

Analysis of the State of the Art of Precast Concrete Bridge Substructure Systems



Arizona Department of Transportation Research Center

Analysis of the State of the Art of Precast Concrete Bridge Substructure Systems

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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SIGNIFICANT TERMS, ACRONYMS, AND ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ABC	Accelerated bridge construction
ACI	American Concrete Institute
ACTT	Accelerated Construction Technology Transfer program
ADOT	Arizona Department of Transportation
AIDOT	Alabama Department of Transportation
AZTrans	The Arizona Laboratory of Transportation, which is the research unit at Northern Arizona University, Department of Civil and Environmental Engineering, that conducted this study
Caltrans	California Department of Transportation
CIP	Cast-in-place
d_b	Diameter of longitudinal reinforcing bar
DDBD	Direct displacement-based design method
DOT	Department of Transportation
ELFD	Equivalent lateral force design method
FHWA	Federal Highway Administration
GDOT	Georgia Department of Transportation
I, IH	Interstate, interstate highway
ITS	Intelligent transportation systems
MDOT	Michigan Department of Transportation
NCHRP	National Highway Cooperative Research Program
NYS DOT	New York State Department of Transportation
ODOT	Oregon Department of Transportation

PBES	Prefabricated bridge elements and systems
PCINE	Precast/Prestressed Concrete Institute Northeast
PT	Post-tensioning; post-tensioned
RC	Reinforced concrete
SCOB	AASHTO Subcommittee on Bridges and Structures
SH	State highway
SPER	Sumitomo precast form for resisting earthquakes and for rapid construction
SPMT	Self-propelled modular transporter
SPUI	Single-point urban interchange
TAC	Technical Advisory Committee: a group of stakeholders and advisors for the research project
TIG	Technology Implementation Group
TRB	Transportation Research Board of the National Academies
TxDOT	Texas Department of Transportation
UAB	University of Alabama at Birmingham
UDOT	Utah Department of Transportation
WSDOT	Washington State Department of Transportation

EXECUTIVE SUMMARY

The impacts of transportation construction activities on the traveling public are increasing significantly as more bridges approach the ends of their useful service lives and require either replacement or rehabilitation. These impacts consist primarily of traffic congestion and the user delays caused by that congestion. Worker and traveler safety is also a concern. To mitigate these deleterious consequences of construction activity, federal and state transportation agencies have focused on decreasing the time required for construction of bridges—i.e., accelerating bridge construction (ABC). In 2001, the American Association of State Highway and Transportation Officials (AASHTO) Technology Implementation Group (TIG) identified prefabricated bridge construction as a technology that should be advanced and implemented as quickly as possible (AASHTO 2002).

Using prefabricated bridge systems and components can also provide other important benefits besides rapid construction, including:

- Improved safety on the jobsite and for the traveling public.
- Ease of construction at sites with difficult access.
- Minimized environmental impacts of construction.
- Improved quality control.
- Ease of use of high-performance concretes.
- Enhanced durability and hence lengthened life cycle.

Bridge designs incorporating prefabricated superstructure elements are not new or innovative, as precast concrete beams or girders have been around since roughly the 1950s. However, until the last 25 years, incorporating precast concrete bridge substructure components into design has been very limited. Some of the main reasons for this limited use include:

- Lack of design and detailing guidelines.
- Concerns regarding connection performance.
- Lack of construction specifications.
- Increased cost compared to cast-in-place (CIP) concrete construction.

This research focused on the collection of information related to the design and construction of precast concrete bridge substructures, with sources including state and federal transportation agency websites and published literature; conference and workshop proceedings and presentations; professional associations and societies; and other published literature sources, such as technical journals. This project reviewed this literature to determine the current state of practice with respect to the use of precast substructures on bridges in the United States. This project also evaluated the various precast substructure technologies for their applicability to “typical” Arizona bridges.

Many transportation agencies have begun to incorporate precast concrete elements into their bridge substructures, including the state departments of transportation (DOTs) in Alabama, California, Florida, Georgia, Maine, Michigan, New Hampshire, New York, Oregon, Texas, Utah, and Washington. The DOTs for these states have either used precast concrete components on constructed bridge projects or have

funded research aimed at developing the technology. The most commonly encountered form of prefabrication of substructure was precast concrete bent cap beams, although precast concrete columns and spread footings are also being used.

The primary differences in technology used for prefabrication relate to how connections are made between precast components. Some states have adopted component connections that use grouted sleeve mechanical couplers, while others have pursued connections based on extending longitudinal rebar from one component into either corrugated metal ducts or formed rectangular voids in the adjoining component. The ducts and voids are then grouted, thereby making the structural connection between the precast elements. Either connection method can be adopted for use on bridges within Arizona. However, no large-scale experimental testing of the grouted sleeve coupler connection has been performed, whereas there have been several research projects that have constructed and tested the longitudinal rebar extensions in grouted ducts and voids connections.

Although there has been considerable activity in regard to developing precast substructure technology, there exist little formal design and construction criteria. The Utah Department of Transportation (UDOT) has published the *Precast Substructures Elements Manual* (UDOT 2010a), which discusses the various issues that should be considered when implementing precast designs. UDOT has also developed detailed precast substructure construction specifications. The Texas Department of Transportation (TxDOT) has funded research, (Billington et al 1998) for developing precast cap beam technology; the results of that research include specific design criteria and construction specifications. For other precast substructure components, this project did not find formal design or construction criteria in the literature review.

Other valuable resources that can be used in planning and designing precast substructures for Arizona bridges include the Federal Highway Administration's (FHWA) *Connection Details for Prefabricated Bridge Elements and Systems* (FHWA 2009) and the Precast/Prestressed Concrete Institute Northeast Bridge Technical Committee's *Guidelines for Accelerated Bridge Construction* (PCINE 2006).

Several state DOTs have developed strategic plans for implementing ABC. The Arizona Department of Transportation (ADOT) should, with consideration of these existing resources, develop its own strategy for adopting ABC. As part of this strategy, ADOT should identify an internal ADOT "champion" who will oversee the development of ABC practices; ADOT should also establish an ABC advisory committee. In addition, although this research project focused only on precast concrete substructure systems, ADOT should also consider other technologies that can be used to decrease the duration of Arizona bridge construction projects.

CHAPTER 1. INTRODUCTION

BACKGROUND

The nation's infrastructure is aging and its population continues to increase, particularly in urban regions. The *2009 Report Card for America's Infrastructure* reports that almost one-third of the bridges in the United States are either structurally deficient or functionally obsolete (ASCE 2009). By 2020, 90 percent of urban interstate highways are expected to be at or exceeding capacity, and today traffic delays are already costing the public 4 billion hours per year in lost time (Mistry 2008). There is thus a growing need to replace, rehabilitate, and expand transportation facilities, including bridge structures. The massive amount of construction that will be required in the near future to address these transportation needs has the potential to severely disrupt day-to-day functioning of the economy and negatively impact the quality of life of the public.

Realizing that new technologies will be needed to address future infrastructure needs while minimizing disruption to the day-to-day activities of Americans, federal and state transportation officials have worked to advance construction methods that will produce safe, durable bridges in shorter construction times. In 2000, the American Association of State Highway and Transportation Officials (AASHTO) formed the Technology Implementation Group (TIG) to identify and promote the use of "high-payoff and innovative technologies"; one of these technologies selected for implementation was prefabricated bridge elements and systems (PBES).

The concept behind PBES is that by prefabricating either portions of a bridge or entire bridges, much of the construction activity that requires detours and causes delays to the traveling public can be removed from the jobsite. In the United States, almost all modern bridges have some features composed of cast-in-place (CIP) reinforced concrete, including footings, abutment stems, wingwalls, columns, girders, decks, and barriers. Although generally durable and maintenance-free, CIP construction is a time-intensive construction method that requires formwork to be built and erected, curing time for concrete to gain adequate strength, and formwork removal. These activities are often on the critical path and represent a significant piece of the total construction time frame.

The national movement to accelerate bridge construction has become known as accelerated bridge construction (ABC). Because faster construction means fewer detours and delays, ABC offers such advantages as reduced traffic impacts to the traveling public and reduced overall risk of injury to workers and to the traveling public. ABC using PBES can lessen the impact on the environment, since often the PBES construction activities require less disruption to the landscape. Prefabrication of bridge components can also lead to improved quality in construction, since work can be performed in a more controlled environment, and this improved quality in turn leads to more durable structures with lower life cycle costs.

An alternative to CIP construction that is considered part of the PBES framework is the use of precast concrete components that are manufactured offsite at a dedicated fabrication plant. Precast concrete bridge girders have been used regularly since the 1950s, but aside from precast concrete piles, the use

of precast concrete in substructure elements is a relatively new technology. The reasons for not using this technology until recently are many; some possible explanations are:

- Lack of design and detailing guidelines.
- Concerns regarding performance, particularly for connections.
- Lack of construction specifications.
- Increased cost compared to CIP concrete construction.

Numerous bridge projects in the United States have incorporated many different types of precast substructure components, including footings, abutments, columns, and cap beams. The successful use of these precast substructure components is promising, and many transportation agencies within the United States are focused on further developing and implementing precast construction for substructures.

SCOPE OF RESEARCH

A main objective of this research project was to collect and synthesize existing information on the use of precast concrete bridge substructures within the United States. Sources for the review included state and federal transportation agency websites and published literature; conference and workshop proceedings and presentations; professional associations and societies; and other published literature sources, such as technical journals.

This project did not collect information on the use of other types of prefabricated elements and systems, such as precast concrete deck panels or whole bridge moves using self-propelled modular transporters (SPMTs); instead, this research focused on precast concrete substructure technology. This project also did not include in this review other ABC methods, such as fabricating a complete bridge offsite and then moving it into the final alignment with an SPMT, or contracting methods that can speed project delivery.

The project objectives were to:

- Based on the review of current practice, analyze the existing precast substructure technologies for relevance to bridge types typically used for Arizona bridges.
- Recommend systems that could be pursued for further development by the Arizona Department of Transportation (ADOT) Bridge Group.
- Suggest steps that are necessary for ADOT's successful practice developing and implementing precast substructure technologies.

To accomplish these objectives, the project's Technical Advisory Committee (TAC) developed and approved a research work plan. No changes were made to the work plan during the project's execution.

The research work plan consisted of the following major tasks:

1. Synthesize existing information on the behavior, analysis, and design of precast substructure systems. In the process, survey literature, including journal publications, federal and state reports and design standards, and conference proceedings. Create a list of constructed

- bridge projects using precast substructures. Collect the experiences of other state DOTs that have pursued or implemented precast substructure systems.
2. Analyze the information collected in Task 1. Identify technologies, concepts, standards, etc. that may be readily exportable to ADOT practice.
 3. Based on Tasks 1 and 2, provide recommendations for implementing precast substructure technology for Arizona bridges.

The project contract was formally initiated in October 2009. The initial meeting with the project sponsors and technical advisors was held on February 8, 2010, at ADOT's Bridge Group Office in Phoenix. The research was actively guided by a technical advisory committee (TAC), whose stakeholder and member sections are:

- ADOT: Jean Nehme, State Bridge Engineer.
- ADOT: Pe Shen Wang, Assistant State Bridge Engineer.
- ADOT: Christ Dimitroplos, Research Project Manager.
- Federal Highway Administration: Aryan Lirange.

ORGANIZATION OF THE REPORT

The report is organized into chapters that address each element of the research.

Chapter 2 provides an overview of the activities of state and federal Departments of Transportation (DOTs) in the area of accelerating bridge construction via prefabricated concrete bridge substructure systems. Summaries of documents, such as research and other reports, presentations, and design manuals, related to use of precast substructures are provided in Chapter 2, while detailed descriptions and evaluations of specific technologies are provided in other chapters in this report, grouped by substructure element. This chapter also contains any other information on the use of precast concrete substructures that was collected as part of the review of the current state of practice.

Chapters 3 through 5 provide an in-depth analysis of precast concrete substructure technologies that have been used on previous bridge projects, and their appropriateness for typical Arizona bridges. The specific topics in these chapters are precast cap beams (Chapter 3), columns (Chapter 4), and footings (Chapter 5).

Chapter 6 provides general recommendations for implementing ABC technologies and precast concrete substructure technologies for Arizona bridges.

Appendices A, B, and C provide design details related to the research discussed under "Implementation of Texas Precast Bent Cap Research" in Chapter 3.

CHAPTER 2. REVIEW OF CURRENT PRACTICE AND LITERATURE

This chapter summarizes relevant activities, publications, and practices of state and federal transportation agencies. This chapter is organized by transportation agency, with the activities of federal and national organizations presented first, and then those of state DOTs following. The reviews presented in this chapter are summaries rather than detailed discussions of technologies; detailed discussions are provided in subsequent chapters of this report.

FEDERAL HIGHWAY ADMINISTRATION

The Federal Highway Administration (FHWA) in collaboration with members of AASHTO has been an integral part of developing and implementing accelerated construction technologies for constructing roadways and bridges in the United States. Under the Highways for Life program, the FHWA has identified numerous technologies and innovations that will:

- Improve safety during and after construction.
- Reduce congestion caused by construction.
- Improve the quality of the highway infrastructure.

Two of these innovations are PBES and Accelerated Construction Technology Transfer (ACTT). These innovations have been developed and/or advanced by FHWA, and are helping to relieve the congestion associated with the rehabilitation and expansion of the nation's highway infrastructure for the needs of the 21st century. This section provides a review of FHWA publications related to implementing ABC.

Prefabricated Bridge Elements and Systems

Prefabricated Bridges: "Get in, get out, stay out." (AASHTO TIG 2002)

The AASHTO TIG produced this document as a celebration of "the emergence and growth of innovative prefabricated bridge technology." This document highlights the use of prefabricated technologies on 15 different bridge projects, and provides a succinct one- or two-paragraph description of each project's constraints, type of prefabrication, and construction schedule and strategy.

Prefabricated Bridges 2004: Good Business—Best Practice (AASHTO TIG and FHWA 2004)

This document is a companion brochure to the AASHTO brochure, "Prefabricated Bridges: 'Get in, get out, stay out.'" It highlights the innovative use of prefabricated bridge technologies to accelerate bridge construction. It describes 12 different projects in the United States that used some aspect of ABC. A one-page summary of each bridge gives such information as project constraints and ABC technologies used.

Framework for Prefabricated Bridge Elements and Systems (PBES) Decision-Making (FHWA 2006a)

The FHWA has developed decision-making tools to be used to evaluate whether a given bridge project is a good candidate for prefabricated bridge construction. This FHWA document contains three levels of decision-making tools, each with an increased level of refinement. The process of deciding whether using prefabricated components "makes sense" depends on a number of decision factors, including the need for rapid replacement, safety, environmental concerns, level of repetition, and cost.

The first “high-level” tool is a flowchart with a series of questions that address the above-listed factors that can influence the appropriateness of a prefabricated design. This flowchart provides for a qualitative evaluation of whether conventional cast-in-place construction or precast construction is preferred. In the end, a “yes” or “no” answer to the question of whether to use prefabricated bridge is obtained. The flowchart is the most simplified of the three decision-making tools.

The second decision-making tool is a matrix with 21 questions that are related to the above-listed decision factors. In the matrix, the decision-making process can apply different weightings to each question, and a total score can be tallied that then can be used to decide whether a prefabricated bridge option is best.

The third tool in the FHWA decision-making guide is a detailed discussion of each decision factor and how it influences the choice of conventional or prefabricated construction. This third tool does not provide a means for developing a quantitative ranking of a prefabricated option, but does provide a more robust consideration of each decision factor than the “yes” or “no” progression of the flowchart.

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

A scanning tour of selected European countries and Japan was conducted in 2004 to collect information on the use of prefabricated bridge technologies. The scanning team consisted of state and local agency transportation officials, representatives from FHWA, industry professionals, and one university professor. Specific countries visited included Belgium, France, Germany, Japan, and the Netherlands, and the scanning team met with representatives from government and the private sector.

The findings include the identification of 10 technologies that could (and perhaps should) be considered for implementation in the United States. The 10 technologies are grouped into the categories of movement systems, superstructure systems, deck systems, and substructure systems. The team reported that use of prefabricated substructures was limited in the countries on the tour, and identified only one possible technology for use in the United States: Japan’s SPER System. SPER stands for Sumitomo precast form for resisting earthquakes and for rapid construction. The system is composed of precast stay-in-place forms that are stacked on top of each other and filled with CIP concrete. For shorter piers, only an outer precast form is used and thus the finished column is solid in section, while for taller piers, inner and outer forms are used and thus the completed column is hollow in section. No specific details of the system are included in the report.

PBES Cost Study: Accelerated Bridge Construction Success Stories (FHWA 2006b)

This document describes the relative successes of nine different ABC bridge replacement projects within the United States. This document provides detailed project information for each project, including existing conditions; contracting strategy; replacement structure type and configuration; and construction sequencing, duration, and cost. Of the nine ABC projects described, three include prefabricated substructure components, including precast abutments and wingwalls, precast bent caps, and precast footings. This cost study truly demonstrates the potential for success in ABC, with construction costs at 13.8 percent less than the engineer’s construction cost estimate calculated as an average for the nine projects.

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

This report by the FHWA provides a comprehensive review of the current state of the practice in accelerated bridge construction. It was created using information gathered from state DOTs, industry, private consultants, and international organizations. The report's intent is to provide practical, ready-to-use information on the design of bridges with the goal of accelerating construction. More specifically, as the title reflects, the focus of the work is on connection details between prefabricated bridge elements. All major structural portions of a bridge are covered (i.e., from the foundation on up to the superstructure).

The connection details manual is divided into four chapters, with the first chapter, titled "General Topics," providing an overview of the issues associated with ABC. Topics covered in Chapter 1 include:

- 1.1 Benefits of Prefabrication.
- 1.2 Accelerated Construction Overview.
- 1.3 Applicability to Typical Bridges.
- 1.4 Typical Accelerated Construction Connection Types.
- 1.5 Seismic Considerations.
- 1.6 Materials.
- 1.7 Tolerances.
- 1.8 Fabrication and Construction Issues.

Chapters 2 through 4 provide information specific to the major portions of a bridge. Each chapter provides a discussion of the various types of connections (e.g., integral pier caps versus non-integral) and the issues associated with their use to accelerate bridge construction.

The chapter headings are:

- Chapter 2 – Superstructure Connections.
- Chapter 3 – Substructure Connections (piers, abutments, walls).
- Chapter 4 – Foundation Connections (footings and piles).

Each chapter contains "Connection Detail Data Sheets" which present possible connection details between prefabricated bridge elements. The details are ranked with respect to their previous use on bridge projects; this ranking gives some implied degree of confidence in the adequacy of the detail.

- Level 1 is assigned to connection details that "have been used on multiple projects or that have become standard practice by at least one owner agency." Level 1 details are considered practical and "adequate."
- Level 2 details are those that have been used only once but were "found to be practical to build and performed adequately."
- The Level 3 classification is assigned to details that are conceptual or experimental and have not been used on a constructed bridge project.

The connection details sheets include the originating organization, a CAD drawing illustrating the detail, a comments section, and a "performance data" section. The performance data section provides a

performance rating on a scale of 0 (zero) to 10 (0 equals the lowest performance, 10 equals the highest performance) on the connection's:

- Speed of construction.
- Constructability.
- Cost.
- Durability.
- Inspection access.
- Future maintenance.

The FHWA connection details manual is one of the most thorough resources for information on the design and construction of bridges using prefabricated components. However, the manual does not provide specific design criteria or design methods. Nevertheless, it can be used as a sort of "menu" for various connections between prefabricated components, and additional information can likely be found by contacting the originating organization directly.

