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Synthesis of Precast Bridge Column Designs

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16. Abstract

Bridge prefabrication minimizes on-site operations and closure times, and can also contribute to improving the quality and durability of bridge elements as well as reducing the environmental impact of bridge construction. To date, bridge prefabrication has mainly focused on superstructure elements. The use of prefabricated substructure elements can also help speed up the construction process and prevent lane closures. This synthesis project has evaluated the state of the art of national research and construction projects involving precast columns for bridges. The primary objectives of this project were to (a) review and synthesize published literature and current DOT practice on precast columns, (b) compile lessons learned from previous projects and studies, (c) evaluate the suitability of existing precast column solutions, and (d) determine criteria for the selection of precast columns over conventional cast-in-place solutions for Texas bridges. The state-of-the-art review has identified a variety of precast column systems that have already been used in 18 states. These systems can be classified as full-height precast columns, precast segmental columns, and precast shells. The review has also identified a variety of connection details, including grouted ducts, grouted splice couplers, post-tensioned joints, socket connection, and pocket connections. The column systems and connection details have been evaluated by considering aspects such as fabrication, construction and durability, and recommendations for their implementation have been provided.

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Chapter 1. Introduction

1.1. Introduction and Scope

Interest is increasing in accelerated bridge construction (ABC) as a means to reduce construction time and minimize traffic disruptions in bridge projects. Implementation of ABC generally involves the use of prefabricated bridge elements and systems, which are fabricated off-site to minimize on-site operations and closure times. In addition to speeding up the construction process and reducing traffic disruptions, bridge prefabrication can also contribute to improving the quality and durability of bridge elements and reducing the environmental impact of construction.

To date, bridge prefabrication has mainly focused on superstructure elements. Steel girders and precast prestressed concrete girders have been commonly used for many years in bridge construction. The use of partial-depth precast deck panels is also common nowadays in Texas and other states. Full-depth precast deck panels have also been used in some states. Such elements can be combined to create modular superstructure systems that allow the completion of the superstructure in less than two days or in overnights shifts. With the increasing needs of the industry to accelerate construction and minimize traffic disruptions, important advances have been made also in the use of precast elements in bridge substructures. In the last two decades, a significant number of bridges have been constructed in Texas using precast bent caps. To date, prefabrication of bridge columns has been very limited as compared to bridge superstructures and bent caps. Nevertheless, some states have started to develop and implement design concepts for precast concrete columns.

This synthesis project has evaluated the state of the art of national research and construction projects involving precast columns for bridges. The primary objectives of this project were to (a) review and synthesize published literature and current department of transportation (DOT) practice on precast columns, (b) compile lessons learned from previous projects and studies, (c) evaluate the suitability of existing precast column solutions for Texas bridges, and (d) determine criteria for the selection of precast columns over conventional cast-in-place (CIP) solutions for Texas bridges.

1.2. Organization of Report

This report is organized in the following chapters:

Chapter 2 presents a review of published literature on precast bridge columns. This review includes precast column systems proposed in previous research studies, existing guidelines for design and construction of precast columns, and bridge projects involving precast columns reported in the literature.

Chapter 3 summarizes the results of a survey with 39 state DOTs to identify and understand their current experience with precast bridge columns.

Chapter 4 presents a synthesis and evaluation of existing precast column systems based on the findings of the literature review and the survey of DOT practice, as well as feedback from industry experts. This chapter also presents general criteria for selecting precast columns over CIP columns.

Chapter 5 summarizes the main finding of this synthesis project and provides recommendations for future implementation and research on precast columns.

Supplementary information about the survey of DOT practice is presented in Appendices A and B.

Chapter 2. Review of Published Literature

This chapter presents a review of published literature related to national research and practice on the use of precast bridge concrete columns. This review includes precast column systems proposed in previous research studies (Section 2.1), guidelines for design and construction of precast columns developed by professional organizations and transportation agencies (Section 2.2), and bridge projects with precast columns reported in the literature (Section 2.3).

2.1. Review of Precast Column Systems Proposed in Research Studies

This section presents a literature review of precast column systems proposed in previous research studies. The description of the column systems is organized by research study, with the studies presented by state in alphabetical order. Research projects sponsored by the Federal Highway Administration (FHWA) are also presented at the end. Although the use of seismic column designs is not justified for Texas, the review includes a number of systems developed for seismic regions because they can provide details and lessons learned which are useful for precast columns in non-seismic applications.

2.1.1. Prefabricated Precast Concrete Bridge System for the State of Alabama (Fouad et al. 2006 - Alabama)

A research study conducted by Fouad et al. (2006) for the Alabama Department of Transportation proposed a prefabricated precast concrete bridge system for short- to medium-span bridges. This system includes bulb-tee girders, rectangular voided bent caps, rectangular hollow columns (see Figure 2-1), and precast abutment caps. A one-piece rectangular hollow precast column was selected for its simplicity and functionality. The use of a hollow section limits the weight of the column and facilitates construction processes. Four different column dimensions are considered in this system, as shown in Figure 2-2. All columns satisfy a maximum weight criterion of 100,000 pounds, and a maximum column slenderness ratio, defined by equation Eq. 2.1, of 100.

$$\frac{(KxL)}{r} \leq 100 \qquad \text{Eq. (2.1)}$$

where L is the length of the column, r is the radius of gyration determined as $r = 0.3xW$, where W is the width of the column, and K is the effective length factor (assumed to be 2.0 considering fixed end-free end condition).

The proposed precast column system uses concrete with a specified compressive strength of 6,000 psi at 28 days. A proprietary mechanical coupling system, which is the Nisso Master Builders (NMB) splice sleeve system, is recommended to connect the column bars with the dowels extending from the footing. After the columns are erected, sleeves are grouted with a non-shrink grout, meeting the requirements set by the American Association of State Highway and Transportation Officials (AASHTO). The column is connected to the bent cap in a similar manner. Figure 2-3 shows the connection details at the bottom and the top of the precast column. In order to reduce cracking in the column, the column's entire length is pretensioned. Also, chamfering of column corners is recommended to avoid breaking and chipping of those corners during transportation and erection. The report by Fouad et al. (2006) includes a design example for the proposed precast column system.

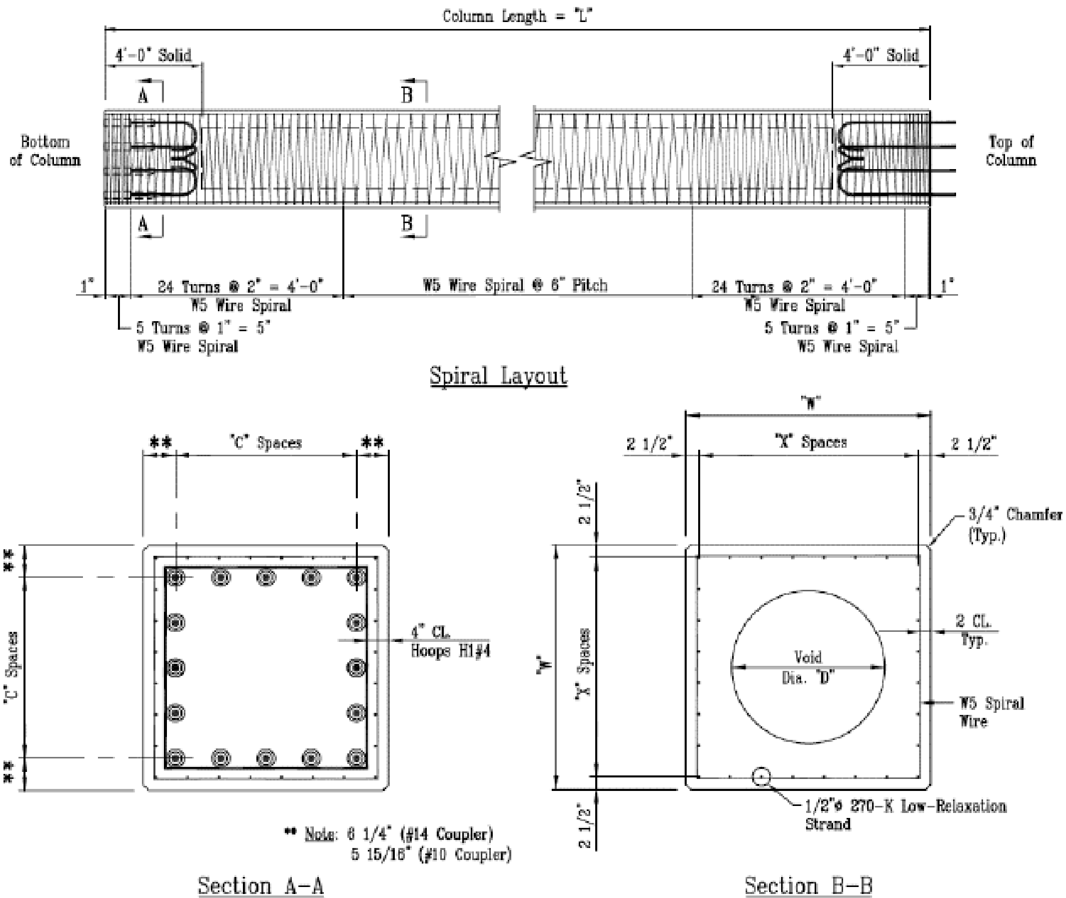


Figure 2-1: Precast column design proposed by Fouad et al. (2006)

Column Properties													
Column Size "W"	Void Diameter "D"	Voided Weight per Lin. ft. (kips./ft.)	Area of Voided Cross Section (in.^{2})	Voided Moment of Inertia (in.^{4})	Strand Layout ("X" Spaces)	Total Number of Strands	Initial Prestress (psi)	Maximum Casting Length "L"	Mechanical Coupler Layout "C" Spaces (Maximum)	Maximum # of Couplers	Mechanical Coupler Size *	Dowel Size
36"	18"	1.085	1,041.53	134,815	5	20	536	45'-0"	3	12	#10	#9
42"	24"	1.366	1,311.61	243,022	6	24	511	52'-0"	3	12	#14	#11
48"	30"	1.664	1,597.14	402,607	7	28	489	56'-0"	4	16	#14	#11
54"	36"	1.977	1,898.12	626,140	8	32	470	46'-0"	5	20	#14	#11

* Mechanical coupler is oversized to provide additional erection tolerance.

36" – 54" Column Details

Figure 2-2: Characteristics of column systems proposed by Fouad et al. (2006)

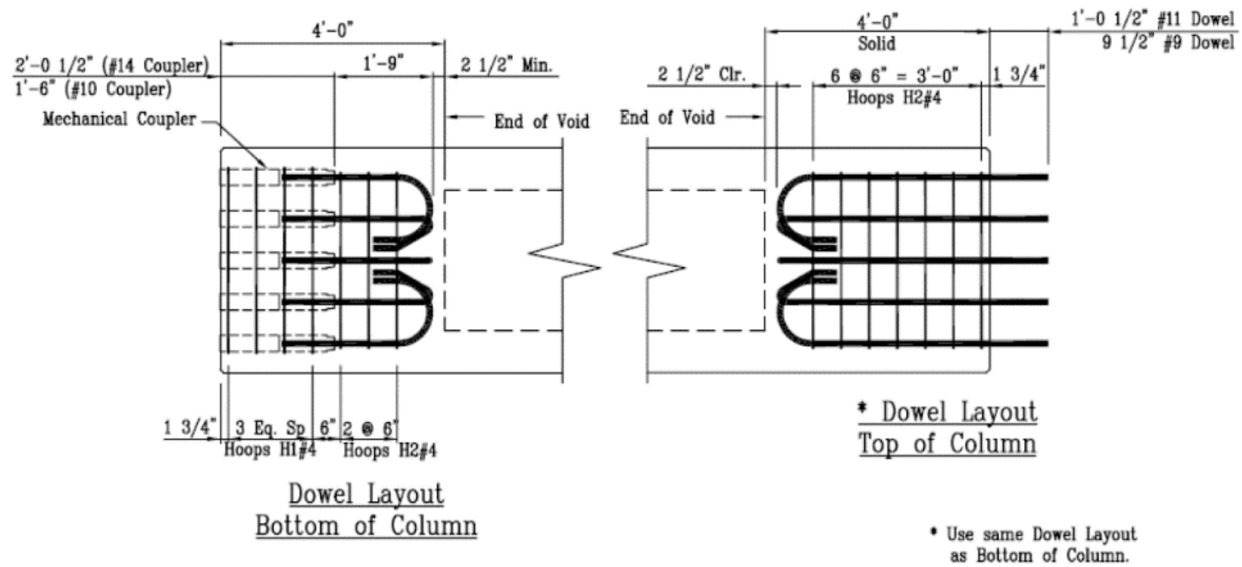


Figure 2-3: Column connections proposed by Fouad et al. (2006)

2.1.2. Seismic Design and Performance of Precast Concrete Segmental Columns (Hewes and Priestley 2002 - California)

Research funded by the California DOT (Caltrans) developed a precast concrete segmental column system intended to reduce damage during a strong earthquake as compared to conventional cast-in-place (CIP) columns (Hewes and Priestley 2002). As part of this research, large-scale tests were conducted at the University of California, San Diego to study the response of precast circular segmental columns under cyclic lateral loading. The geometry of the test specimens is shown in Figure 2-4. An epoxy layer was applied at the column joints, as shown in Figure 2-5. The columns had unbonded longitudinal post-tensioning bars to provide re-centering capabilities after large inelastic deformations occur. Also, steel jackets were used to confine the plastic end region at the base of each column. Figure 2-6 shows one of the column specimens during construction. According to the test results, the proposed precast column system can undergo very large deformations without significant reduction in strength and with minimal residual deformations.

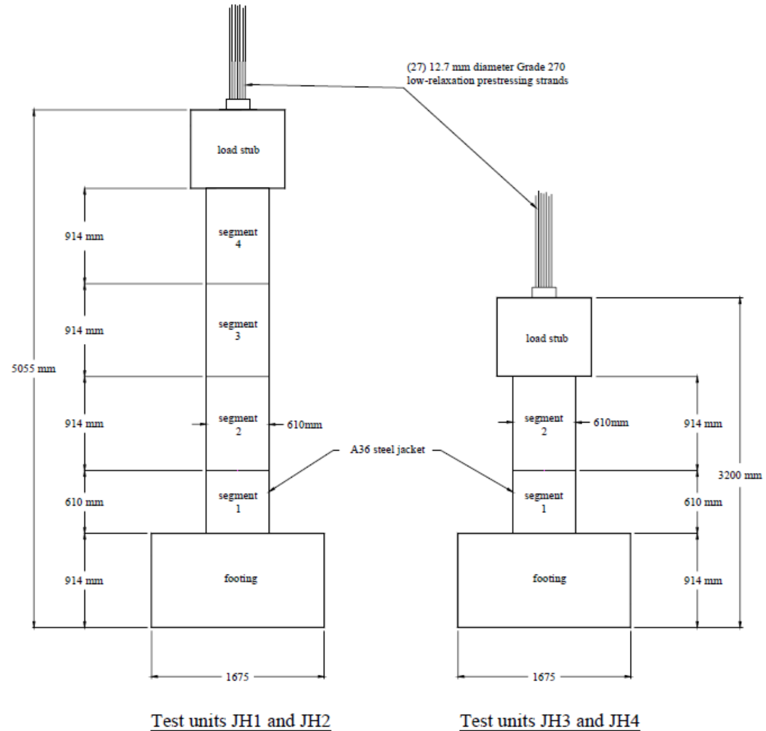


Figure 2-4: Geometry of precast column units tested by Hewes and Priestley (2002)

Figure 2-5: Application of epoxy at interface between column segments used by Hewes and Priestley (2002)

Figure 2-6: Construction of precast column tested by Hewes and Priestley (2002)

2.1.3. Development of Precast Bridge Substructure (LoBuono, Armstrong and Associates 1996 - Florida)

LoBuono, Armstrong and Associates et al. (1996) conducted a study to develop a standardized precast substructure system for moderate-span bridges for the Florida Department of Transportation. The study was divided into two phases. The first phase was a survey of the use of precast substructures. The survey revealed a general concern about connection details. The second phase of the study was assessing different precast substructure element options. The evaluation performance was based on previous performance, ease of design, material cost, aesthetics, ease of shipping, ease of fabrication, and erection. The study did not propose a particular column system, but recommended limiting the weight of precast element to 120 kips and reducing the number of connections as much as possible. This study also recommended further investigation of selected precast substructure elements.

2.1.4. Improving Bridges with Prefabricated Precast Concrete Systems (Aktan and Attanayake 2013 - Michigan)

The purpose of this project was to investigate prefabricated bridge elements and systems (PBES) and accelerated bridge construction (ABC) technologies to be implemented by the state of

Michigan. The study reviewed ABC implementations and provided recommendations for project planning and design, precast fabrication procedures, and construction and operation methods. Recommendations addressed different superstructure and substructure elements, including precast columns and their connections to adjacent elements. The study recommended using rectangular, square, or octagonal column sections over circular sections—circular cross-section columns can only be cast vertically and this makes the fabrication process harder. Also, the octagonal columns and square/rectangular columns are more stable during the shipping and handling process. Some fabrication procedures were recommended in order to overcome the weight limitations of precast segments.

Two types of column-footing connection were recommended in this study. The first one is a grouted splice sleeve and a socket at the footing level (see Figure 2-7) and the second is a pocket connection with a shear key (see Figure 2-8). Three types of pier cap-to-column connections were recommended: a grouted pocket with two layers of reinforcement (see Figure 2-9), a grouted corrugated duct connection (see Figure 2-10), and a vertical splice duct connection (see Figure 2-11). As for the vertical connection between column segments, the study recommended two connections: grouted splice coupler connection (see Figure 2-12) and epoxy grouted shear key with post-tensioning connection (see Figure 2-13). For the different types of connections, the use of a template was recommended, as shown in Figure 2-14, for the column splice connection. This will allow stringent tolerances for enhanced constructability. This study also provided recommendations for grout material and construction techniques.

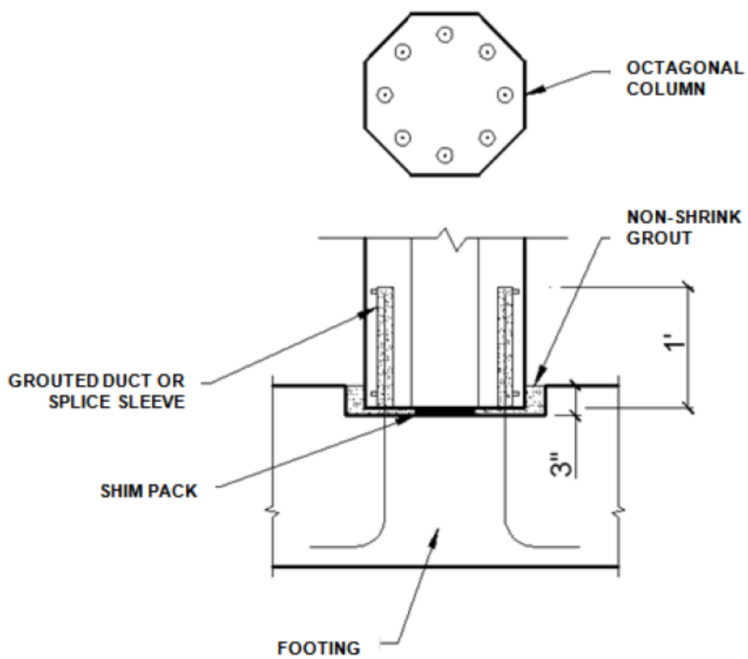


Figure 2-7: Precast column-footing connection with grouted duct/splice sleeve and socket connection proposed by Aktan and Attanayake (2013)

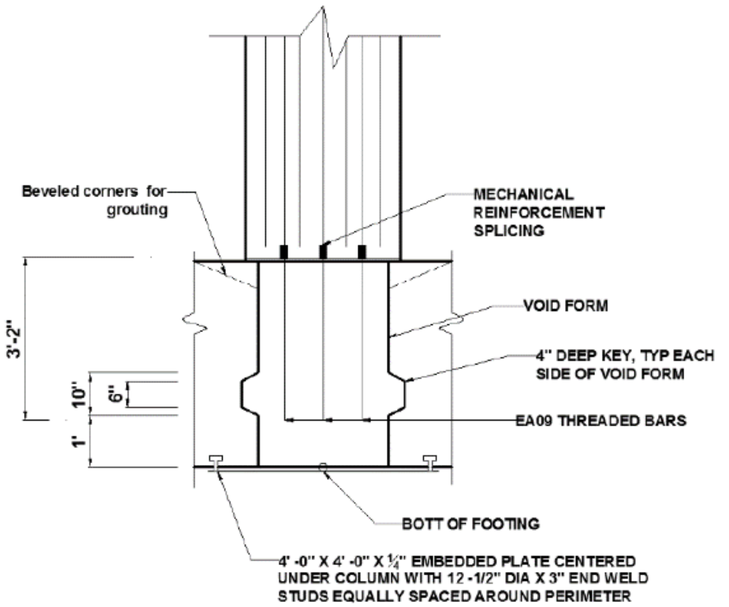


Figure 2-8: Precast column-footing connection with grouted void/pocket and shear key proposed by Aktan and Attanayake (2013)

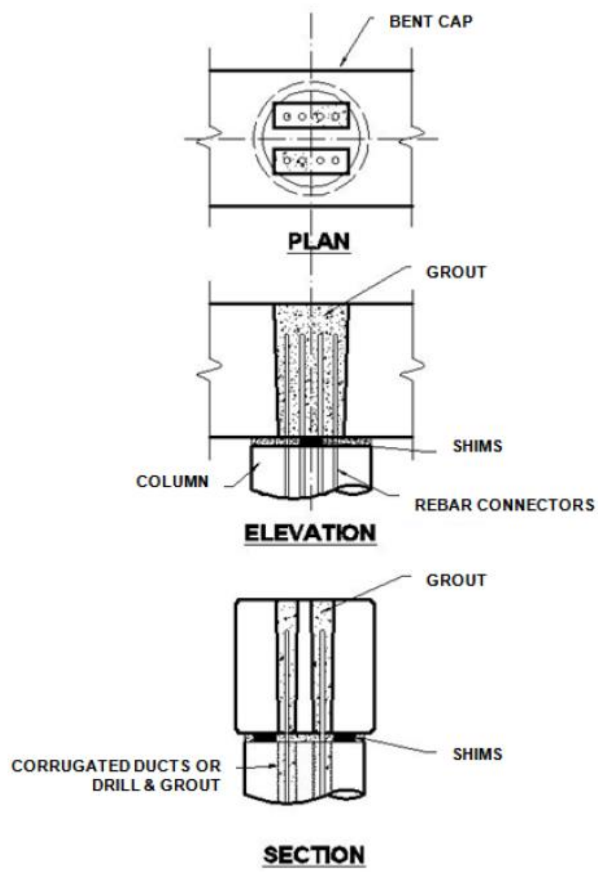


Figure 2-9: Precast column to bent cap connection with grouted pocket (Restrepo et al. 2011)

