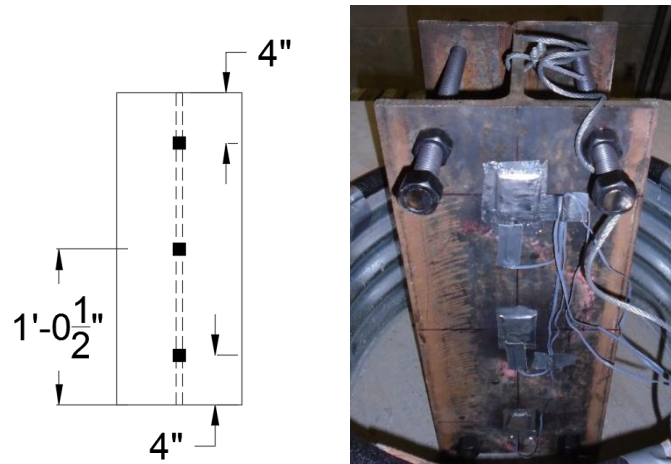
Figure 64. HP instrumentation

The use of the concrete and reinforcing steel strain gauges allows study of the failure mechanisms of the abutments tested. This information allows for the strength of the ABC specimens and the standard integral abutment design to be compared as well as allows for comment on the relative strengh of the abutment in comparison to the foundation piling.

Additional displacement instrumentation using string pods to measure the displacements between the specimen and the laboratory floor was used. This instrumentation was used to evaluate the tie down system used to restrain the specimen by measuring the slip and calculating the rotation of the specimen. In the examination of this information, no significant rotations or slip were found to have occurred during the testing of any of the three specimens.

5.3 Results

To summarize the results from the instrumentation placed on the laboratory specimen, a numbering system was created as shown in Figures 65 and 66.
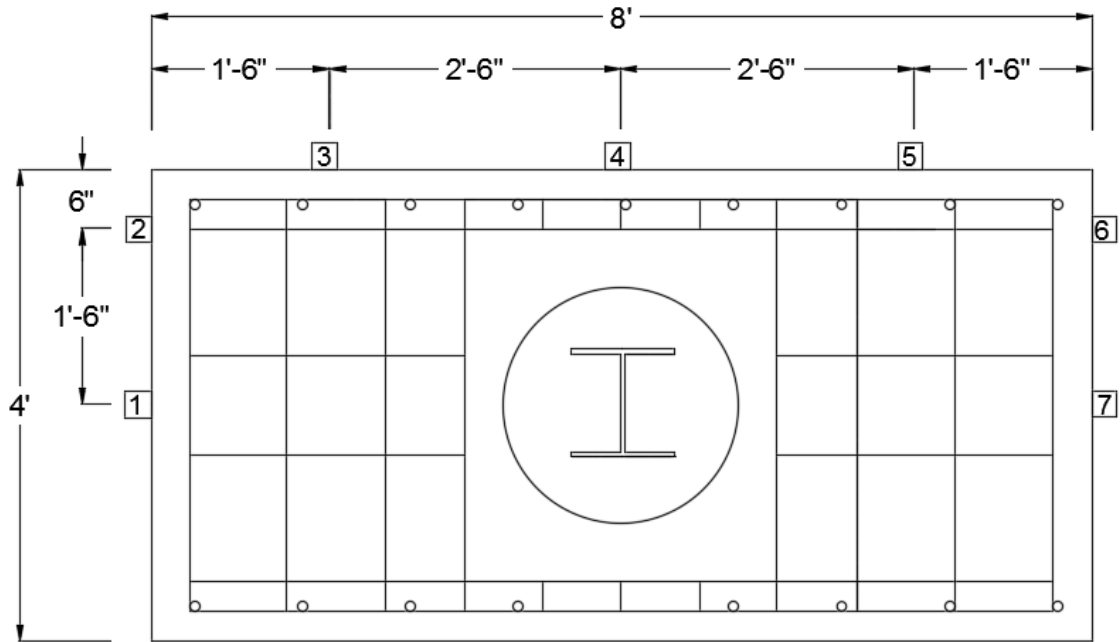
Figure 65. Displacement transducer numbering
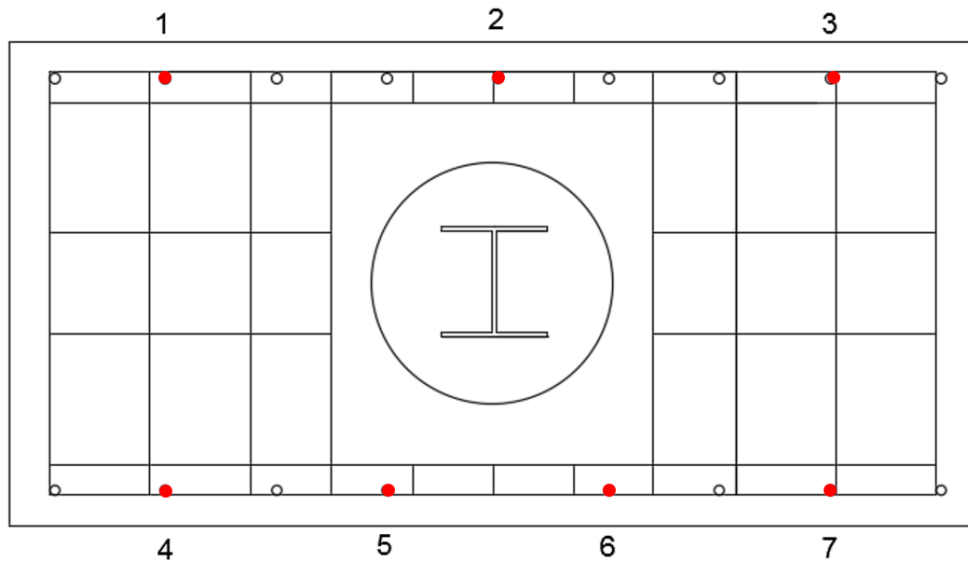
Figure 66. Reinforcing bar strain gauge numbering

The displacement transducers that measured the crack width were numbered. This numbering was used for both the vertical and horizontal testing, where the transducers were on the tension side of the abutment. In Figure 66, the strain gauges present on the vertical reinforcing steel in the cast-in-place and grouted reinforcing bar coupler specimen have been labeled as well.