Accelerated Construction Technology Transfer (ACTT)

ACTT: A "How To" Guide for State Highway Agencies (FHWA 2005)

In 2002, the Transportation Research Board (TRB), FHWA, and AASHTO TIG initiated a program to help owner-agencies implement solutions that will speed construction of new roadway projects. The program, named Accelerated Construction Technology Transfer (ACTT), is defined by FHWA (FHWA 2005) as:

"...a process that assembles a team of 'best in the field' national leaders in common skill sets and delivers them to State project sites for structured workshops hosted by State highway agencies planning major construction projects."

In the ACTT process, the given state DOT hosts a three-day ACTT workshop where national experts from 11 different disciplines help to identify solutions and processes that will effectively accelerate the construction process on a specific project that has been programmed for construction. The ACTT program is now well-established, with 25 states having hosted an ACTT workshop, with project sizes ranging from \$1 million to \$3.5 billion. The FHWA's ACTT Management Team works with the transportation agency to identify skill set experts that will participate in the workshop, but funding for participant expenses related to the workshop is the responsibility of the host state.

The FHWA "How To" guide provides the necessary information on how to plan and execute an ACTT workshop, from setting the workshop budget to identifying the project that will be the focus of the workshop. In order to maximize the benefits of ACTT, the process should be initiated as early on in the project life cycle as possible. The basic steps for planning and presenting an ACTT workshop include:

1. Identify a project for an ACTT workshop.
2. Contact the FHWA Division office to give notice of intent to host an ACTT workshop.
3. Hold a pre-workshop meeting to plan the event (the attendees are the host agency and ACTT Management Team officials).

4. Announce the workshop to ACTT Skill Set leaders 90 days in advance of the ACTT workshop (the ACTT Program Manager makes this announcement).
5. Provide guidance to the host state in planning, facilitating and conducting the workshop (the ACTT Management Team provides this guidance).
6. Document the results of the workshop using a report template provided by the ACTT Team. The host agency writes the report; the FHWA assists with final editing and distribution of the report.

The skill sets typically represented by the ACTT workshop participants include:

- Innovative financing and innovative contracting.
- Right of way, utilities, and railroad coordination.
- Environment.
- Geotechnical, materials, and accelerated testing.
- Traffic engineering, safety, and intelligent transportation systems (ITS).
- Structures.
- Roadway and geometric design.
- Long-life pavements and maintenance.
- Construction.
- Public relations.

Accelerated Construction Technology Transfer: Building on Success (FHWA 2007)

This report documents the progress of the ACTT Program and the successes and lessons learned from the various ACTT workshops held to date. The report also discusses the top recommendations from five ACTT workshops held in 2006, including workshops in Ohio, New Hampshire, New York, Hawaii, and North Carolina. A section on “recurring recommendations” is provided, organized by the various ACTT skill sets identified previously (see the earlier discussion under “ACTT: A ‘How To’ Guide for State Highway Agencies”). Also provided in this report are the top recommendations from the specific ACTT workshops held in 2006.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

The National Cooperative Highway Research Program (NCHRP) addresses national highway research needs identified by leaders of state DOTs within the context of AASHTO. NCHRP research work is jointly funded by participating member states and is administered by TRB and the National Research Council.

NCHRP Synthesis 324 (TRB 2003)

In 2003, the NCHRP published a report titled “Prefabricated Bridge Elements and Systems to Limit Traffic Disruption During Construction.” This report is part of the NCHRP report series, *Synthesis of Highway Practice*. It provides a review and analysis of the use of prefabricated elements in both highway and rail bridges. Existing literature and available information were collected and summarized. The research project also included developing a survey questionnaire, which was sent to state and local agency DOTs within the United States and Canada, to collect information on the use and effectiveness of prefabrication technologies. This report is classified as “non-technical” in the sense that no specific

information is provided on topics such as design criteria, methods, details, or construction specifications. The report is mostly a presentation on the types of prefabrication currently used or in development. The report's literature review section documents the use of prefabricated bridge components on previous projects, and discusses substructure and superstructure elements.

Development of Precast Bent Cap Systems for Seismic Regions; NCHRP Report 681 (Restrepo et al. 2011)

In 2005, the NCHRP initiated a research project to “develop a design methodology, connection details, and design and construction specifications for precast bent cap systems under seismic loading.” Precast bent caps are being developed with two different distinct “flavors”: designs that are intended to emulate the response of traditional CIP reinforced concrete (RC) bent cap construction, and designs that are termed “hybrid,” which are not specifically intended to behave the same as conventional construction. The hybrid designs are based on the inclusion of unbonded post-tensioning (PT) steel in the connection between the cap and column. This PT steel helps to provide a re-centering force that minimizes bent residual deformation after a seismic event. The research project has been completed, and included the following major tasks:

1. Literature review on precast bent cap systems.
2. Precast bent cap concept development.
3. Analytical and experimental work to validate precast bent cap concepts.
4. Development of connection details, design methodologies, design and construction specifications, commentary, and design examples.

The project principal investigators gave a presentation on the status of the project at the AASHTO Annual Bridge Meeting in May 2010.

PCI “GUIDELINES FOR ABC”

In 2006, the Precast/Prestressed Concrete Institute Northeast (PCINE) Technical Bridge Committee published a manual titled *Guidelines for Accelerated Bridge Construction Using Precast/Prestressed Concrete Components* (PCINE 2006). PCINE developed this manual with input from members of academia, the engineering community, state DOTs, and precast producers with the purpose of “promoting a greater degree of uniformity among owners, engineers, and industry of the Northeast.” The manual provides guidance on planning, designing, fabricating, and constructing highway bridges with a focus on accelerated bridge construction.

The PCINE manual is a nontechnical document in the sense that it does not provide specific design or construction specifications. Rather, the manual includes in-depth background information on the topic and discusses the many considerations that must be understood and addressed regarding using prefabricated concrete components to accelerate bridge construction. It addresses all bridge components that could be prefabricated, including foundations, abutments, piers, pier caps, and superstructure.

The manual is organized into the following sections:

- Section 1: Application Overview.
- Section 2: General Requirements.

- Section 3: Precast Components.
- Section 4: Joints.
- Section 5: Grouting.
- Section 6: Seismic Considerations.
- Section 7: Fabrication/Construction.

In addition to these sections, the manual also provides three case studies. A brief summary of two of the case studies is provided in a later section of this chapter (“Review of Precast Substructure Projects”).

STATE DOT PRACTICE AND RESEARCH

This section includes a review of state DOT literature and practices related to prefabricated bridge construction. The information summarized here includes state-sponsored research reports and information from state DOT bridge websites, such as presentations and policy and practice documents. For a review of specific precast substructure projects performed within the United States, see “Review of Precast Substructure Projects” later in this chapter.

Alabama

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

Performed for the Alabama Department of Transportation, this research project included collecting and summarizing available information on the use of prefabricated concrete bridges in the United States and Europe. Based on the gathered information, the researchers developed a prefabricated concrete bridge system for use for typical short- to medium-span Alabama bridges, and wrote guidelines for selecting, designing, and constructing that system.

Section 2 of the report describes the various types of prefabrication of precast concrete bridge components, including precast columns and pier walls, precast abutments, precast bent caps, and various precast superstructure elements. Section 3 of the report describes the development of the precast bridge system, including design details for precast whole length columns, precast bent caps, and deck bulb-T girders. It also includes a discussion of the proposed design details. In Section 4, a design example using the proposed precast concrete bridge system is provided for a hypothetical three-span bridge with end spans of 60 ft and center span of 130 ft. In the design example, the bridge roadway width is 44 ft and the structure is designed according to the *AASHTO Standard Specifications for Highway Bridges* (AASHTO 2002) for HS20-44 live loading.

California

The California Department of Transportation (Caltrans) has begun efforts to develop ABC technologies in support of “enhancing mobility across California” (Chung et al. 2009). Although there have been several bridge projects constructed in California using ABC methods such as whole bridge moves and prefabrication of bridge components, widespread use of ABC has been prevented because of the very high seismic hazard present throughout California and uncertainties about the performance of connections between components during earthquakes. However, recognizing the many benefits of ABC, and with the focus on ABC implementation by other state and federal transportation agencies, Caltrans established an ABC Executive Committee and Advisory Council in 2008 to work toward practice

developing and implementing ABC. As described next, Caltrans has a long-term goal of ABC as the standard of practice for California bridges (Caltrans 2008).

Caltrans ABC Strategic Plan: Development of Practice and Policy for Future Bridge Projects (Caltrans 2008)

This report by the Caltrans ABC Advisory Council describes California's ABC implementation strategic plan, which includes the following aspects:

- "Lessons Learned" Report and Survey.
- ABC Decision Criteria and Type Selection.
- Industry Engagement.
- Technical Research.
- Technical Standards Development.
- Contract Development.
- ABC Pilot Program.

The first task of the strategic plan is to document past projects within the state that have used ABC methods, and to report on "lessons learned" from those projects. This task has been completed and is documented in the Caltrans report, "Accelerated Bridge Construction Applications in California: A Lessons Learned Report," which I summarize in a few pages.

The second aspect of the strategic plan includes developing formal decision criteria and a decision matrix that can be used to quantify the need for ABC on a particular project, and the economic impact of ABC. The economic impact will be measured as a total cost that accounts for construction impact time and construction completion time.

The third task of the Caltrans Strategic Plan is to gather input from the industry on issues such as constructability, tolerances, transportation of prefabricated components, new high performance materials, and contracting methods. To garner the widest possible input from all parties involved in the bridge construction process, Caltrans has conducted workshops with fabricators, erectors, and contractors, with the goal of developing practical and economical ABC practices.

A major aspect of the Caltrans Strategic Plan is technical research on ABC. Caltrans is monitoring current research projects being conducted within the United States, and is also soliciting support for research topics, including:

- Connection details between precast columns and superstructures.
- Response of segmental girder systems.
- Precast segmental post-tensioned columns.
- Precast columns to foundation connections.
- Innovative materials.
- Long-term performance and maintenance of ABC connections.

Based on the above described tasks, Caltrans will develop design and construction specifications and standard details for ABC. Caltrans will also create a maintenance guide specification to address issues

such as inspection practices, non-destructive evaluation methods, long-term performance data, and post-earthquake rapid evaluation methods.

Caltrans will also use existing contracting methods or develop new ones that promote reduced construction time and impact. These methods could include design-build, A+B, incentive/disincentive, lane rental, etc.

The final step in the Caltrans Strategic Plan is a phased implementation of ABC on California projects. Phase I of ABC implementation will include using the Caltrans ABC Decision Criteria on select pilot projects within the state. Based on the results from Phase I, Caltrans will document “lessons learned” in an effort to improve future ABC projects. Phase II of Caltrans’ implementation of ABC will be based on use of new details developed through research funded by Caltrans and research by others, and will include pilot projects testing the feasibility of the details. Through the lessons learned from the ABC pilot projects, Caltrans expects that ABC will become widely adopted for California bridge construction.

Accelerated Bridge Construction Applications in California: A Lessons Learned Report (Chung et al. 2008)

This report documents past and planned ABC projects within California, with discussion on what worked and what did not work on the projects. For each project, the report provides information on project background, project goals, ABC implementation, design, construction, challenges, and lessons learned. Because the use of ABC technologies for California bridges is limited, the report only provides details on seven projects. Of those projects, only one includes ABC technologies for substructures: the Marble Wash Bridge on the I-40 Bridges Project, which is discussed under “Review of Precast Substructure Projects” later in this chapter.

Seismic Design and Performance of Precast Concrete Segmental Columns (Hewes and Priestley 2002)

The post-Loma Prieta and Northridge earthquakes era saw an increased focus nationally on research to improve the seismic performance of bridges. This Caltrans-funded project developed a precast column system with reduced damage as compared to traditional CIP RC columns. This report documents experimental and analytical studies on the response of precast concrete segmental columns with unbonded longitudinal post-tensioning under seismic loading. The research was one of the first studies of the use of unbonded post-tensioning steel as the main column vertical reinforcement, and provided foundational information on the behavior and performance of this new column system.

In this research, large-scale test columns were designed and constructed at the University of California, San Diego’s Charles Lee Powell Structural Research Laboratories. Columns were circular in cross-section and contained a single unbonded post-tensioned tendon concentric with the section, and anchored in precast foundation and cap segments. Column segments were cast individually, and joints between segments used leveling shims and epoxy during assembly. Columns were tested as vertical cantilevers in the lab under lateral point loads simulating seismic input.

The research demonstrated that precast columns with unbonded tendons can undergo large lateral displacements without significant loss in strength—i.e., the columns possess significant ductility. Lateral drifts on the order of 4 to 6 percent were achieved with little or no decrease in lateral load capacity. Also shown in the research was much improved performance of the system compared to conventional RC columns, which experience significant damage in the form of spalled cover concrete and longitudinal

rebar yielding within plastic end regions. The researchers developed a design procedure based on a displacement design method rather than a force-based design method.

Florida

Development of Precast Bridge Substructure (LoBuono, Armstrong and Associates 1996)

In the mid-1990s, the Florida Department of Transportation (FDOT) hired engineering consultant firm LoBuono, Armstrong and Associates to study the development of a standardized precast bridge substructure system for Florida bridges. “Development of Precast Bridge Substructures” documents the results of the study, which focuses on the qualitative evaluation of precast concrete pier cap, column, and pile cap geometries and configurations. This FDOT project was intended to serve as the basis for a follow-on project to develop in detail standardized precast substructure systems, with options for single and multi-column bents, and cap beams for pile foundations.

The report first describes the various issues that should be considered by the engineer when evaluating a precast concrete substructure option. These include:

- Number of units (i.e., project size).
- Location over land or water.
- Shape (i.e., cross-section shape).
- Maximum size and weight (i.e., shipping and handling limits on components).
- Connections between components (i.e., types of connections, with considerations such as tolerances in the field, need for moment connection).
- Pier type and type of foundation.
- Type of superstructure (i.e., individual girders versus box girder).
- Speed of construction.

Two additional considerations are presented that influence the development of a standardized system:

- How the system is applicable to a large variety of situations.
- What shape can easily be manufactured by the precaster.

The next section of the report presents advantages and disadvantages of various potential shapes of columns and cap beams, with the discussion organized by whether the bent is a single-column, multi-column, or pile supported bent. Both solid and voided sections are evaluated. Considerations in the lists of advantages and disadvantages include ease of design, ease of fabrication (rebar cages, forming, casting, and handling), aesthetics, and weight.

The bulk of the report describes various conceptual component shapes and the results of a survey of engineers, fabricators, and contractors on their preferences for the options. For multi-columns bents, the cap beams considered included solid and voided rectangular, inverted-T, and inverted-U shapes. The column geometries considered for multi-column bents included circular, rectangular, H-shaped, and multi-sided (e.g., octagonal), with solid and voided options (except for the H-shaped sections). For pile supported bents, the cap beam options evaluated included solid and voided rectangular, and inverted-T and inverted-U shaped. For single-column (hammerhead) bents, the cap beam geometries included solid

and voided rectangular cross-sections with depth taper along their length. The evaluation criteria used in the survey, along with their relative weighting (higher weighting equals greater importance) are:

- Successful previous use (1).
- Design (ease of difficulty of design) (3).
- Material cost (reinforcing steel and concrete) (5).
- Aesthetics (3).
- Shipping (ease of shipping) (4).
- Fabrication (ease of fabrication) (4).
- Erection (handling loads and connection tolerances) (2).

The report does not provide any discussion of or specific recommendations for design procedures, connection details, tolerances, erection schemes, and decision-making.

Michigan

The Michigan Department of Transportation (MDOT) has funded research related to accelerating bridge construction using prefabricated concrete bridge components, and has implemented precast substructure construction on at least one known bridge project to date (Jansson 2008).

One research project by MDOT investigated the performance of grout-filled splice sleeve mechanical rebar couplers under axial tensile loading (Jansson 2008). Grouted splice sleeve couplers were first developed in the 1970s, and, starting in the 1980s, have been used extensively in the precast concrete building industry. They potentially offer a quick and structurally sound means of making connections between precast bridge components. The MDOT research tested #6 and #11 grade 60 rebar spliced with two different brands of splice sleeves to investigate their load-slip behavior, fatigue response, ultimate strength, and creep behavior. The testing demonstrated that the splice sleeve couplers tested can meet the relevant AASHTO and American Concrete Institute (ACI) performance requirements. For additional details of the research, see Chapter 3, which contains a discussion of the couplers within the context of precast bent cap beams and their connections to columns.

In October 2010, MDOT began a second research project to investigate the use of precast construction to speed construction of bridges within Michigan. Sponsored by MDOT, the research project, "Improving Bridges with Precast Concrete Components," is being conducted by researchers at Western Michigan University. This research has the following goals (TRB 2010):

- Determine the state of practice of precast concrete bridge construction.
- Determine appropriate steps for evaluating and implementing possible systems in Michigan.
- Identify systems with greatest potential for use in Michigan.
- Provide implementation recommendations.

The research will span approximately two years; it is scheduled to end December 31, 2013. The results of this research project should be reviewed once it is completed for applicability to Arizona's implementing precast concrete substructures.

Oregon

The Oregon Department of Transportation (ODOT) has embraced the goal of minimizing disruption to the traveling public and impacts to the environment via acceleration of bridge construction, and has incorporated ABC methods on 16 bridge projects within the state, with 11 occurring in the past five years (Tang 2009). Although a few of these projects incorporated ABC methods at the start of design, most cases in which ABC methods were incorporated resulted from value engineering proposals, incentive/disincentive clauses, and design-build contracts. ABC techniques employed by ODOT include contracting methods (e.g., A+B bidding, incentives/disincentives, etc.), SPMTs, skidding or floating of superstructures into place, and prefabrication of superstructures and pile caps.

ODOT has established an ABC committee comprised of ODOT employees and engineering consultants, and, in 2010, incorporated ABC guidelines in their *Bridge Design and Drafting Manual* (BDDM) (ODOT 2010). The ABC guidelines within the BDDM are organized into the following sections:

- ABC Decision-Making.
- Steel Structures.
- Concrete Structures.
- Full-depth Deck and End Panels and Wingwalls.
- Seismic Related.
- Use of SPMT.
- Geotechnical Consideration.
- QA/QC for Prefabricated Elements.
- Cost Consideration.
- ABC Project Listing.

The ODOT BDDM does not contain specific ABC technical design or construction specifications, but rather discusses important considerations related to selecting and incorporating ABC methods on their bridge projects. Further, ODOT does not have any standard drawings or details specifically focused on ABC construction technologies except those for precast concrete superstructure components.

ODOT also took the lead in an FHWA-sponsored state pool-funded research project focusing on ABC decision-making, with a title of *Accelerated Bridge Construction (ABC) Decision Making and Economic Modeling Tool*. Other state sponsors included the states of California, Iowa, Minnesota, Montana, Texas, Utah, and Washington. The study objective was “...to develop a set of tools for transportation and decision-makers to determine whether or not ABC is more economically effective than traditional construction for a given bridge replacement or rehabilitation project” (Doolen 2009). The tool set addresses both construction costs and “soft costs” that are typically hard to quantify, such as those associated with user delays. Project-specific characteristics such as bridge length, complexity, road user characteristics, environmental concerns, and traffic patterns were modeled and accounted for in the tool. The final project report was completed in December 2011 (Doolen et al. 2011).

Texas

The Texas Department of Transportation (TxDOT) has been taking advantage of the many benefits of ABC construction since the early 1990s. In the early 1990s, TxDOT began using precast concrete bent

caps on projects where conventional CIP construction would create significant user delays on adjacent traveled ways, or where use of prefabricated caps could reduce project costs and improve safety. TxDOT does not have any formal design standards or drawings focused on ABC of bridge substructures, nor do they provide guidance on ABC use in their design manual. TxDOT has funded several research projects focused on the development of precast concrete substructures. The research was conducted at the Center for Transportation Research at the University of Texas at Austin in the late 1990s and early 2000s. The following paragraphs provide detailed reviews of the two most pertinent research studies.