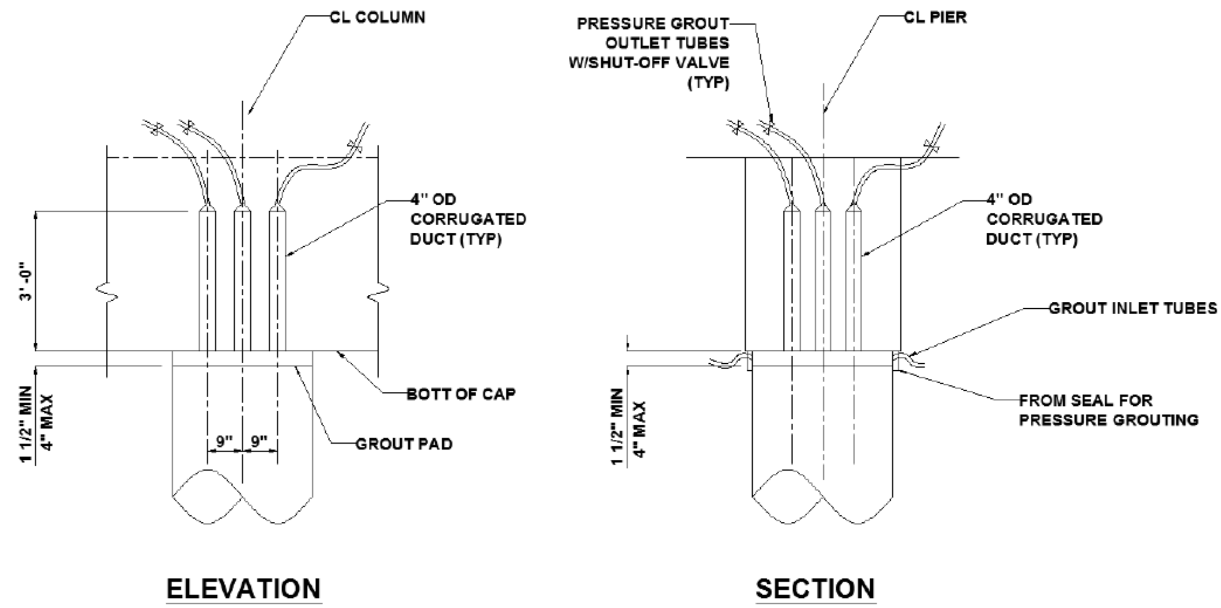
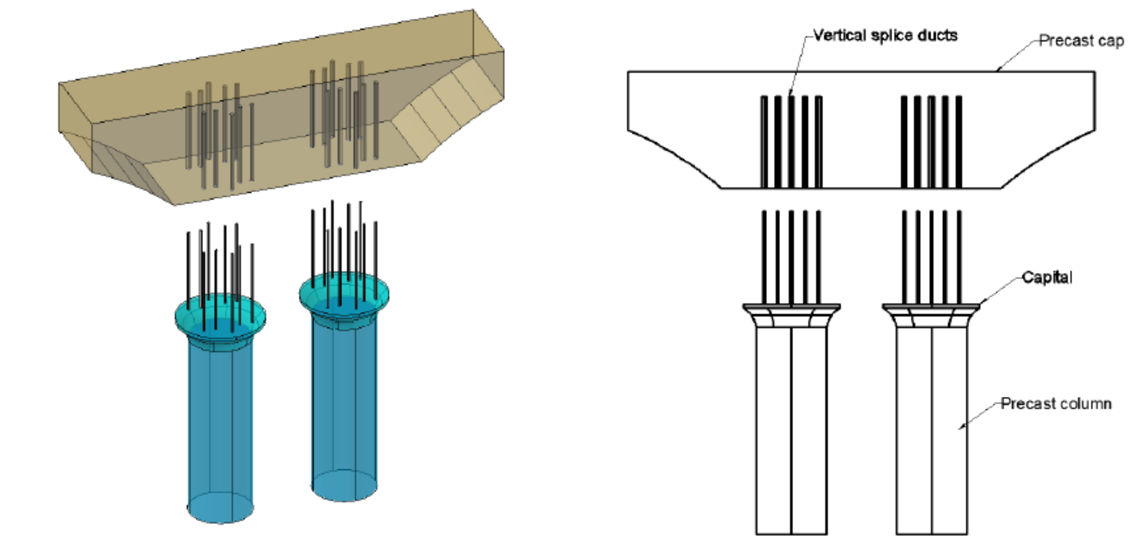


Figure 2-10: Precast column to bent cap with grouted corrugated duct connection (Aktan and Attanayake 2013)



(a) 3D-view of the bent cap to column connection detail (b) 2D-view of the bent cap to column connection detail

Figure 2-11: Vertical splice duct connection between precast column and precast bent cap (FHWA 2009)

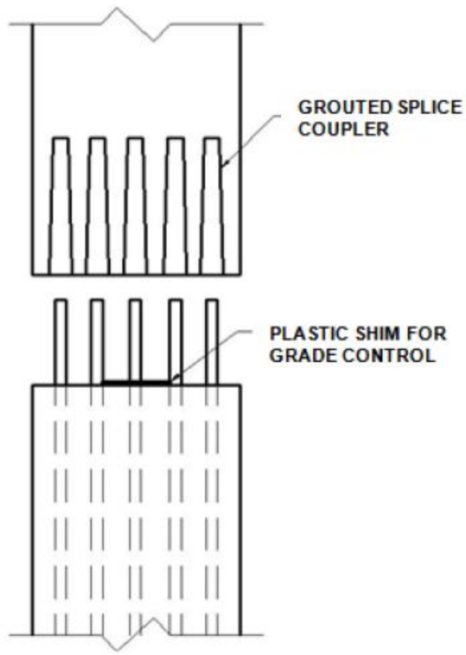


Figure 2-12: Column splice with grouted splice coupler (FHWA 2009)

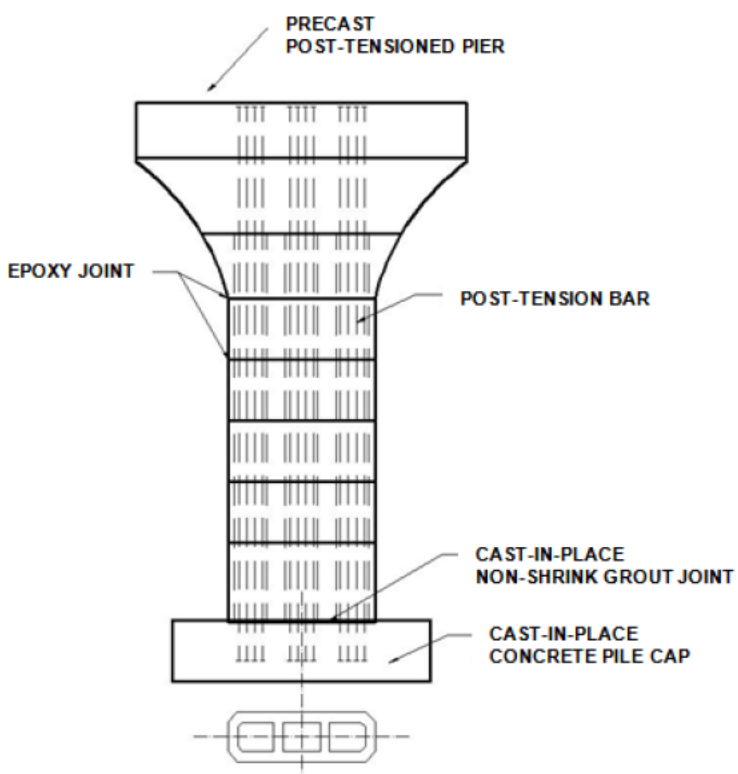


Figure 2-13: Vertical connection of precast post-tensioned pier (FHWA 2009)

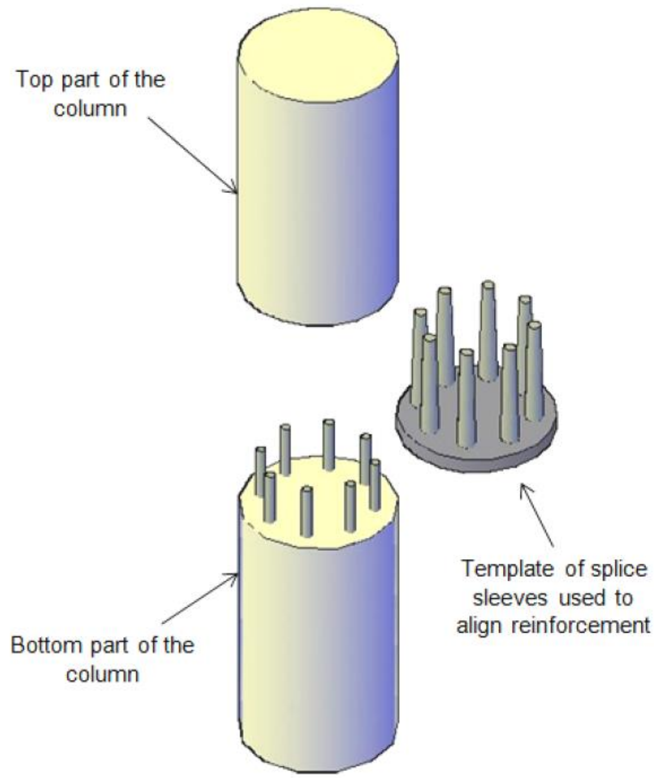


Figure 2-14: Template used for a column splice with grouted splice coupler (Aktan and Attanayake 2013)

2.1.5. A Precast Segmental Substructure System for Standard Bridges (Billington et al. 1998 - Texas)

Based on previous experiences with precast segmental columns on US 183 in Austin and Louetta Road Overpass in Texas (see Section 2.3), research was conducted in the late 1990s to develop a standard precast segmental system for bridge substructures in Texas. TxDOT Project 1410 developed a precast substructure system for short-span and moderate-span bridges in Texas (Billington et al. 1998). This design was conceived for projects in which speed of construction and final appearance were particularly important. The proposed substructure system was designed to be compatible with the existing, commonly used precast beam superstructures. Another criterion for the proposed system was to size precast elements according to available construction plants and construction equipment, taking into account the experience of precasters and contractors.

Figure 2-15 illustrates the design concept proposed by Billington et al. (1998) for different bridge configurations. The system consists of segmentally match-cast columns and a match-cast cap, with the column segments and cap being post-tensioned together on site. Four different hollow pier cross-sections were proposed, as shown in Figure 2-16. The precast system has two designated geometry control joints per columns that require field concreting or grouting. The proposed erection sequence of the pier segments and the connections at the joints are similar to the method used in the US-183 project in Austin, which is shown in Figure 2-17.

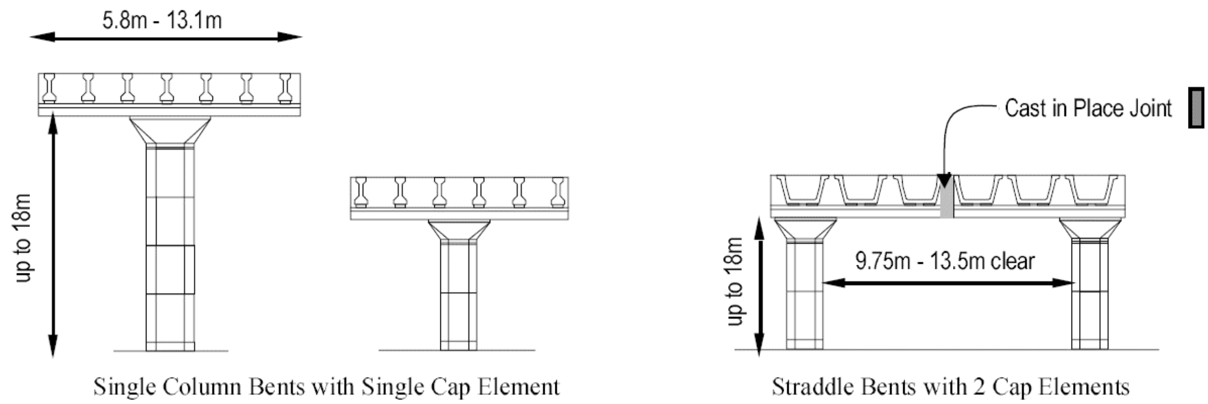


Figure 2-15: Substructure configurations proposed by Billington et al. (1998)

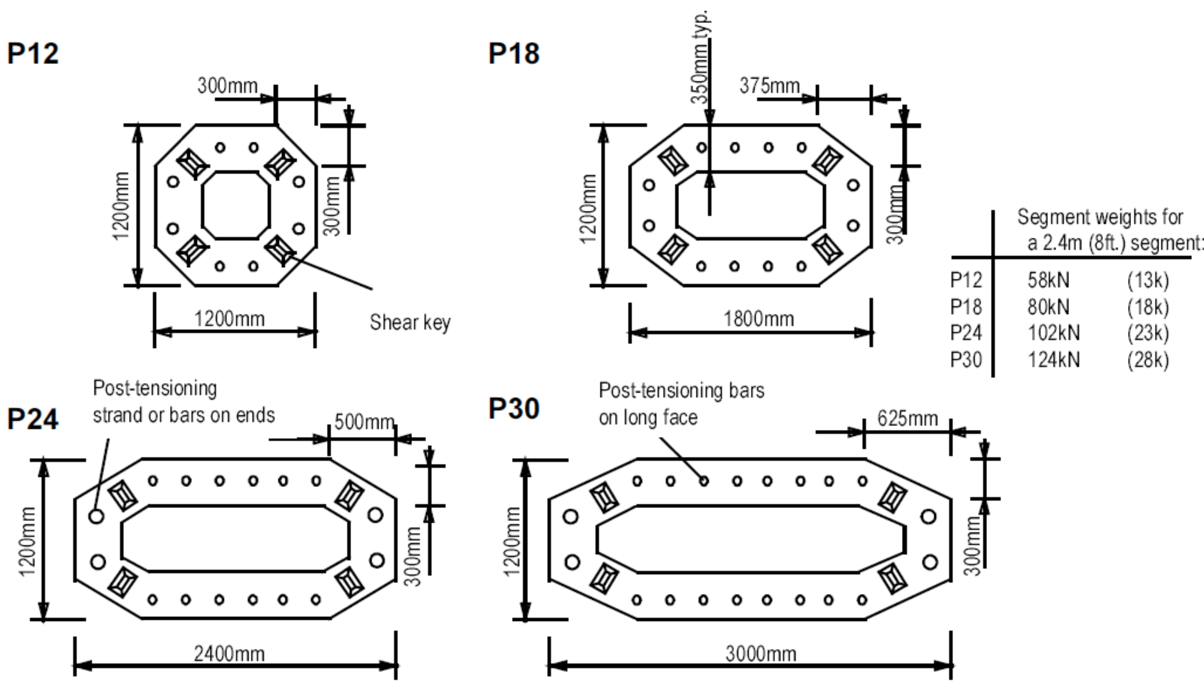
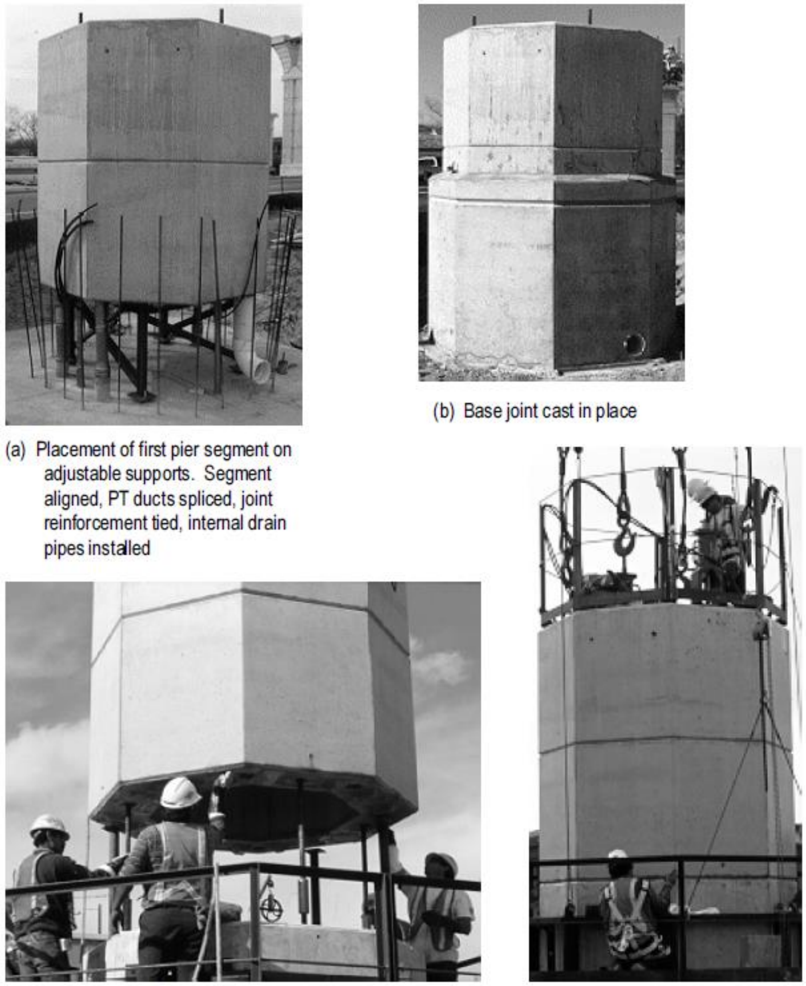


Figure 2-16: Pier cross-sections proposed by Billington et al. (1998)



(a) Placement of first pier segment on adjustable supports. Segment aligned, PT ducts spliced, joint reinforcement tied, internal drain pipes installed

(b) Base joint cast in place

(c) PT bars coupled, placement of subsequent segments with epoxy applied to adjoining segment faces

(d) New segment post-tensioned down to previously erected segments

Figure 2-17: Erection sequence for precast piers at US 183 in Austin, Texas (Billington et al. 1998)

2.1.6. Precast Concrete Pier Systems for Rapid Construction of Bridges in Seismic Regions (Hieber et al. 2005 - Washington)

Research conducted by Hieber et al. (2005) and sponsored by the Washington State DOT proposed and studied analytically two different precast column solutions. One has longitudinal reinforcing steel only, and the other one is a hybrid system with longitudinal reinforcing steel and unbonded post-tensioning steel to provide re-centering capabilities. Full-height precast columns were proposed in both cases. The configurations of the reinforced concrete system and hybrid system are shown in Figure 2-18 and Figure 2-19, respectively. A socket-type of connection was proposed to connect the precast column to the footing, as shown in Figure 2-20. Figure 2-21 through Figure 2-23 show three different details proposed to connect the column with the cap beam. They correspond to a slotted opening connection, a complete opening connection, and an individual splice sleeve connection. While the first two types of connections can be used in both column systems, the individual splice sleeve connection was proposed for the hybrid system, which has less mild reinforcing steel. The results of the analytical study conducted by Hieber et al. (2005) showed that both proposed systems are adequate for seismic applications.

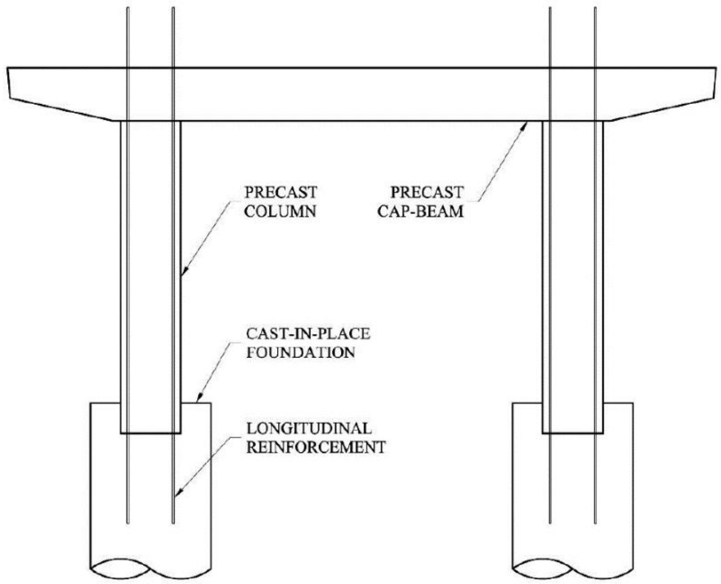


Figure 2-18: Reinforced concrete precast column system proposed by Hieber et al. (2005)

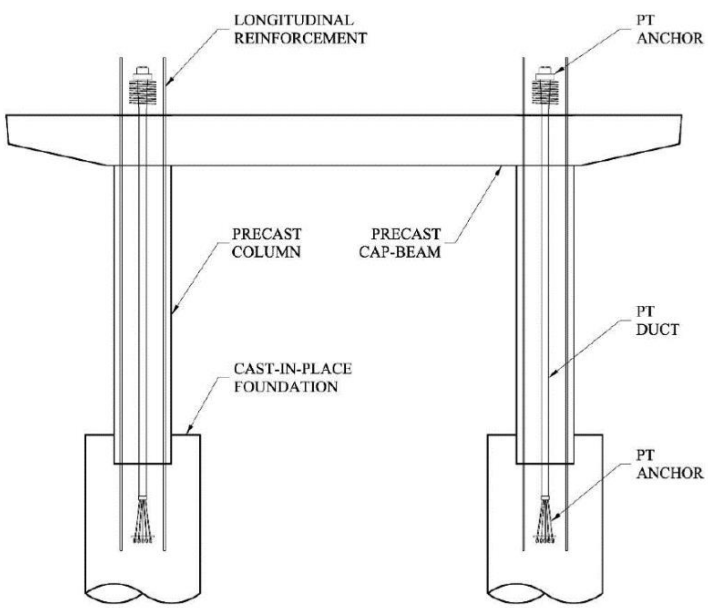


Figure 2-19: Hybrid precast column system proposed by Hieber et al. (2005)

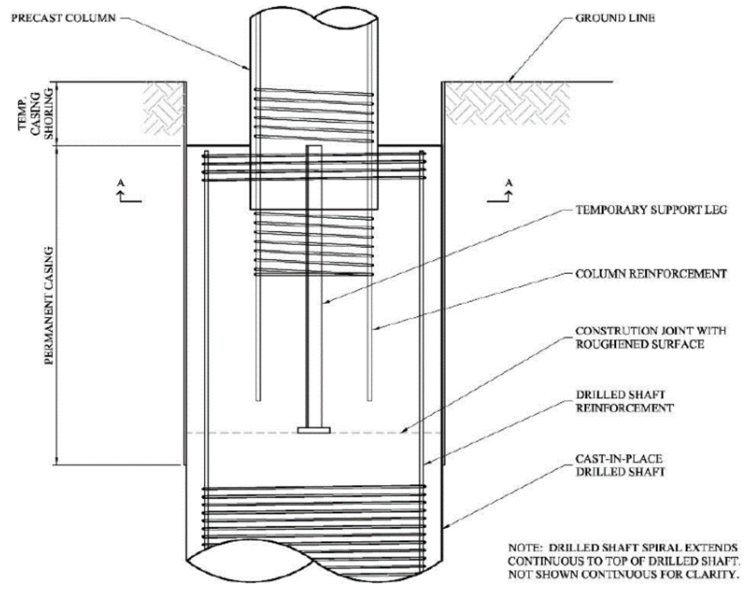


Figure 2-20: Footing-to-column connection proposed by Hieber et al. (2005)