5.3.1 Cast in Place

First, a horizontal load of 100 kips was applied to the cast-in-place specimen. This loading resulted in no significant signs of distress; only a minor crack that opened at the cold joint measuring 0.001 inches wide was observed. In Figure 67, the width of the crack that developed between the pile cap and diaphragm at various locations is plotted against the applied moment.
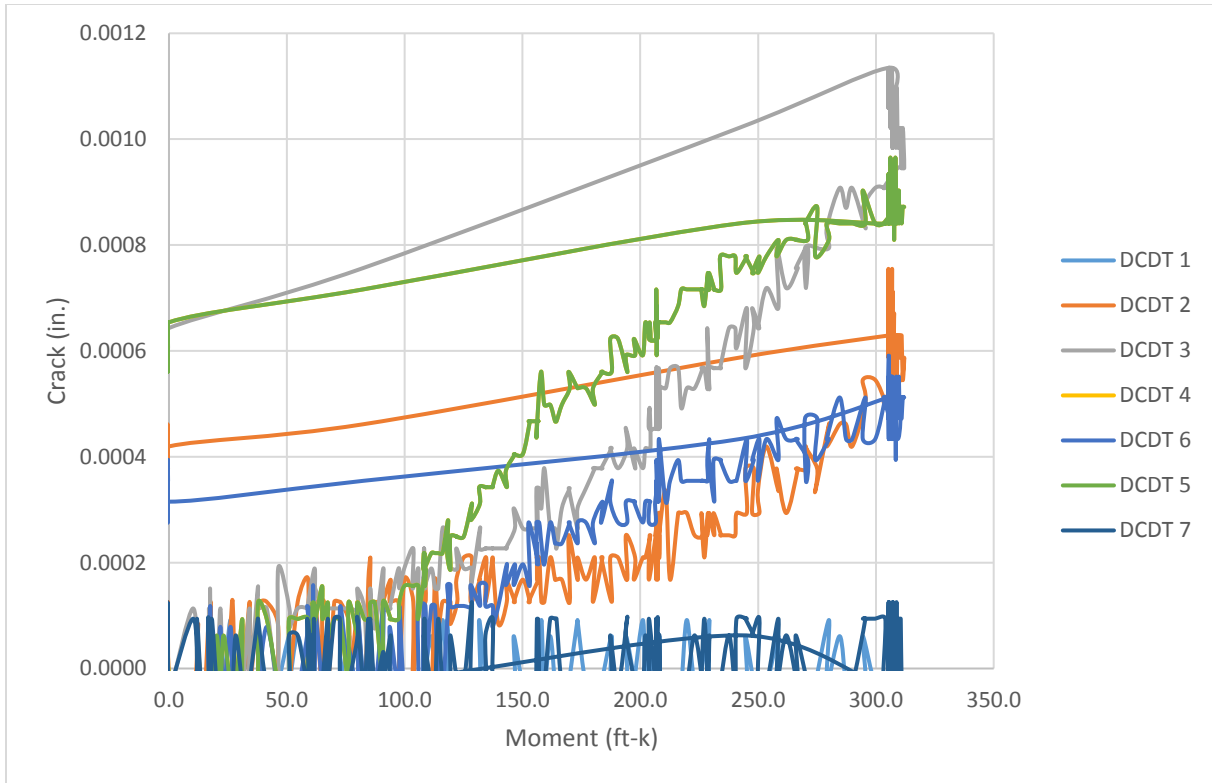
Figure 67. Crack versus applied moment from horizontal load

The applied moment is calculated by multiplying the load by the vertical distance from the load to the joint between the pile cap and diaphragm. The cast-in-place specimen had a maximum crack opening of 0.001 inches at an applied moment of approximately 310 ft-k and experienced no horizontal slip between the pile cap and integral diaphragm during the test.

Next, the vertical load was applied up to approximately 385 kips. The specimen showed no visible signs of distress at this point other than the crack that developed at the cold joint, which reached a maximum width of 0.025 inches at a peak moment of approximately 1,800 ft-k. The crack width versus applied moment is plotted in Figure 68, where the moment is calculated by multiplying the load by the horizontal distance to the center of the integral diaphragm/pile cap.
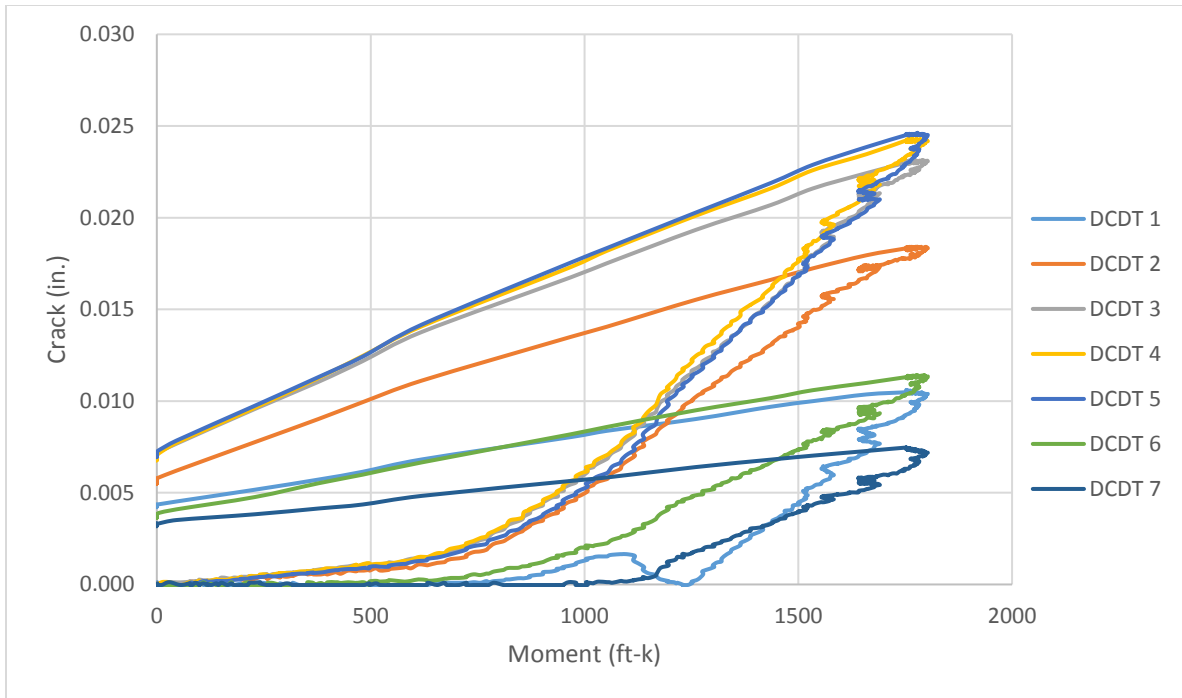
Figure 68. Crack width versus moment from vertical load