A Precast Substructure Design for Standard Bridge Systems (Billington et al. 1998)

This research report focuses on the development of a precast concrete bridge substructure system for standardization for short- to medium-span bridges within Texas. The research work was conducted with input from various groups, including precast producers, construction contractors, engineers, and owners, with the goal of developing a prefabricated concrete bent system that could be used with standard Texas precast superstructures. The motivation for this research work was primarily the TxDOT goals of improving the durability and speed of construction of new Texas bridges.

The report presents information on the following issues related to prefabricated concrete bents:

- Review of literature on precast concrete substructure design and construction.
- Development of a new precast concrete bent system, including standard column and bent cap segments, fabrication and erection guidelines, design guidelines, and design details.
- Alternative substructure design of CIP concrete bents.
- Applications of the research to two Texas bridges.
- Implementation of precast bents for the state of Texas.

Development of a Precast Bent Cap System (Matsumoto et al. 2001)

This work focused on the development of a design methodology, construction guidelines, and connection details for precast bent caps in low seismic regions. The basis of the precast bent cap concept developed and tested by Matsumoto et al. (2001) is the use of column longitudinal rebar extensions that insert into voids in the precast cap. The voids are either vertical corrugated metal ducts or tapered rectangular grout pockets, and the column rebar extensions are grouted into place. The research first examined the pullout behavior of mild steel rebar embedded in corrugated metal ducts and rectangular pockets. Then, the researchers constructed connection subassemblies with a portion of column and cap beam, and tested the subassemblies under realistic loading conditions. Finally, the researchers constructed and tested two full-scale bents. The research results indicated that the column-to-cap connection is capable of transferring forces adequately between concrete columns and precast concrete cap beams. The researchers give recommendations for design and construction.

Utah

UDOT has aggressively pursued ABC implementation; as of the writing of this report, over 80 bridge projects have been completed in the state with ABC methods (UDOT 2010b). The relatively large number of ABC projects in Utah is a result of UDOT's goal of implementing ABC as a standard of practice by 2010. ABC techniques employed by UDOT include contracting methods, prefabrication of bridge components (precast deck panels, voided slabs, precast abutments and bent caps, precast

superstructures), and structure placement methods (SPMTs, skidding, etc.). Of all state DOTs, UDOT has the most extensive compilation of ABC-related documents available online, and thus might be considered the most advanced DOT with regard to ABC implementation.

UDOT has invested significant resources in the development of formal ABC precast substructure standards, including standard drawings, special provisions, and a precast substructures manual. UDOT also has developed an “Accelerated Bridge Construction Decision Flowchart” which provides a means of determining whether conventional construction or ABC is most appropriate for a given bridge project.

UDOT standard drawings (UDOT 2010c) related to prefabricated substructures include:

- Precast Integral Abutment Typical Detail Sheets.
- Precast Cantilevered Abutment Typical Detail Sheets.
- Precast Pier and Footing Typical Detail Sheets.

The UDOT *Precast Substructure Elements Manual* (UDOT 2010a) contains information on the design and detailing of precast concrete substructure components, with consideration of the provisions of the *AASHTO LRFD Bridge Design Specifications, Fifth Edition* (AASHTO 2009). The UDOT manual contains sections that address the following topics; see Chapters 3 and 4 of this report for a discussion of specific information from the UDOT manual.

1. General Information.
2. Typical Substructure Elements.
3. Use of Typical Detail Sheets.
4. Sheet Checklist.
5. Foundation Types.
6. Mild Reinforcing and Concrete Properties.
7. Design.
8. Lifting Devices, Handling, and Storage.
9. Vertical Adjustment.
10. Grouted Splice Couplers.
11. Closure Pours.
12. Tolerances.
13. Assembly Plans.

Washington

The State of Washington has used a variety of ABC methods on bridge projects and is one of a handful of states leading the way toward developing accelerated project delivery as a standard of practice. The Washington State Department of Transportation (WSDOT) has used both precast concrete superstructures and substructures including columns and bent caps. As with California’s significant seismic demand, Washington state’s high level of earthquake hazard requires additional consideration of ABC connections beyond that required for low seismic regions. WSDOT has established an ABC advisory committee composed of WSDOT personnel, consultants, precast producers, contractors, and academicians, and has also published a first draft of an ABC strategic plan. WSDOT has funded a number of research projects focused on developing rapid bridge construction technologies for regions with high seismicity, which are reviewed next.

WSDOT Strategic Plan Accelerated Bridge Construction (ABC): Practice and Policy for ABC Bridge Projects (WSDOT 2009)

The WSDOT strategic plan, published in 2009, is almost word-for-word identical to that adopted by Caltrans (Caltrans 2008). As there is no new or unique information contained in the WSDOT document, no further review is needed or provided.

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

This research focused on developing a precast concrete pier system to accelerate bridge construction in high seismic zones in Washington state. After gathering information from discussions with WSDOT and other engineers, and with representatives from the precasting and construction industry, the researchers developed two conceptual systems that use precast columns and cap beams. The first system has columns with longitudinal mild steel reinforcement only, while the second uses both longitudinal mild steel and unbonded post-tensioning in the precast columns. The researchers refer to the second system as the hybrid system; the intent of the post-tensioning in this system is to help provide a restoring force and hence less residual displacement after the seismic event. In both systems, column longitudinal reinforcement protrudes from either end of the precast component, and the reinforcement is embedded in CIP concrete in the foundation and cap beam.

The bulk of the research work focused on analytical investigations into the lateral seismic response of a two-column bridge bent based on a prototype “typical” Washington bridge with precast prestressed concrete girders. The influence of deck and abutment transverse stiffness and restraint was not considered in the pushover and time-history analyses. Very few meaningful conclusions are provided that specifically relate to the design and behavior of the precast systems, and many of the results focus on variations in effective stiffness, expected damage, lateral strength, expected versus analytical displacement and ductility demands, etc. within a parametric study. Later in this report, there is more specific information on the proposed concepts for precast columns and cap components.

Design of Precast Concrete Piers for Rapid Bridge Construction in Seismic Regions (Wacker et al. 2005)

This research report is a companion report to *Precast Concrete Pier Systems for Rapid Construction of Bridges in Seismic Regions* (described in the preceding section). It documents analytical studies on the design of precast concrete columns for seismic effects. The bulk of the work focuses on two design methods: an equivalent lateral force design (ELFD) method, and a direct displacement-based design (DDBD) method. The researchers investigated how equivalent viscous damping should be calculated for use in the DDBD method and how yields displacements should be determined in the precast column system. They also evaluated the expected damage in the precast column system for various levels of seismic shaking, with results expressed as a probability for a given damage limit state. The report does not provide any specific information on design details of the precast columns or connections to foundation and cap beam.

State of the Art Report on Precast Concrete Systems for Rapid Construction of Bridges (Hieber et al. 2005b)

This report provides a review of precast concrete systems used by states other than Washington, with the objective of identifying rapid construction technologies that are most suitable for use in Washington

state. The report identifies the following four broad superstructure categories with a separate chapter devoted to each:

- Full-depth precast concrete deck panels.
- Partial-depth precast concrete deck panels.
- Prestressed concrete multibeam superstructures.
- Pre-constructed composite systems.

One additional chapter of the report addresses precast concrete substructure systems, including columns and cap beams.

In reviewing previous use of precast components in substructures, the authors found that typically either the columns were precast and the cap beams were CIP, or vice versa—i.e., they did not observe simultaneous use of both precast columns and caps. Because of economies of scale, precasting of substructure components was found more often on large-scale bridge projects than on short- and moderate-span bridges. The authors discuss key issues related to use of precast substructure systems. These issues, discussed in detail later in this report, include:

- Connection between footing and precast column.
- Connection between column segments.
- Connection of column and cap beam.
- Connection between cap beam segments.
- Weight and size limitations.

The report does not provide any specific recommendations on which precast substructure systems are most applicable to Washington bridges, and does not provide any meaningful specific design details that could be considered for Arizona bridges.

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

This research focused on the development and evaluation of a rapidly constructible column-to-cap beam precast concrete moment connection for high seismic loading. The research consisted primarily of experimental testing of four large-scale (40 percent scale) column-cap beam connection subassemblies and monotonic pull-out tests on individual large-diameter bars. The “rapid construction” feature of the connection was based on the use of relatively few large-diameter longitudinal bars in the column, which were grouted in large-diameter corrugated metal ducts embedded within the cap beam. The smaller number of bars reduces the numbers of bar-duct alignments required in the field to make the connection. The use of fewer larger-diameter bars allowed for less congestion in the connection and more room for tolerances—a critical aspect in design of precast connections.

Of the four connection subassemblies, one was a traditional CIP monolithic connection, and this test specimen served as a baseline for evaluation of the performance of the precast connections. The prototype large-diameter bar connection used six #18 (2.25-inch diameter) column bars, 8.5-inch-diameter ducts. The scaled test specimens used six #8 longitudinal bars in the large-diameter bar connection. Of the three rapid construction connections, two had local debonding of the longitudinal bars near the connection interface to reduce the concentration of bar normal strains and to cover

concrete spalling at the connection joint. The subassemblies were tested under cyclic lateral seismic loads simulating seismic input. Figure 1 depicts the subassemblies tested in the research.

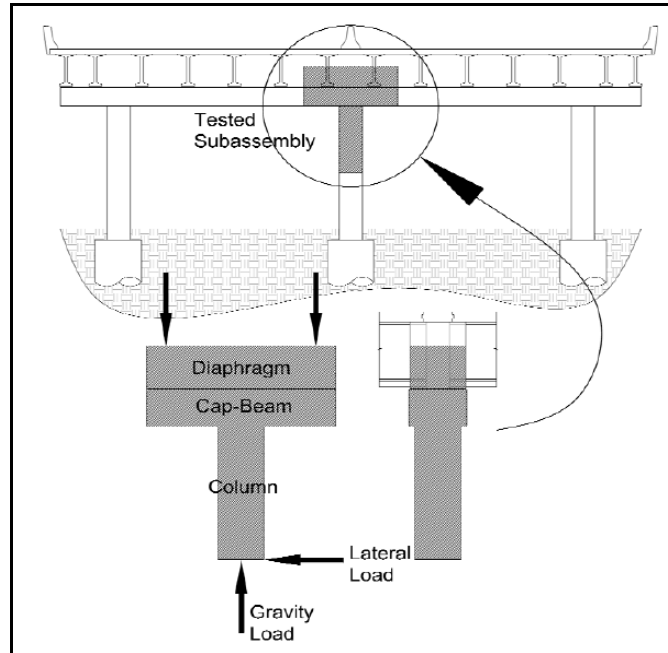


Figure 1. Column-Cap Beam Subassemblies Tested.
(Pang et al. 2008.)

The test results demonstrated that the precast rapid connection detail provided a force-displacement response that is similar to the traditional CIP connection, with all subassemblies reaching 5.5 percent before a drop in lateral strength of 20 percent. Specimens with the deliberate debonding experienced less concrete damage (concrete spalling and radial cracks at bars) at the connection interface than the rapid connection with full bar bonding. However, specimens with debonding achieved maximum lateral strengths on the order of 10 percent to 15 percent less than those of the traditional CIP and fully bonded precast subassemblies.

The researchers conclude that the proposed precast connection provides for rapid construction in the field and can be expected to perform nearly identically to a traditional CIP column-cap beam connection. For a more comprehensive description of specific design recommendations, see Chapter 3.

A Precast Concrete Bridge Bent Designed to Re-Center After an Earthquake (Cohagen et al. 2009)

This research is similar to that performed by Pang et al. (2008), except that, in addition to the longitudinal mild steel reinforcement, the precast column-to-cap beam subassemblies contained a single PT high-strength steel bar at the center of the circular section. The intent of the PT steel is to provide a restoring force to the column, which acts to re-center the column after the seismic event. Two 40-percent-scale column-cap beam subassemblies were constructed and tested in the laboratory under loads simulating seismic input. The column and cap beam were individually precast, and then the fixed connection was made between the two by grouting the mild steel column bar extensions in large-diameter corrugated metal ducts embedded within the cap beam. The connection was also

strengthened by the presence of the unbonded PT steel that was anchored within the cap beam. The test specimens were different in the amount of mild steel longitudinal reinforcement, with one having 1.1 percent longitudinal mild steel and the other having 0.84 percent mild steel. The amount of prestressing steel reinforcement was equal to 5 percent of the column theoretical axial compression capacity (i.e., $f'_c A_g$).

Testing of the connection subassemblies demonstrated that the presence of the PT steel indeed helps minimize residual lateral column displacements, and the specimens performed similarly to a reference connection subassembly tested by Pang et al. (2008) that did not contain any prestressing steel. The researchers observed slightly fewer residual displacements in the test specimen with less mild steel longitudinal reinforcement. This smaller number of residual displacements is because the moment capacity contribution of the mild steel was smaller, so the total force required to yield the steel back in compression after inelastic tensile deformations is smaller (because the total steel area is smaller).

REVIEW OF PRECAST SUBSTRUCTURE PROJECTS

This section provides a general review of various bridge projects where some of the bridge substructure components were prefabricated. This section is not meant to provide an exhaustive summary of all prefabricated substructure bridge projects that have been constructed; instead, the intention is to provide both examples of the types of technologies that have successfully been put into practice and an indication of the degree to which states are using these technologies. The focus is on using prefabricated concrete substructure components. This section is organized by state in alphabetical order.

California

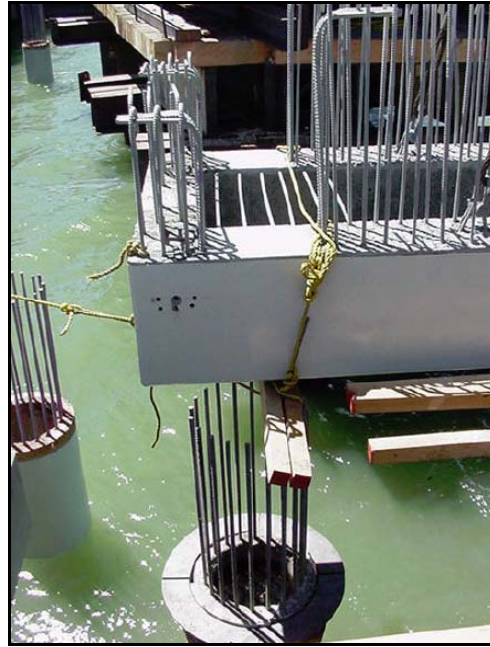
Getty Museum People Mover Viaduct (Josten et al. 1995)

Construction of an elevated tram guideway for the J. Paul Getty Museum near Los Angeles, California, was accelerated through the use of precast concrete bent cap beams, or crossheads. The elevated structure had a total length of 3535 ft, with precast girder spans between 63 ft and 86 ft, and CIP reinforced concrete columns heights up to 42 ft above grade. Single-column and two-column bents were used, and crossheads were connected to the CIP columns via a grouted vertical duct connection. The main column steel consisted of 16 bars with sizes up to #11 bars. These bars extended above the top of the columns and were inserted into corrugated metal ducts embedded in the precast crossheads. Because of the crosshead reinforcement, duct sizes were limited to 1.5 inches in diameter, and thus very tight tolerances were required in placement of the column rebar cage. Templates were used at the precast plant to ensure that the duct locations in the crossheads would align with the column steel in the field. Complicating the alignment issue was the fact that the column rebar cage and drilled shaft rebar cage were fabricated as one unit, and thus very tight control during placement of the rebar cages was required. The vertical ducts in the crossheads were grouted with a high strength grout once the crossheads were erected and aligned.

San Mateo – Hayward Bridge

The San Mateo – Hayward Bridge carries heavily traveled Route 92 across the south end of San Francisco Bay in Northern California. A widening project was initiated in 1999 that included 4.7 miles of new trestle structure situated parallel to the existing bridge. The new three-lane structure with 90-ft spans

uses precast bulb-T girders, precast drop caps, and 3.5-ft-diameter precast prestressed cylindrical piles. Because of the very high level of seismic activity in the region, a fixed connection was needed between the superstructure and substructure. This was achieved by extending the bottom longitudinal reinforcement in the precast girders into the CIP portion of the bent cap and connecting the steel with mechanical couplers. The precast bent caps were temporarily supported by erection collars at the tops of the driven piles, and stay-in-place precast deck panels were also used to speed construction. Construction progressed at a speed of 300 ft of structure per week, and was completed ahead of schedule in 2001 at a cost of \$138 million. Figures 2 and 3 show construction of the bridge bents.



**Figure 2. Precast Bent Cap Being Lowered into Position on San Mateo Bridge.
(Chung et al. 2009.)**



Figure 3. Integral Bent Connection Region on San Mateo Bridge. (Chung et al. 2009.)

I-40 Bridges Replacement – Marble Wash Bridge

In 2006, inspection of six pairs of bridges along I-40 100 miles east of Barstow, California, revealed significant structural distress in the concrete decks, bent caps, and girders, with shear cracks in some locations. Emergency shoring was installed and design of 12 separate replacement bridges was initiated immediately. Because this section of I-40 is a heavily traveled route, ABC methods were necessary. These methods included precasting girders and abutments. Normally a project of this size would require two to three years for planning and design, but design was completed in less than three months, and the entire project from discovery of the problem to completion of construction lasted only 14 months (Chung et al. 2008).

The two-span deteriorated Marble Wash Bridges were replaced with single-span bridges using precast concrete I- and bulb-T girders. To expedite substructure construction, precast concrete abutments were selected for the design and constructed at a precast plant approximately 200 miles from the site. Each abutment was cast as a single piece approximately 50 ft long, 6.5 ft wide, and 6 ft high, with the larger of the two abutments weighing 82 tons (Blanchard et al 2009). This project required special trucking permits and heavier cranes than would normally be required for a project of similar size. Low strength slurry pads (200 psi) were used to prepare the site for the precast abutments. The abutment backwalls and shear keys, and the approach wingwalls, are CIP concrete. Figure 4 is a photograph of the installation of the precast concrete abutment during construction.



Figure 4. Precast Concrete Abutment at Marble Wash Bridge, I-40. (Blanchard et al. 2009.)

The “lessons learned” from this project, as described in Chung et al. (2008), include primarily those related to the size of the whole-width precast abutment pieces. Precasting the abutment in segments would have saved money and time related to premiums for trucking, and would have allowed for the

use of smaller cranes. Fabricating the abutment in segments would also have allowed for better staging of construction activities.

Florida

Reedy Creek Bridge, Orlando

The Reedy Creek Bridge provides access to Walt Disney World's Animal Kingdom over an environmentally sensitive wetlands area. This bridge was constructed in the 1990s using a top-down technique in order to minimize construction impacts on the landscape. The contractor worked with the original engineer to redesign the bridge using a prefabricated option, which saved \$950,000 on the \$8.3 million project (Ralls and Tang 2003). The 1000-ft long bridge uses variable-depth precast concrete deck panels 6 ft in width, which are supported by precast concrete pile caps. Piles were driven and precast panels were erected using a traveling erection platform.

Seven Mile Bridge, Florida Keys

At the time of its completion, Seven Mile Bridge in the Florida Keys was the longest continuous concrete segmental bridge in the world. The bridge uses a precast, post-tensioned box girder superstructure and hollow precast segmental piers, which increased the speed of erection. This was the first use in America of precast, match-cast box piers, which were assembled with vertical post-tensioning. The entire structure was completed six months ahead of schedule. The design saved the owner \$7 million in alternate bidding.