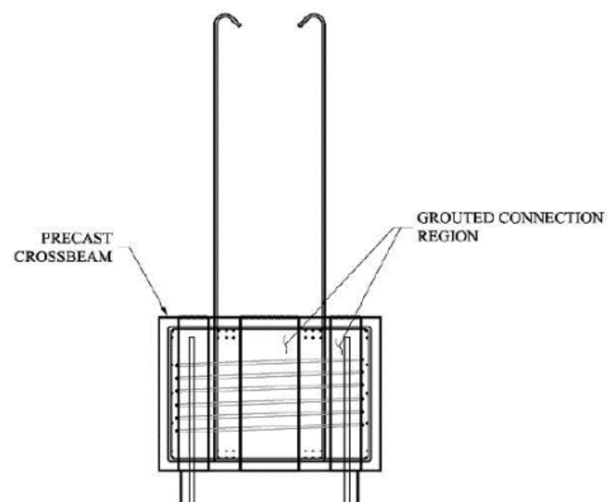


Figure 2-21: Column and cap beam slotted opening connection proposed by Hieber et al. (2005)

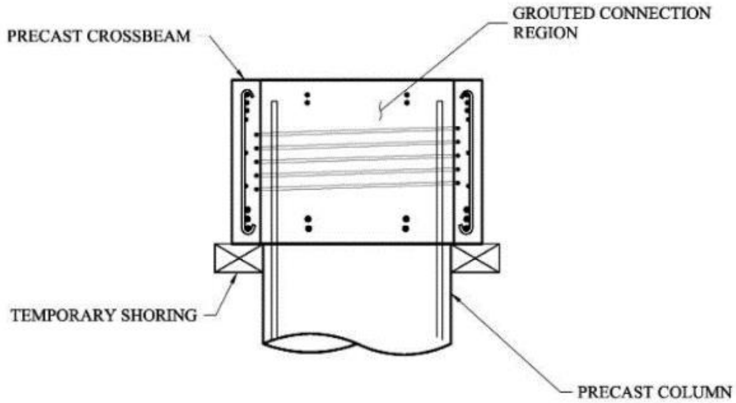


Figure 2-22: Column and cap beam complete opening connection (Hieber et al. 2005)

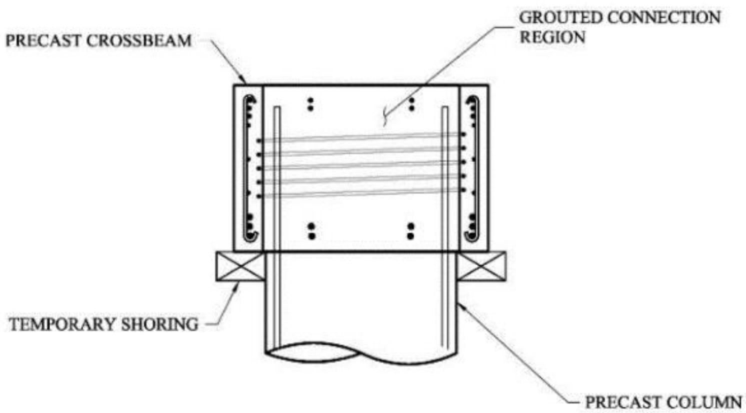


Figure 2-23: Column and cap beam splice sleeve connection proposed by Hieber et al. (2005)

2.1.7. Rapidly Constructible Large- Bar Precast Bridge- Bent Seismic Connection (Pang et al. 2008 - Washington)

Sponsored by Washington State DOT, this research studied experimentally the connection between precast columns and bent caps using large-diameter vertical column bars extended into corrugated grouted ducts embedded in the cap beam. Using a smaller number of large bars speeds up the connection process and results in more generous construction tolerances. Large-scale tests were conducted on column-cap beam subassemblies, as shown in Figure 2-24. The cap beam joint reinforcement and grouted ducts are shown in Figure 2-25. Figure 2-26 shows one of the test specimens, which were subjected to cyclic lateral loading. The test specimens included a reference CIP specimen, and three precast specimens with large bar connection. The bars of one of the precast specimens were fully grouted into the corrugated ducts, while in the other two specimens the bars were debonded over a length of 8 bar diameters using two different debonding methods.

Test results showed that the cyclic behavior of the proposed connection is comparable to a CIP connection in terms of both strength and ductility. Short length debonding had little effect on the seismic performance of the connection. The study provided recommendations for design and field implementation of the system. The development lengths of the vertical column bars in the grouted ducts were selected based on the recommendations of Steuck et al. (2007). These recommendations established minimum development lengths of 6 times the bar diameter (d_b) and 14d_b to yield and fracture the bar, respectively, for an 8,000-psi grout and monotonic loading. For cyclic loading, the minimum lengths were increased by 50%.

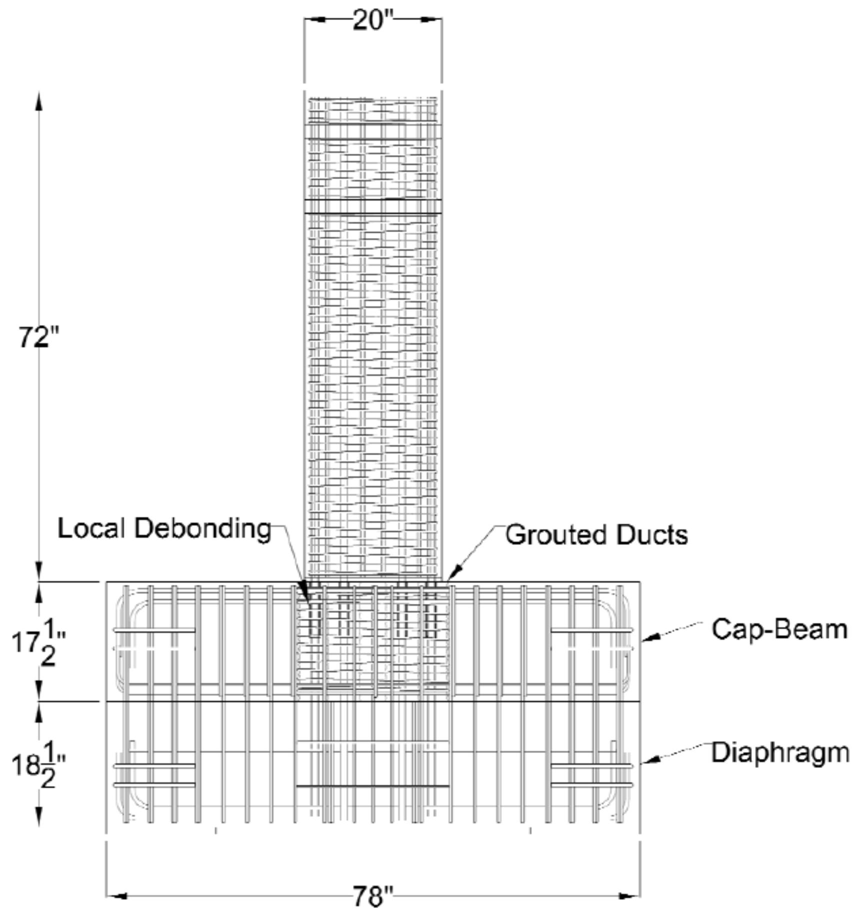


Figure 2-24: Geometry and reinforcement of column - bent cap subassembly tested by Pang et al. (2008)

Figure 2-25: Cap beam joint region with grouted ducts (Pang et al. 2008)

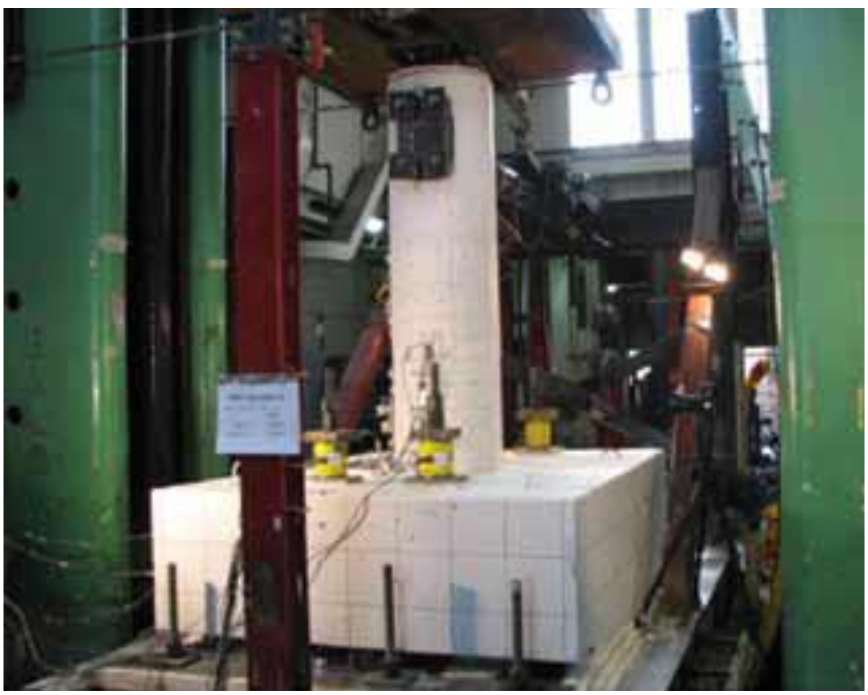


Figure 2-26: Testing of the column – bent cap connection by Pang et al. (2008)

2.1.8. Seismic resistance of socket connection between footing and precast column (Haraldsson et al. 2013 - Washington)

Sponsored by the Washington State DOT, this research developed and tested a socket connection between a precast column and a footing. This system can result in major construction time reductions and provide better constructability with no bars crossing the column-footing interface and no required grouting. The socket connection can also result in better transfer of forces in the connection region as illustrated in strut-and-tie model presented in Figure 2-27. Column-footing subassemblies using this type of connection were tested under axial and cyclic lateral loading. The columns had a circular cross-section and 20 in. of diameter. The embedment length of the column inside the footing was 1.1 times the column diameter. The portion of the column embedded in the footing had an octagonal cross-section and was roughened using the saw-tooth pattern prior to casting the footing (see Figure 2-28). The roughening detail, which is in accordance with Washington State DOT design manual, satisfies the AASHTO LRFD requirement for surface transfer shear friction terms of minimum amplitude. Some additional diagonal reinforcement was provided in the horizontal plane to induce shear friction resistance to the column pushing through the footing.

Test results showed that columns with this type of connection behave similarly to CIP systems under cyclic loading and no column slip was observed in the tested specimens under axial loading. Diagonal reinforcement was found unnecessary, and the study concluded that it can be eliminated. In addition, the study recommended the use of headed bars in the column to provide partial anchorage.

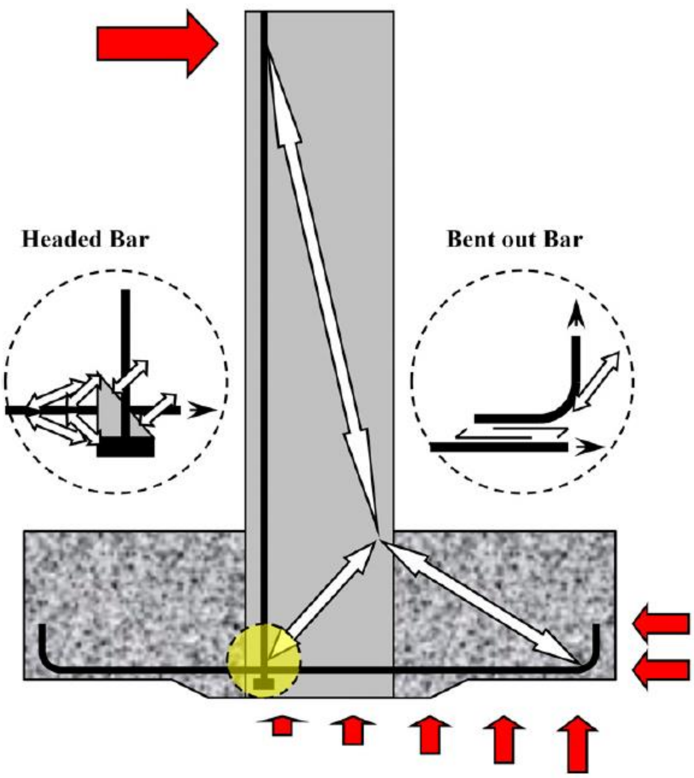


Figure 2-27: Strut-and-tie model for socket connection by Haraldsson et al. (2013)

Figure 2-28: Socket connection proposed by Haraldsson et al. (2013)

2.1.9. Precast Segmental Post-tensioned Concrete Bridge Columns for Seismic Regions (Yu-Chen 2007 – FHWA)

Sponsored by FHWA and Taiwan's National Center on Research for Earthquake Engineering, this research was performed at the University of New York at Buffalo to investigate the seismic behavior of segmental post-tensioned concrete bridge columns. Large-scale tests were conducted on column systems with unbonded post-tensioning rods and mild steel at the column joints. Mild steel bars were used for energy dissipation (ED), and they were debonded at the critical section of the column to avoid premature fracture. Column rebar extended into the footing and the cap beam through grouted corrugated ducts, and column segments were assembled using mechanical couplers. Figure 2-29 shows a schematic representation of the system, and a photograph during the erection of the system is shown in Figure 2-30.

A preliminary analytical study conducted by the authors showed three different hysteretic behaviors for segmental columns with ductile joints. The first one has high ED and residual deformation, the second one has minimal ED and residual displacement, and the third one has moderate ED and small residual displacement. Achieving either one of these three behaviors depends on the joint detailing. The required unbonded lengths, the type of grout and the construction method for the ED bars were investigated experimentally. Seven precast hollow segmental columns were tested with different ED capacities and levels of prestressing force. Test results confirmed the analytical predictions on the effects of ED bar design on the column hysteretic behavior.

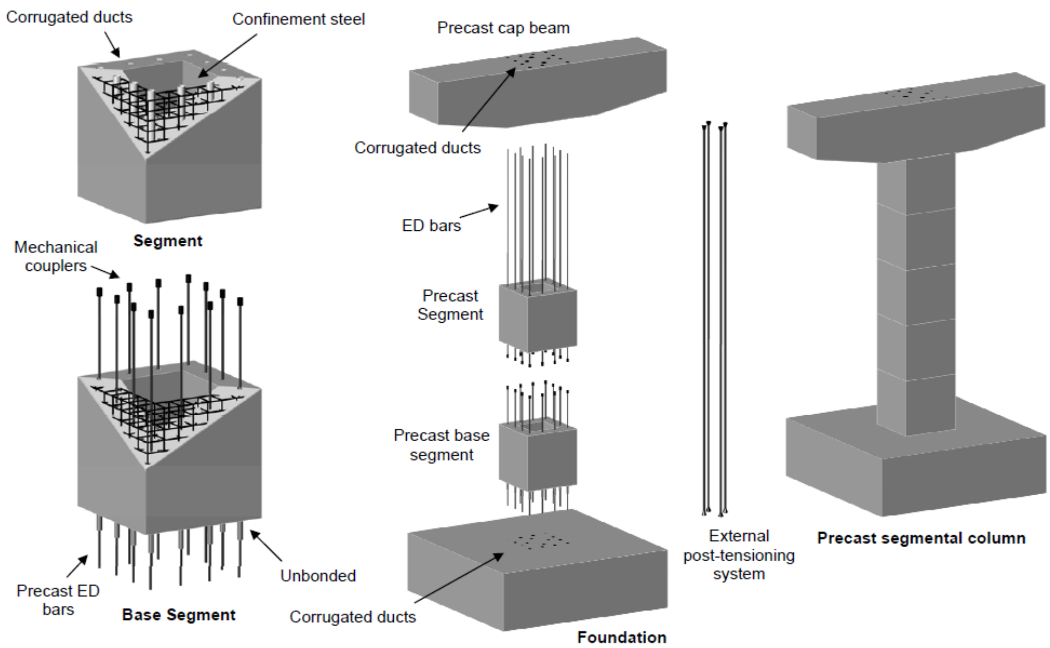


Figure 2-29: Precast segmental column proposed by Yu-Chen (2007)

Figure 2-30: Construction of precast column specimen tested by Yu-Chen (2007)

2.1.10. Review of Prefabricated Bridge Elements and Systems in Japan and Europe (Ralls et al. 2005)

In 2004, the FHWA, AASHTO, and the National Cooperative Highway Research Program (NCHRP) sponsored a scanning study to collect information about the use prefabricated bridge elements and systems in Japan and Europe. The outcome of the study was a report entitled "Prefabricated Bridge Elements and Systems in Japan and Europe." Regarding the use of precast substructure systems, the report only recommended the Japanese SPER (Sumitomo Precast form for resisting Earthquakes and for Rapid construction) system. The system comprises bridge piers that employ stay-in-place precast concrete panels to work as both structural elements and formwork for a CIP concrete core. In this system, short piers are solid and have precast panels in the exterior, as shown in Figure 2-31. Tall, hollow piers have panels for both the inner and outer faces, as shown in Figure 2-32. For both short and tall panels, segments are stacked on top of each other using epoxy joints and then are filled with CIP concrete. The system was proven to have a very good seismic performance, while reducing construction time and providing a high quality, durable external finish.

Figure 2-31: SPER system using short pier panels (Ralls et al. 2005)

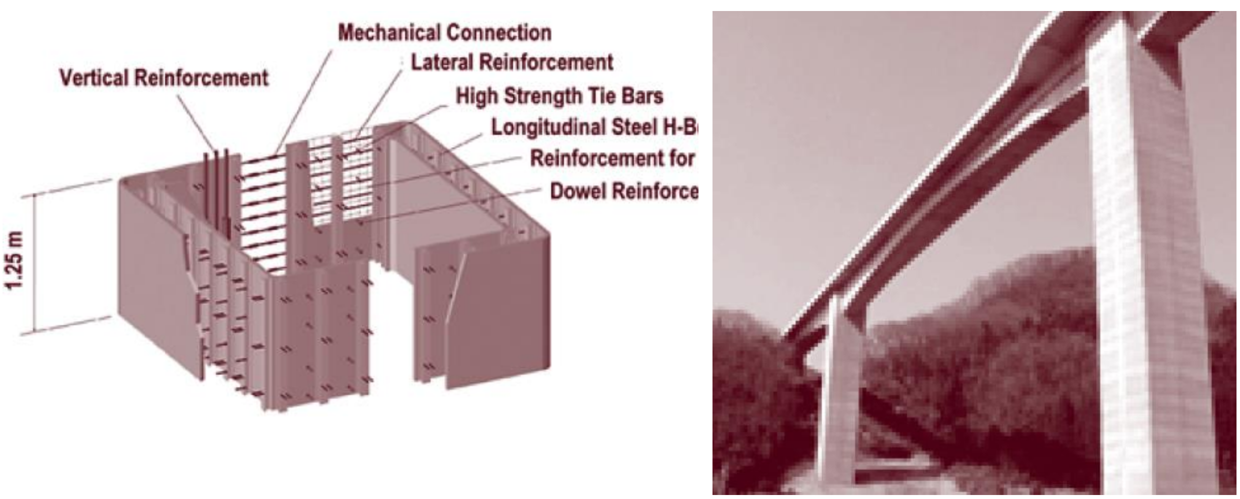


Figure 2-32: SPER system using tall pier panels (Ralls et al. 2005)

2.2. Review of Existing Guidelines for Design and Construction of Precast Columns

This section presents a review of existing recommendations for the design and construction of precast columns developed by the Precast Concrete Institute (PCI) and FHWA.

2.2.1. Guidelines for Accelerated Bridge Construction Using Precast/Prestressed Concrete Components (PCINE 2006)

This manual, developed by the PCI Northeast Bridge Technical Committee, provides guidelines on the use of precast/prestressed concrete components to accelerate the construction of bridge projects. While this guide is not intended as a stand-alone document, it presents information that applies to the entire bridge structure including precast columns. The manual is divided into the following sections: application overview, general requirements, precast components, joints, grouting, seismic considerations, and fabrication/construction. Section 3 of the manual (precast components) recommends using rectangular precast columns over round precast columns for bridge structures to enhance efficiency and reduce fabrication costs. Section 6 (seismic considerations) presents specific guidelines for column connections in seismic regions. For example, grouted mechanical splices are considered for moment connections, where the steel bars can develop 125% of their yield strength.

2.2.2. Connection Details for Prefabricated Bridge Elements and Systems (FHWA 2009)

This document represents a detailed overview of connections between precast elements in ABC projects. Chapter 3 of this document, which covers substructure connections, provides the following observations and recommendations concerning connections for precast columns:

- *Precast cap beam-to-precast column connections:* Florida DOT has used in the past with proprietary grouted splice couplers. These couplers were embedded in the precast components and were grouted after installation.
- *Precast column-to-column connections:* One way to connect column segments is combining post-tensioning and the match-cast method of construction. Another possible method, which is recommended by the PCI Bridge Technical Committee, uses grouted reinforcing splice couplers to connect longitudinal reinforcement between adjacent segments.
- *Precast column-to-CIP footing connections:* Two methods are presented. The first one is used by the Washington State DOT and involves casting the footing under a precast column element, with the column reinforcement projected from the column base into the footing. This requires a temporary support of the precast column. The second method involves mechanical connectors and/or post-tensioning. This method requires more careful coordination during construction. Figure 2-33 shows the detail with the mechanical coupler.
- *Precast column-to-precast footing connections:* This connection has not been used in the United States. The manual recommends using connection details presented in the PCI Bridge manual that are used in building and garage construction.

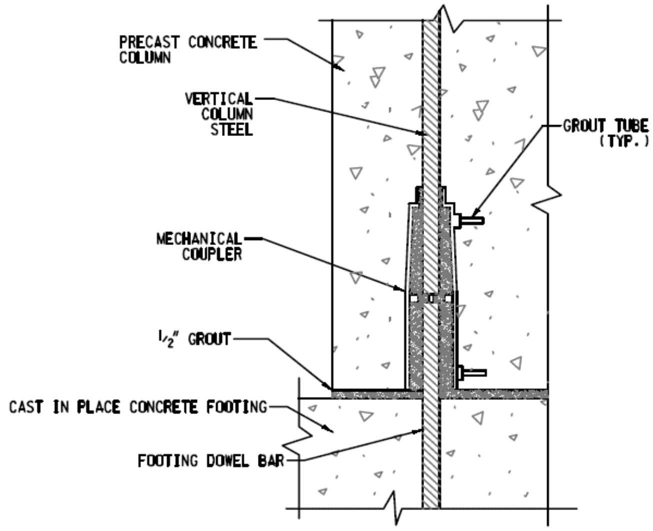


Figure 2-33: Precast column to CIP footing connection (FHWA 2009)

To facilitate the use of the manual, simple data sheets (see Figure 2-34 and Figure 2-35) including the following information are provided for each connection:

- Originating organization information
- Connection details
- Description, comments, specifications, and special design procedures
- Performance data: agencies were asked to rate the performance of the connection according to the speed of construction, constructability, cost, durability, inspection access, and future maintenance

Based on the frequency of use and effectiveness, the manual also categorizes the connections in three different levels:

- **Level 1**: connections that have been used in multiple projects or have become a standard practice by at least one agency.
- **Level 2**: connections that have been used once and present an adequate performance.
- **Level 3**: connections that have been tested experimentally or have been proposed conceptually by researchers but have not been used in practice.

Figure 2-34 and Figure 2-35 present an example of a data sheet for a precast column-to-precast cap beam connection used in the Edison Bridge in Florida. A total of 10 data sheets involving precast column connections are included in this FHWA manual.