The maximum stress measured in the vertical reinforcing steel connecting the pile cap to the diaphragm was 42 ksi. Since the specimen was still in the linear elastic range, the reinforcing steel would not have yielded until an applied vertical load of 550 kips, corresponding to an applied moment of 2,590 ft-k (Figure 69). According to the strain measurements in the concrete, the failure would have been ductile in accordance with *AASHTO LRFD Bridge Design Specifications* (AASHTO 2012). The strains recorded in the strain gauge located 18 inches above the construction joint were low, as the section remained uncracked at this location throughout the testing.
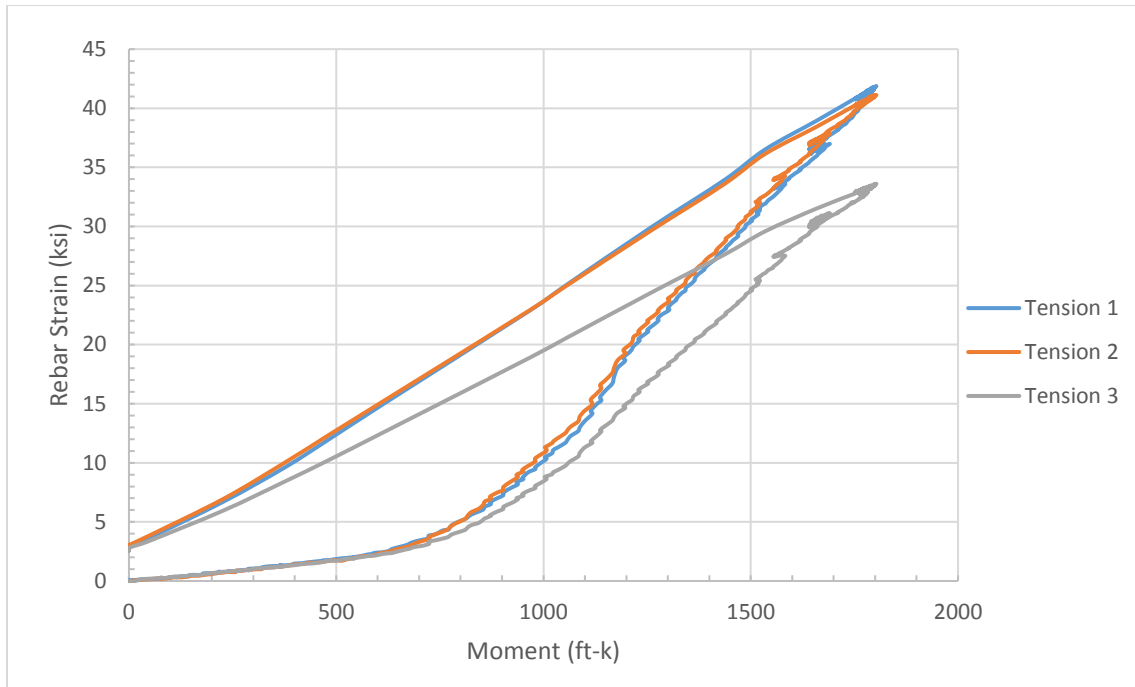
Figure 69. Tension reinforcing bar stress versus moment from vertical load

5.3.2 Grouted Reinforcing Bar Coupler

The grouted reinforcing bar coupler specimen was loaded horizontally up to 100 kips, at which point the maximum crack width on the front side of the specimen was 0.001 inches (Figure 70), which indicates a performance nearly identical to that of the cast-in-place specimen (0.001 inches).
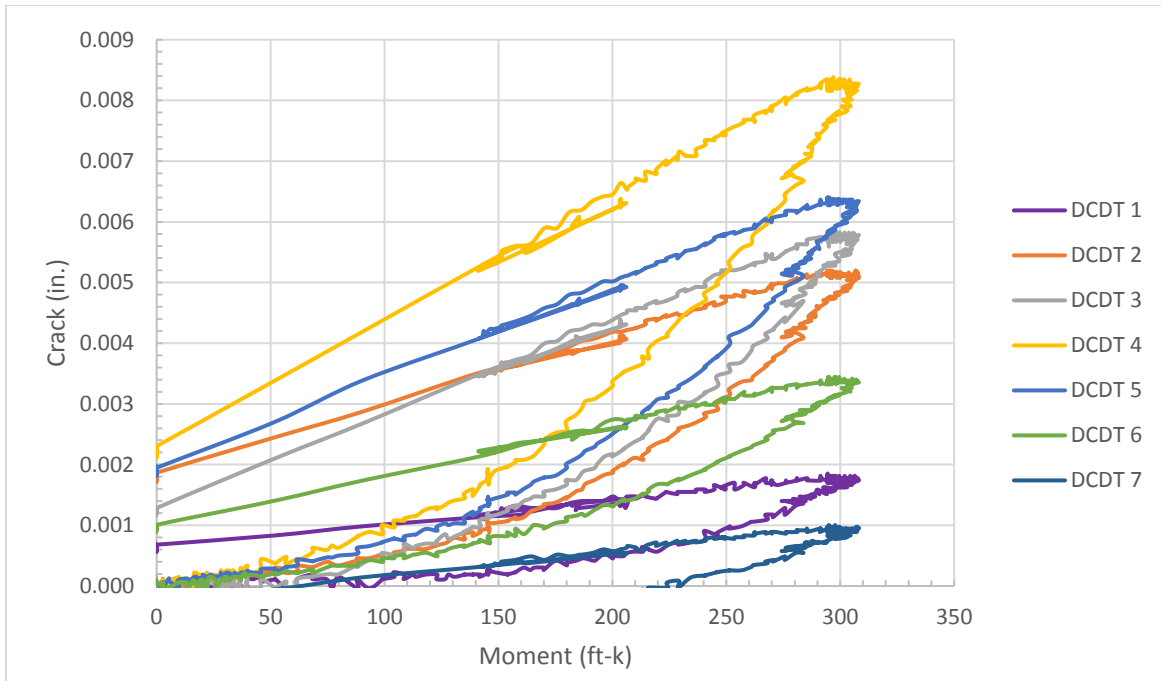
Figure 70. Crack width versus moment from horizontal load