Edison Bridge, Fort Meyers

The Edison Bridge in Florida spans the Caloosahatchee River and connects downtown Fort Myers with North Fort Myers. The superstructure consists of 142-ft spans of 72-inch-deep Florida bulb-T girders. The bridge bents consist of precast columns and bent caps which are connected structurally via non-prestressed reinforcement and grouted splice sleeves. Columns are founded on a CIP pile cap. The precast columns use an H-shaped cross-section with 12-inch-thick walls, with two #14 vertical reinforcing bars in each leg of the H-shape. The H-shape of the columns not only minimizes segment weight, but also provides for ease of inspection. The precast concrete caps use an inverted U-shape to save weight, but are solid over the columns. Connections between the footings and columns and the columns and cap beams were made with grouted splice sleeve connectors. The columns were erected at a rate of six per day, and the prefabrication of components saved two months of project time. Figure 5 shows a photograph of a column segment, while Figure 6 shows the bridge bents during construction.



Figure 5. Precast Column Segment on Edison Bridge. (FHWA 2009.)



Figure 6. Erection of Precast Bents on Edison Bridge. (Ericson 2005.)

Georgia

Kia Boulevard over Interstate 8, West Point, Georgia

As part of a new interchange on Interstate 85 in Troup County, Georgia, the Georgia State Department of Transportation (GDOT) used prefabricated precast concrete columns and bent caps for intermediate bridge bents in order to accelerate the construction schedule. CIP concrete footings founded on piles were used on the project, and rebar extensions at the top of footing were grouted into splice couplers embedded in the bottom of columns to connect footings and columns. Before placing the precast caps, workers used a template to check alignment of the longitudinal bar extensions at the column tops to

ensure that installation of the caps would proceed smoothly. The connection between the precast columns and cap beam were also made using the grouted splice couplers. The intermediate bents consisted of three two-column frames. Details of the frames are shown in Figure 7. Photos of the intermediate bents during construction are shown in Figures 8 and 9.

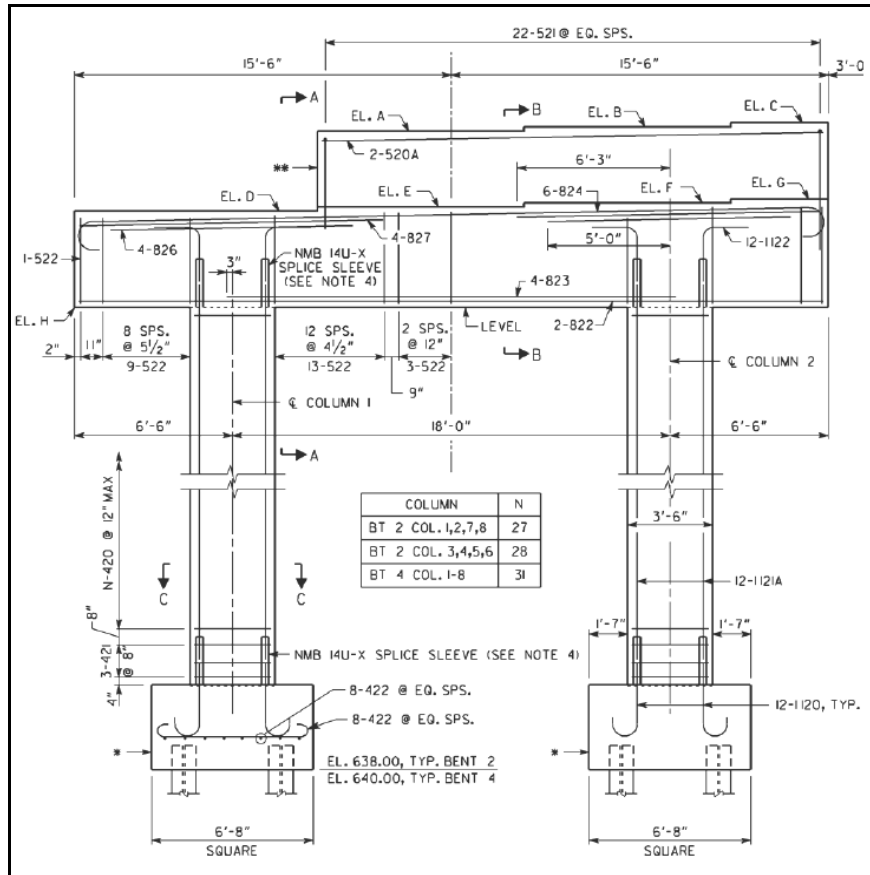


Figure 7. Precast Concrete Bents on Kia Boulevard Bridge. (FHWA 2010b.)



Figure 8. Erection of Precast Concrete Columns on Kia Boulevard Bridge. (FHWA 2010b.)



Figure 9. Completed Intermediate Bents on Kia Boulevard Bridge. (FHWA 2010b.)

Maine

65-ft Single-Span All-Prefabricated Bridge in Upton, Maine

The project was built in 2004 to replace a load-posted pony truss bridge in a rural area. As part of the accelerated construction alternative, a long detour route was used and a temporary bridge was eliminated, saving \$75,000. The savings were used to provide a contractor incentive for completing the work early. The contract allowed a total of 192 closure hours, with an incentive of \$10,000 for meeting that deadline, and an additional incentive of \$200 for each hour less than the 192 hours allotted.

An all-precast bridge was selected in order to reduce road closure time from the approximately 40 days that a cast-in-place substructure option would have taken to the actual total closure time of 96 hours. Precast abutments were founded on driven steel piles. The piles were installed while the existing bridge remained open but with lane restrictions. After pile driving, the route was closed to traffic and the existing bridge was removed.

Abutments were match cast in two segments and post-tensioned together once in place. The bridge superstructure consisted of precast, prestressed concrete box beams; precast approach slabs were also used to eliminate cast-in-place concrete construction.

89-ft Single-Span All-Prefabricated Bridge in Brooksville, Maine

The project was built in 2005 to replace a structurally deficient rolled steel beam constructed in 1941 and spanning the Bagaduce River. Construction with minimal disturbance to the surrounding environment was desired due to the presence of an oyster farm and horseshoe crab breeding grounds. Also, the existing bridge abutments of dry stacked granite blocks were desired left in place so as to not alter the hydraulics of the channel. An all-precast bridge was thus selected.

Match cast precast concrete integral abutments were located behind the existing bridge stone abutments and were founded on driven steel piles. Figure 10 shows installation of the precast abutments during construction. The precast segments contained recesses or blockouts for the pile heads that were filled with self-consolidating concrete after abutment placement. Precast concrete wingwalls were also used, and the entire abutment/wingwall system was post-tensioned together. The superstructure consisted of eight butted precast prestressed box beams post-tensioned transversely, and precast approach slabs were used.

The construction contract allowed for 35 days of closure, with \$1000 per day incentive/disincentive. The bridge was completed in only 30 days from closure to re-opening.



(a)



(b)

Figure 10. Construction of the All-Prefabricated David Narrows Bridge. (PCINE 2006.)

Michigan

Parkview Avenue over U.S. 131, Kalamazoo, Michigan

As a first step in fully embracing accelerated bridge construction technology, MDOT chose to adopt an almost entirely precast concrete bridge design for the replacement of the Parkview Avenue Bridge, which carries traffic across U.S. 131 near Western Michigan University. The replacement bridge has four spans and is 250 ft long. It uses CIP spread footings, precast circular columns, precast abutment pile caps, precast bent cap beams, and precast deck panels. The precast abutment pile caps were founded on steel H-piles, which were grouted into pockets at the pile cap soffit. A tolerance of 6 inches on pile location was accounted for in the design and prescribed in the construction specifications. CIP footings contained 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 column longitudinal rebar extensions grouted into vertical metal corrugated ducts embedded in the cap beams. Grout pads between the column tops and cap beam soffit were used for grade control and to provide a uniform bearing surface at the joint. Figures 11 through 13 illustrate various stages of bridge construction.



Figure 11. Precast Pile Cap Being Lowered into Position on Parkview Avenue Bridge. (Photo Courtesy of MDOT.)



Figure 12. Precast Columns in Casting Yard on Parkview Avenue Bridge. (Photo Courtesy of MDOT)



Figure 13. Precast Bent Cap Being Lowered into Position on Parkview Avenue Bridge. (Cooper 2009, courtesy of MDOT.)

New Hampshire

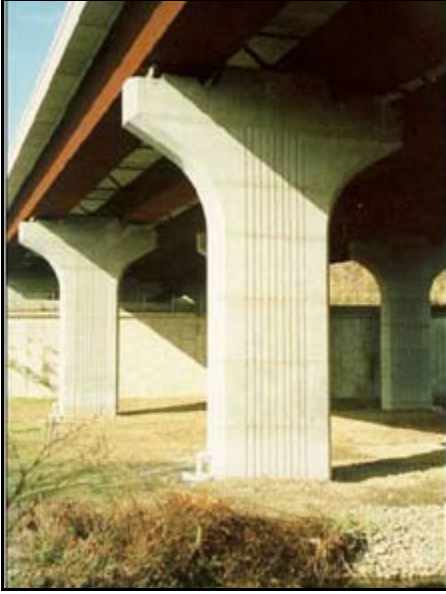
Mill Street Crossing Bridge, Epping, New Hampshire (Stamnas and Whittemore 2005)

The Mill Street Crossing bridge carries traffic over the Lamprey River in Epping, New Hampshire. This replacement bridge was selected in 2002 by the New Hampshire DOT to be a test site for using accelerated bridge construction techniques, and an all-precast solution was implemented. Side-by-side precast box beams, 115 ft long, were used for the single-span superstructure, while precast spread footings and abutment stem walls and seats were used in the substructure. Precast substructure components were connected using grouted splice coupler connectors. The construction contract called for a maximum of two weeks of closure time for construction, but the contractor finished well ahead of schedule, completing construction in only eight days from the time of closure to re-opening.

New York

Cross Westchester Expressway Viaducts, New York

New York State DOT was required to maintain six lanes of congested traffic and limit construction on a restricted site during replacement of two major I-287 viaducts in Westchester County. NYSDOT accepted the contractor's value-engineering proposal to incorporate precast segmental voided pier sections for each of the 42 piers, which consisted of 8-ft match-cast segments vertically post-tensioned together and to the footings. The proposal also changed the cast-in-place deck to 10-ft-long by 9-inch-thick precast panels, 42 to 50 ft wide to match longitudinal construction stages, supported on pairs of multi-span continuous steel tub girders. Figure 14 shows photographs of the piers during construction, while Figure 15 is a CAD drawing of the pier details.

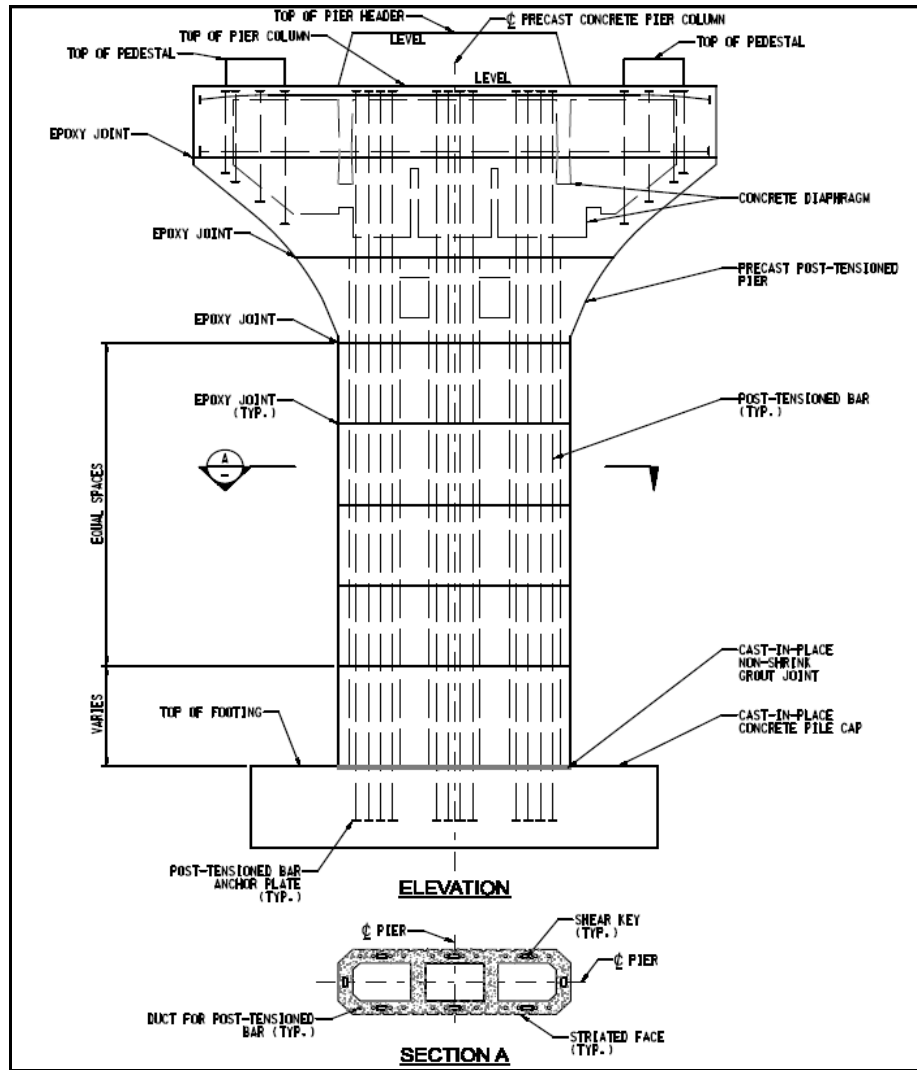


(a) Pier Footing in Grout Bed



(b) Pier Footing Connection

Figure 14. Precast Concrete Piers on Cross Westchester Expressway Viaduct. (FHWA 2009.)



**Figure 15. Pier Details on the Cross Westchester Expressway Viaduct.
(FHWA 2009.)**

Texas

Red Fish Bay and Morris-Cummings Cut Bridge, SH 361, Port Aransas, Texas

The Red Fish Bay Bridge was constructed in 1994; it consists of two 2020-ft-long parallel structures carrying State Highway 361 traffic over Red Fish Bay and the Morris-Cummings Cut. The contractor requested that precast bent caps be used to minimize construction time over water, and the caps were seated on precast concrete square piles. The connection between the piles and caps was made using epoxy coated hairpin bars embedded in the piles. The bars were inserted into blockouts formed in the caps and then grouted in place. The total construction time was reduced by approximately 40 percent (FHWA 2010a). Figures 16 and 17 show the precast concrete bent caps in the casting yard and being lowered into position onto the piles, respectively.



Figure 16. Precast Cap on Red Fish Bay and Morris and Cummings Cut Bridge. (Wolf 2005.)



Figure 17. Precast Cap on Red Fish Bay and Morris and Cummings Cut Bridge. (Wolf 2005.)

Louetta Road Overpass, Houston, Texas

The Louetta Road Overpass structures were designed and constructed in the early 1990s as part of an upgrade to State Highway 249 near Houston, Texas. The bridges use partial-depth precast concrete deck panels and precast segmental columns. The hollow column segments were match cast and used a high performance 10,000 psi concrete mix design. A CIP concrete section with bar couplers forms the connection between the bottommost precast segment and the top of the concrete drilled shaft foundations. The columns were post-tensioned from the top of the capital segment with six high-strength PT bars, which were grouted after PT operations. Figures 18 and 19 illustrate construction of the precast columns.



Figure 18. Assembly of Precast Segmental Columns on Louetta Road Overpass. (CABA, ND Slide 24.)



Figure 19. Completed Precast Columns and Cap, Louetta Road Overpass. (CABA, ND, Slide 6.)

U.S. 290 Ramp E-3, Austin, Texas

The original design of the U.S. 290 Ramp E-3 in Austin, Texas called for CIP substructures and precast prestressed I beam superstructure. However, after construction had already begun, it was determined that the formwork for the CIP bent cap would interfere with traffic on an existing route passing below the ramp. Because of this issue, the contractor requested that TxDOT allow for a precast concrete bent cap alternative, which led to a reduction in ramp closure from an estimated several weeks to only six hours (Marin 2008). The cap-to-column connection consisted of PT bars embedded in the column tops and in the caps, and fixed in place with grout. Photographs of the precast cap during and after placement are shown in Figures 20 and 21, respectively.



Figure 20. Precast Bent Cap Lowered into Position on Ramp E-3 Structure. (Marin 2008.)



Figure 21. Precast Superstructure Beams Resting on Precast Bent Cap on Ramp E-3. (Marin 2008.)

Pierce Elevated Freeway, IH-45, Houston, Texas

The Pierce Elevated Freeway carrying Interstate Highway 45 through downtown Houston consists of identical bridge structures with one carrying northbound and the other carrying southbound traffic. The viaduct was originally constructed in the mid-1960s; by the early 1990s, 113 spans in each structure needed to be replaced. To accelerate the construction schedule, engineers at TxDOT decided to use new precast concrete bent caps along with the original reinforced concrete columns. The precast caps were connected structurally to the columns using high strength post-tensioning bars embedded in the tops of the columns and passing through the caps. Implementing this accelerated construction scheme reduced the construction time from approximately one and a half years (which would have been required for the CIP bent cap option) to 190 total days (FHWA 2006b). User delay costs were estimated at \$100,000 per day, with a total reduction in cost of \$36.0 million (Ralls and Newman 2008). Figure 22 shows a precast cap being lowered into position on top of the columns.



Figure 22. Precast Cap Placement on Pierce Elevated Freeway, Houston. (Wolf 2005.)

Lake Ray Hubbard Bridge, Texas

The new Lake Ray Hubbard Bridge was completed in 2002. It replaced a narrow 40-year-old two-lane bridge. The superstructure consisted of precast I-beams and precast prestressed deck panels, and the original design called for CIP substructures. In order to improve safety by reducing the amount of time workers would be required to operate near high-power overhead lines, the contractor requested a no-cost change to the precast concrete bent cap alternative. The precast caps were connected to concrete piles and columns using rebar doweled into the tops of the piles and columns and inserted into PT ducts within the caps. A total of 43 precast caps were used, with a time savings of approximately one week per bent cap and a total of 215 fewer days of onsite construction (FHWA 2009). Figure 23 shows a precast bent cap being lowered into place atop columns.



**Figure 23. Placement of Precast Bent Cap on Lake Ray Hubbard Bridge.
(FHWA 2009.)**

Lake Belton Bridge, Texas

This 3840-ft-long bridge carries State Highway 36 over Lake Belton. It was completed in 2004. The bridge superstructure consists of 120-ft spans of precast U-beams with precast prestressed deck panels and a 4-inch concrete topping. The substructure consists of 62 precast concrete bent caps on CIP concrete columns. Although the bridge was constructed adjacent to an existing bridge, construction materials could not be delivered via the existing bridge because of its low load-carrying capacity (FHWA 2009). Bent caps are connected structurally to the columns via 14 #11 bars doweled into the top of each column and embedded in grout-filled PT ducts within the cap. Figure 24 is a photograph of the erection of the precast bent cap beams, while Figure 25 is a photograph of the completed bridge.



**Figure 24. Precast Cap Beam Being Lowered into Position on Lake Belton Bridge.
(FHWA 2009.)**



Figure 25. Completed Lake Belton Bridge. (Marin 2008.)

LP340/SH 6 at IH-35, Waco, Texas

The LP340/State Highway 6 project included four new four span bridges constructed over Interstate Highway-35 near Waco. Span lengths were each 115 ft; precast concrete U-beams with slab topping were used for the superstructure. The substructure consists of conventional drilled shaft foundations and precast column shells infilled with CIP concrete. CIP footings were constructed at the top of the drilled shafts, and column rebar cages were cast integrally with the footings. Full-height precast concrete column shells with rectangular cross-section and 7-inch-thick walls were lowered down over the column cages and secured in place. The cores of the precast shells were then filled with CIP concrete. Construction was completed in 2007 at a cost of \$86 per square foot of bridge. Figures 26 through 29 show various stages of construction of the LP340/SH 6 bridges.