Connection Details for Prefabricated Bridge Elements **Federal Highway Administration**

Organization:	Florida DOT	Detail Number	3.1.1.2 A
Contact Name:	Thomas Andres	Phone Number:	850-414-4269
Address:	605 Suwannee Street, MS 33 Tallahassee, FL 32399-0450	E-mail:	thomas.andres@dot.stata.fl.us
		Detail Classification	**Level 2**

Components Connected Precast Pier Column to Precast Pier Cap

Name of Project where the detail was used Edison Bridge

Connection Details: **Manual Reference Section 3.1.1.2** See Reverse side for more information on this connection

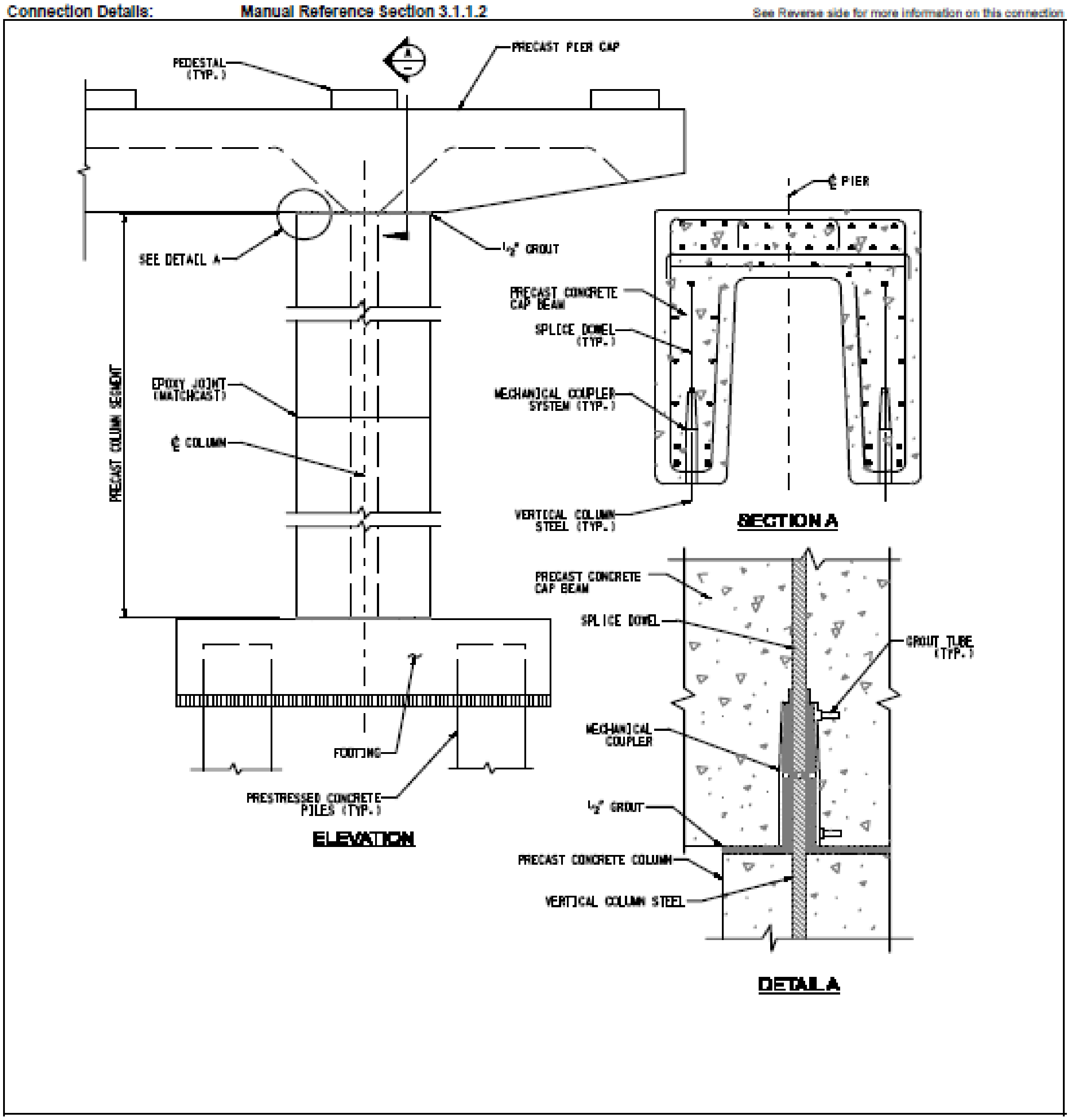


Figure 2-34: Data sheet for precast column connection in Edison Bridge in Florida (1/2) (FHWA 2009)

Description, comments, specifications, and special design procedures See Reverse side for more information on this connection

This Connection was made with a steel grouted reinforcing bar splicer system.

The grouted splicers can develop over 150% of bar yield. Quality control on bar and splicer locations are critical. The splicers can be oversized to accommodate approximately 1/2" of tolerance. The only design effect is that the bars must be moved closer to the center of the members in order to maintain cover around the splicers (approx. 1"). This design incorporates an H shaped column section and a U shaped cap section to reduce weight. Weight of cap did not control crane requirements (approx. same weight as beams). Contractor's labor and insurance costs less due to reduced time on the water.

Editor's Notes

What forces are the connection designed to transmit? (place x in appropriate boxes)

Shear	Moment	Compression	Tension	Torsion
X	X	X	X	X

What year was this detail first used? 1992

Condition at last inspection (if known) Good

How many times has this detail been used? one

Year of last inspection 2005

Would you use it again? yes (yes/no/maybe)

On a scale of 1 to 10, how would you rate the performance of this connection in the following categories?

Speed of Construction	8	(0 very slow, 10 very fast) When compared to conventional construction
Constructability	8	(0 difficulty making connection, 10 went together easily)
Cost	8	(0 expensive, 10 cost effective) When compared to other connection methods
Durability	8	(0 not durable, 10 very durable)
Inspection Access	5	(0 not visible, 10 easily inspected)
Future Maintenance	8	(0 will need maintenance, 10 no maintenance anticipated)

Figure 2-35: Data sheet for precast column connection in Edison Bridge in Florida (2/2) (FHWA 2009)

2.2.3. PBES/ABC Design Manual (FHWA 2013)

In 2013, the FHWA developed an ABC manual titled “Engineering Design, fabrication, and Erection of Prefabricated Bridge Elements and Systems.” The manual focuses on the design aspects of ABC using PBES. It provides an overview of material specifications, typical design, planning, and construction processes. This manual includes a number of design and detailing recommendations for precast columns and their connections to adjacent elements.

Chapter 5 of the manual addresses the design of precast piers and includes information about the most common pier connections. These connections include grouted reinforcing splice couplers, grouted post-tensioning ducts, corrugated metal pipe voids, post-tensioning systems, and corrugated column ends. Chapter 7, which presents the design of foundation elements, includes a section on precast columns connected to drilled shafts and recommend the detail shown in Figure 2-36. This detail is taken from Washington State DOT Bridge Design Manual. Noncontact lap splice should be considered in this detail. Chapter 9 of the manual addresses durability in precast connections including a footing to column connection, which is a critical joint as water might settle in that area and lead to increased potential of long-term deterioration. Two methods are presented to overcome the problem. The first method is having a recess in the grout and then installing a flexible sealer along the joint. The second method is to place the joint in the recess and then grout it into place (see detail in Figure 2-37). Finally, Chapter 10 provides an example on how to account for fabrication and erection tolerances between a precast footing and a precast column in the joint thickness estimation (Example 10.2-2).

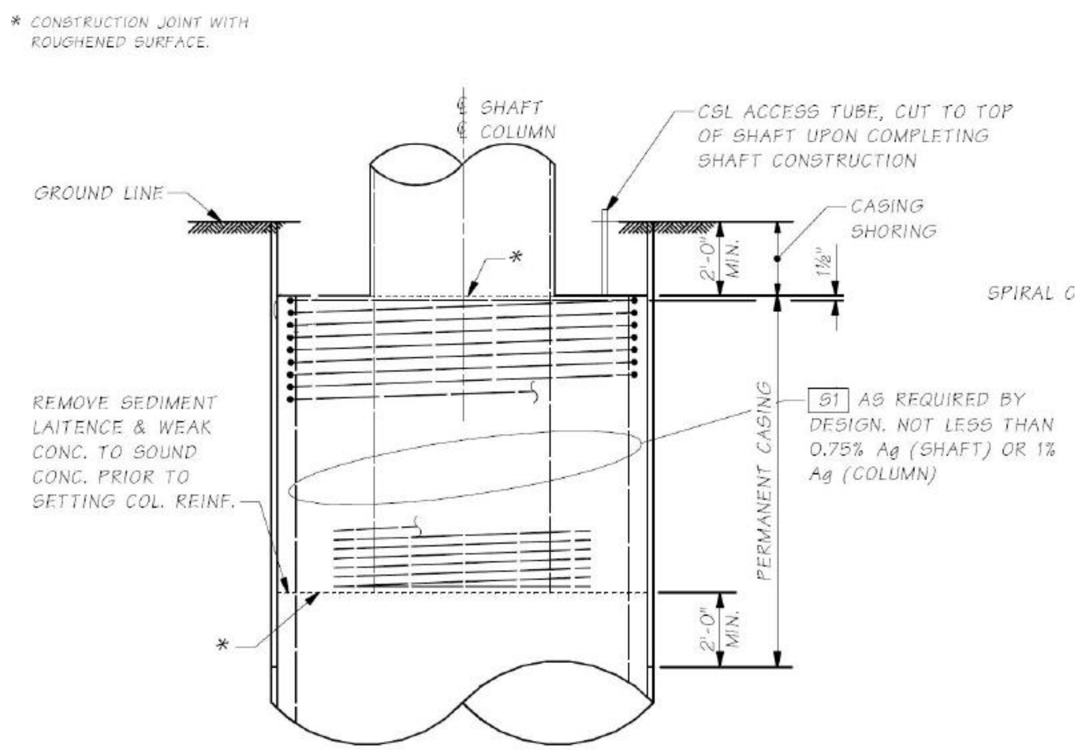


Figure 2-36: Connection of pier column to large diameter drilled shaft (FHWA 2013)

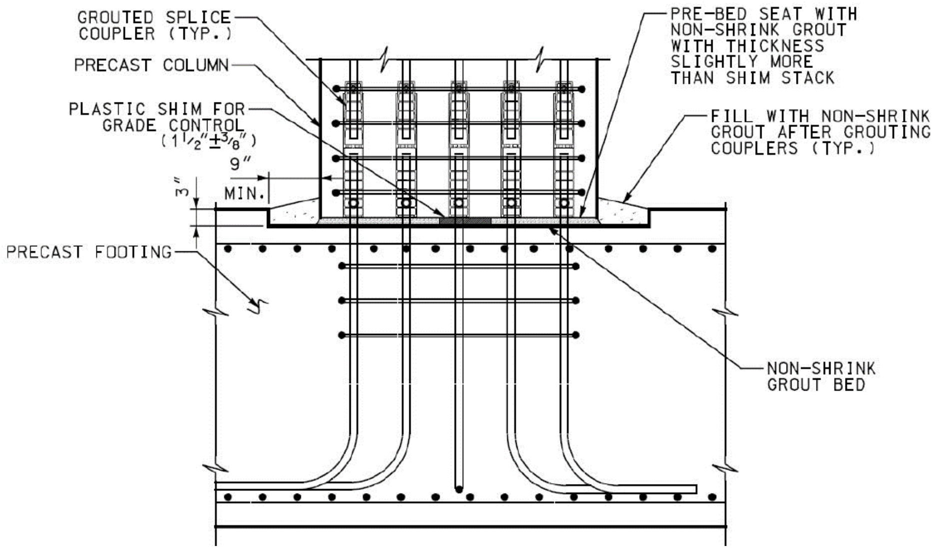


Figure 2-37: Recessed precast column to precast footing connection (PCINE 2006)

2.3. Review of Projects with Precast Columns

This section presents an overview of bridge projects reported in the literature that employed precast columns. The case studies are presented by state in alphabetical order. Each case study includes a brief description of the project, and the type of precast column system and connection details used in the project.

2.3.1. Moore's Mill Road Bridge over IH 85, Auburn (Alabama)

The Moore's Mill Road Bridge is a five-lane prestressed concrete bridge that was built to replace an old two-lane reinforced concrete deck bridge. Six full-height precast columns were used in this project. The use of precast columns resulted in a time-savings of eight days and improved safety in the construction site. The columns were 19 ft 9 in. tall and had a 3-ft-square section. They were fabricated using metal forms with interior buildup. The forms included a faux brick formliner to improve the column surface aesthetics, as shown in Figure 2-39. The columns were connected to the footing using grouted splice couplers. To provide reasonable tolerances during the erection, #14 sleeves were used for the #11 longitudinal dowel bars (see Figure 2-38). Some complications were reported for injecting the grout in the bottom port of the couplers. The contractor solved the problem by partially grouting the couplers from the top port and then continuing the grouting in the bottom port.

Figure 2-38: Connection bars in footing (left) and coupler in column (right) in Moore's Mill Road Bridge (City of Auburn 2019)

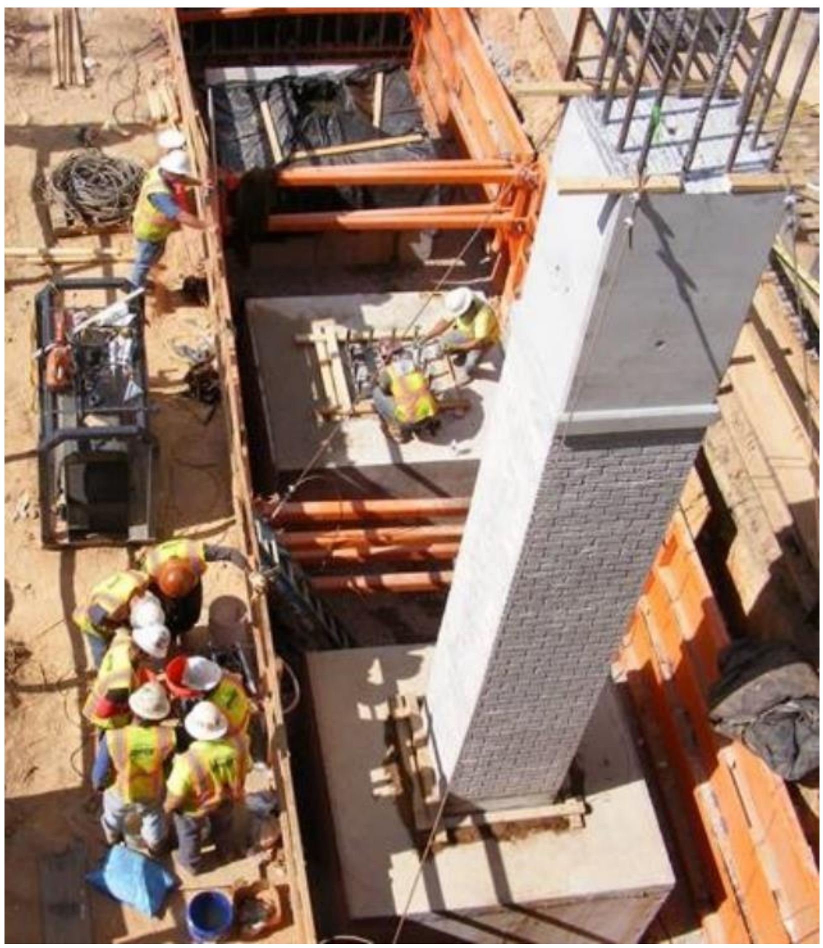


Figure 2-39: Erection of the precast column in Moore's Mill Road Bridge (City of Auburn 2019)

Figure 2-40: Elevation of New Moore's Mill Bridge after construction (City of Auburn 2019)

2.3.2. Laurel Street Overcrossing (California)

The Laurel Street Overcrossing in Vallejo is the first multi-span full ABC project in California. This pilot project, conducted in 2017, implemented research on the seismic connections of precast elements. The project involved round precast columns (19-ft-long and 5-ft-diameter), precast bent caps, and precast wide flange girders. Columns were cast with an oversized formed hole (20 in.) to be connected to the footings using a 12-in.-diameter shear key as shown in Figure 2-41 and Figure 2-42. The column-to-cap connection was done using ducts filled with ultra-high performance concrete (UHPC). Twenty # 14 column reinforcing bars extended in 4-in.-diameter galvanized metal ducts embedded in the bent cap (see Figure 2-43). After installing the bent cap, the shear keys at the base of the columns supporting the bent cap were grouted with non-shrink grout (see Figure 2-42), and the ducts of the column-to-cap connection were filled with UHPC. The full erection of the two column and the bent cap took only one morning. After this project, a second ABC pilot project was conducted by Caltrans on Route 46/99. The main difference with the Laurel Street Overcrossing was the use of slightly smaller diameter columns (4.5 ft instead of 5 ft), which caused congestion issues in the cap. Accordingly, Caltrans recommended the use of a larger column size to alleviate congestion in the cap.

Figure 2-41: Precast column in Laurel Street Overcrossing (Mellon 2018)

Figure 2-42: Erection of precast column in Laurel Street Overcrossing (Mellon 2018)

Figure 2-43: Erection of precast bent cap in Laurel Street Overcrossing (Mellon 2018)

Figure 2-44: Laurel Street Overcrossing after construction (Mellon 2018)

2.3.3. Seven Mile Bridge, Florida Keys (Florida)

At the time of its completion in 1982, the Seven Mile Bridge was the longest continuous concrete segmental bridge in the world with 264 spans. Due to the use of precast construction methods, the project was completed six months ahead of the schedule. This bridge utilizes precast post-tensioned box girders and hollow precast segmental piers for the substructure. The bridge was the first use of precast, match-cast box piers that were assembled using vertical post-tensioning (Figg and Denney Pate 2004). Figure 2-45 shows the bridge after construction.

Figure 2-45: Seven Mile Bridge after construction (FIGG Bridge Group-www.figgbridge.com)

2.3.4. Edison Bridge, Fort Meyers (Florida)

The Edison Bridge in Florida crosses the Caloosahatchee River and connects downtown Fort Myers with North Fort Myers. The construction of this bridge was completed in 1992. The superstructure uses 72-inch-deep Florida bulb-T girders and has 143-feet-long spans. The substructure involves precast segmental columns and precast bent caps.

The precast columns have an H-shaped cross-section with 12-in.-thick walls (see Figure 2-46). The open shape column cross-section was selected to reduce the shipping and lifting weight of the elements (FHWA 2009). The longitudinal reinforcement of the column consists of eight #14 bars, two on each leg of the H section. Grouted splice sleeves connectors are used for the connection of the precast columns to the footings and bent caps. The columns were erected at a rate of six per day.

Overall, prefabrication of bridge components saved two months of project time. Being exposed to brackish water, the environment for this bridge can be considered severe, especially considering that Florida has a history of bridges with column deterioration problems. A review of bridge inspection files showed that this bridge is still in good condition with no deficiencies in the joints after 15 years in service (FHWA 2013). Figure 2-47 and Figure 2-48 show the Edison Bridge during and after construction.

Figure 2-46: H-shaped precast Concrete Column used in Edison Bridge (FHWA 2009)

Figure 2-47: Erection of Precast Bents on Edison Bridge (Ericson 2005)

Figure 2-48: Edison Bridge after the completion of construction (FHWA 2009)

2.3.5. IH 85 Interchange, West Point (Georgia)

This bridge, completed in 2006, is part of a new Interstate 85 interchange. This project represents the first use of prefabricated substructure elements in the state of Georgia. With the use of a prefabricated substructure, construction time was reduced, impact to traffic was minimized, and worker and work zone safety was increased. The project used the design-build contracting method, which, in combination with the precast construction methods, saved 45% over traditional methods according to Mallela et al. (2013).

Full-height precast columns and precast pier caps were used in this bridge. Figure 2-49 and Figure 2-50 show the column and pier cap installation procedure. The connection between the column and the footing consists of reinforcing bars extending from the footing and grouted into splice couplers embedded at the base of the column. The connections between the columns and bent caps also comprise grouted splice couplers. The splice couplers had a built-in tolerance in order to account for construction errors facilitating the assembly of the substructure elements. The splice coupler detail is shown in Figure 2-51, and a typical column detail is shown in Figure 2-52.

Figure 2-49: Erection of precast columns in the IH-85 Interchange project (Mallela et al. 2013)

Figure 2-50: Precast columns and pier caps in the IH-85 Interchange project (Mallela et al. 2013)

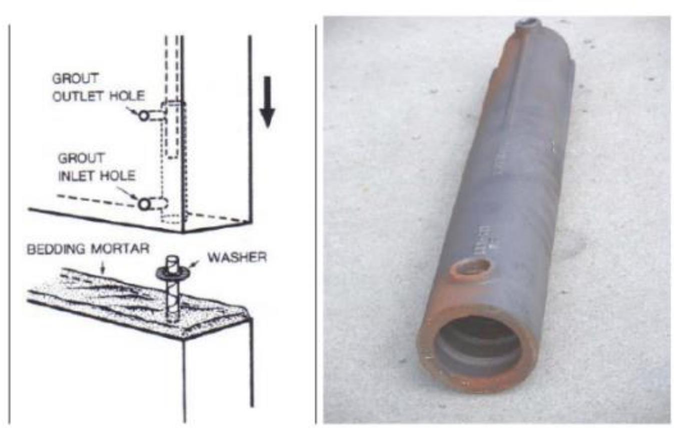


Figure 2-51: Coupler used to splice rebar used in the IH-85 Interchange project (Mallela et al. 2013)

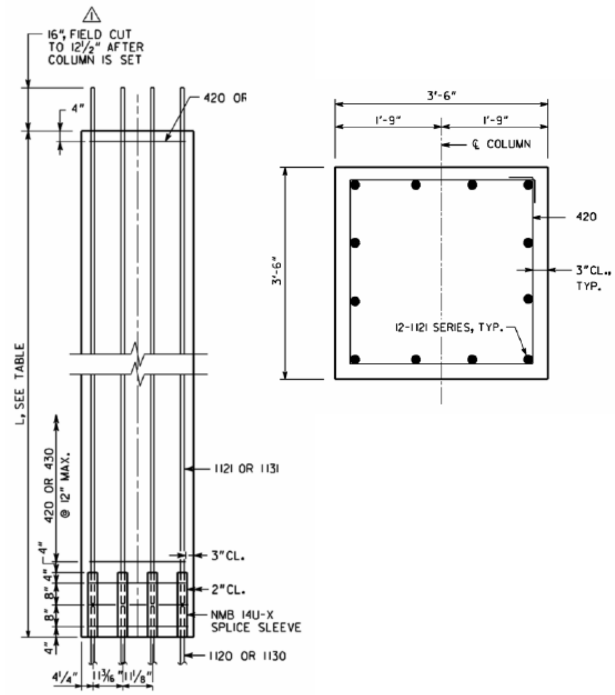


Figure 2-52: Column detail used in the IH-85 Interchange project (Mallela et al. 2013)

2.3.6. Keg Creek Bridge (Iowa)

The existing US 6 Bridge over the Keg Creek in Iowa was replaced in 2014 using a completely prefabricated structure. The use of prefabricated elements reduced the time the bridge was out of service to 16 days, which implied significant benefits to the mobility of the area. Figure 2-53 shows the installation of the full-height precast columns in the new Keg Creek Bridge. The project was the first bridge to use grouted splice couplers in Iowa. Individual grouting was used instead of mass grouting. Figure 2-54 and Figure 2-55 show the column connection to the column cap and drilled shaft respectively. Based on the project experience, it was recommended to have templates for the grouted splice connections given their reduced tolerances.