Again, no horizontal slip was measured between the pile cap and the integral diaphragm. The vertical load placed on the specimen peaked at 338 kips, at which point the reaction frame used on this specimen unexpectedly reached capacity, resulting in a maximum applied moment of 1,550 ft-k. The maximum crack width versus applied moment for the vertical loading is shown in Figure 71, which shows a maximum value of 0.035 inches. The crack is pictured in Figure 72.
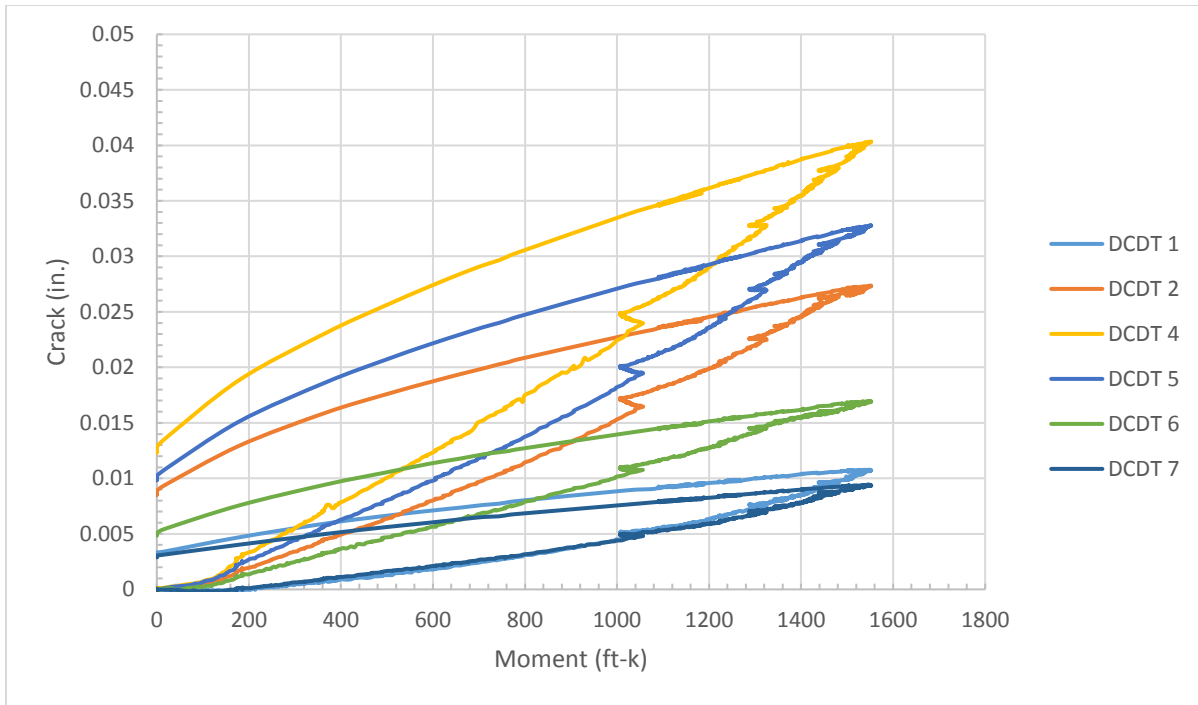
Figure 71. Crack width versus moment from vertical load

Figure 72. Crack between grout bed and diaphragm

This value was larger than the crack that developed on the cast-in-place specimen, having a value of 0.020 inches measured at the same applied moment of 1,550 ft-k.

The tensile stress in the reinforcing steel and the applied moment are plotted in Figure 73. As can be observed, the measurement reached a maximum stress of 43 ksi.
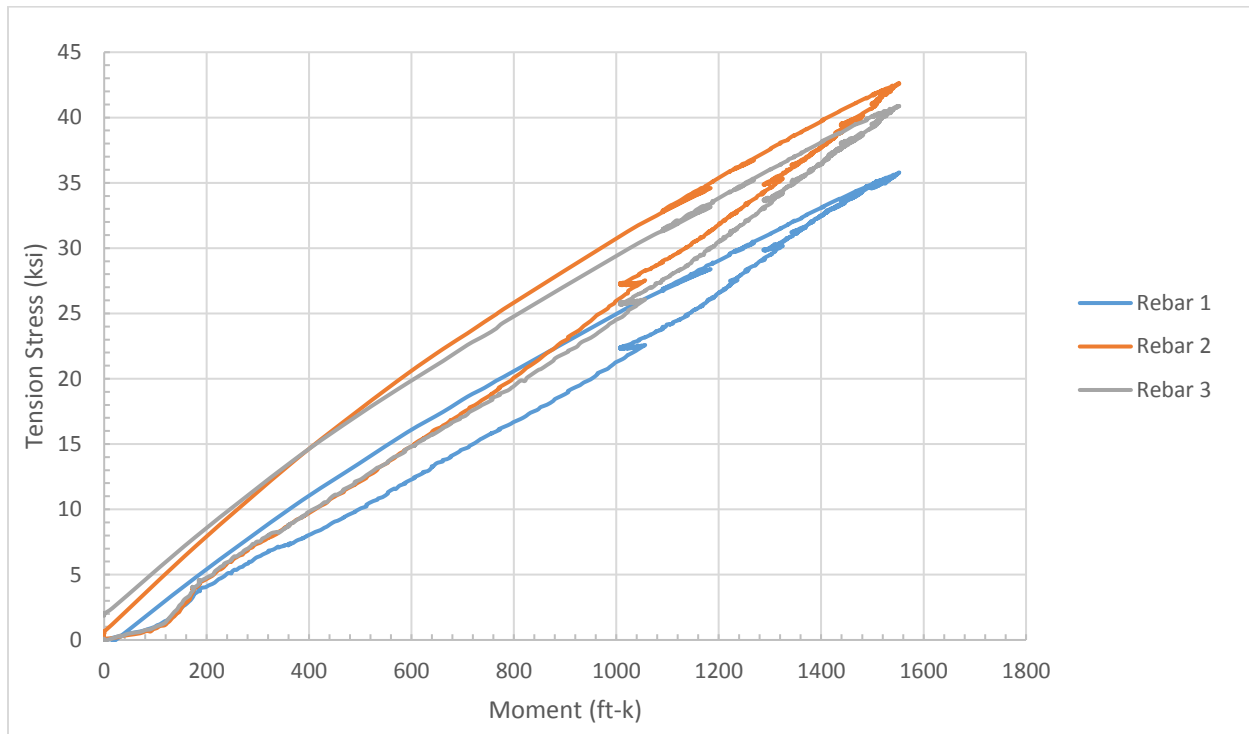
Figure 73. Tension reinforcing bar stress versus moment from vertical load