Figure 26. Lifting Precast Column Shell into Place, SB 340 over IH-35. (Wolf 2005.)



Figure 27. Precast Column Shells Before Core Filling on SB 340 over IH-35. (Wolf 2005.)



Figure 28. Base of Precast Column Shell After Core Concrete Filling. (Wolf 2005.)



Figure 29. Completed SB Bridge 340 over IH-35. (Marin 2008.)

Cottonwood Creek Bridge, Williamson County, Texas

Because of the long detour route required when the road was closed, accelerated bridge construction methods were desired for the replacement of an existing bridge carrying two lanes of traffic in a rural area. The new two-span bridge used precast, prestressed decked slab beams, precast abutments and bent caps, and driven steel H-piles. Each span was 50 ft long, and the bridge was 42 ft wide. The connection between the H-piles and the precast caps and abutments was made by welding the piles to steel plates embedded in the bottom side of the precast units. The total time for construction of the bridge was six days, and total project road closure duration was 33 days. Figures 30 and 31 provide photographs of the bridge during and after construction, respectively.



Figure 30. Installation of Precast Abutment, Cottonwood Creek Bridge. (Marin 2008.)



Figure 31. Completed Cottonwood Creek Bridge. (Marin 2008.)

Utah

Riverdale Road over I-84, Riverdale, Utah

The Riverdale Road over Interstate 84 bridge in Riverdale, Utah, required replacement in conjunction with roadway widening and upgrading the interchange from a diamond to a single-point urban interchange (SPUI). The new SPUI bridge was constructed in phases using almost all pre-fabricated elements. H-piles were driven for the pile foundations, and cast-in-place footings were cast on the piles. Precast blocks were stacked and post-tensioned together for the abutments. Precast columns and bent caps were placed and post-tensioned for the bent. Steel plate girders were installed on the two spans. Precast end diaphragms were installed on the girder ends, and then precast non-composite deck panels

were installed on the girders. Precast approach slabs were installed as the last link. The non-composite precast deck panels were placed on neoprene foam strips on the outside of the top flanges of the girders. There were no shear studs connecting the panels to the girders. This feature greatly accelerated the installation of the deck panels since shear studs did not have to be installed and grout pockets did not have to be filled. The panels were connected with grout closure pours and then longitudinally post-tensioned. Grout was then pumped into the haunch area between the foam strips to provide full bearing of the deck onto the girder. Figure 32 shows the completed bridge.



Figure 32. Riverdale Road Bridge in Utah. (Burns 2008.)

Washington

SR 520 West Lake Sammamish Parkway to SR 202, Washington

As part of a conventional design-bid-build widening project of Washington State Route 520, a precast concrete bent cap alternative was proposed by the contractor in order to speed construction. The contractor worked with WSDOT engineers to develop the precast alternative. This was the first use of a precast bent cap in the state of Washington (Pang et al. 2008). The precast caps were used on the flyover ramp connecting the two routes and were cast partial height on the ground while the footings and columns were constructed. The connection between the 5-ft-diameter CIP RC columns and precast cap beam consisted of grouting the extended longitudinal bars in ducts located in the cap beam. To ensure that the column steel lined up with the ducts embedded in the caps, a template was made based on longitudinal bar layout once the columns were cast. Each bent cap was erected in approximately only 1.5 hours. Figures 33 and 34 provide photographs of construction of the bents.



Figure 33. Template for Aligning Column Bars and Bent Cap Connection Ducts. (Pang et al. 2008.)



Figure 34. Precast Bent Cap in Place on SR 520 / SR 202 Interchange Flyover Ramp. (Pang et al. 2008.)

CHAPTER 3. PRECAST BENT CAPS

Precast concrete bent caps are the most widely used precast substructure component, and there has been significant research to develop this technology for advancement of ABC. Precast caps can be used for single and multi-column bridge bents as well as on pile-supported bents. Use of precast cap technology on bridges removes construction activities from the site that contribute significantly to the overall bridge construction schedule, including fabrication of the cap rebar cage, formwork placement and removal, and curing of the CIP cap concrete. Because construction of conventional CIP bent cap beams is time intensive and typically is on the construction critical path, of all precast substructure technologies, implementing precast caps probably has the largest overall payoff in terms of saving time. Previous projects have shown that caps that normally would take several weeks to construct if conventionally constructed can be erected in a couple of days when a precast cap is used. Precast caps can also help alleviate problems associated with constructing bridges near existing transportation routes, such as limited vertical clearance over existing traffic lanes.

This chapter presents information on various precast cap beam technologies and designs, and discusses the issues related to implementing precast caps for ABC. Because much of the information collected, such as design recommendations, is specific to the particular precast cap system and can't be used outside of the context within which it was intended to be applied, this chapter is organized by source rather than topic.

TEXAS PRECAST BENT CAP SYSTEM

This section discusses research conducted at the University of Texas at Austin for the TxDOT on the behavior and design of precast concrete bent cap beams for "typical" Texas bridges and low seismic zones (Matsumoto et al. 2001). The research is focused on bridges with bents that are assumed pinned at the top in the longitudinal direction and with full moment connections between the columns and cap in the transverse direction. The "typical" cap beam geometry included a rectangular section and inverted-T section. The goals of the research program focused on developing connection details for precast concrete cap beams on multi-column bents with CIP RC columns or trestle pile bents (single column bents were not included in the investigation), and included the following:

1. Develop practical and economical connection concepts.
2. Construct and test selected connection details to examine constructability and behavior under loading.
3. Develop design methods, examples of connection details, and construction specifications for precast cap beam-to-CIP concrete column connections.

The research project was organized into three phases. In the first phase, researchers examined the pull-out behavior of bars (straight, headed, and bent) embedded in grouted pockets and grouted ducts. The second phase of work included construction and load testing of full-scale bent cap-to-column connection sub-assemblages, with grout pocket, grout ducts, and bolted connections tested. The final phase included the construction and testing of two full-scale bridge bents to examine constructability (primarily) and response under loading.

The research report is organized into the following chapters:

- 1. Introduction.
- 2. Development of Connection Details.
- 3. Phase 1 Pullout Tests.
- 4. Phase 2 Connection Tests.
- 5. Phase 3 Bent Tests.
- 6. Development of a Design Methodology.
- 7. Development of a Precast Connection Specification.
- 8. Recommendations for Design and Construction.
- 9. Summary and Conclusions.

Connection Types

The research team used input from an industry review committee (IRC) to develop potential connection details, with emphasis being placed on economy, constructability, durability, and force transfer. In their report, the researchers discuss each of the four connection types, presenting advantages and disadvantages for each. The four basic connection types considered include:

- Grout pocket.
- Grouted vertical ducts.
- Grouted sleeve mechanical couplers.
- Bolted connections.

Grout Pocket

Grout pocket connections consist of a void or pocket cast inside of the cap beam, within which column or pile longitudinal reinforcement or connectors are inserted and then grouted in place. Caps can have a single grout pocket or two side-by-side grout pockets (which is called a “double-line” grout pocket connection). The rectangular cross-section is tapered vertically, with the smaller section at the bottom of the cap beam and the larger section at the top. This arrangement provides enhanced resistance to pullout compared to a non-tapered pocket cross-section, and also allows for ease of removal of reusable pocket forms. However, for double-line grout pockets as shown in Figure 35, pocket taper should only be along the length of the cap beam in order to reduce interference with cap beam longitudinal reinforcement (note that Figure 35 depicts pocket taper in the transverse cap beam direction).

Advantages of the grout pocket connection include:

- Large tolerances for location of column steel or connectors (2.5 inches in the longitudinal direction and 1 inch in the transverse direction).
- A variety of connector shapes that can be used (such as headed, straight, bent, and U-shape).
- Successful previous use in building industry.

There are several disadvantages to the grout pocket connection, including:

- The large surface area at the top of the cap provides a large ingress area for moisture.
- The volume of grout required can be large compared to other connection types.
- The relatively large size of the pocket causes cap beam longitudinal bar congestion issues.

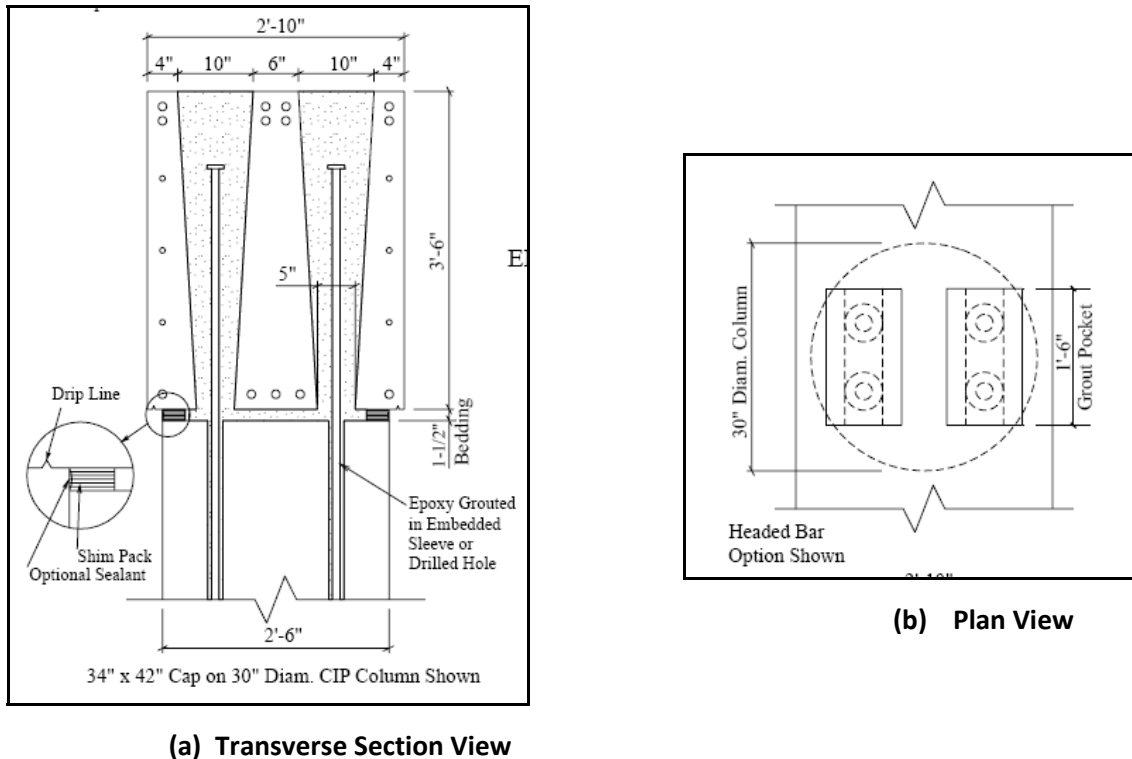


Figure 35. Double Line Grout Pocket Connection. (Matsumoto et al. 2001).

Grouted Vertical Duct

As the name implies, the grouted vertical duct connection consists of corrugated metal ducts cast vertically within the cap beam, with connectors extending from the columns or piles into the ducts. These connections are secured in place with grout. Use of metal ducts in the precast industry is standard, and there is a wide variety of duct manufacturers. Large-diameter ducts are available that allow for large tolerances in location of connectors. Figure 36 illustrates a grouted duct connection for an inverted-T cap cross-section. For rectangular cap cross-sections, it will be more economical to use full-depth ducts in the cap. Some of the advantages of the grouted vertical duct connection are that these connections:

- Are capable of providing large tolerances.
- Are inexpensive and can stay in place rather than needing to be removed.
- Provide less interference with cap beam longitudinal steel than grout pocket connections.

The major disadvantage of the grouted duct connections is the exposed surface at the top of the cap, which may allow moisture to penetrate the connections, which in turn poses durability concerns. However, a sealant can be applied to the top surface of the cap at the duct locations if desired.

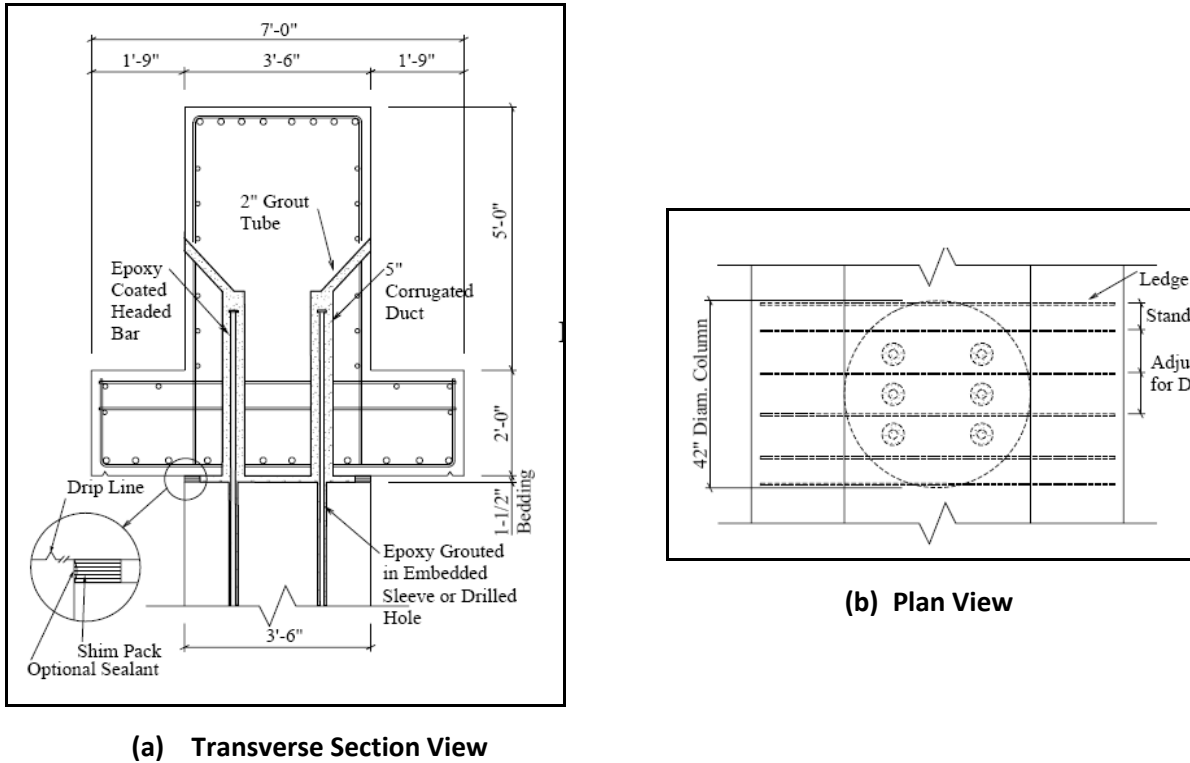
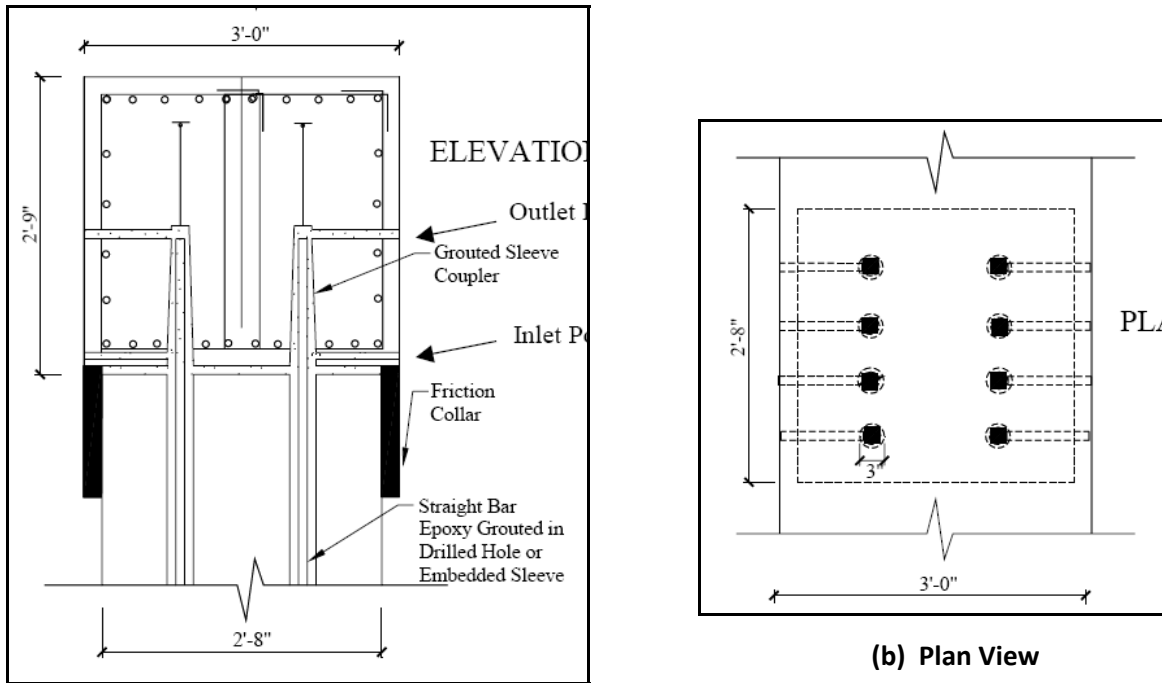


Figure 36. A Three-Row/Two Connections Per Row Line Grouted Vertical Duct Connection. (Matsumoto et al. 2001.)

Grouted Splice Sleeve Couplers

Grouted sleeve couplers consist of a cylindrical sleeve embedded in the precast cap beam into which column or pile rebar extensions are inserted and grouted in place. Although these connectors are proprietary, three manufacturers produce them. Figure 37 illustrates a precast cap-to-column connection using grouted splice sleeve connectors. Because the Utah system relies solely on this connection type, see the more detailed discussion of this connection type later in this chapter (under “Utah Precast Bent Cap System”).



(a) Transverse Section View

(b) Plan View

Figure 37. Grouted Splice Sleeve Connection Proposed by Matsumoto et al. (2001).

Design Recommendations

In Chapter 8 of the final University of Texas-Austin research report (Matsumoto et al. 2001), the researchers summarize recommendations for the analysis, design, and construction of precast bent caps for Texas bridges. The recommendations apply to multi-column bents and pile trestle bents in regions of low seismicity. Specific analysis and design recommendations are given in the research report only where differences exist between the requirements for traditional CIP RC bents and the newly developed precast concrete bent system. The design recommendations section is organized into the following subsections:

- 1. Design Scope and Philosophy.
- 2. Definitions.
- 3. Notation.
- 4. Design Loads.
- 5. Analysis.
- 6. Material Properties.
- 7. Connection Types.
- 8. Connection Design for Strength Limit State.
- 9. Connection Design for Serviceability Limit State.
- 10. Connection Embedment.
- 11. Connection Detailing.
- 12. Connector Development Length.

- 13. Durability Enhancement.
- 14. References.

From a review of the Chapter 8 recommendations in the University of Texas-Austin research report (Matsumoto et al. 2001), all provisions appear to be directly exportable to an application of the Texas precast bent cap system for an Arizona bridge. Because of this direct application, there is no need for this report to make an in-depth description of the recommendations in the Texas report.

Construction specifications for the precast bent cap system are also provided in Chapter 8 of the Texas research report. The specifications are presented in TxDOT format and could be easily adapted to be incorporated into an ADOT specification for the precast bent cap. The following specifications are included in the work:

- 1. Description.
- 2. Materials.
- 3. Contractor Submittals.
- 4. Construction Methods.
- 5. Measurement.
- 6. Payment.