Figure 2-53: Precast column installation using grouted splice couplers in Keg Creek Bridge (Littleton 2013)

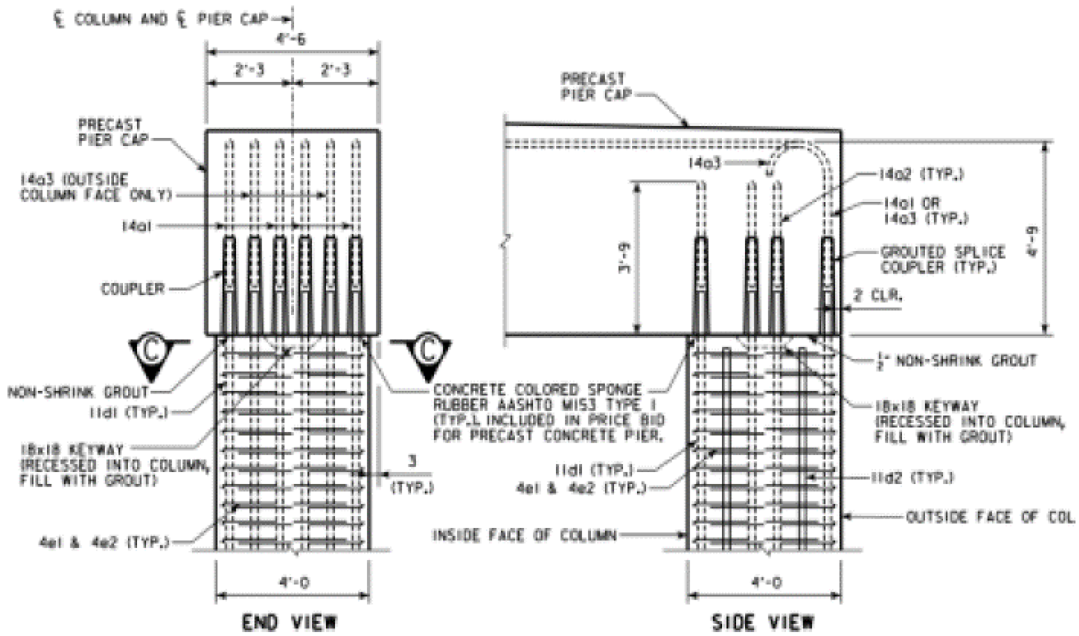


Figure 2-54: Precast column-to-cap beam connection in Keg Creek Bridge (Littleton 2013)

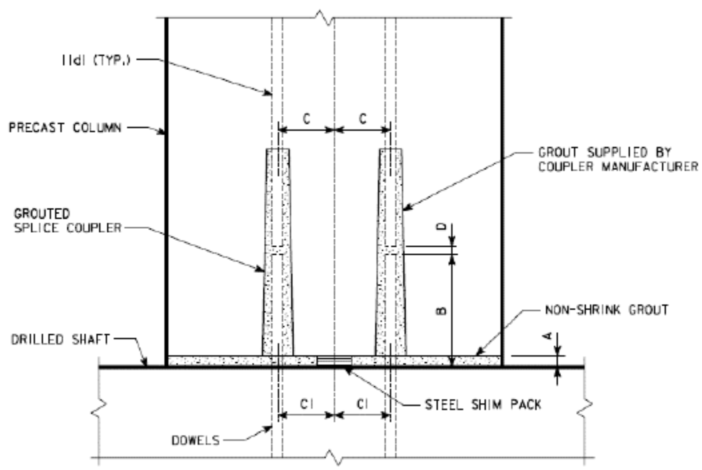


Figure 2-55: Precast column-to-footing connection in Keg Creek Bridge (Littleton 2013)

2.3.7. Parkview Avenue over US 131, Kalamazoo (Michigan)

In 2008, the Michigan DOT built the first ABC project in the state. The Parkview Bridge in Kalamazoo has four spans and three lanes. Piers, abutments, I-beam girders, and full-depth deck panels were all prefabricated off-site. Four 10-ton round precast columns were used for each interior support (see Figure 2-56). CIP footings contained square pockets at the column locations, and column longitudinal steel extended into the pockets and was grouted in place. Columns were connected to the precast caps by means of column longitudinal rebar extensions grouted into vertical metal corrugated ducts embedded in the cap beams. The ducts had a diameter of 4 in. Difficulties in aligning the column bars and the corrugated ducts in the cap beam have been reported by Attanyake et al. (2012). Figure 2-57 through Figure 2-59 show the bridge at different construction stages.

Figure 2-56: Precast columns in casting yard in Parkview Avenue Bridge (Attanyake et al. 2012)

Figure 2-57: Precast column-to-footing connection in Parkview Avenue Bridge (Attanyake et al. 2012)

Figure 2-58: Precast bent cap being erected in Parkview Avenue Bridge (Attanyake et al. 2012)

Figure 2-59: Parkview Avenue Bridge in service (Attanyake et al. 2012)

2.3.8. Cross Westchester Expressway Viaducts, New York City, New York)

The Cross Westchester Expressway Viaducts were constructed in the 1990s. The project included precast segmental hollow columns to speed up the construction of the 24 piers comprising the viaducts. While this approach can be expensive for small projects, it can be fast and economical for multiple span bridges with heavy traffic.

Figure 2-60 shows the precast pier after construction, and the pier-footing connection is shown in Figure 2-61. As shown in Figure 2-62, the lowest precast column element was placed on a grout bed. Intermediate joints were connected and bonded with epoxy adhesive. Shear was transferred between different match-cast segments by means of shear keys. Post-tensioning rods were embedded in the CIP footing and spliced with couplers at several levels. Once the segments were in place, the entire pier was post-tensioned. Figure 2-63 shows a drawing of the full pier.

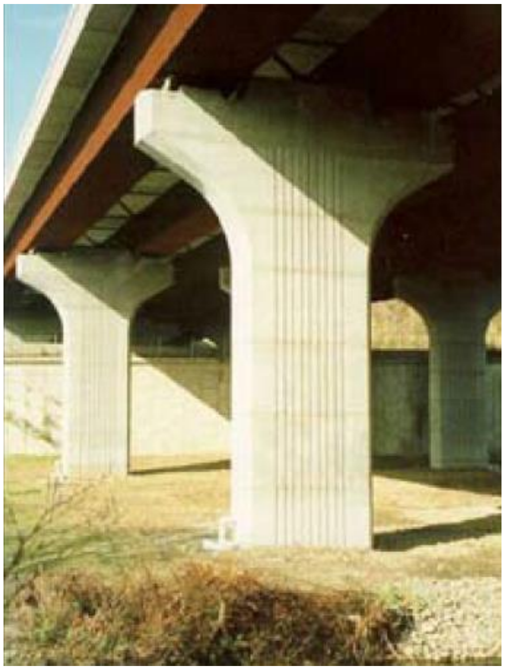


Figure 2-60: Pier after construction in Cross Westchester Expressway Viaduct (FHWA 2009)

Figure 2-61: Pier-footing connection in Cross Westchester Expressway Viaduct (FHWA 2009)

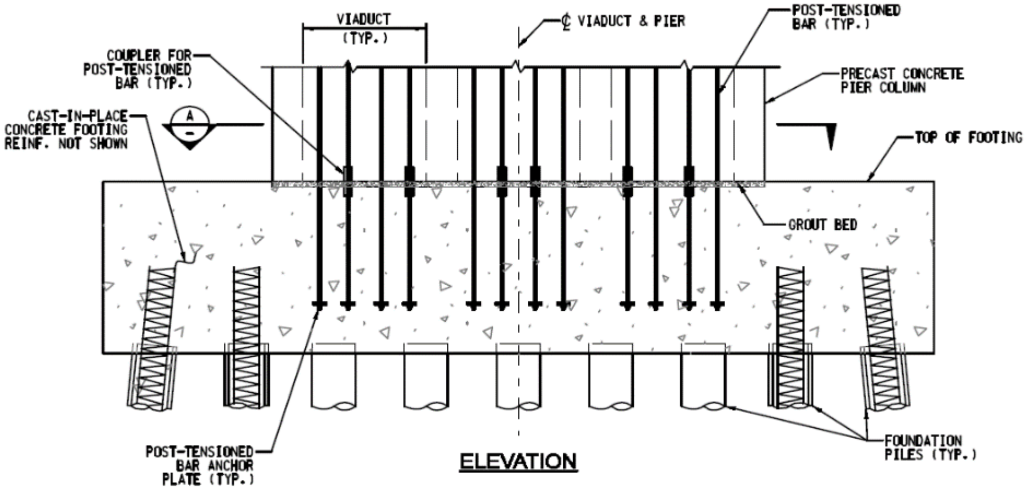


Figure 2-62: Precast concrete pier-to-footing detail in Cross Westchester Expressway Viaduct (FHWA 2009)

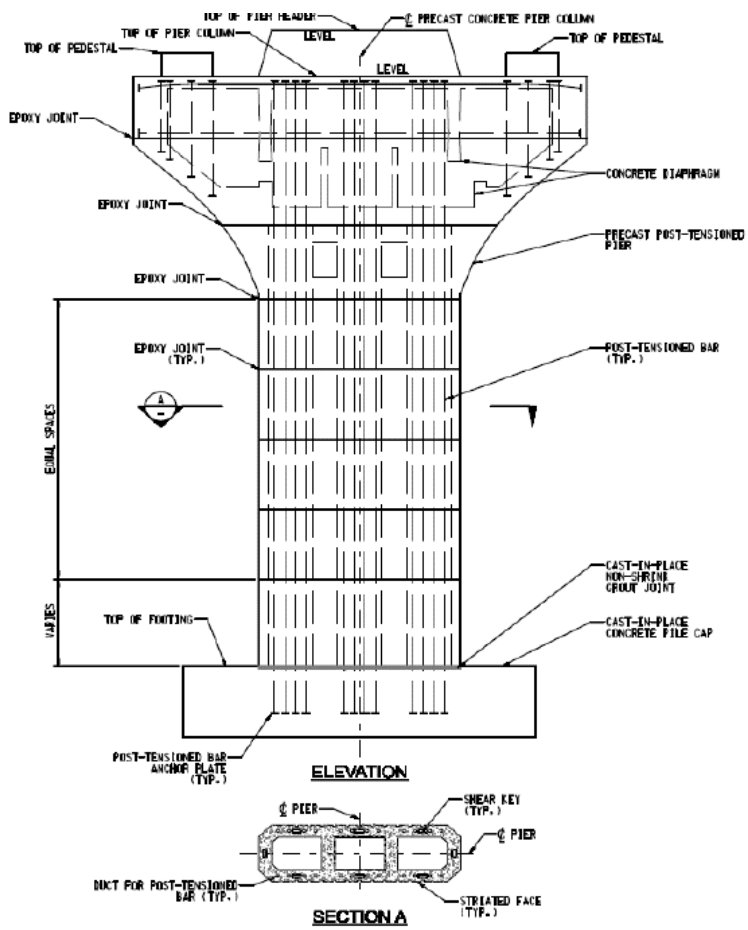


Figure 2-63: Precast concrete piers details in Cross Westchester Expressway Viaduct (FHWA 2009)

2.3.9. Louetta Road Overpass, Houston (Texas)

This three-span bridge project, which was the first project in the United States to fully use high-strength concrete in all aspects of design and construction, was an upgrade of the Texas State Highway 249 and was completed in the early 1990s (Ralls and Carrasquillo 1994). The bridge substructure consists of individual hollow post-tensioned piers that were match-cast and used 10,000 psi concrete. The segments were post-tensioned from the top of the column capital. This pier system was selected for aesthetic reasons, practical and economical construction, and time and costs reduction. The bottom segment of the column was filled with concrete as a protection from possible vehicle collision (Medlock et al. 2002). Figure 2-64 shows the assembly of a typical precast segmental column, and Figure 2-65 shows a photograph of the completed precast piers.

Figure 2-64: Assembly of Precast Segmental Columns in Louetta Road Overpass (Hewes 2013)

Figure 2-65: Completed Precast Columns and Cap in Louetta Road Overpass (Hewes 2013)

2.3.10. LP 340/SH 6 at IH 35, Waco (Texas)

In the late 2000s, four multi-span bridges were constructed on LP 340 over IH 35 in Waco using full-height precast column shells infilled with CIP concrete. The column shells, which had 7-inch-thick walls, were lowered down over the column cages, secured in place, and filled with CIP concrete. The use of column shells eliminated the need for column forms and accelerated the construction process. The use of a CIP core reduced the weight of the precast elements, which allowed the use of larger elements and eased the handling on site. However, this concept presented some limitations related to the grade control and reduced effective depth of the column longitudinal reinforcement, as reported by Hewes (2013). Figure 2-66 through Figure 2-70 show various stages of construction of the LP-340/SH-6 bridges.

Figure 2-66: Shipping precast column shells into place, LP 340 over IH 35 (Wolf 2005)

Figure 2-67: Lifting precast column shells into place, LP 340 over IH 35 (Wolf 2005)

Figure 2-68: Precast column shells before core filling, LP 340 over IH 35 (Wolf 2005)

Figure 2-69: Precast column shells before core filling, LP 340 over IH 35 (Wolf 2005)

Figure 2-70: Base of precast column shell after core concrete filling, LP 340 over IH 35 (Wolf 2005)

2.3.11. US 183 Elevated Highway in Austin (Texas)

The US 183 segmental viaduct in Austin was constructed in the 1990s. The original design comprised three types of precast piers. However, the contractor used precast elements for the largest piers only as the first two pier types were relatively short, which made CIP construction adequate. The used precast piers (see Figure 2-71), ranging in height from 27 ft to 71 ft, were designed as hollow, octagonal segmental columns. The segmental piers were post-tensioned from the top segment. Figure 2-72 shows the general configuration of the large precast pier, and Figure 2-73 shows the pier during construction.

Figure 2-71: Completed US 183 Elevated Highway (Billington et al. 1998)

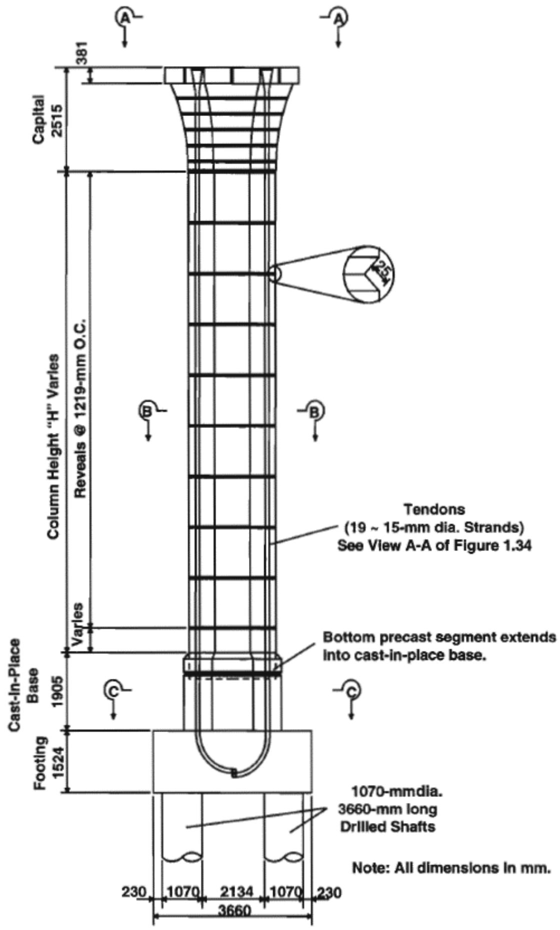


Figure 2-72: Typical Large ramp pier in US 183 bridge: elevation view (Davis et al. 1998)

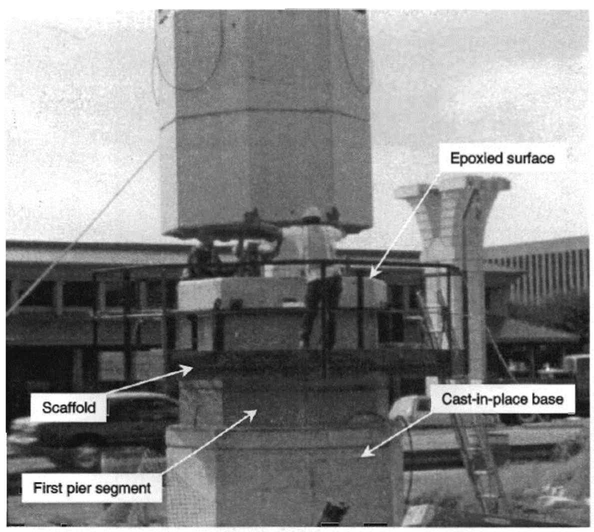


Figure 2-73: CIP base forming a rigid moment connection between base segment PC16-1 and foundation in the US-183 bridge (Davis et al. 1998)

2.3.12. Riverdale Road over IH 84, Riverdale (Utah)

This two-span bridge, completed in 2008, is a replacement project that accommodates a Single Point Urban Interchange (SPUI) over Interstate 84 in Riverdale, Utah. The interior pier consists of four separate precast caps, each supported on two precast segmental columns (see Figure 2-74 and Figure 2-75) founded on steel HP piles. Post-tensioning bars and ducts, dead anchor accessories, and anchorage zone reinforcement were placed in the footing forms. After the specified footing strength was achieved, the precast columns were erected over the post-tensioning bars embedded in the footings. Precast segments were epoxy coated prior to erection. After the top segment was erected and the epoxy reached its specified strength, the vertical post-tensioning strands were stressed and duct connections were grouted. The precast caps were also post-tensioned to the columns.

Figure 2-74: Riverdale Road Bridge in Utah (Burns 2008)

Figure 2-75: Precast column in Riverdale Road Bridge (Burns 2008)

2.3.13. US 12 Bridge over Interstate 5 (Washington)

The replacement of the US 12 bridge over Interstate 5 in Washington State was accomplished in 2011 using a precast concrete bridge system specifically developed for regions with high seismic hazard (Khalegi et al. 2012). This demonstration project used a new bent system developed by Washington State DOT based on the results of several research studies reported in Section 1 of this report. The proposed system is simple, rapid to construct, and offers excellent seismic performance according to Khalegi et al. (2010). The precast concrete columns were fabricated in segments and were joined by bars grouted in ducts, as shown in Figure 2-77. The precast column was connected to the bent cap using bars grouted in ducts, and a unique socket connection was used to connect the precast column to a CIP footing, as shown in Figure 2-76. These connections were tested at the University of Washington prior to its implementation. The construction sequence for the placement of the column segment into the footing is shown in Figure 2-78.

Based on the contractor's experience in this project, it was concluded that is preferable that the columns be in a single precast piece with the grout connection at the precast bent cap and using a socket connection for the footing. Also, the contractor recommended grouting all joints (joints between column segments and the column-to-cap beam) at one time as that allowed the use of high-pressure grout pump without the risk of accidental lifting of column segments.

Figure 2-76: Socket connection between precast column and footing in US 12 bridge (Khalegi et al. 2012)

Figure 2-77: Placement of column segments in US 12 bridge (Khalegi et al. 2012)

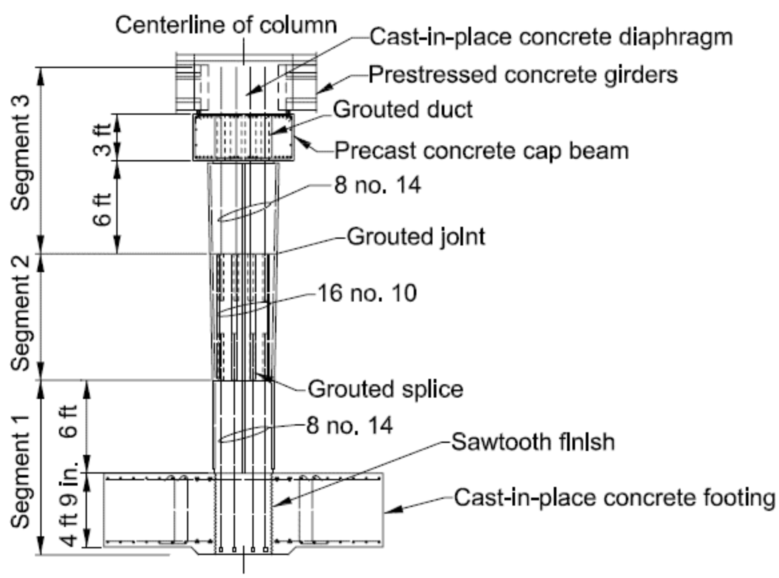


Figure 2-78: Construction sequence for placement of column segment into footing, US 12 bridge (Khalegi et al. 2012)

2.3.14. Rawson Avenue Bridge (Wisconsin)

The Wisconsin DOT's IH-94 North-South Corridor mega-project included the replacement of the two-span bridge crossing IH 94 on Rawson Avenue. Both IH 94 and Rawson Avenue have high traffic volumes, which justified the use of accelerated construction methods for the 2013 bridge replacement. Project goals included limiting the impact to IH 94 to just one 12-hour closure and reducing the Rawson Avenue closure from six months (as required using conventional construction methods) to three weeks. Precast caps and full-height precast columns were used in this project. Figure 2-79 through Figure 2-82 show different stages of the bridge construction. Grouted couplers were used in the column connections, as shown in Figure 2-83.

Figure 2-79: Completed Rawson Avenue Bridge (Olivia 2014)

Figure 2-80: Pier cap erection in Rawson Avenue Bridge (Olivia 2014)

Figure 2-81: Bars extended from the footing in Rawson Avenue (Olivia 2014)

Figure 2-82: Precast column in Rawson Avenue (Olivia 2014)

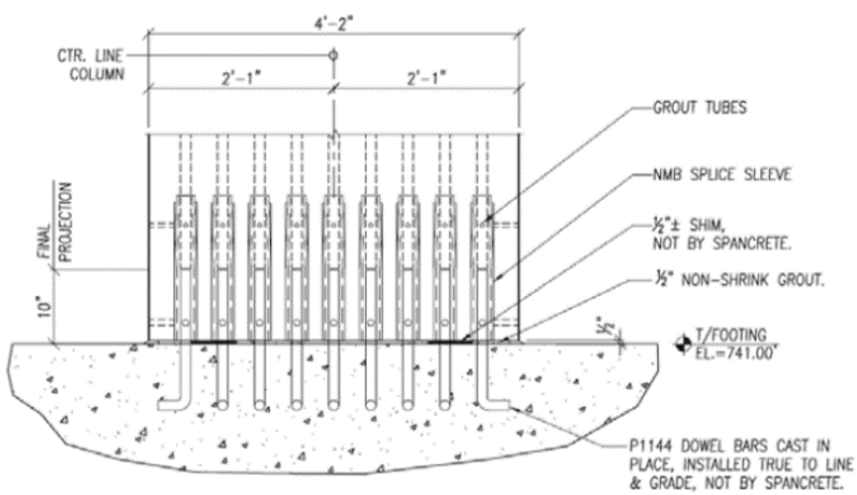


Figure 2-83: Column-to-footing connection detail Rawson Avenue (Olivia 2014)

2.3.15. Siggelkow Road (Wisconsin)

The Siggelkow Road Bridge on IH 39 is part of the IH-39/90 Expansion Project in Madison, Wisconsin. Due to its heavy use, officials decided to use ABC methods. Completed in 2014, it was the first bridge project on IH 39 to use ABC techniques. The project used five 16-5”- tall precast columns, erected over CIP footings (see Figure 2-84 and Figure 2-85). Grouted sleeves were used to connect the precast columns to the footings and pier caps. During construction, the contractor found that the size and location of the couplers left no room for to place stirrups in the column. This required DOT involvement to approve a change in design, but no major delays were reported.