Extrapolating the data within the linear elastic range, the vertical reinforcing steel in the specimen would yield at an applied moment of 2,180 ft-k, which is 17% less than the yield point in the cast-in-place specimen. The point at which cracking first occurred in the grouted coupler specimen was also earlier than that of the cast-in-place specimen, which occurred at an applied moment of approximately 180 ft-kip versus 700 ft-kip, respectively. The reduced strength of the grouted reinforcing bar coupler specimen is most likely due to several factors. The first factor is that two of the grouted reinforcing bar couplers experienced a grouting failure during construction of the abutment; thus, these bars were not contributing to the behavior. There was also a decrease in the distance between the compression and tension force couple within the section as a result of the increased concrete cover demand for the grouted couplers. Lastly, the bond strength between the grout bed and the precast element was lower than the bond strength of the cold joint in the cast-in-place specimen.

5.3.3 Pile Coupler

The pile coupler specimen was also loaded to 100 kips in the horizontal load case, and the maximum crack that occurred at the front of the precast joint was 0.050 inches (Figure 74).
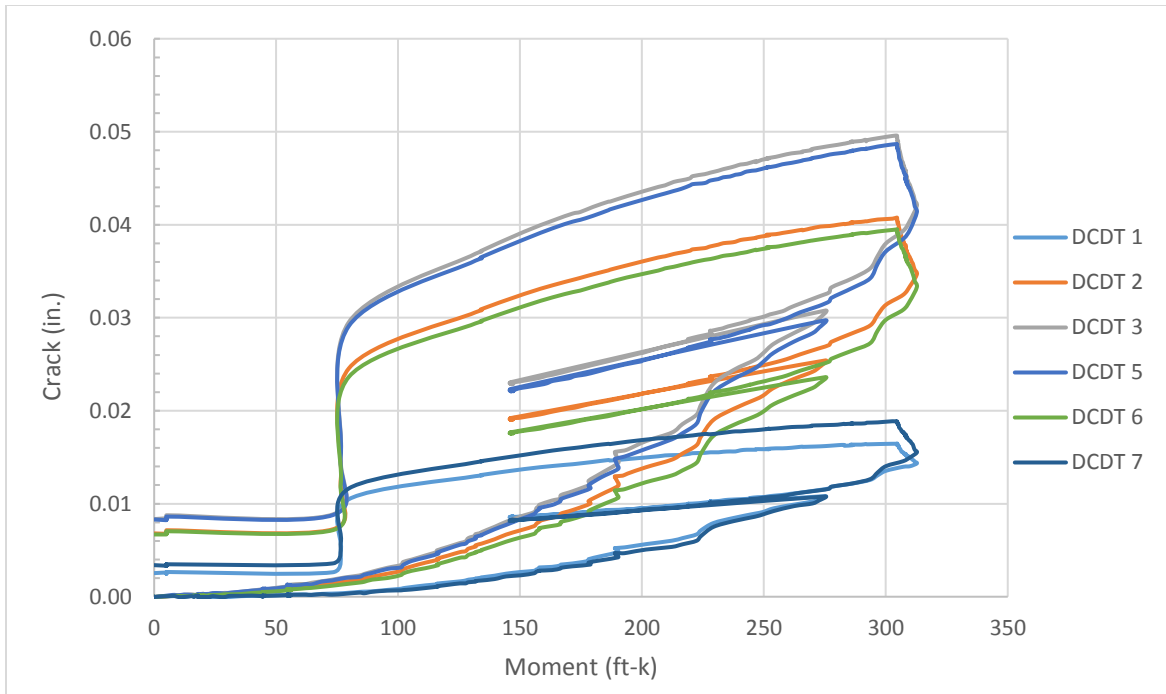
Figure 74. Crack versus moment from horizontal load