Implementation of Texas Precast Bent Cap Research

The results of the Texas precast bent cap research report have proven to be useful and practical, having been implemented on numerous new Texas bridges in the last decade. Based on a review of bridge projects using precast bent caps, it appears that the grouted vertical and grouted pocket connections have been the most frequently used precast bent cap connection method. To date, there do not appear to be any significant problems with the Texas bridges using the precast bent cap system.

Appendix A provides design details from the Lake Belton Bridge, which used precast bent caps and the grouted vertical duct connection method. The CIP RC columns were circular in cross-section, and the connection between the precast cap and columns was made via a rectangular pattern of dowel bars grouted into the core region of the columns and the bent cap. Included in Appendix A are construction notes and the grout performance specification used on the project.

Appendix B provides precast cap design details from the Lake Ray Hubbard Bridge, which used both grouted vertical duct and grouted pocket connections in conjunction with circular RC columns.

Appendix C provides design details from the Red Fish Bay and Morris and Cummings Cut Bridge, which is a low water crossing bridge that used precast pile cap beams on driven precast piles. The piles had U-shaped rebar extensions at the top, which extended into the grout pocket.

The advantages and disadvantages associated with the four connection types discussed at the beginning of this section are summarized in Table 1. In that table, a “+” symbolizes an advantage, while a “-” indicates a disadvantage.

Table 1. Advantages and Disadvantages of Connection Types. (Matsumoto et al. 2001.)

Connection Type	Constructability	Durability	Force Transfer
Grout Pocket	<ul style="list-style-type: none"> + large construction tolerances + tailored pocket shapes + easy to place confining reinforcement + fairly simple grouting operations - congestion reinforcement - large spacing between reinforcement 	<ul style="list-style-type: none"> + epoxy coated connectors viable - cracking at large top surface - cracking through connectors 	<ul style="list-style-type: none"> + simple to tailor number of connectors roughening + excellent anchorage of connectors + excellent ductility of connectors + simple anchorage design approach - potentially small rotational stiffness
Grouted Vertical Duct	<ul style="list-style-type: none"> + acceptable construction tolerances + inexpensive stay-in-place ducts + minimal interference with cap reinforcement + easy to place continuing reinforcement - more difficult grouting operations required 	<ul style="list-style-type: none"> + more limited exposed top surface + well-protected connectors + epoxy-coated connectors viable 	<ul style="list-style-type: none"> + excellent interlock at all interfaces + excellent anchorage of connectors + excellent ductility of connectors + simple anchorage design approach - potentially small rotational stiffness
Grouted Sleeve Coupler	<ul style="list-style-type: none"> + minimal interference with cap reinforcement - excessively tight horizontal tolerances - proprietary hardware and grout - higher level of construction skill required - grout pumping required in all cases - multiple grouting operations require 	<ul style="list-style-type: none"> + well-protected connectors + epoxy-coated connectors viable 	<ul style="list-style-type: none"> + excellent anchorage of connectors + excellent ductility of connectors + anchorage not desired for cap - potentially small rotational stiffness
Bolted Connection	<ul style="list-style-type: none"> + acceptable construction tolerances + inexpensive stay in place ducts + minimal interference with cap reinforcement + easy to place continuing reinforcement + cap setting option using leveling nuts & plates + temporary support using during erection - more difficult grouting operations required - multiple grouting operations possibly required 	<ul style="list-style-type: none"> + galvanized connectors viable + optional post-tensioning - grouting of cap tone recess - exposed cap top anchorage 	<ul style="list-style-type: none"> + resistance to large moments possible + full continuity of bars through connection anchorage + excellent ductility of connectors + anchorage not desired for cap - potentially small rotational stiffness

UTAH PRECAST BENT CAP SYSTEM

Overview

UDOT has published various documents related to use of precast substructures for Utah bridges; see Chapter 2 for a brief review. The UDOT precast bent cap system is based on the idea of emulating the response and performance of conventional CIP RC construction with precast RC construction. Practices and recommendations for this construction technique can be found in the document, “ACI 550.1R-09 Guide to Emulating Cast-in-Place Detailing for Seismic Design of Precast Concrete Structures,” published by the American Concrete Institute (Joint ACI/ASCE Committee 550 2009).

The basis for the Utah system is the grouted splice coupler, essentially a non-contact butt-splice for non-prestressed deformed rebar. The UDOT *Precast Substructures Elements Manual* (UDOT 2010a) states that the grouted splice sleeve coupler has been used successfully in the vertical precast building industry for over 25 years, and UDOT chose this technology for making connections between all precast substructure components (footings to columns, columns to caps, etc.). For more discussion of the grouted splice sleeve rebar coupler, see “Grout-Filled Splice Sleeve Couplers” later in this chapter.

UDOT Precast Cap Beam Details

UDOT has developed typical details sheets for their precast bridge pier system; various details are shown in Figures 38 through 44. Since the UDOT approach with the grouted splice sleeve coupler is to simply emulate the behavior of conventional CIP RC construction, much of the analysis, design, detailing, and construction of the UDOT precast cap is the same as for CIP construction.

Figure 38 shows an elevation view of the cap beam at the connection region with the column. The splice sleeves are embedded in the underside of the precast cap, which is the preferred arrangement so that debris, etc. do not get into the splice sleeve before the connection is made. A plan view of the cap-to-column connection region within the precast cap beam appears in Figure 39, while a cap beam cross-section view is in Figure 40. The column top (column could be CIP or precast) in the proposed UDOT precast system is shown in Figure 41, where it can be seen that a shim stack in combination with a non-shrink grout bedding layer is used at the joint between the precast cap and column. Column longitudinal bars protrude from the column top, and these bars are inserted into their corresponding grouted splice sleeve coupler located at the bottom of the precast cap.

Figures 42 and 43 depict an all-precast concrete bridge pier system for a single-column bent and two-column bent, respectively. For single-column bridge bents, because of the fewer number of connections between column longitudinal bars and splice sleeve couplers, construction of the bent using a precast cap beam should be relatively straightforward compared to the multi-column bent arrangement. With a two-column system, very tight control of column steel and embedded cap beam coupler locations is required to avoid conflicts during assembly in the field. For wide bents with more than two columns, separate two-column bents can be used side by side to minimize assembly effort in the field. A closure pour could be used between the separate cap beams if a continuous cap is required. The UDOT typical detail plan sheets also include details on tolerances for locations of column longitudinal rebar and grouted splice couplers, as shown in Figure 44. For locations of couplers and column steel in plain view, the stipulated tolerance is ± 0.25 inch; extremely tight tolerances are thus required.

The UDOT precast cap system would seem to be best suited for application to a precast girder superstructure bridge type. Girders can be made to be integral with the precast cap, and thus continuous for live load, via a CIP diaphragm. In this situation, the precast cap stirrups could extend above the top surface of the precast beam into the region where the diaphragm will be poured. Alternatively, the precast cap beam can also be easily used with a simply supported precast girder bridge superstructure.

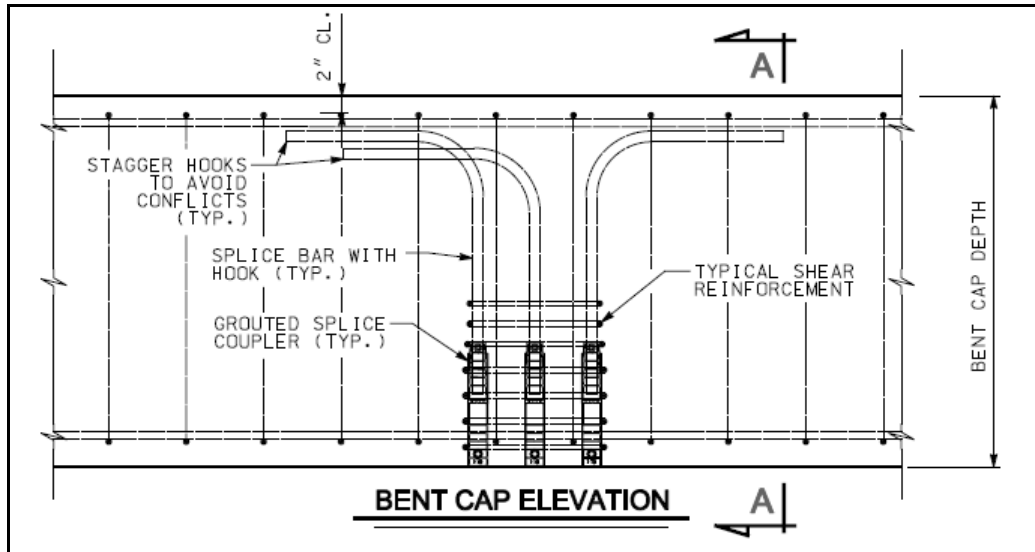


Figure 38. UDOT Precast Cap Beam Connection, Elevation View. (UDOT 2010d.)

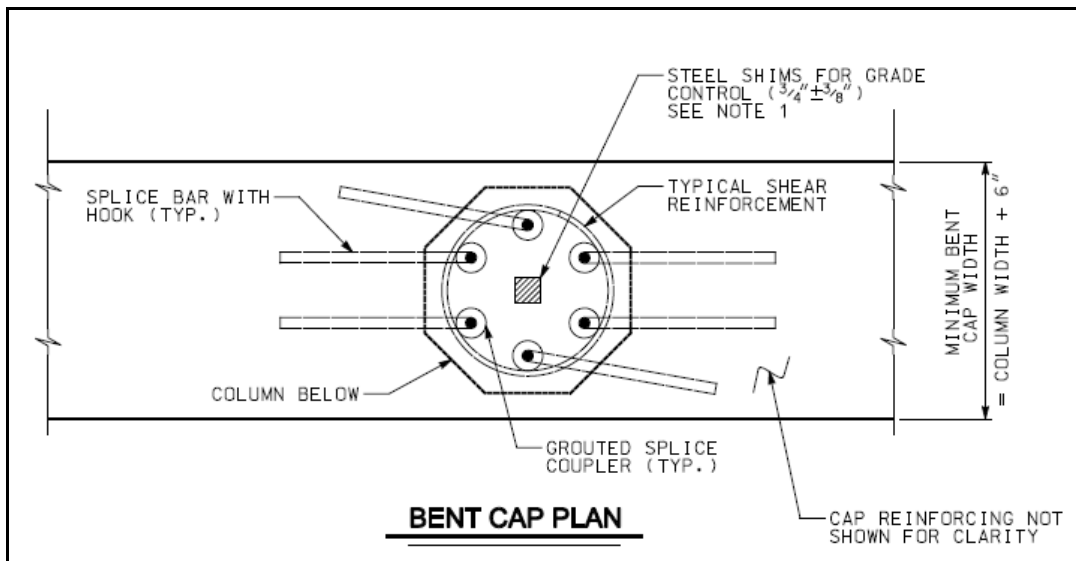


Figure 39. UDOT Precast Cap Beam Connection Plan View. (UDOT 2010d.)

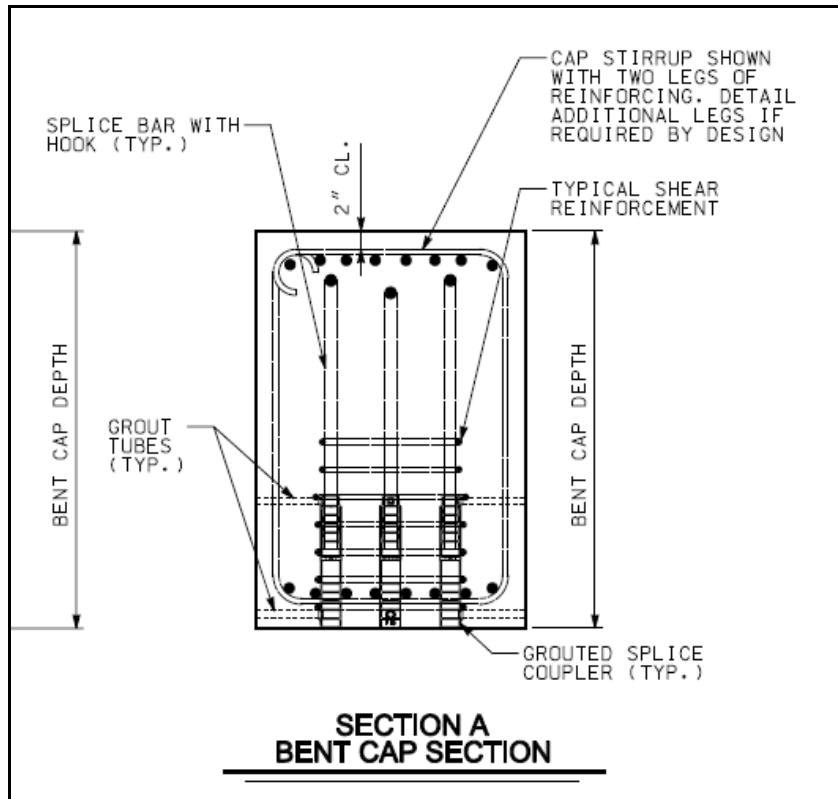


Figure 40. UDOT Precast Cap Beam Cross-Section View. (UDOT 2010d.)

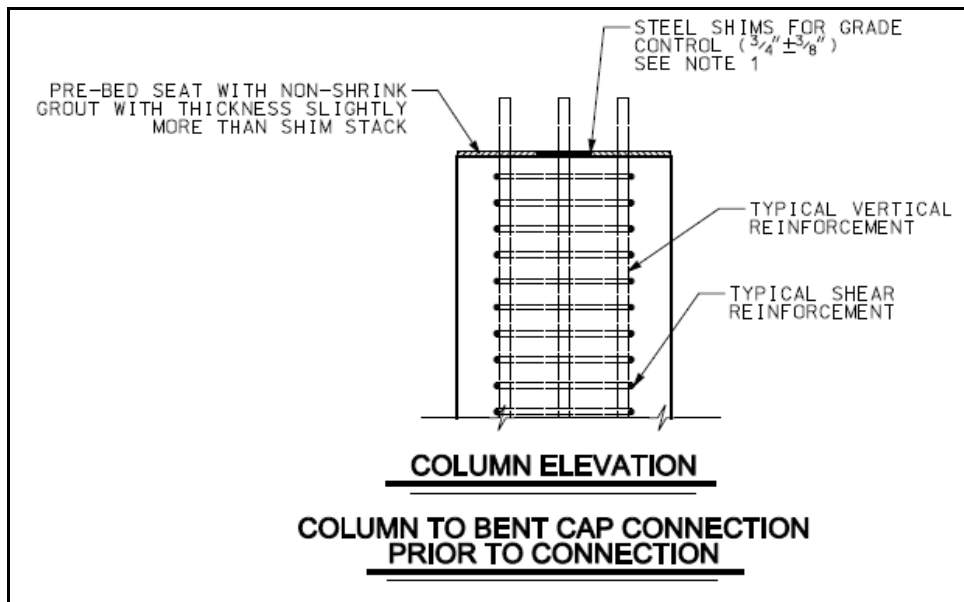


Figure 41. UDOT Precast Cap Beam Connection to Column. (UDOT 2010d.)

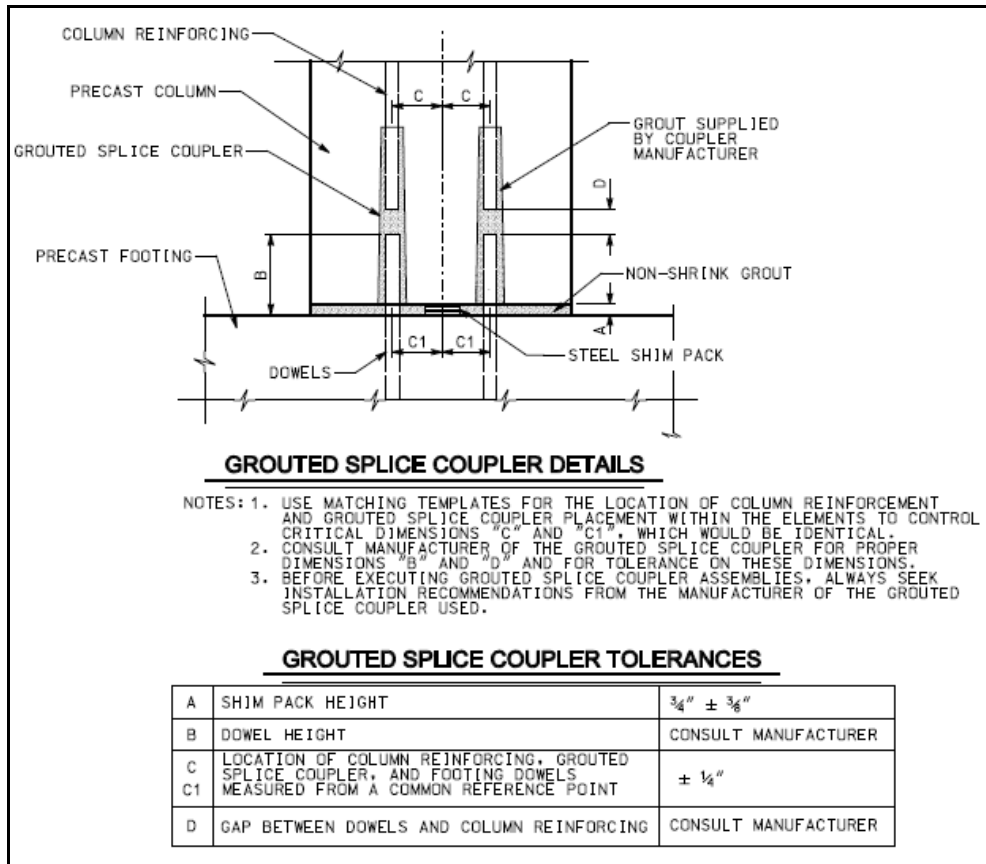


Figure 44. UDOT Precast Concrete Components Tolerances. (UDOT 2010e.)

Grout-Filled Splice Sleeve Couplers

Chapter 2 and "Texas Precast Bent Cap System" earlier in this chapter briefly mention grouted splice sleeves. The non-bridge precast structure industry commonly uses these mechanical rebar connectors with a well-established record of acceptable in-service performance. Their use for making structurally sound connections between separate, major (e.g., columns and footings) precast components in bridges has been increasing as well, and is not uncommon in some states. Advantages include:

- A long track record of use and good performance in the precast building industry.
- A track record of use and good performance in the bridge construction industry.
- Continuity of longitudinal reinforcement with full development (supported by testing).
- Little exposed surface and hence fewer pathways for moisture ingress.

The grouted splice sleeve coupler connections have significant disadvantages, including:

- Very tight tolerances—less than 0.25 inch.
- Two grout operations required—pumping grout to fill the sleeve, and then grouting the bedding layer.

Made by several companies, these couplers are capable of splicing large-diameter bars in very short distances. The splice sleeve is cast in one end of a precast element, and longitudinal steel is left protruding from the end of the adjacent precast segment. The protruding longitudinal bars are inserted into the pocket of the splice connector, and are then grouted to make the connection. The coupler essentially forms a non-contact butt splice between the rebar. This type of connection is termed “emulative” because it emulates the response of a cast-in-place connection.

These grouted sleeve connectors have been used many years in the precast building industry, and are capable of developing up to approximately 160 percent of the specified grade 60 rebar yield strength. The manufacturers of grouted splice couplers include:

- Splice Sleeve North American (“NMB Splice Sleeve”).
- Dayton Superior (“Dayton Superior DB Grout Sleeve”).
- ERICO United States (“Lenton Interlok”).

The *AASHTO LRFD Bridge Design Specifications* manual (AASHTO 2009) requires that mechanical couplers have the following capabilities:

- Be able to attain at least 125 percent of the tensile yield strength of the connected rebar.
- Have load-slip limits.
- Have fatigue criteria.