Figure 2-84: Precast column during placement, Siggelkow Road Bridge (source: www.countymaterials.com)

Figure 2-85: Precast columns after being erected, Siggelkow Road Bridge (source: www.countymaterials.com)

Chapter 3. Survey of Current DOT Practice

This chapter presents results of a survey conducted to identify and characterize the current experience of state DOTs with precast bridge columns. An online questionnaire was developed and sent to 50 state DOTs. A total of 39 DOTs responded to the survey (78% response rate). The chapter presents a summary and an analysis of the DOT responses. In addition, Appendix A lists the DOTs that responded to the survey and Appendix B contains a copy of the questionnaire.

3.1. Bridge Projects Involving Precast Columns

Of the 39 state DOTs that responded to the survey, 18 DOTs reported having used precast columns in bridge projects and 21 DOTs reported not having used them at all. Figure 3-1 shows the number of bridge projects that have involved the use of precast columns across different states. Ten (10) DOTs reported having used precast columns in 1 or 2 bridge projects, 5 DOTs (including Texas) reported having used precast columns in 3 to 5 bridge projects, and 2 DOTs (Florida and Utah) reported using precast columns in 6 to 10 bridge projects.

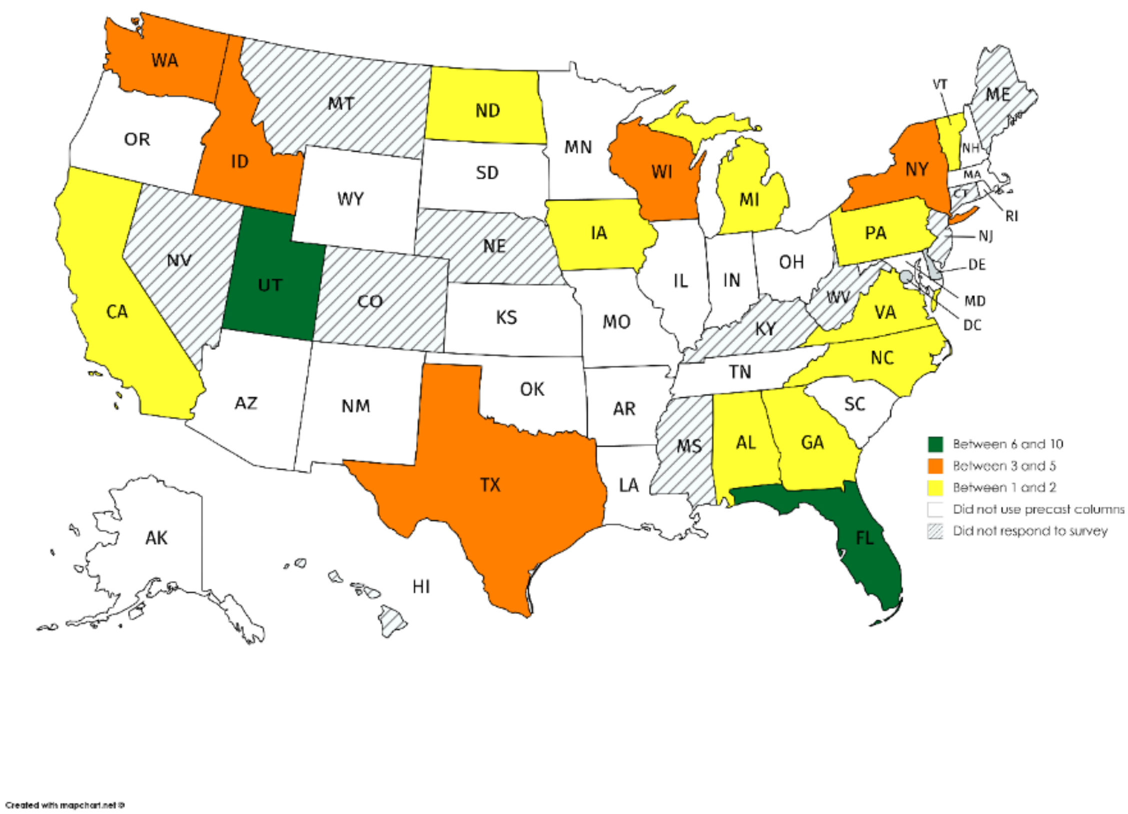


Figure 3-1: Number of bridge projects involving precast columns

3.2. Reasons for Selecting Precast Columns over Conventional Cast-in-place Concrete Columns

For those DOTs with experience in precast column construction, it was very important to understand the reason for selecting precast columns over CIP concrete columns. Figure 3-2 shows the responses of the 18 DOTs that have used precast columns (multiple answers could be selected). All 18 DOTs selected speeding up the construction as one of the reasons or the only reason for using precast columns. Some DOTs selected additional criteria such as improving quality and durability (4 responses), safety (4 responses), and reducing environmental impact (2 responses). A few other reasons were provided by some DOTs, such as construction needs in water/coastal projects, remoteness of the site, using the system as part of a research project, and compatibility with other precast superstructure elements.

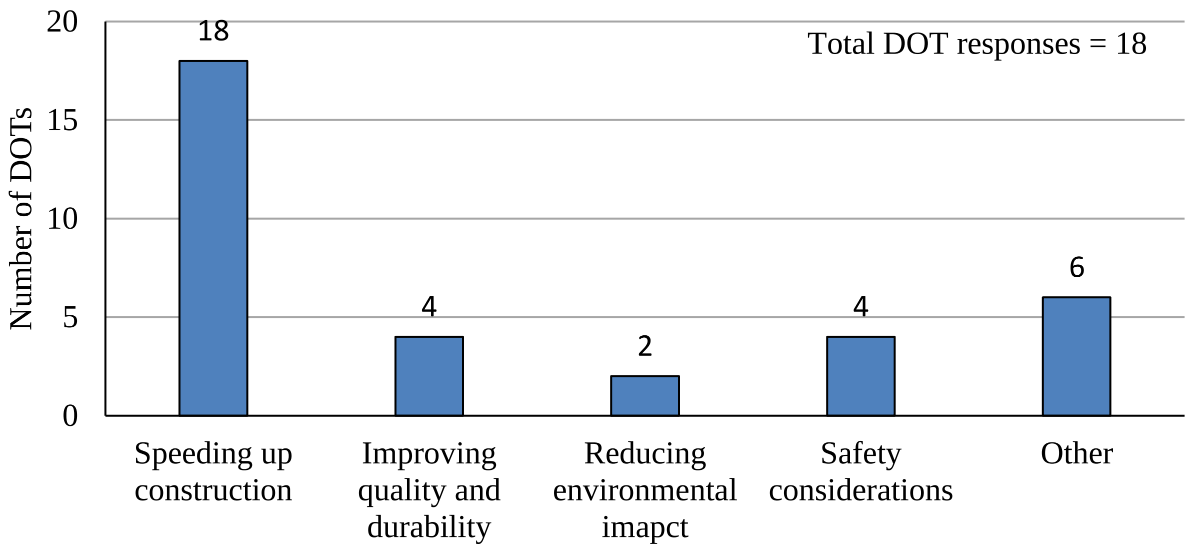


Figure 3-2: Reasons of selecting precast columns over conventional columns

3.3. Types of Precast Column Systems

The survey included a question to identify the type(s) of precast columns used by different DOTs. Three different types of precast systems had been identified in the literature review: full-height columns, segmental columns, and columns shells (brief descriptions of these systems are provided in Appendix B). As shown in Figure 3-3, 15 out of the 18 DOTs with precast column construction experience reported having used the full-height system. Ten (10) out of these 18 DOTs had used the precast segmental system, and only Texas had used the precast shell system (corresponding to the project completed on LP 340/SH 6 at IH 35).

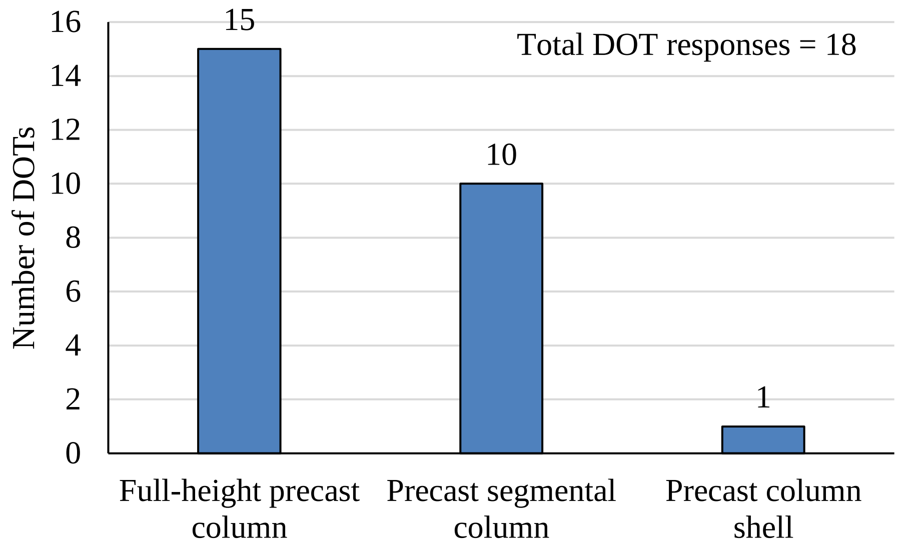


Figure 3-3: Type of precast columns

3.4. Types of Connections

The survey also included a multiple-choice question about the types of connections to adjacent elements, which is one of the critical design and detailing aspects of precast systems. Figure 3-4 shows a summary of the responses from the 18 DOTs with precast column construction experience. According to the results, grouted splice couplers are the most commonly used type of connection (11 DOTs have used this connection). Post-tensioned connections have been used by seven DOTs, and rebar extensions into grouted ducts have been used by five DOTs. Other solutions that are less common are mechanical couplers (two responses), socket-type connection (used by Washington State), and inner CIP connection inside the precast shell (used by Texas).

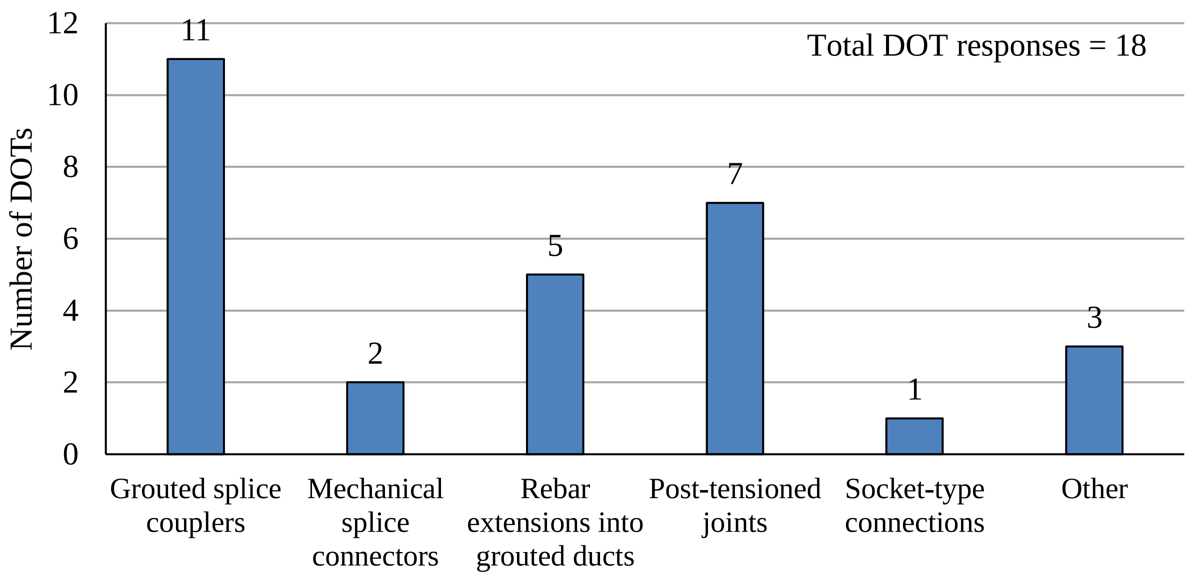


Figure 3-4: Types of connections to adjacent elements

3.5. Construction Costs of Precast Columns vs. Conventional Columns

The DOTs using precast columns were also asked to provide an assessment about the construction cost of these systems as compared to conventional columns (see Figure 3-5). Eleven (11) DOTs responded that precast columns are more costly than conventional CIP solutions, and only one (Utah) reported similar construction costs. The other seven DOTs did not know whether the costs were higher, similar, or lower.

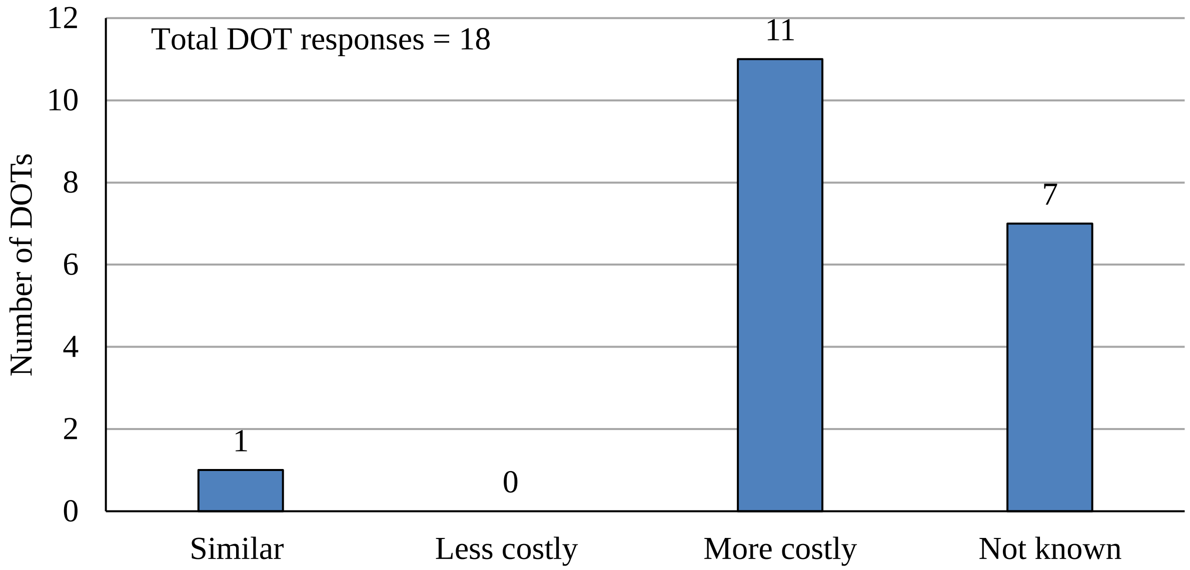


Figure 3-5: Precast columns construction costs vs. conventional columns

3.6. Challenges for the Implementation of Precast Columns

All DOTs were asked to select the main challenges associated to the implementation of precast columns in bridge construction. The responses of DOTs with and without experience in precast column construction have been analyzed separately, given their different degree of familiarity with the system. Figure 3-6 summarizes the responses of DOTs using precast columns and Figure 3-7 summarizes the responses of DOTs not using precast columns. For DOTs with precast column construction experience, most responses indicated that contractors' expertise and cost-effectiveness are the main challenges to the use of these systems. Weight limits, seismic performance, and tolerances were other reported challenges for their implementation. For DOTs with no experiences in precast column construction, the responses were closely distributed among the different options. It is worth mentioning that the lack of awareness of the system and its benefits was identified as one of the main factors hindering the use of precast columns in bridges.

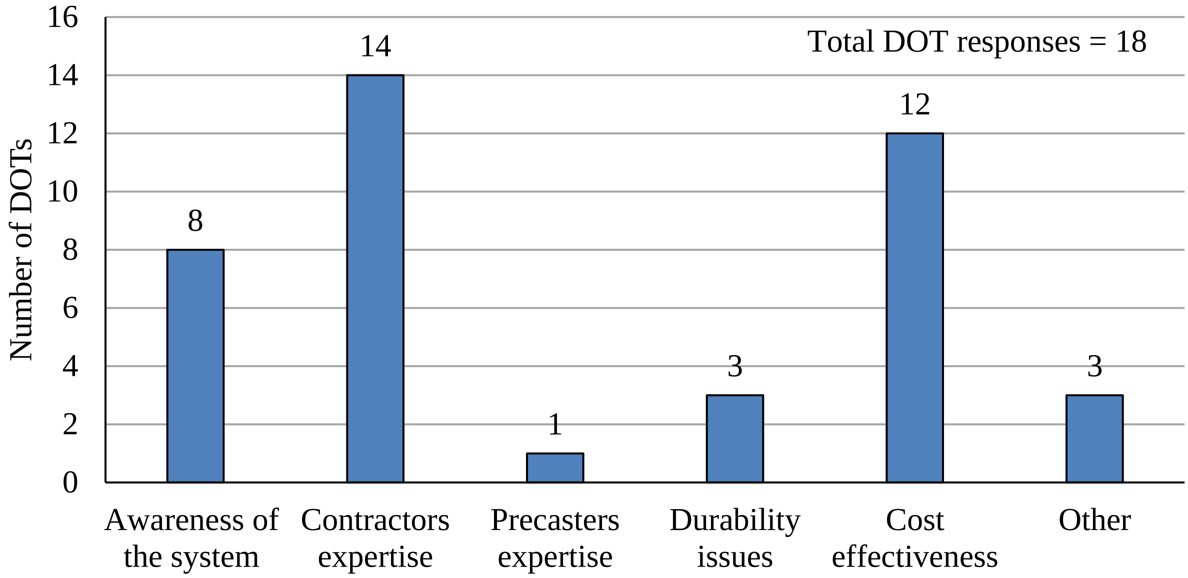


Figure 3-6: Challenges for implementing precast columns (DOTs using precast columns)

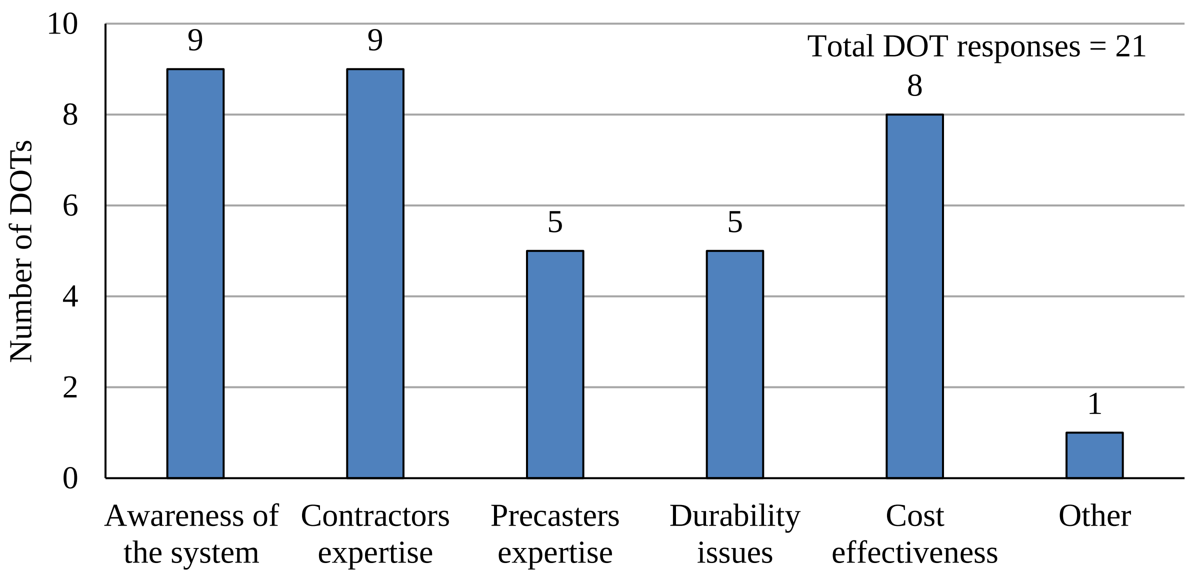


Figure 3-7: Challenges for implementing precast columns (DOTs not using precast columns)

3.7. DOTs' Standards and Guidelines for the Design or Construction of Precast Columns

Most DOTs using precast columns did indicate that they are not following standards or guidelines that are specific for the design or construction of precast columns. Only three DOTs have reported using the following guidelines:

- *Pennsylvania*: PennDOT uses the "Precast Concrete Substructure Standards and Precast Structure Guidelines," which were developed by CABA-Central Atlantic Bridge

Associates. The document includes specifications and details related to the design and construction of precast columns.

- *Utah*: UDOT referred to their manual "Structures Design and Detailing Manual." No specific guidelines for precast columns were identified in this manual, except that mechanical splices (meeting ACI Type 2 requirements) are permitted at the top and bottom of columns.
- *Wisconsin*: The DOT representative referred to a special provision "Special Provisions for Precast Pier Columns and Caps" that describes the manufacture, transportation, storage, installation and bracing as required for precast pier columns and precast pier caps.

3.8. DOTs' Guidelines for Selecting Precast Columns over Conventional Columns

Of all the DOTs that used precast columns, only Wisconsin reported the following policy related to the use of precast columns: "Pier configurations shall be determined by providing the most efficient cast-in-place concrete pier design, unless approved otherwise. When the cast-in-place design can accommodate a precast option, a noted allowance has to be included."

3.9. Serviceability and Durability Issues for Precast Columns

The DOTs that had used precast columns were asked whether they had experienced any serviceability or durability problem with these systems. Virginia was the only one that reported a problem in which a grout failure had resulted in corrosion and strand failure in a segmental column.

3.10. Ongoing Research and Implementation Projects

The DOTs were also asked about ongoing research or implementation efforts related to precast columns. At the time the survey was administered (January 2019), there were five ongoing research projects on precast columns in four different states:

- Precast column connection by using UHPC under seismic loading (California).
- Precast cap to precast column connection (Idaho).
- Design and performance verification of a bridge column/footing/pile system for accelerated bridge construction (Iowa).
- Seismic performance of connections that facilitate accelerated bridge construction (Iowa).
- Synthesis of precast column designs for Texas bridges (Texas).

3.11. DOTs' Additional Comments

An open-ended question was included at the end of the questionnaire to obtain additional feedback from the DOTs regarding the use of precast columns. The comments received addressed a variety of issues concerning the implementation of precast columns, such as construction, contractor preferences, durability, and structural performance. The main comments are summarized below.

A number of comments were received regarding construction procedures and details. For example, California recommended having construction specifications for column bracing. North Carolina reported that construction tolerances had slowed down construction. Virginia showed concerns about the different performance of galvanized ducts and plastic ducts, and about the excessive cracking at precast joints and cracking due to shipping. For this reason, the Virginia DOT has required stainless bars at precast joints and corrosion resistant rebar in the precast elements. They have also restricted the location of column joints so they can be inspected after construction on all four sides (they will need to be above ground and above barriers if barriers are within 2 ft of the columns).