This crack width is significantly greater than the crack width measured in the cast-in-place specimen of 0.0011 inches. The vertical loading of this specimen reached the ultimate strength of the detail at an applied moment of 1,124 ft-k (Figure 75).
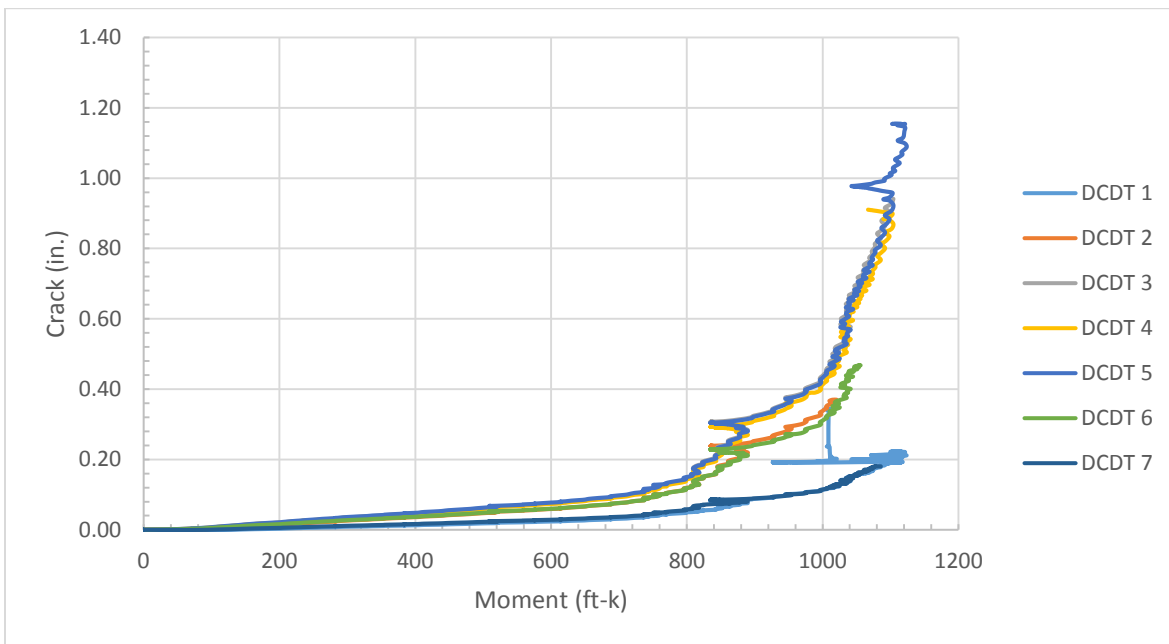
Figure 75. Crack width versus moment from vertical load

The joint opening on the rear face of the specimen became so large that the displacement transducers were out of range. At the ultimate load applied to the specimen, the crack width between the pile cap and integral diaphragm was measured to be 1.75 inches.

Cracking in the integral diaphragm became prominent at an applied bending moment of approximately 800 ft-kips and is shown at the maximum load applied in Figures 76 and 77.

Figure 76. Pile coupler damaged west side

Figure 77. Pile coupler damaged east side

The vertical crack on the integral diaphragm is at the centerline of the CMP, and the horizontal cracks correspond to the top and bottom of the CMP used to create the pile coupler voids in the pile cap and diaphragm.

Most likely some amount of slip occurring between the HP section and the grout, as well as between the CMP and the grout/concrete, allowed for the initial crack between the pile cap and integral diaphragm to develop. Once the concrete in the integral diaphragm began to crack, which occurred at around 800 ft-k (Figure 75), the opening at the precast joint began to significantly increase. At this point, large amounts of rotation and cracking began to develop within the abutment until ultimate failure occurred.

The maximum stress captured by the gauges attached to the HP section was 26 ksi, indicating that yielding of the HP section was likely not a failure mechanism of the detail. The failure mechanism between the pile coupler/CMP/concrete within the detail is unknown. An attempt was made to jackhammer through the cracked concrete to investigate the failure mechanism; however, no definitive conclusions could be made. Jackhammering exposed the CMP (Figures 78 and 79) and showed that slip had occurred between the CMP and the concrete in the diaphragm, as well as that the grout had failed in tension within the CMP.

Figure 78. Pile coupler deconstruction

Figure 79. Deconstruction up close

Examining the image in Figure 77, deformation within the integral diaphragm is noticeable as a result of the large crack that developed within the section.

This reveals that a less than ideal amount or distribution of reinforcing steel was present within the abutment to resist the tension stresses developed by the pile coupler mechanism.