MDOT investigated the performance of the Lenton Interlok and NMB Splice Sleeve grouted mechanical couplers. The research tested #6 and #11 grade 60 rebar under various loading conditions and in accordance with ASTM A1034 *Standard Test Methods for Testing Mechanical Splices for Steel Reinforcing Bars*. The testing conducted by MDOT included:

- Load-slip tests where specimens were loaded to 30 ksi, and then unloaded, with axial slip measured after unloading.
- High cycle fatigue tests with a stress range of 18 ksi, cycled between 6 ksi and 24 ksi, for one-million cycles.
- Repeat of load-slip tests after the fatigue tests.
- Ultimate load tests.
- Creep tests—specimens loaded to 40 ksi and then held under constant load for 42 days.

All of the testing indicated that both manufacturers’ products meet the requirements prescribed in the *AASHTO LRFD Bridge Design Specifications*.

ALABAMA PRECAST BENT CAP SYSTEM

Research at the University of Alabama at Birmingham (UAB) has been conducted to develop concepts for an all precast bridge bent system to be used on “typical” Alabama bridges (Fouad et al. 2006). The Alabama concept for a precast bent cap beam is essentially the same as that adopted by the UDOT—it is a precast RC component that connects structurally to columns via column longitudinal rebar extensions and grouted splice sleeve couplers embedded at the cap beam soffit. The precast bent cap is intended for use with precast concrete girders that sit on pedestals cast on top of the cap beam (i.e., simply supported girder boundary conditions).

Figure 45 illustrates the UAB precast cap beam system. The system is based on an assumed maximum cap depth of 5 ft, maximum width of 4.5 ft, and maximum out-to-out cap beam length of 45 ft. With these maximum dimensions, a maximum bent cap beam component weight of approximately 150 kips is obtained. Similar to the UDOT precast cap system, the UAB system also requires the use of shim packs at the top of columns for grade control and a grout bed between the cap soffit and column top. This study did not find any precast concrete bent specifications for the Alabama system in its literature review. The UAB research report states that the precast cap can be designed by conventional methods used to design CIP RC bridges.

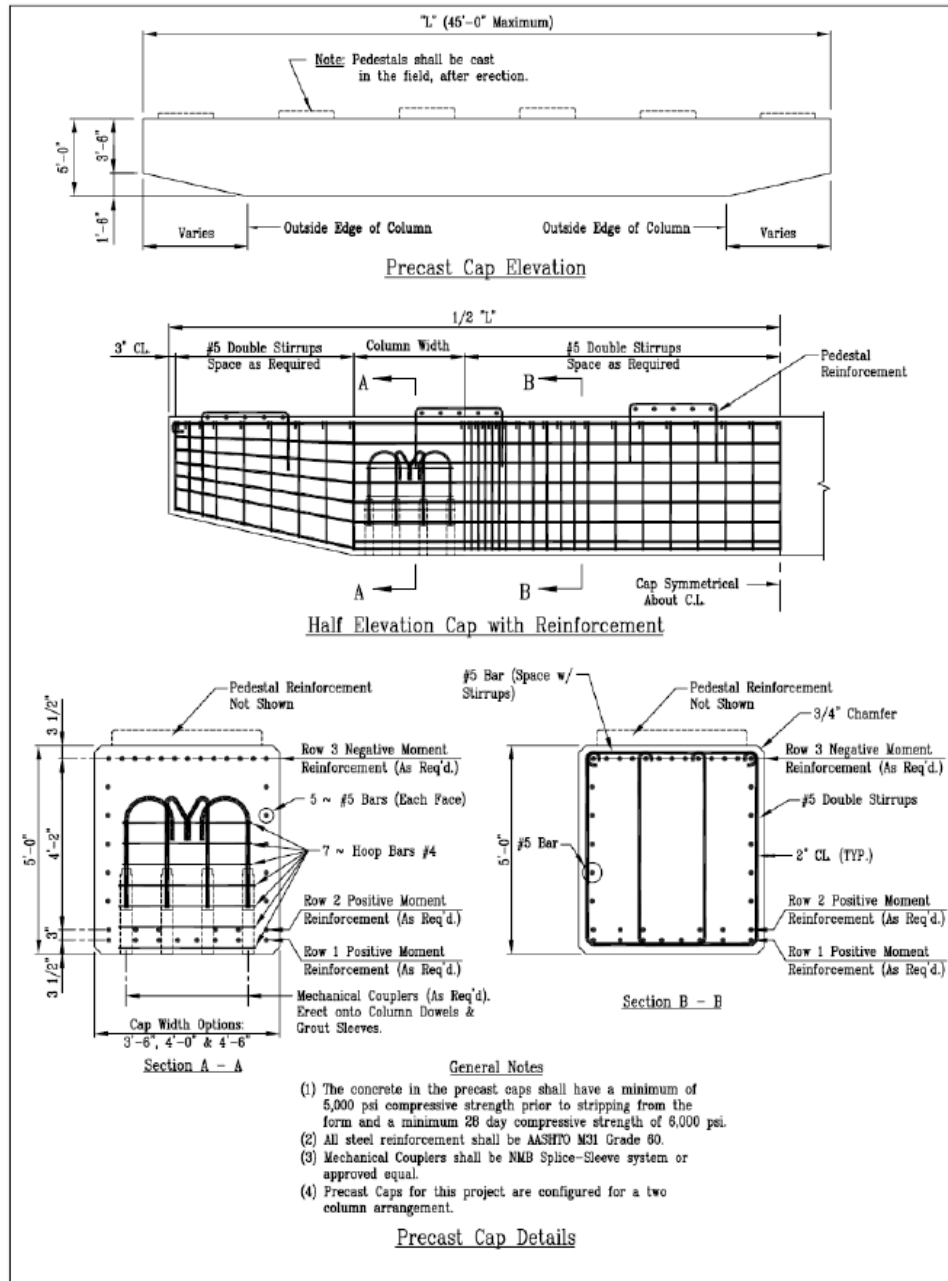


Figure 45. Precast Bent Cap for Prefabricated Alabama Bridge. (Fouad et al. 2006.)

WASHINGTON DOT PRECAST BENT CAP SYSTEM

Much of the research conducted in the state of Washington on the behavior and design of precast concrete substructures focuses on connections between precast columns and bent cap beams, and how they perform under the high seismic loading prevalent in much of the state. Several research projects focused on developing precast column systems that re-center under lateral earthquake loading, thus resulting in minimal residual deformations once the earthquake has ended.

The most relevant work conducted in Washington is that by Pang et al. (2008), who tested the design and behavior of a column-to-precast cap beam connection where large-diameter column longitudinal bars are grouted into vertical ducts embedded in the precast cap beam. The proposed connection was developed with the goal of emulating the response of a traditional CIP column-to-cap beam connection. Figure 46 illustrates the column-to-cap beam connection concept. In the figure, a precast concrete column contains six #18 longitudinal bars that protrude above the top of the column surface.

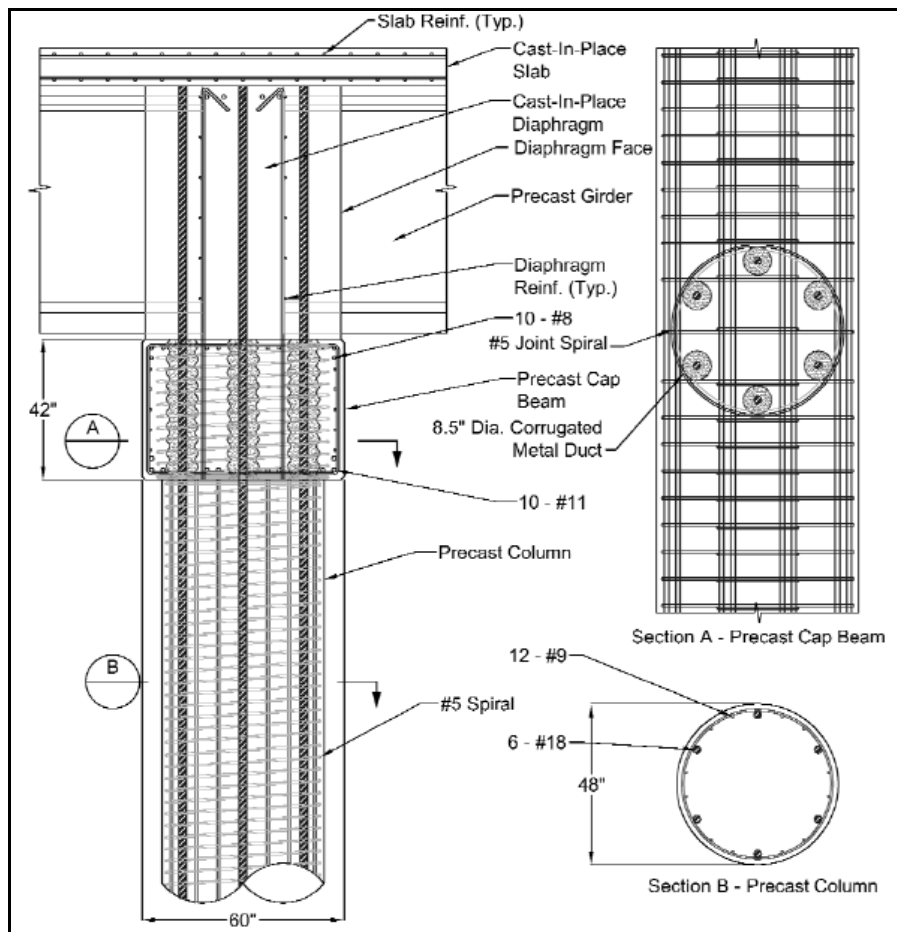


Figure 46. Large-Diameter Bar Column-to-Cap Beam Connection.
(Pang et al. 2008.)

The columns also contain other, smaller-diameter longitudinal bars that terminate within the column; these are provided so that the AASHTO longitudinal bar maximum spacing requirements are met. A partial-height precast cap beam contains 8.5-inch-diameter vertical corrugated metal ducts, through

which the column #18 bars are inserted as the cap beam is lowered down onto the tops of the columns. The basic concept is that by using the fewest number of longitudinal bars possible, the number of required bar-duct alignments is minimized. Once the precast cap is set into position atop the columns, precast girders are placed, and then a CIP concrete diaphragm is poured. As shown in Figure 46, the longitudinal bars extend through the precast cap beam and into the CIP diaphragm region.

One of the issues with using such large-diameter column bars is the very long development lengths required by the *AASHTO LRFD Bridge Design Specifications* and the American Concrete Institute (ACI 2008). The length required to fully develop a #18 bar within the precast cap beam could be prohibitively large in that it is greater than “typical” cap beam heights. However, the basis for the work by Pang et al. (2008) is research by Steuck et al. (2007), which tested the monotonic pullout resistance of #18 bars grouted into corrugated metal ducts. The research showed that #18 bars could be yielded with an embedment length of only $6 d_b$, and could be fractured with an embedment of $14 d_b$, where “ d_b ” is the diameter of the rebar. The results by Steuck are profound, as they drastically reduce the embedment that would be required to satisfy conventional structural concrete design provisions, thus making the few large-diameter bars connection feasible with typical cap beam heights.

The research program included four column-to-cap beam connection subassemblies tested under axial compressive and lateral loading. The specimens consisted of a T-shape beam-column connection at a 40 percent scale, and Figure 47 provides an elevation view of the specimens. The test specimens were designed according to the *AASHTO LRFD Bridge Design Spec.* and ACI 318-05 for parameters not specifically being evaluated in the research. For more detailed information on the test specimens and testing setup, see Pang et al. (2008).

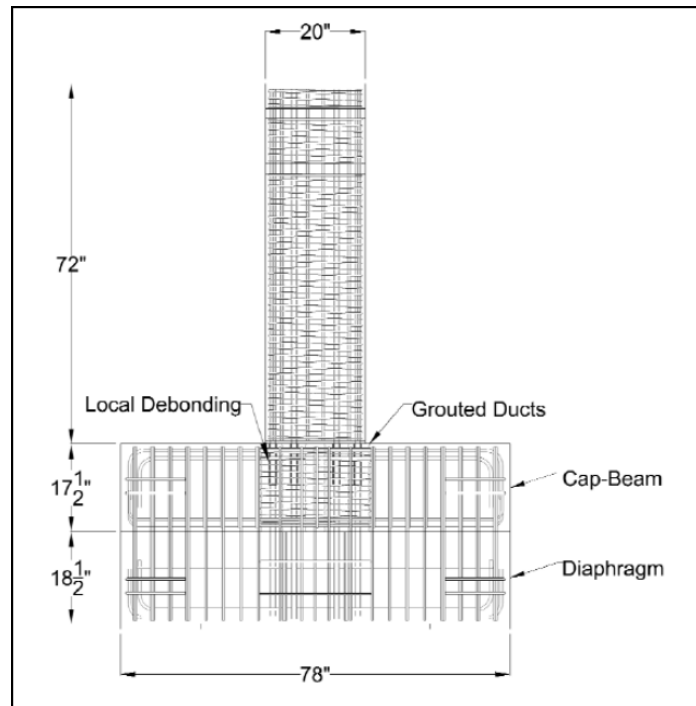


Figure 47. Details of the Specimens Tested by Pang et al. (Pang et al. 2008.)

The experimental testing conducted by Pang et al. (2008) demonstrated that the few large-diameter bars connection concept performs essentially in an equivalent manner to conventional CIP construction. The design recommendations and research conclusions given by Pang et al. (2008) include:

- The proposed connection behavior is equivalent to that of conventional CIP construction, and bent frame forces can be found by analysis methods that are used for conventional construction.
- The flexural strength of the column at the connection interface can be calculated using a cross-sectional analysis procedure (either moment-curvature or ACI 318-05 strength calculation).
- Connection stiffness can be found in the same manner as that used for conventional CIP construction.
- The connection is capable of achieving lateral drifts on the order of 5 percent.
- The bar development lengths for non-seismic (non-cyclic) applications can be determined as specified in the work by Steuck et al. (2007).
- For seismic loading, the column rebar development lengths should be 50 percent greater than that specified by Steuck et al. (2007).
- Shear friction principles can be used to calculate the shear transfer across the column-to-cap beam joint; a coefficient of friction of 0.65 can be used as a lower bound.
- Extension of the column bars through the precast portion of the cap beam into the CIP diaphragm provides for adequate transfer of forces within the joint; detailing of the joint should be the same as for conventional CIP construction.
- Termination of the column longitudinal bars at different heights within the diaphragm will help with field assembly, since only one bar-duct alignment will need to take place at a time.
- Roughening of the column-cap beam interface should be done in order to aid in the transfer of shear across the grout pad (more specific details of the roughening can be found in Pang et al. 2008).

CHAPTER 4. PRECAST COLUMNS

The use of precast columns and walls for bridge construction in the United States is much less common than construction using precast bent cap beams; therefore, as might be expected, the availability of information regarding the design and construction of prefabricated columns and walls is more limited than for precast bent caps. However, the increased national focus on rapid construction and improved durability has led some state DOTs to begin to develop concepts and design standards for precast concrete columns. A few states have either already used precast columns or walls on bridge projects, or have invested significant resources in development of prefabricated column technology. This chapter provides a description of concrete column prefabrication methods used or proposed by other state DOTs and university researchers.

PRECAST CONCRETE COLUMN SYSTEMS

Three basic precast column systems are found in practice or literature:

- Precast concrete column shells that serve as stay-in-place formwork for a CIP concrete core.
- All-precast concrete columns reinforced longitudinally with conventional mild steel reinforcing bars.
- All-precast concrete columns reinforced with prestressing steel, which may be bonded or unbonded.

The following sections describe these three precast column technologies and discussions of the issues related to their implementation for ABC.

Precast Concrete Shells

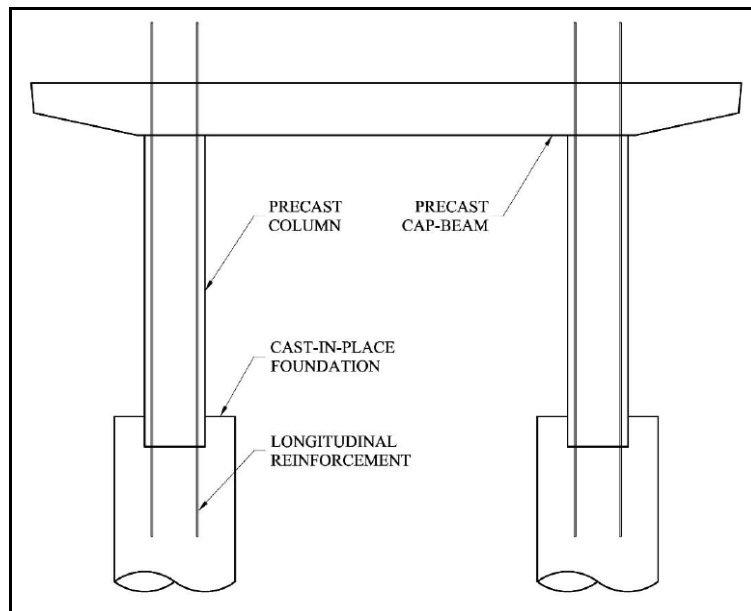
Precast concrete column “shells” have been used on projects to eliminate the need for construction of column forms, hence accelerating construction of the columns. The shells are thin-walled and serve as stay-in-place formwork for the column core, which contains the main longitudinal reinforcing cage and CIP concrete. Using a precast shell with CIP core significantly reduces component weight; because of this reduced weight, larger columns (larger in cross-section size and column height) can be precast than if all of the column concrete is precast (i.e., if there is no CIP core). Also, with the reduced precast component weight, the columns can be more easily handled at the fabrication plant and the bridge construction site. The reduced weight can also eliminate issues associated with transportation of very heavy precast pieces to the site from the precast plant. However, because this precast column technology does still use a rebar cage that must be cast integrally with the foundation and includes a CIP concrete core, the ABC advantages are not as significant compared to an all-precast column design.

Some of the issues related to implementing this column technology include grade control and a reduced effective depth to main longitudinal steel within the cross-section. Control of elevation can be achieved with either shims or CIP pedestals at the foundation/column shell interface. The CIP pedestal option will add time to the construction schedule, while the shimming option requires less effort and time. Because of the wall thickness of the precast shells and the need to provide adequate tolerances for the gap between the inside face of the shell and main rebar cage, the location of the column main longitudinal

steel will be closer to the center of the cross-section than if the longitudinal steel was embedded in an all-precast component. Thus, the column will have a reduced internal lever arm, which may lead to the need for larger longitudinal reinforcement levels. Larger longitudinal reinforcement levels will exacerbate rebar cage congestion problems. Since the column rebar cage must fit within the precast shell, spacing between longitudinal bars will be reduced unless larger section dimensions are used.

Conventionally Reinforced Precast Columns

Precast bridge columns with only mild steel, or “conventional precast,” are essentially identical to those used in the precast concrete building industry, where the members are designed and detailed to emulate conventional CIP reinforced concrete construction. Connections of these members are the critical aspect in their design. Figure 48 illustrates a two-column bridge bent with conventional precast concrete columns for the case of column longitudinal rebar extensions embedded in the foundation and cap beam.



**Figure 48. Precast Bridge Bent Proposed by Hieber et al.
(Hieber et al. 2005a.)**

WSDOT has sponsored research at the University of Washington to develop rapid column construction technologies for use in high seismic regions. One of the concepts developed in the research was the use of large-diameter mild steel longitudinal column reinforcement anchored in grouted corrugated metal ducts in the cap beam to form a moment connection (Pang et al. 2008). The benefit of the large-diameter bar concept is that fewer total bars can be used, which reduces the number of potential conflict points when connections are being made. The research work by Pang et al. consisted of experimental testing of column-to-cap beam subassemblies under simulated lateral loading. The column segments contained six #18 longitudinal bars; a duct for each bar embedded in the precast cap beam had a diameter of 8.5 inches. A circular column cross-section was used, but the “few large bars” concept could be adapted to columns with other cross-section shapes.