A number of comments addressed the involvement of contractors and fabricators. Both Georgia and Washington responded that contractors prefer CIP construction for columns as time savings is not an issue. Texas considered that improvements should be made in time savings to increase the potential of precast columns, and that there should be more engagement of local fabricators and contractors. Michigan mentioned that there is little interest in precast columns and the state is moving towards the use of solid walls.

Some DOTs that have not used precast columns have also provided additional comments of interest. Louisiana reported a bad record for the fabrication of precast elements, which leads to a lower quality construction as compared to CIP construction. Alaska, Kansas, Minnesota, Oregon, and South Carolina responded that they have concerns related to the behavior of the connections.

Chapter 4. Synthesis and Evaluation of Existing Precast Systems

This chapter presents a synthesis and evaluation of existing precast column systems based on the findings of the literature review and survey of current DOT practice. Section 4.1 summarizes the different precast column systems and connection details identified in the state-of-the-art review. Section 4.2 presents an evaluation (advantages vs. disadvantages) of the different precast systems and connection details considering aspects such as fabrication, construction time and cost, and durability. A number of recommendations are also made for the implementation of these systems. The evaluation and recommendations have been developed considering lessons learned as reported from the literature, as well as input from industry experts in Texas. The compatibility of the column systems with existing precast bent caps solutions in Texas is discussed in Section 4.3. Finally, Section 4.4 presents a summary of the *Framework for Prefabricated Bridge Elements and Systems Decision-Making* of the Federal Highway Administration (FHWA), which is recommended here to determine when it is advantageous to use precast columns over conventional cast-in-place (CIP) systems.

4.1. Summary of Precast Column Systems Reported in the Literature

This section presents a summary of the precast column systems and connection details identified in the literature review. Different precast systems have been proposed in the literature and some of them have already been used in bridge projects. Several factors contribute to the selection of one system over the other. These factors include, but not are not limited to, bridge span and height, availability of special erection equipment, familiarity of precasters and contractors with the technologies, cost effectiveness, and whether the systems are to be used in a region of high seismicity.

The precast column systems identified in the literature review can be grouped in the following three categories:

- <u>Precast reinforced concrete columns</u>: This system comprises a full-height precast column element that is designed and detailed like conventional CIP reinforced concrete columns (see Figure 4-1a). Connections to foundations and bent caps are typically executed by connecting the column longitudinal bars to the adjacent member using grouted splice couplers or by extending the column longitudinal bars into the adjacent member. These connections must ensure that the bars have sufficient development length within the splice coupler or the embedment region. Another way to connect the precast column to the footing is through a socket connection where the precast column is embedded in the CIP footing prior to concrete casting.
- <u>Precast segmental columns</u>: This system is efficient for tall bridges in which the size of the columns is such that the use of full-height elements is not practical or not possible

due to limitations in weight and dimensions for their transportation and on-site erection. Column segment connections can be made by splicing the vertical reinforcement with grouted splice couplers, or by post-tensioning the joints. Column segments can be either match-cast or epoxy grouted between segments. Figure 4-1b shows a photograph of this type of system.

- Precast concrete column shells: This system comprises precast hollow elements with thin walls that serve as permanent formwork of a CIP concrete core. In the system used in Waco, TX, the precast shell element was lowered down over a column reinforcement cage, secured in place, and filled with concrete (see Figure 4-1c). A similar system developed in Japan uses precast panels as permanent formwork for short solid piers; for taller piers, the panels are used as structural elements to build hollow sections (Ralls et al. 2005). The structural performance of the Japanese system is similar to that of the CIP piers according to experimental testing.

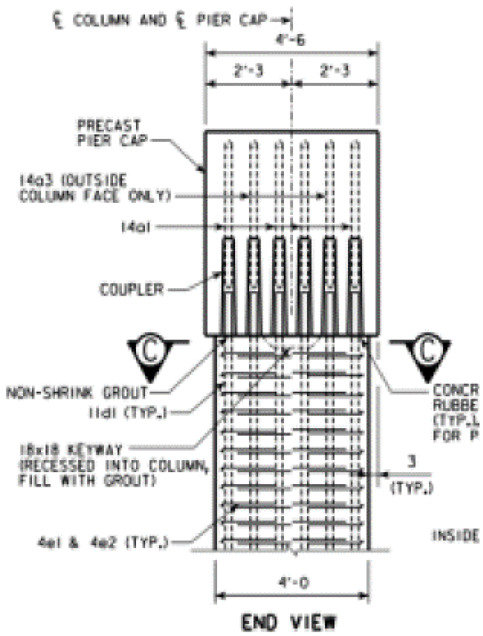
(a) full-height precast column *(b) precast segmental column* *(c) precast column shell*

Figure 4-1: Main types of precast column systems

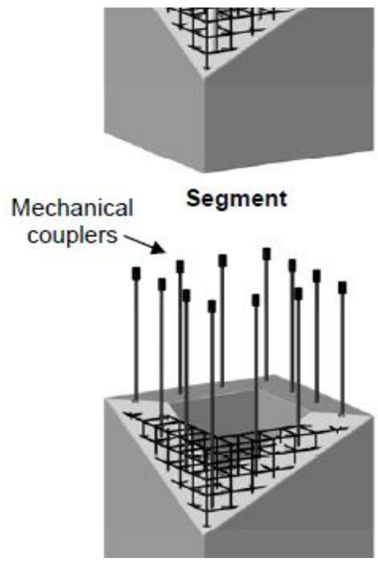
The literature review has also identified the following technologies and details to connect a precast column to a footing or cap beam, and to connect precast column segments together:

- Grouted splice/sleeve couplers (see Figure 4-2a): The connection is executed by splicing the vertical reinforcing bars in grouted coupling devices, which are typically proprietary. Sleeves are first cast in the precast element and are grouted after the connecting reinforcement is inserted into the sleeves during erection.
- Mechanical splice connectors (see Figure 4-2b): Mechanical couplers are used to connect vertical reinforcing bars extending from the column or adjacent member.

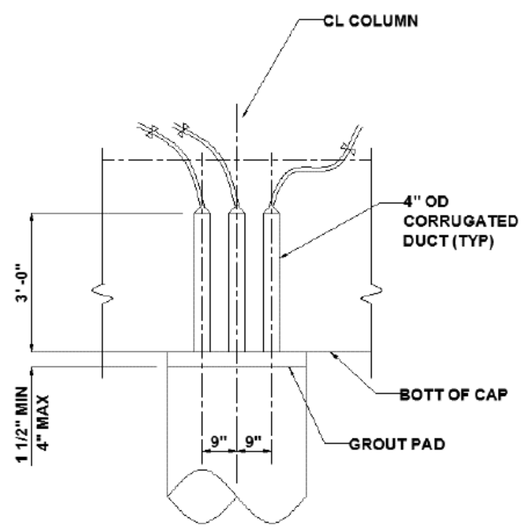
- Rebar extension into corrugated ducts (see Figure 4-2c): These connections use corrugated ducts that are installed in the precast element during fabrication. During erection, the vertical bars are inserted into those ducts before grouting is applied.
- Rebar extensions into grouted pockets (see Figure 4-2d): This type of connection requires voided pockets in the adjacent elements. During erection, rebars extending from the columns are inserted into the pockets before grouting is applied.
- Post-tensioned joints (see Figure 4-3a): Post-tensioning steel bars are installed in the column elements and adjacent members. The bars are coupled at the joint levels and post-tensioned.
- Socket-type connections (see Figure 4-3b): This connection is executed by extending the precast column into the footing and casting the reinforced concrete footing around it.



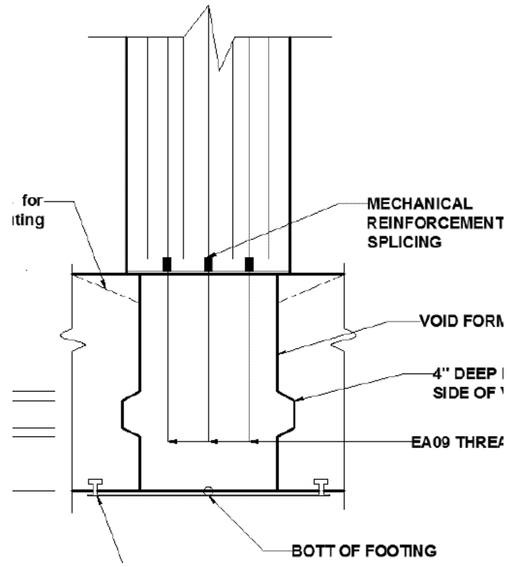
(a) Grouted splice/sleeve couplers



(b) Mechanical splice connectors

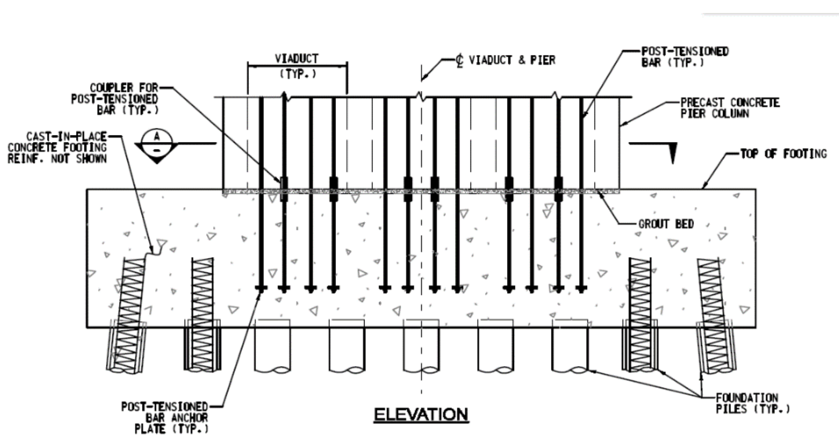


(c) Rebar extended in to corrugated ducts

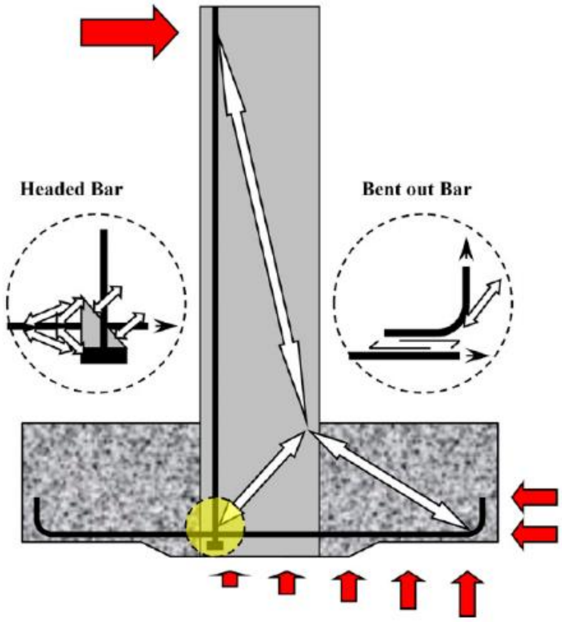


(d) Rebar extensions into grouted pockets

Figure 4-2: Summary of precast column connection details (1/2)



(a) Post-tensioned joints



(b) Socket-type connections

Figure 4-3: Summary of precast column connection details (2/2)

4.2. Evaluation of Existing Precast Column Systems

An evaluation of the different precast column systems and connection details is presented in this section. Table 4-1 presents advantages, disadvantages, lessons learned, and recommendations for the three types of precast column systems identified in the literature review (full-height, segmental, and precast shell systems). In addition to the system-specific recommendations of Table 4-1, the following recommendations apply to all systems: precast column cross-sections should be standardized to minimize fabrication costs; hollow sections are recommended over solid sections to reduce column weight; some level of prestressing is recommended to prevent excessive cracking of the column during shipping.

Table 4-1: Evaluation of precast column systems

Precast reinforced concrete column	
Advantages	▪ Most practical system in terms of fabrication and construction because it has fewer connections.
Disadvantages (limitations)	▪ The self-weight and height of the system is limited by erection equipment capacity. As a result, it is not feasible for large/tall piers.
Lessons learned/ Recommendations	▪ Rectilinear cross-section shapes are preferred over curvilinear geometries for fabrication (Atkan and Attanayake 2013). ▪ A study conducted by Fouad et al. (2006) for the Alabama DOT recommended a maximum slenderness ratio of 100. ▪ The weight of the precast column will be limited by the capacity of the lifting equipment. As a general guideline, it is recommended that the weight of the column does not exceed the weight of the girders so that the same crane can be used. For example, for a bridge with 150-ft long TxGirder Tx70, the maximum weight would be around 150 kips.
Additional comments	▪ This system has not been used in Texas.
Precast segmental column	
Advantages	▪ Efficient for tall bridges when the use of a full-height column is not feasible. ▪ Provides more flexibility for columns with large cross-sections.
Disadvantages (limitations)	▪ More work is required to connect the column segments.
Lessons learned/ Recommendations	▪ Using taller segments can speed up construction. ▪ Epoxied match-cast is in general preferred over “dry” match-cast (more efficient assembly, good durability, and avoids crushing of segment edges). ▪ Hollow sections may require the bottom segment be filled with concrete for protection from vehicle collision. ▪ FHWA (2009) suggests performing a dry fit-up of each connection in the shop before shipping.
Additional comments	▪ This system has been used in US 183 Elevated Highway, Austin, TX, and Louetta Road Overpass, Houston, TX.

Table 4-1: Evaluation of precast column systems (cont.)

Precast concrete column shell	
Advantages	▪ Reduced weight. Allows for larger cross-section size and column heights.
Disadvantages (limitations)	▪ Grade control is challenging during the erection of the column. ▪ The system employed in Waco, TX required installing a reinforcing cage in the CIP core. Not placing main reinforcement in the shell leads to reduced effective depth of the section and does not provide significant time saving.
Additional comments	▪ This system has been used in the project at LP 340/SH 6 at IH 35, Waco, TX. ▪ Non-shrink concrete is recommended to avoid reduction bond between the fill concrete and the shell.

The following five different connection details, which are the most common for precast columns, have been evaluated: grouted ducts, grouted splice couplers, post-tensioned joints, socket connection, and pocket connection. Table 4-2 presents the type of joints for which these details have been used. Table 4-3 presents the advantages, disadvantages, lessons learned, and recommendations for each of these five connection details.

Table 4-2: Connection details per joint type

Connection detail	Column to cap beam	Column to footing	Column to column
Grouted vertical duct	Yes	Yes	Yes
Grouted splice sleeve coupler	Yes	Yes	Yes
Post-tensioned joints	No	Yes	Yes
Socket connection	No	Yes	No
Pocket connection	Yes [1]	Yes	No

[1] Used in connections between precast bent caps and CIP columns

Table 4-3: Evaluation of recommended connections

Grouted vertical duct	
Advantages	▪ This connection accommodates large tolerances. ▪ The system is not expensive. ▪ The connection results in less interference with reinforcement as compared to pocket connections.
Disadvantages (limitations)	▪ Durability problems can be present due to relatively large exposed surface.
Lessons learned/ Recommendations	▪ Moisture penetration can be prevented by applying a sealant at duct locations.
Additional comments	▪ Ducts can be standard post-tensioned ducts. ▪ The connection is ranked level 1 (highest rank in terms of frequency of use and effectiveness) according to FHWA (2009). ▪ The connection is frequently used in Texas. ▪ Using large-diameter bars provides equivalent structural performance (Pang et al. 2008) with reduced congestion and improved constructability.
Grouted splice sleeve coupler	
Advantages	▪ Reliable performance in the bridge construction industry. ▪ Full development of longitudinal can be provided. ▪ No durability problems are expected due to minimal exposed surface.
Disadvantages (limitations)	▪ Couplers are typically proprietary, which can lead to higher costs. ▪ Higher construction skills are required due to very tight tolerances. ▪ Pressure grouting required.
Lessons learned/ Recommendations	▪ Template is recommended to improve the erection process. ▪ Temporary supports are required until the grout in the couplers cures. ▪ Shim packs can be used for grade control. Polymer shim material are better than metallic shim material.
Additional comments	▪ Utah DOT relies solely in this connection system. ▪ The connection is ranked level 1 (highest rank in terms of frequency of use and effectiveness) according to FHWA (2009). ▪ The following are manufacturers of grouted splice couplers: Splice Sleeve North American (“NMB Splice Sleeve”) Dayton Superior (“Dayton Superior DB Grout Sleeve”) ERICO United States (“Lenton Interlok”) ▪ Using large-diameter bars provides equivalent structural performance (Pang et al. 2008) with reduced congestion and improved constructability.

Table 4-3: Evaluation of recommended connections (cont.)

Post-tensioned joints	
Advantages	▪ Precast segmental columns system generally requires the use of this type of connection.
Disadvantages (limitations)	▪ The connection execution is time consuming.
Additional comments	▪ The connection is ranked level 1 (highest rank in terms of frequency of use and effectiveness) according to FHWA (2009).
Socket connection	
Advantages	▪ This type of connection provides very good structural performance according to experimental tests (Haraldsson et al. 2013). ▪ Better constructability can be achieved since no bars cross the footing bar interface. ▪ Grouting is not required.
Disadvantages (limitations)	▪ Footing needs to be casted after column erection is done.
Lessons learned/ Recommendations	▪ Column embedment region should be roughened. ▪ Column embedment is required to be 1.1 times the column dimension according to Haraldsson et al. (2013)
Additional comments	▪ This type of connection has only been used in Washington State.
Pocket connection	
Advantages	▪ This connection provides largest tolerances. ▪ The system is not expensive. ▪ The connection can be used with grout or concrete.
Disadvantages (limitations)	▪ Durability problems can be present due to large exposed surface. ▪ The interference with reinforcement leads to reinforcement congestion problems and possibly result in large spacing between rebars.
Lessons learned/ Recommendations	▪ Moisture penetration can be prevented by applying a sealant at duct locations.
Additional comments	▪ The connection is frequently used in Texas.

4.3. Compatibility with Precast Bent Solutions for Texas Bridges

In the last two decades, several bridges have been constructed in Texas using precast bent caps. Figure 4-4 shows the bent cap system used in the State Highway 66 crossing over Lake Ray Hubbard near Dallas. Research funded by TxDOT has examined the constructability and structural behavior of the connection of precast bent caps and CIP columns using different details (Matsumoto et al. 2001) and the performance of grouted vertical ducts in precast bent caps (Brenes et al. 2006). Based on the research findings, TxDOT established standard connection cap to column details, such as the one shown in Figure 4-5.

The two most common connections used by TxDOT are the pocket connections and the grouted vertical duct connection. In the pocket connection, the precast bent cap is voided at the location of the columns where the column longitudinal reinforcement is extended. The pockets are then filled with concrete or grout (see Figure 4-6a). The grouted vertical duct connections incorporate the use of corrugated ducts embedded in the bent cap during fabrication in order to house the column reinforcement after which those ducts are grouted (see Figure 4-6b). Although the bent cap system has been developed and used for CIP columns, the system can be used with precast columns as well. Mockups can be used to ensure proper alignment of the precast column reinforcement with the existing corrugated ducts in the bent cap. The available flexibility in precast fabrication can easily allow to produce precast column systems that match the aesthetics of the used bent caps and super structure in Texas.

(a) Grouted-duct connection (b) Placement of precast concrete bent cap

Figure 4-4: Precast concrete bent cap system used in the State Highway 66 crossing over Lake Ray Hubbard near Dallas (Matsumoto et al. 2008)

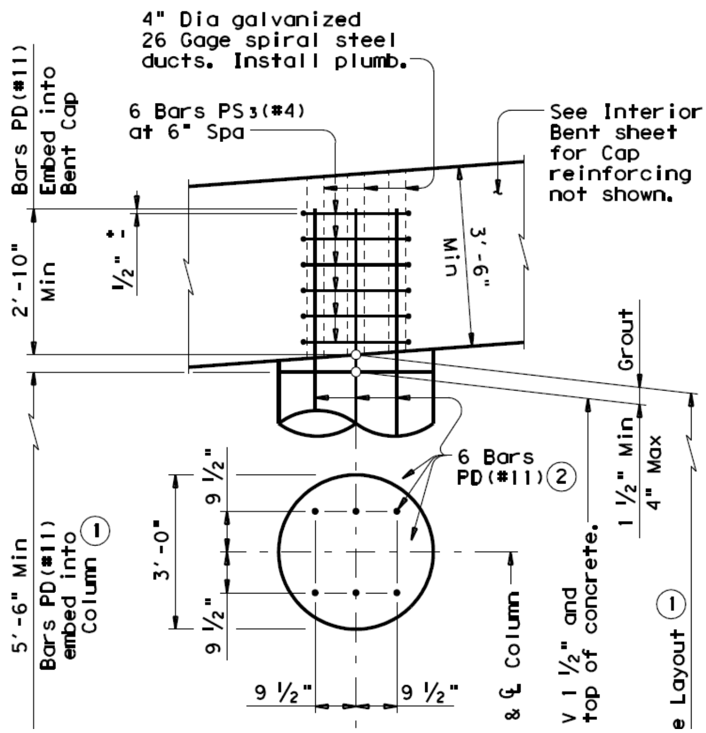
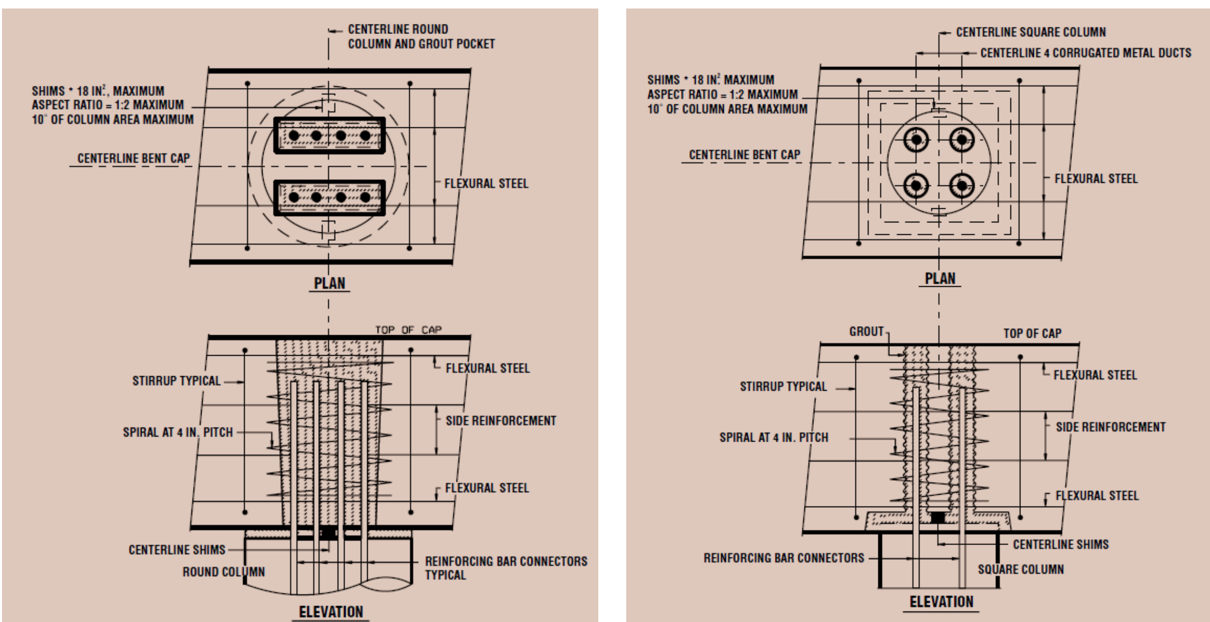


Figure 4-5: Standard connection between precast bent cap and round CIP column



(a) Pocket connection (b) Grouted duct connection

Figure 4-6: Bent cap connections (Matsumoto et al. 2008)

4.4. Criteria of Selecting Precast Columns over CIP Columns

The research team recommends using the *Framework for Prefabricated Bridge Elements and Systems Decision-Making of the Federal Highway Administration* (FHWA 2006) as the decision-making tool for selecting precast column systems over CIP columns. This framework provides criteria and a decision-making procedure for using prefabricated bridge elements, so it is also applicable to precast columns. Figure 4-7 and Figure 4-8 present the decision flow-chart and supporting questions to consider in this framework.