5.3.4 Foundation Pile Strength

To design an integral abutment, the connection between the pile cap and the integral diaphragm is designed to be stronger in shear and flexure than the driven foundation piling. Thus, the plastic moment capacity of the foundation piling limits the flexural stresses that can be developed in the abutment. This laboratory investigation did not include foundation piles in the testing; however, it is important to understand the performance of the abutment relative to the system in which it will be used in the field. In Figures 80 and Figure 81, the plastic moment capacity of two foundation H-pile sections of various sizes are plotted along the x-axis, which represents the applied moment.
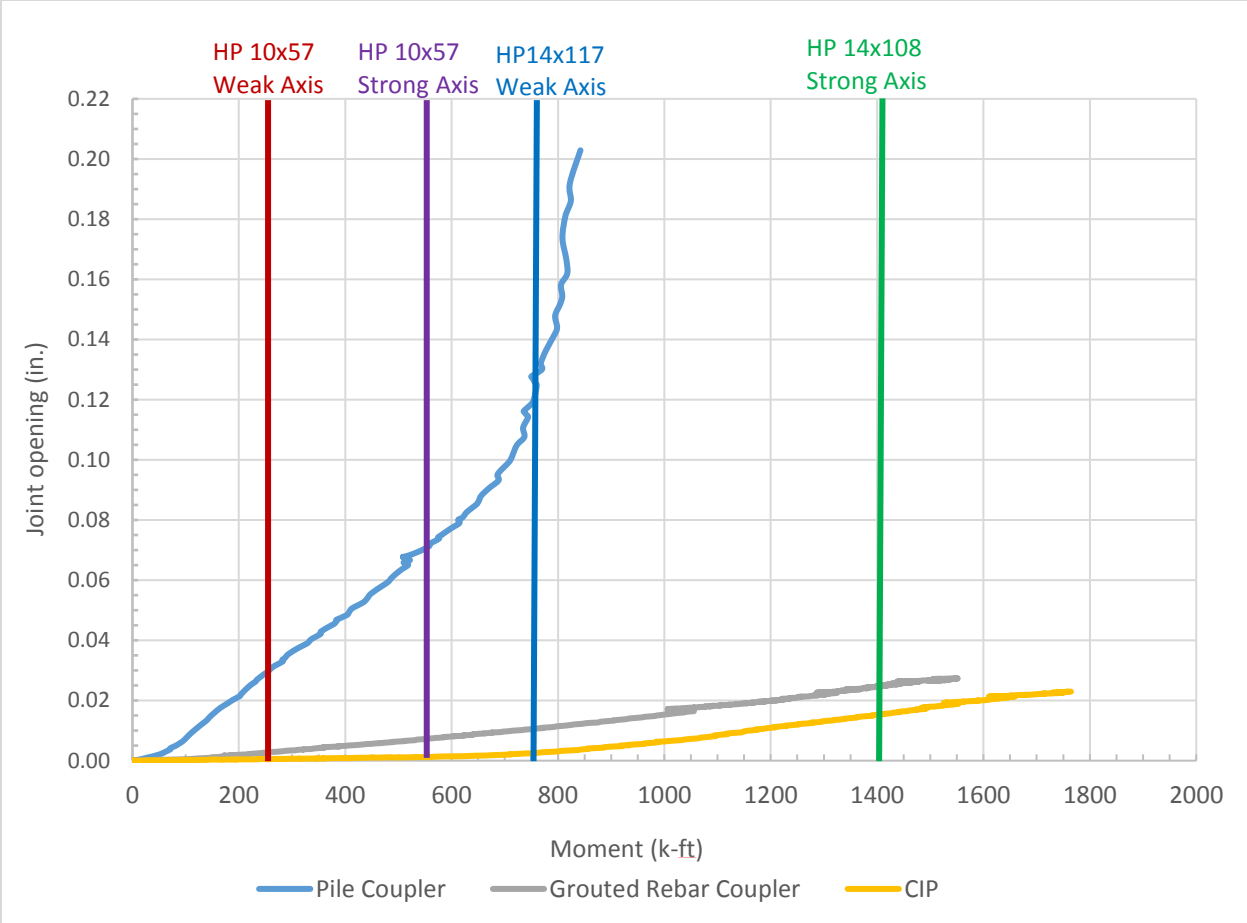
Figure 80. Foundation pile strength (two piles) versus abutment joint opening
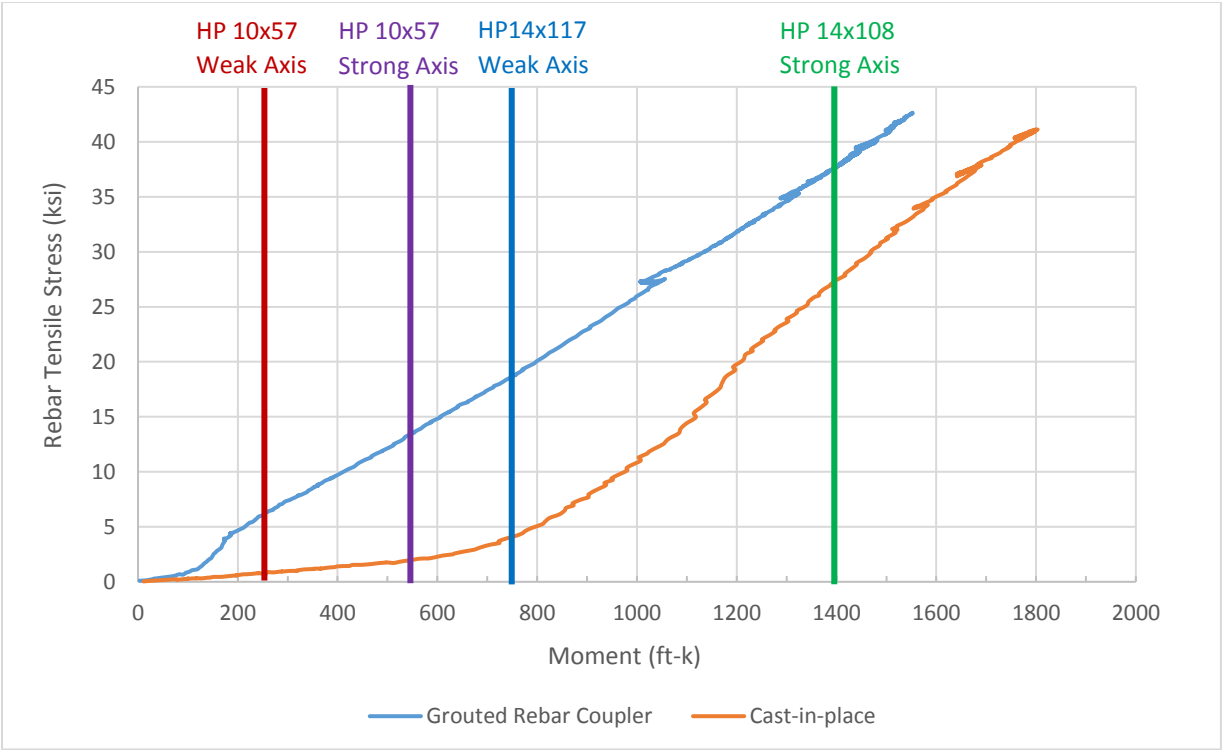
Figure 81. Foundation pile strength (two piles) versus abutment reinforcing bar stress

Along the y-axis in Figure 80, and in the accompanying Table 1, the crack width at the cold/precast joints in all three specimens were plotted to illustrate durability as a measurement of the joint opening.

Table 1. Foundation pile strength (two piles) versus abutment joint opening

	Joint opening at pile yield (inches)			
Specimen	**HP 10x57 weak axis (252 ft-k)**	**HP 10x57 strong axis (554 ft-k)**	**HP 14x117 weak axis (762 ft-k)**	**HP 14x102 strong axis (1408 ft-k)**
Cast-in-place	0.000	0.001	0.003	0.015
Grouted reinforcing bar coupler	0.004	0.011	0.016	0.035
Pile coupler	0.028	0.069	0.127	N/A

In Figure 81 and in the accompanying Table 2, the tensile stress in the center reinforcing steel is plotted along the y-axis to illustrate the strength of the detail.

Table 2. Foundation pile strength (two piles) versus abutment reinforcing bar stress

Specimen	Stress in reinforcing bar (ksi)			
	HP 10x57 weak axis (252 ft-k)	HP 10x57 strong axis (554 ft-k)	HP 14x117 weak axis (762 ft-k)	HP 14x102 strong axis (1408 ft-k)
Cast-in-place	0.1	2.1	4.4	27.9
Grouted reinforcing bar coupler	6.4	13.6	18.8	37.9

The plastic moment capacity for two piles is plotted because the laboratory specimen was 8 feet in width and a pile spacing of 4 feet was chosen to make this comparison.

The crack width of the cold/precast joints for the cast-in-place specimen and grouted coupler specimen were both relatively low in magnitude. The grouted reinforcing bar coupler detail experienced a wider crack width than the cast-in-place specimen due to several factors, including bond strength between the grout bed and precast element, incomplete grouting of two couplers, and increased concrete cover for the reinforcing steel. Engineering judgment is required to determine tolerable crack widths in concrete structures based on many factors. These factors are climate, soil type, length of the bridge, and type of foundation pile, all of which vary greatly from agency to agency. Examining these factors will play a role in the engineering judgment used to select joint protection, amount of concrete cover, and type of corrosion-resistant bar in order to establish a service life for the structure. Additionally, the crack widths presented in this report are after one loading of the abutment. These values are expected to increase over many cycles of loading and as deterioration starts to occur.

While the strength of the grouted reinforcing bar coupler specimen was also slightly less than that of the cast-in-place specimen, it is clear that both details satisfy the design philosophies stated in this report. The relative strength of the cast-in-place specimen and grouted reinforcing bar coupler detail in comparison to the foundation piling suggest that a smaller abutment could be used to satisfy the design. This reduction in weight or number of spliced connections is advantageous to the constructability of the detail, which is often a driving factor in ABC. Further investigations and calculations, which will likely vary greatly based on the individual needs of a particular agency, are needed to support this claim. However, a reduction in the overall strength of the design will likely increase the crack width between the pile cap and integral diaphragm, which may already be governing the design.

CHAPTER 7. SUMMARY

Integral abutments have rarely been used in ABC because they are often large and heavy and have complex reinforcing details. These aspects make the integral abutment difficult to precast because of weight and construction tolerances. As a result, integral abutments constructed for ABC projects have typically relied on cast-in-place closure pours. However, there are certain benefits to precasting the abutment, as material closure pours add significant cost to the project and add curing time to the project schedule.

In order to investigate precast integral abutments, two details were designed, constructed, and tested in the structures laboratory. The two ABC details investigated in this research spliced the integral abutment at the typical construction joint between the pile cap and integral diaphragm.

The first detail, called the grouted reinforcing bar coupler, utilized grouted reinforcing splice couplers to splice the vertical reinforcing steel that passed through the precast joint. The second detail, called the pile coupler, utilized a 2 foot section of steel H-pile and a grouted void to create the spliced connection. In addition to these ABC details, a cast-in-place specimen was constructed and tested in order to establish baseline performances for the integral abutment design. The integral abutments were evaluated and compared on three criteria: constructability, strength, and durability, which were seen as critical to the needs and implementation of the details in ABC projects.

Prior to constructing the grouted reinforcing bar coupler specimen, previous research, and also engineers on the TAC, expressed concern for the tight construction tolerances that arise when using grouted reinforcing bar couplers.

The grouted coupler specimen in the laboratory was 8 feet wide and had 17 reinforcing steel bars that required splicing in order to make the precast connection. Through the use of a plywood template, the locations of the 17 steel bars on the pile cap were marked and transferred to the base of the integral diaphragm formwork. Form plugs were installed into the template, which held the grouted reinforcing bar couplers in place during the construction of the integral diaphragm, effectively "match casting" the two elements.

This technique proved to be simple and cost effective and resulted in the successful alignment of 17 couplers and steel bars in the laboratory. Constructing and erecting a precast element system in the field that requires alignment on one end should not pose a challenge to a prefabricator/contractor team. Significant complications arise in constructability when a precast element requires alignment on two ends; placement of the pile caps and grouted couplers within the integral diaphragm would likely need to be exact.

The strength and durability of the grouted reinforcing bar coupler specimen is comparable to that of the cast-in-place specimen. The crack width that developed at the precast joint in the grouted reinforcing bar coupler was 0.035 inches, compared to 0.019 inches in the cast-in-place

specimen. Additionally, the yield strength of the grouted reinforcing bar coupler detail was estimated to be 17% lower than that of the cast-in-place detail.

These reductions in performance are likely due to three factors: grouting failures within the coupler, reduced internal moment arm, and a lower tensile strength between the grout bed and the concrete. Even with this reduction, the performance of the grouted reinforcing bar coupler should not be evaluated entirely based on the maximum load applied in the laboratory. Rather, the performance should be based on the maximum stresses that could be developed by the foundation piling used in a design.

While the detail's strength likely satisfies the conditions met by even the stiffest of foundation piles, the durability or maximum tolerable crack width of the detail will likely be controlled. While the crack widths developed under load will satisfy some, there is no definitive conclusion to be made because a variety of factors come into play: climate, soil type, type of corrosion-resistant reinforcing, joint protection, design service life, and use of de-icing salts. For some scenarios, the performance of the grouted coupler detail will be more than adequate. For these scenarios, further investigations in the reduction of weight or amount of spliced reinforcing should be made to facilitate the needs of ABC projects.

The pile coupler detail attempted to create an integral abutment that facilitates the construction and erection of a full slide-in bridge. This detail aimed to reduce the number of grouted connections between the pile cap and the integral diaphragm while also eliminating any protruding reinforcement in the pile cap that obstructs the sliding process. The grouted pile connections had a spacing of 4 feet in the spliced abutment, which drastically reduced the number of connections required compared to the grouted reinforcing bar coupler detail. Construction of the pile coupler proved to facilitate the needs of ABC, at least on a small scale, because the process of lowering two piles and grouting the connections was fast and simple.

While the pile coupler detail is promising in terms of constructability, the performance in strength and durability was less than ideal. The ultimate strength and durability of this detail was significantly less than that of the cast-in-place specimen and grouted reinforcing bar coupler detail. The laboratory specimen experienced significant cracking within the integral diaphragm and pile cap, indicating a poor distribution of reinforcing steel to resist the stresses developed by the HP coupling system. The exact failure mechanism of this detail in the laboratory is unknown; however, after the testing several improvements became apparent.

These improvements are using a longer length of pile, increasing the number of threaded rods/shear studs on the pile, increasing/modifying the amount of reinforcing steel in the abutment, and using two pile couplers acting as a force couple. In addition to these improvements, taking a different route and utilizing the pile coupler as a hinge may be a better design alternative. Instead of a pile, a thin rod could be used to allow the superstructure to rotate without inducing large stresses in the abutment, while the successful lowering and grouting mechanism would be preserved.

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