In summary, the decision-making framework proposed by FHWA (2006) considers the specific needs of a bridge project for rapid onsite construction as well as other project considerations. The benefits of rapid construction are evaluated in terms of the average daily traffic of the bridge, impact of lane closures and detours, and the need to complete bridge construction within a specific time due to emergency requirements. In addition to rapid construction requirements, prefabricated construction can be recommended due to safety issues, environmental reasons, cost-effectiveness reasons resulting from standardizing sections, and specific site issues. A cost analysis is essential in the decision-making process. This analysis includes traffic-related costs, contractor's operations, owner agency's operations, and the service life of the bridge project. The final decision should be based on a comprehensive objective evaluation that takes into account all the criteria presented in Figure 4-7 and Figure 4-8.

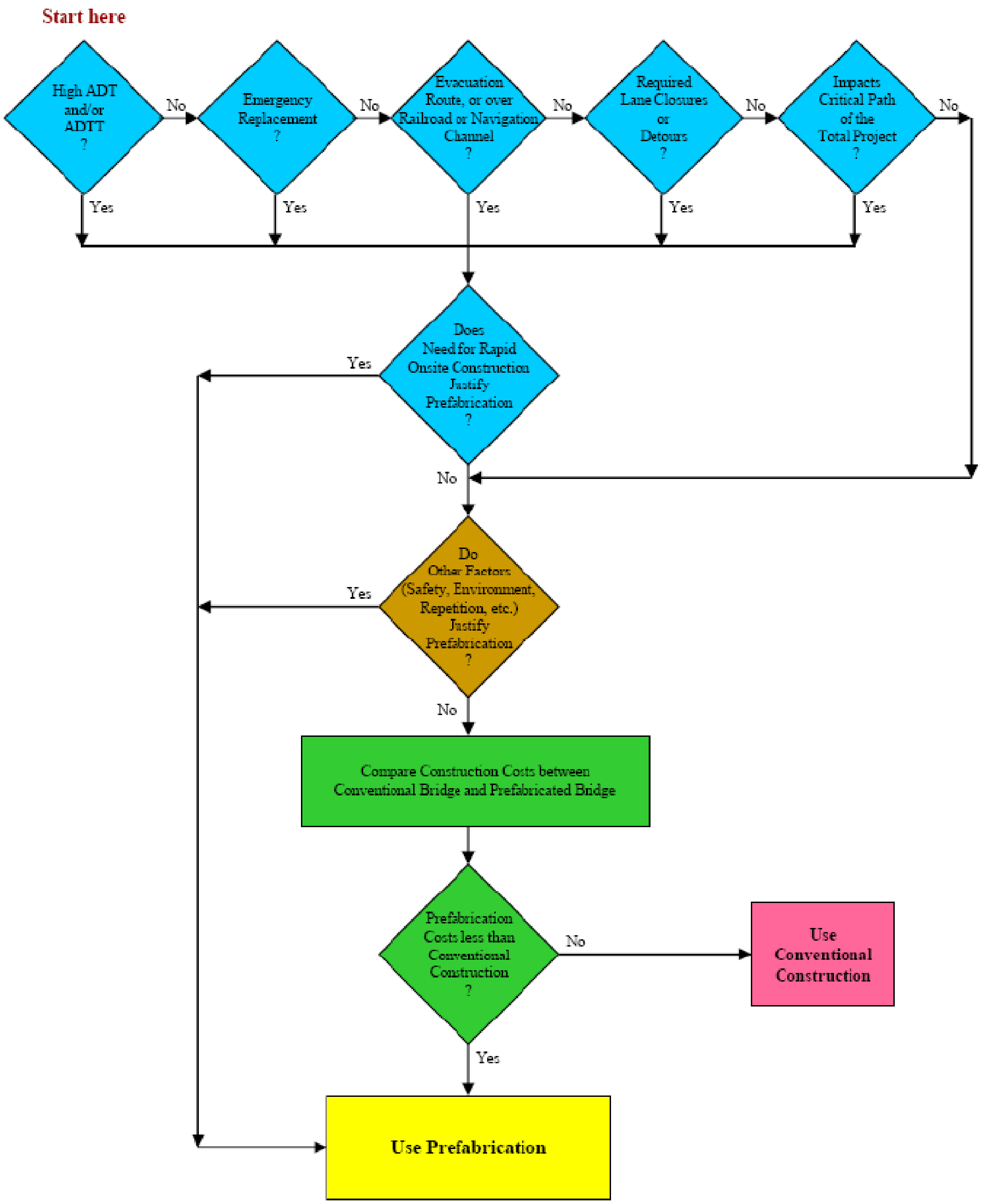


Figure 4-7: Flowchart for high-level decision for bridge prefabrication (FHWA 2006)

Question	Yes	Maybe	No
Does the bridge have high average daily traffic (ADT) or average daily truck traffic (ADTT), or is it over an existing high-traffic-volume highway?			
Is this project an emergency bridge replacement?			
Is the bridge on an emergency evacuation route or over a railroad or navigable waterway?			
Will the bridge construction impact traffic in terms of requiring lane closures or detours?			
Will the bridge construction impact the critical path of the total project?			
Can the bridge be closed during off-peak traffic periods, e.g., nights and weekends?			
Is rapid recovery from natural/manmade hazards or rapid completion of future planned repair/replacement needed for this bridge?			
Is the bridge location subject to construction time restrictions due to adverse economic impact?			
Does the local weather limit the time of year when cast-in-place construction is practical?			
Do worker safety concerns at the site limit conventional methods, e.g., adjacent power lines or over water?			
Is the site in an environmentally sensitive area requiring minimum disruption (e.g., wetlands, air quality, and noise)?			
Are there natural or endangered species at the bridge site that necessitate short construction time windows or suspension of work for a significant time period, e.g., fish passage or peregrine falcon nesting?			
If the bridge is on or eligible for the National Register of Historic Places, is prefabrication feasible for replacement/rehabilitation per the Memorandum of Agreement?			
Can this bridge be designed with multiple similar spans?			
Does the location of the bridge site create problems for delivery of ready-mix concrete?			
Will the traffic control plan change significantly through the course of the project due to development, local expansion, or other projects in the area?			
Are delay-related user costs a concern to the agency?			
Can innovative contracting strategies to achieve accelerated construction be included in the contract documents?			
Can the owner agency provide the necessary staffing to effectively administer the project?			
Can the bridge be grouped with other bridges for economy of scale?			
Will the design be used on a broader scale in a geographic area?			
Totals:			

Figure 4-8: Matrix questions for high-level decision for bridge prefabrication (FHWA 2006)

Chapter 5. Conclusions and Recommendations

This chapter includes a summary of the main findings and conclusions of this synthesis project on the use of precast column systems in bridge construction. Based on the literature review and a survey of state DOTs' practice, as well as feedback from some industry experts, a number of recommendations are also made for the implementation of precast columns systems in Texas. Finally, a list of research needs is provided based on the identified knowledge gaps for a successful, statewide implementation of precast column systems in Texas.

5.1. Conclusions

A variety of precast column systems have been used by a number of state DOTs. These systems can be classified into three main types: precast full-height reinforced concrete columns, precast segmental columns, and precast column shells. Their main characteristics are presented next:

- **Precast reinforced concrete column:** This system uses a full-height column that is designed and detailed like CIP columns. According to the DOT survey conducted as part of this study, 15 of 18 the DOTs with precast column experience have already used this system. To date, this system has not been used in Texas. This is one of the most practical systems because it requires fewer connections, but its application may be limited by the column weight and the capacity of erection equipment. At typical scale of concrete bridge substructures, the weight limitations can be quite challenging and may necessitate precasting columns on the job site.
- **Precast segmental column**: This system comprises precast column segments that are joined together through post-tensioning or grouted splice couplers. For some bridge projects, this is the only feasible system due to the height (weight) of the piers. This system has been used in 10 of the 18 DOTs with precast column experience. Texas has used the system twice in the 1990s. As for the connection, the decision between match-cast or grouted joints is project specific, where match-cast can be preferred if there is a lot of repetition. The potential need for post-tensioning of the segments can create an added construction expense and as such may be viewed as a negative in some bridge projects.
- **Precast column shell**: The system comprises a precast shell which is filled with CIP concrete. It was used only once in the U.S. in a bridge in Texas. The system can be used to reduce the weight of the precast column element(s). In the system used in Texas, the shell was used as stay-in-place formwork for a CIP reinforced concrete structural core.

This synthesis project has also identified a number of lessons learned and recommendations that are applicable to different precast column systems. The following conclusions and recommendations are provided regarding the design, construction, and connection of precast columns:

- **Preferred shapes:** Due to fabrication and shipment purposes, cross-sections with straight faces are preferred over circular geometry. The design of the section should be compatible with that of adjacent elements, and in particular with existing precast bent cap solutions for Texas bridges.
- **Limits on weight:** A good criterion for designing precast columns is to limit their weight (or that of the column segments) to the maximum weight of the precast elements in the superstructure. This will allow the contractor to use the same lifting equipment for the erection of the superstructure and substructure. It is important to note that the maximum crane capacity depends on the crane reach, as well. This means that the crane layout on site is a major factor to be considered during the planning phase of the project.
- **Connection details**: A critical aspect of the design and construction of precast column systems is the connection between the column and adjacent members, and between column segments in segmental columns. The research team has summarized and evaluated a number of connection details, including grouted ducts, grouted splice couplers, post-tensioned joints, socket connections, and pocket connections. Specific recommendations for each connection detail are provided in Chapter 4.
- **Column to cap beam connection:** TxDOT has been using successfully precast bent caps in bridge projects with CIP columns. Pockets filled with concrete (or grout) and bars extended into corrugated grouted ducts are the most common connections in Texas. These connections have proven adequate performance and good durability. The same connections could be used with precast columns.
- **Column to column connection:** Post-tensioned joints are commonly used in precast segmental column systems. These connections have a well-established record of use and good performance.
- **Column to footing connection:** Pocket and socket connections, reinforcing bars extending into corrugated grouted ducts, and grouted sleeve splice couplers can be used to connect precast columns to footings. Grouted sleeve splice couplers have been widely used in other states and some state DOTs recommend using them over other types of connections. Socket connections offer some unique advantages and they have been tested under seismic loading and proven structurally adequacy.

5.2. Recommendations for Implementation in Texas

This section presents specific recommendations for the implementation of precast column solutions in Texas based on the findings of this synthesis project. The following recommendations are provided regarding the selection, design, and construction of precast column systems:

- **Selection of precast column system**: The full-height precast column system has a well-established record of implementation in bridge projects in different states. The research team recommends the use of this system when there are no restrictions on the maximum column weight/height because it currently provides the most practical and efficient construction method. When the self-weight of the column is a constraint, the use of precast column shells with a CIP core is recommended. However, the system previously used in Texas in which the reinforcing cage was embedded in the CIP core is not efficient and will not result in significant construction time savings. The design of the precast column shell system should be improved by embedding the steel reinforcement in the concrete shell. This modification will require further investigation as explained in the next section. For tall piers, the precast segmental column system is recommended to overcome height and weight limitations related to transportation and erection.

- **Connection details**: For the column to cap beam connections, the research team recommends using details similar to the standard TxDOT connections for precast bent caps and CIP columns (i.e., pocket connections and connections with column bars extending into corrugated grouted ducts). Post-tensioned joints are recommended for column to column connections (precast segmental column). Several connection details have been identified for the column to footing joints. These include the pocket connection, the corrugated duct connection, the socket connection, and grouted sleeve splice couplers. The selection of one detail over the other depends on the project characteristics and contractor's experience. For example, significant experience is required for a successful execution of grouted connections, such as the grouted sleeve splice couplers, because of their complex execution and tighter tolerances. The grouted duct connections have been used in several bridge projects and could be readily implemented in Texas. The socket connection is a promising solution because of its simplicity but there is currently very limited experience with this type of connection. Further research is recommended for this type of connection.
- **Compatibility with precast bent cap solutions:** The research team recommends that the precast column system be compatible with precast bent cap solutions currently used in Texas to streamline the implementation of precast substructures. This implies using the same type of connection details as for CIP columns and ensuring the architectural and structural compatibility between the bent cap and the column.

Aside from technical considerations, it is very important to have in place guidelines on how to select precast columns over CIP columns and strategies to accelerate their implementation. The following recommendations are provided in this regard:

- **Criteria of selecting precast columns over CIP columns:** None of the state DOTs is using any specific criteria for using precast columns over conventional columns. The research team recommends using the *Framework for Prefabricated Bridge Elements and Systems Decision-Making of the Federal Highway Administration* (FHWA 2006) as the decision-making tool for selecting precast column systems over CIP columns. This framework considers the potential contributions of precast elements to rapid construction, improved safety in the constructions site, improved service life of the bridge, and reduction of environmental impact. The selection of the type of precast column system and connection details will be project specific.

- **Strategies to accelerate implementation:** The use of precast column systems presents several advantages, but in Texas these systems have been employed in only three bridge projects. It is important to develop strategies that raise awareness and incentivize their use in Texas. Texas has a very well established prefabrication industry and producing precast columns will not be an issue. A number of reasons explain the limited use of precast columns, including a lack of familiarity with the system and a lack of experimental substantiation of new structural systems. There are also general durability concerns related to connections, but there are almost no reported durability problems with the connections. Another concern may be the cost, which can be addressed by standardizing column sections. Prior to statewide implementation of precast columns, collaboration between Texas precasters (PCMA), contractors (AGC) and TxDOT is recommended, as part of a research project that develops final structural details in a collaborative fashion.

5.3. Recommendations for Future Research

A number of research gaps and implementation challenges have also been identified in the course of this project. These gaps and challenges will require further research to enable effective and confident use of these systems in Texas. Some of the most important gaps and ideas on possible ways to overcome them are presented next:

- There are a number of uncertainties and concerns related to existing connection details. Splice sleeve coupler connections are the most widely used system, but DOTs have raised concerns about the cost of proprietary systems and complexity of this solution. There is also significant experience with grouted ducts, but the constant evolution of grout technology could contribute to optimize this type of connections. The research team recommends focusing the investigation efforts in footing to column connections. Most of the experimental studies on this type of connections have been conducted for systems subjected to seismic loads. The experimentally validated details could be simplified when considering typical loading conditions in Texas. In addition, socket connections have shown promise but there is very limited experience with them. More research is needed to characterize this type of connections and develop appropriate design recommendations.
- The precast column shell system can be regarded as an alternative to segmental systems when full-height column systems cannot be used due to weight limitations. In the system used in Texas, the shell was basically serving a stay-in-place formwork since the column reinforcing cage was embedded in the CIP core. This design reduces the effective depth of the reinforcement and does not provide major savings. The system could be significantly simplified by embedding the column reinforcing cage in the precast shell, and eliminating the rebar cage within the CIP core. However, the composite action between the shell and the core would need to be investigated to ensure good structural performance.
- There are currently no specific procedures in place to check the durability of connections. Inspection methods and techniques, including non-destructive evaluation techniques,

should be studied to enable a systematic and cost-efficient way for evaluating the condition of connections.

- Aside from potential construction cost savings, the use of precast columns can contribute to reducing traffic disruption (improving traffic flow and driving safety), improving safety in the construction site, and reducing environmental impact. Investigations are needed to quantify these effects and associated indirect cost savings. This would allow a more objective and systematic decision-making approach related to the use of precast columns.

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APPENDIX A: LIST OF DOT RESPONSES

States responding to survey (39)	
States using precast columns (18)	**States not using precast columns (21)**
Alabama	Alaska
California	Arizona
Delaware	Arkansas
Florida	Illinois
Georgia	Indiana
Idaho	Kansas
Iowa	Louisiana
Michigan	Maryland SHA
North Carolina	Massachusetts
North Dakota	Minnesota DOT
New York	Missouri
Pennsylvania	New Hampshire
Texas	New Mexico
Utah	Ohio
Vermont	Oklahoma
Virginia	Oregon
Wisconsin	Rhode Island
Washington	South Carolina
	South Dakota DOT
	Tennessee
	Wyoming

APPENDIX B: SURVEY QUESTIONNAIRE

1. **Please Provide your Name and the DOT you are representing:**

   Name: ________________________________
   DOT: ________________________________

2. **Does you DOT use (or has used) precast concrete columns in bridge construction?**

   - ☐ Yes
   - ☐ No

(Note: DOTs responding "No" to Question 2 were not given the option to respond to Questions 3 through 10)

3. **How many bridge projects have involved precast columns in your DOT?**

   - ☐ Between 1 and 2
   - ☐ Between 3 and 5
   - ☐ Between 6 and 10
   - ☐ More than 10
   - ☐ If you know the exact number, please specify:________________________________

4. **What was the reason of selecting precast columns over conventional cast-in-place concrete columns? Select all that apply.**

   - ☐ Speeding up the construction process
   - ☐ Improving the quality and durability of bridge elements
   - ☐ Reducing the environmental impact
   - ☐ Safety considerations
   - ☐ Other (Please specify): ____

5. What type(s) of precast columns is used by your DOT? Select all that apply.

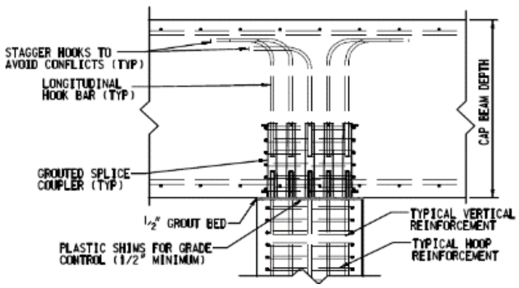
(a) example of full-height precast column

(b) example of precast segmental column

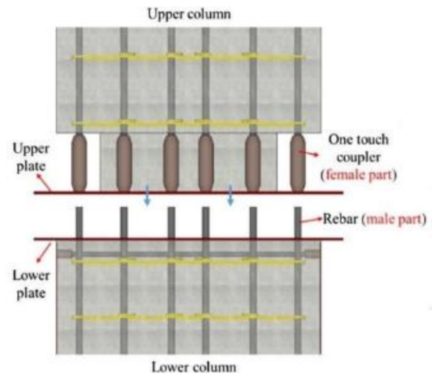
(c) example of precast column shell

- ☐ Full-height precast reinforced concrete column (single precast element designed like a conventional cast-in-place column except for the connection with adjacent members)
- ☐ Precast segmental column (precast columns built in segments that are connected together on site
- ☐ Precast column shell (precast hollow column that serves as permanent formwork of a cast-in-place core)
- ☐ Other (Please specify): ____

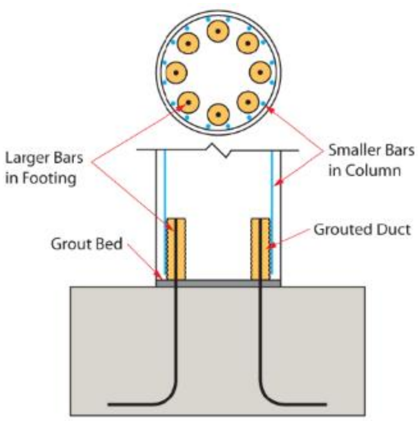
6. **What type(s) of connection is used between precast columns and adjacent members (foundation, bent cap, superstructure) by your DOT? Select all that apply.**



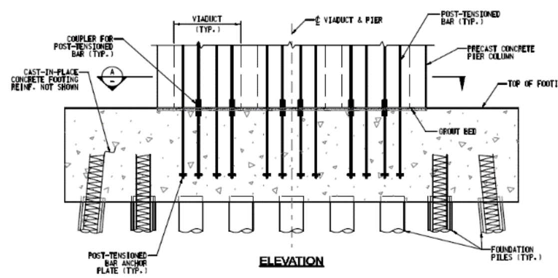
(a) example of grouted splice couplers



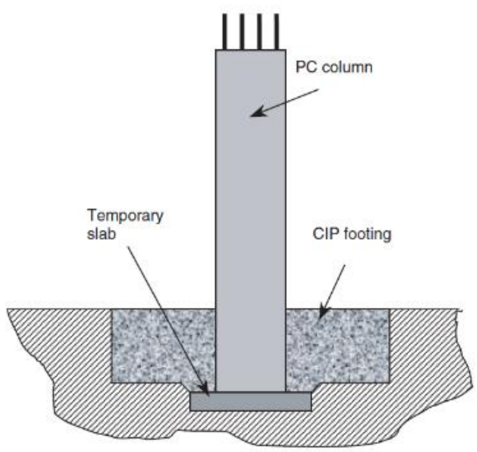
(b) example of mechanical splice connectors



(c) example of rebar extensions into grouted ducts



(d) example of post-tensioned joint



(e) example of socket-type connection

- ☐ Grouted splice couplers
- ☐ Mechanical splice connectors
- ☐ Rebar extensions into grouted ducts
- ☐ Post-tensioned joints
- ☐ Socket-type connections
- ☐ Other (Please specify):______________________________________

7. Does your DOT follow standards or guidelines that are specific for the design and construction of precast columns? If so, please provide a reference or link to the document

- ☐ Yes, please specify:____
- ☐ No

8. Are there specific criteria or guidelines that your DOT follows for selecting precast columns over conventional columns?

- ☐ Yes, please specify:____
- ☐ No

9. Have you identified any serviceability/durability issues with projects that involved precast columns in your DOT? If so, please elaborate.

- ☐ Yes, please specify:____
- ☐ No

10. How are the construction costs of precast columns in your DOT as compared to conventional cast-in-place columns?

- ☐ Similar to conventional construction
- ☐ Less costly than conventional construction
- ☐ More costly than conventional construction
- ☐ Don't know

11. Which of the following do you think is/are the most important challenge for the implementation of precast columns? Please select only the most relevant (no more than three).

- ☐ Awareness of the system and its benefits
- ☐ Familiarity of contractors with the system
- ☐ Familiarity of precasters with the system
- ☐ Durability issues
- ☐ Cost effectiveness

☐ Other (Please specify): ______________________________

12. Is your DOT currently supporting research or implementation projects related to precast columns

☐ Yes, please specify: ______________________________
☐ No

13. Do you have additional comments regarding the use of precast bridge columns? (for example, specific constructability issues to be considered)

14. Can we contact you directly for more information regarding the use of precast columns in your DOT? If yes, please enter your contact information below.

Phone: ______________________
Email: ______________________