One of the possible problems of using large-diameter bars for column longitudinal reinforcement is the very large development length required for the bars, and thus the large cap beam height required. However, the research by Pang et al. (2008), and additional work by Steuck et al. (2007), has demonstrated that large-diameter bars embedded in grout in corrugated metal ducts can be fully developed in much shorter distances than given by AASHTO and ACI development length equations. Steuck et al. (2007) showed that a #18 bar can achieve its yield strength when embedded 6 db (six bar diameters), and can be fractured when embedded 14 db (14 bar diameters). Thus, the lengths required for embedment to make a strong column-cap connection are reasonable and are within the dimensions of cap beam heights typically found on Arizona bridges.

One additional note regarding the use of a few large-diameter bars for main column reinforcement: AASHTO requirements for maximum horizontal spacing between longitudinal bars will require placement of smaller-diameter bars between the large bars. These smaller-diameter bars will terminate within the precast column component—i.e., they will not extend across joints at the top and bottom of the column.

Hybrid Precast Columns

Within the other category of precast columns—those with prestressing steel—there are two subcategories with distinctly different behaviors and design requirements: columns with bonded longitudinal reinforcement, and columns with prestressing steel that remains unbonded from the surrounding concrete after construction is complete. Columns may be prestressed during fabrication in order to prevent excessive cracking during handling and transportation; this practice is found most often with very long precast column components. For short column lengths, there is both a lack of need for the prestressing and the lack of efficiency of the prestressing steel due to the development lengths at either end of the reinforcement. Typically, precast columns that have been prestressed have bonded steel. The other arrangement is to post-tension columns once they have been erected, with PT steel anchored in the foundation and column cap. Segmented columns are often post-tensioned; the typical arrangement is to grout the PT ducts after the PT operation. Precast columns with bonded prestressing steel—both prestressed and post-tensioned—behave according to principles of prestressed concrete and are designed by well-established engineering principles.

Recently there has been interest in a new type of precast column with prestressing steel that remains unbonded. The application of this “hybrid” system is primarily for regions with high seismic loading, such as California and Washington. The concept of using unbonded post-tensioning comes from the precast concrete building industry and the PRESSS Research Program (Priestley et al. 1999) that developed the technology for building systems. The key attribute in the response of the hybrid system to earthquakes is the unbonded nature of the longitudinal reinforcement. When a hybrid column is loaded laterally during a seismic event, it displaces laterally and the PT steel on the tension side of the neutral surface is stretched. Typically, a single large flexural crack opens at the section with highest moment demand, and as displacements become significant, the hybrid column essentially rotates rigidly about the compression toe at the critical section (with highest moment demand). The key is that because the PT steel is unbonded from the surrounding concrete, the elongation of the steel is accommodated over the full unbonded length and, if designed correctly, the PT steel will remain in the elastic range—i.e., axial

strains will remain below the yield strain, or limit of proportionality. Thus, the lateral restoring force provided by the PT reinforcement will not decrease as would be the case if bonded prestressing steel yields at the high moment demand regions.

Because the PT steel does not yield during an earthquake in a properly designed hybrid column, energy dissipation—an important requirement for minimizing seismic response—is very limited. One option for enhancing the hysteretic energy dissipation of the column is to include mild steel longitudinal reinforcement across the critical section, which will yield under opening of the flexural crack. This yielding of conventional rebar “fattens” the hysteretic loops and helps decrease the lateral displacement response of the structure. If yielding mild steel is included in the hybrid column, it is important to ensure that the restoring force of the PT acting to re-center the column is greater than the force required to yield the mild steel in compression to close the opened critical section flexural crack. Figure 49 depicts a two-column bridge bent with hybrid precast columns, where the post-tensioned steel is anchored in the foundation and cap beam.

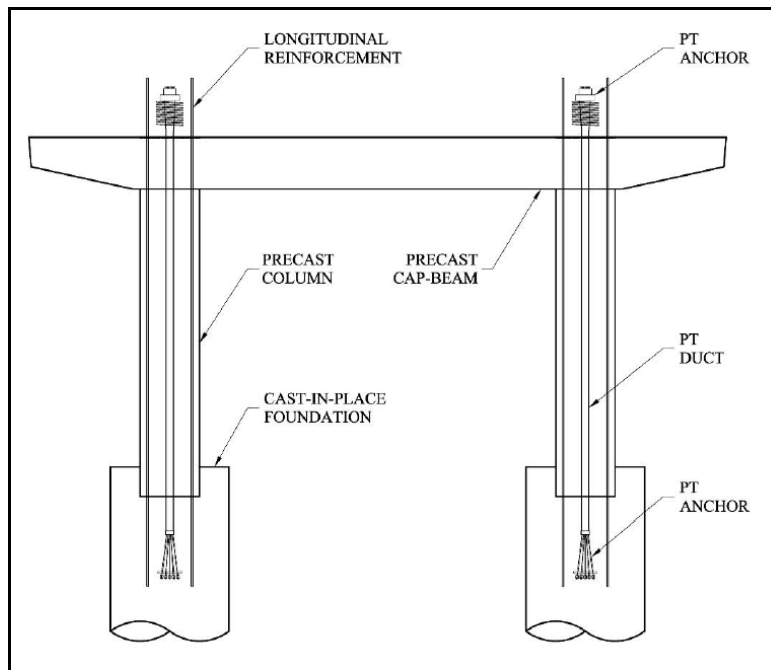


Figure 49. Hybrid Precast Bridge Bent Proposed by Hieber et al. (Hieber et al. 2005a.)

Research into the behavior and design of the hybrid column system has been conducted worldwide, but there are no known applications of the bridge in practice. This is in contrast to the use of precast columns with bonded prestressed or post-tensioned reinforcement, which is becoming more common. The reason for hybrid column systems not being used is the previous lack of understanding of the behavior of this column type and lack of any design specifications and design tools. Because the steel reinforcement is not bonded to the surrounding concrete, strain compatibility between the reinforcement and surrounding concrete does not exist—i.e., the steel reinforcement axial strain can't be determined based on concrete axial strains at the location of the reinforcement. This is a crucial

deviation from basic reinforced and prestressed concrete principles. Furthermore, the lateral seismic response of the hybrid column system differs markedly from that of conventional construction, since lateral deformations are a result of rigid column rotation, not plastic deformation of materials within the plastic end region at the highest moment demand area. Experimental and analytical research has now sufficiently advanced our understanding of how the hybrid column responds to various loads and how various design variables influence that response, so that application of the system for actual bridge projects in the near future is likely. Still, some details remain to be worked out, including corrosion protection of the unbonded steel and long-term performance and durability of the joints that are expected to open significantly under seismic loading.

Because of the additional complications of detailing and the more complicated analysis and design methods required for the hybrid system, and due to the low-to-moderate seismic hazard within Arizona, the recommendation is that the hybrid system with unbonded PT not be considered for use in a precast column for Arizona bridges.

Full-Height and Segmental Columns

The preferred precast concrete column component is a full-height column segment, since this arrangement requires making structural connections at only the footing level and at the column top with the cap beam. However, based on lifting weight limitations (both at the fabrication yard and at the construction site) and trucking weight limits, full-length fabrication of columns may not always be possible. Where a full-height column segment is not practical, a segmented column design can be adopted. However, this will result in increased fabrication and construction costs. In the precast facility, it would be more efficient to cast the entire column as a single unit, since this eliminates moving the formwork. During assembly at the construction site, a segmented column will require additional work to make the connection between individual segments, which will entail either grouting rebar splices at the segment joints or splicing post-tensioning bars at the joints. Additionally, if a grouted (non-match cast) joint design is used, this will also add construction effort and hence increase overall costs. Thus, to achieve the maximum benefit from prefabricating substructure components, the recommendation is that precast columns be used where a full-height column component is possible.

Cross-Section Geometry

A variety of possible cross-section geometries can be used for a precast concrete column. Sections can be solid or hollow, though certain shapes are easier to fabricate than others. Whereas conventional CIP reinforced concrete bridge columns are often circular in cross-section, a circular form has several drawbacks when precasting the component is desired. A circular column cast in horizontal formwork will result in a portion of the column face that must be hand finished, and thus will have a different finish than the surfaces cast against the form. A solution to this problem would be to cast the column component vertically, but this arrangement is more difficult in the precast facility, and hence would result in higher costs. Casting vertically would also limit the component length, since very tall formwork in the casting yard would also be an expensive manner of fabrication.

For these reasons, rectilinear cross-section shapes are preferred over curvilinear geometries, and there are a number of different options available. These include square and rectangular sections, octagonal, hexagonal, I-shaped, etc. In order to hold fabrication costs as low as possible via re-use of standard

formwork, the recommendation is that a standard cross-section shape be selected and used exclusively, rather than changing column cross-sections from job to job. Because of the expenses required to “re-tool” at the precasting plant, initial projects using precast concrete columns might be slightly more costly than if conventional CIP RC columns were used but in the long term, costs will decrease, because precasters can re-use formwork developed for previous projects.

UDOT has developed standard precast concrete column sections for use with grouted splice coupler connections, described in Chapter 3. The column cross-section is solid with an octagonal shape; Figure 50 shows a few standard sections adopted by UDOT.

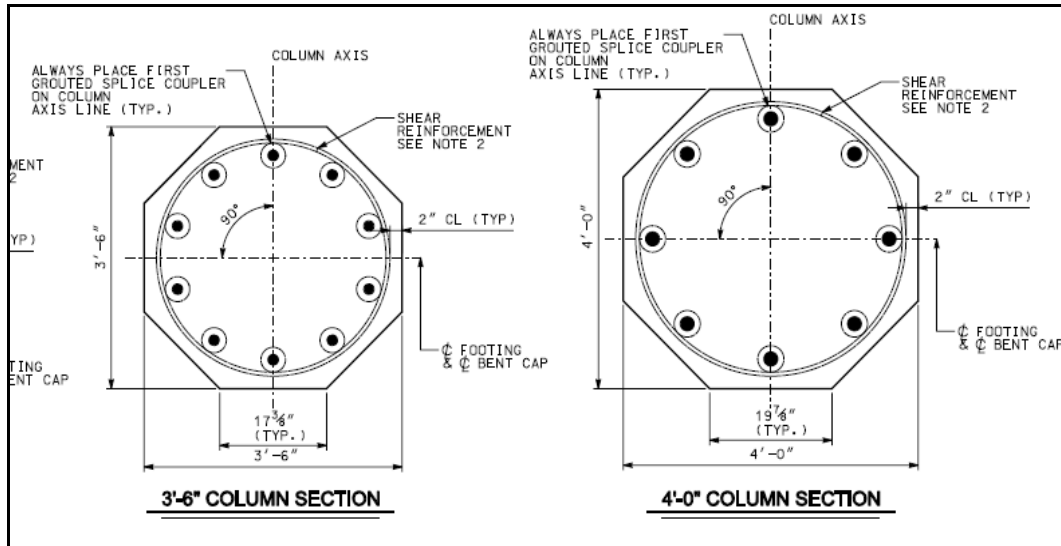


Figure 50. UDOT Precast Concrete Column Standard Sections. (UDOT 2010d.)

Where column cross-section dimensions become large, leading to very heavy segment weights, hollow sections can be used. The void can be created using either Sonotube® or rectangular collapsible formwork. The Alabama Department of Transportation (AIDOT) has developed standard precast concrete columns with circular internal voids to reduce component weight. The void regions end a given distance from either end of the precast column to provide regions for development and anchorage of splicing reinforcement. The AIDOT system is shown in Figures 51 through 53. As shown in Figure 51, assuming a maximum desirable component weight of 100 kips, square columns up to 54 inches x 54 inches in section can be used with lengths up to 46 ft.

The AIDOT standard precast column system uses grouted splice couplers to make the connection between the precast column and foundation and cap beam (for more discussion on this detail, see “Connections Between Columns and Foundations” later in this chapter). The columns also contain bonded prestressing steel along their length in order to prevent cracking during shipping and handling.

Another option for reducing column component weight is an I-shaped cross-section such as that shown in Figure 54. However, the column reinforcing cage for this cross-section will be more difficult to fabricate and hence more costly, and the shape is potentially less aesthetically pleasing than other

closed section shapes. The Edison Bridge in Fort Myers, Florida, is an example of precast columns with I-shaped sections.

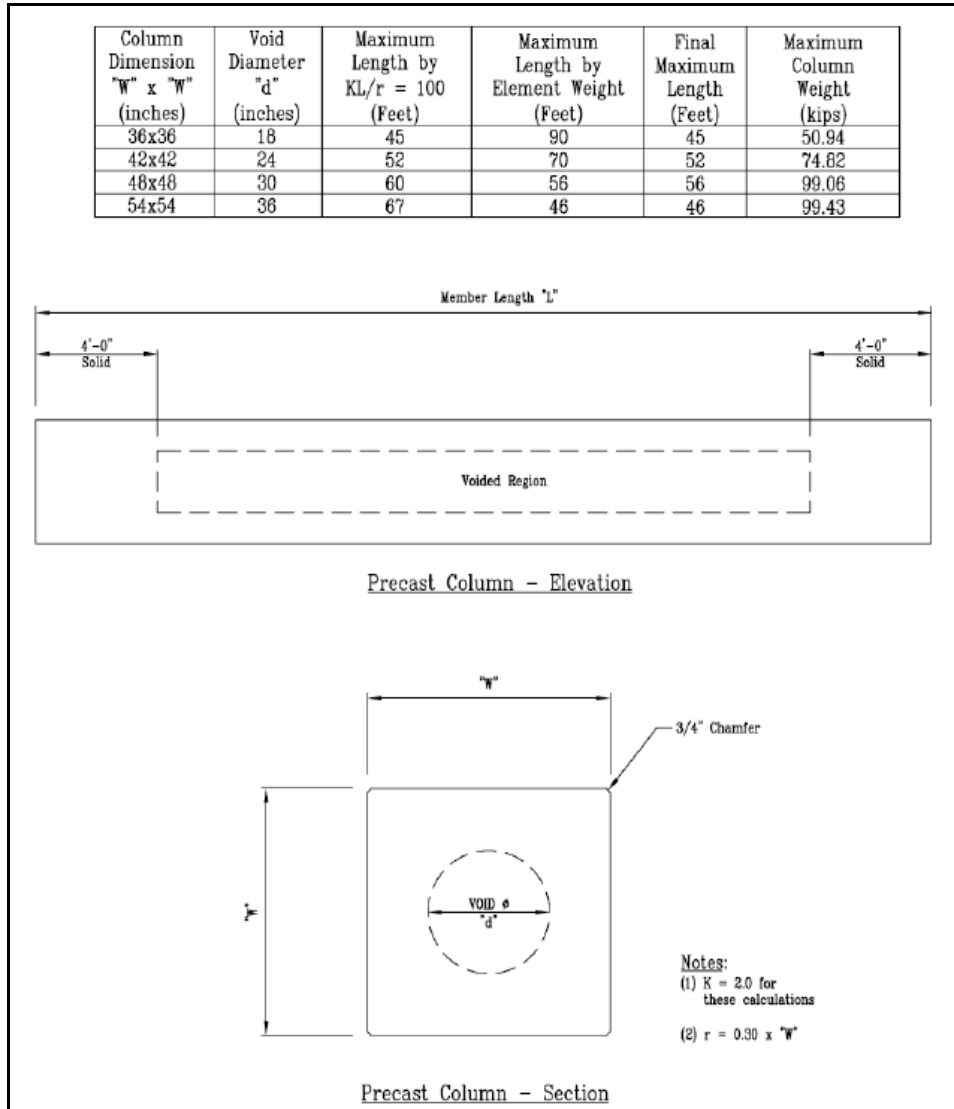


Figure 51. Precast Column Developed for Standard Alabama Bridges. (Fouad et al. 2006.)

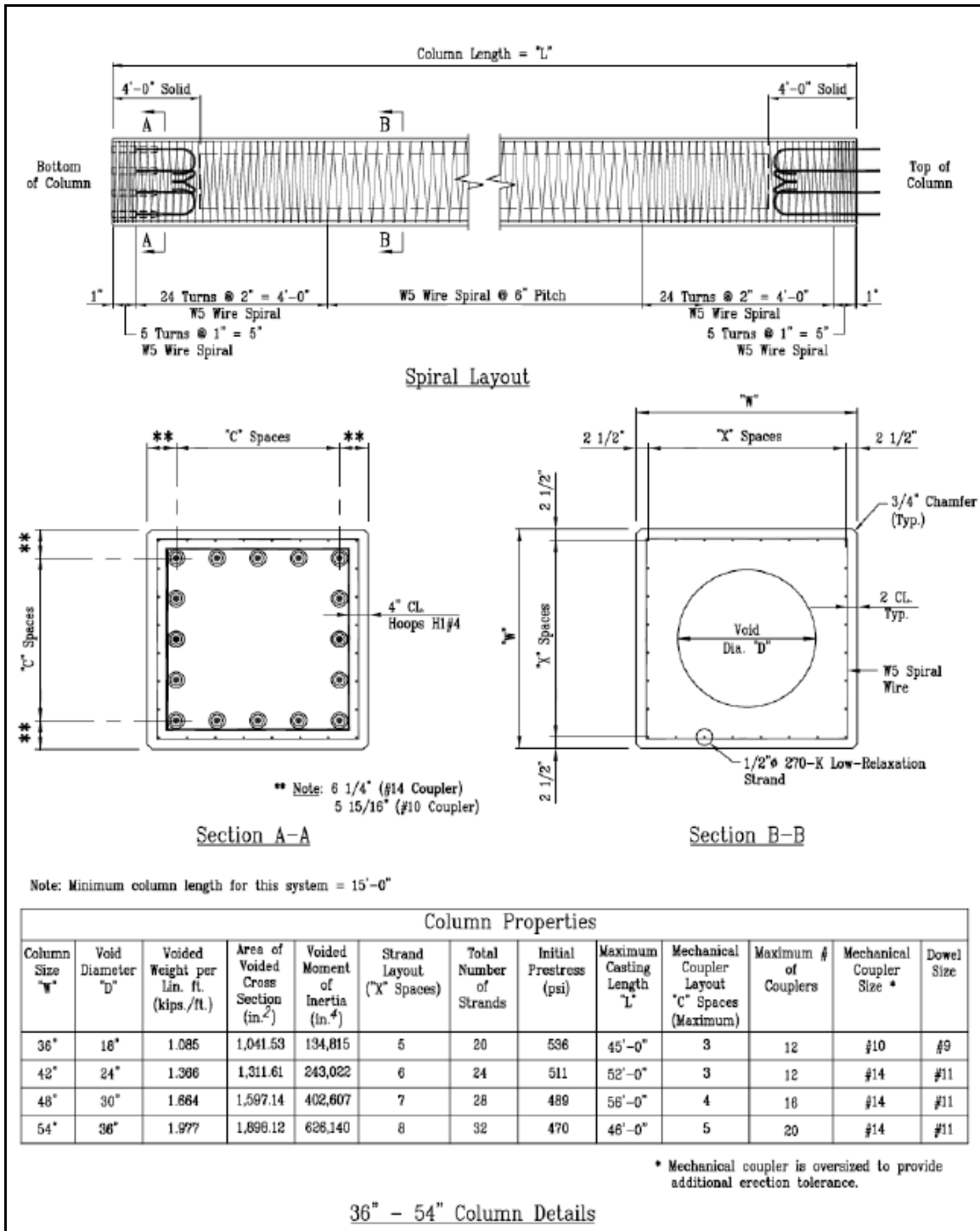


Figure 52. Precast Column Details for Prefabricated Alabama Bridge. (Fouad et al. 2006.)

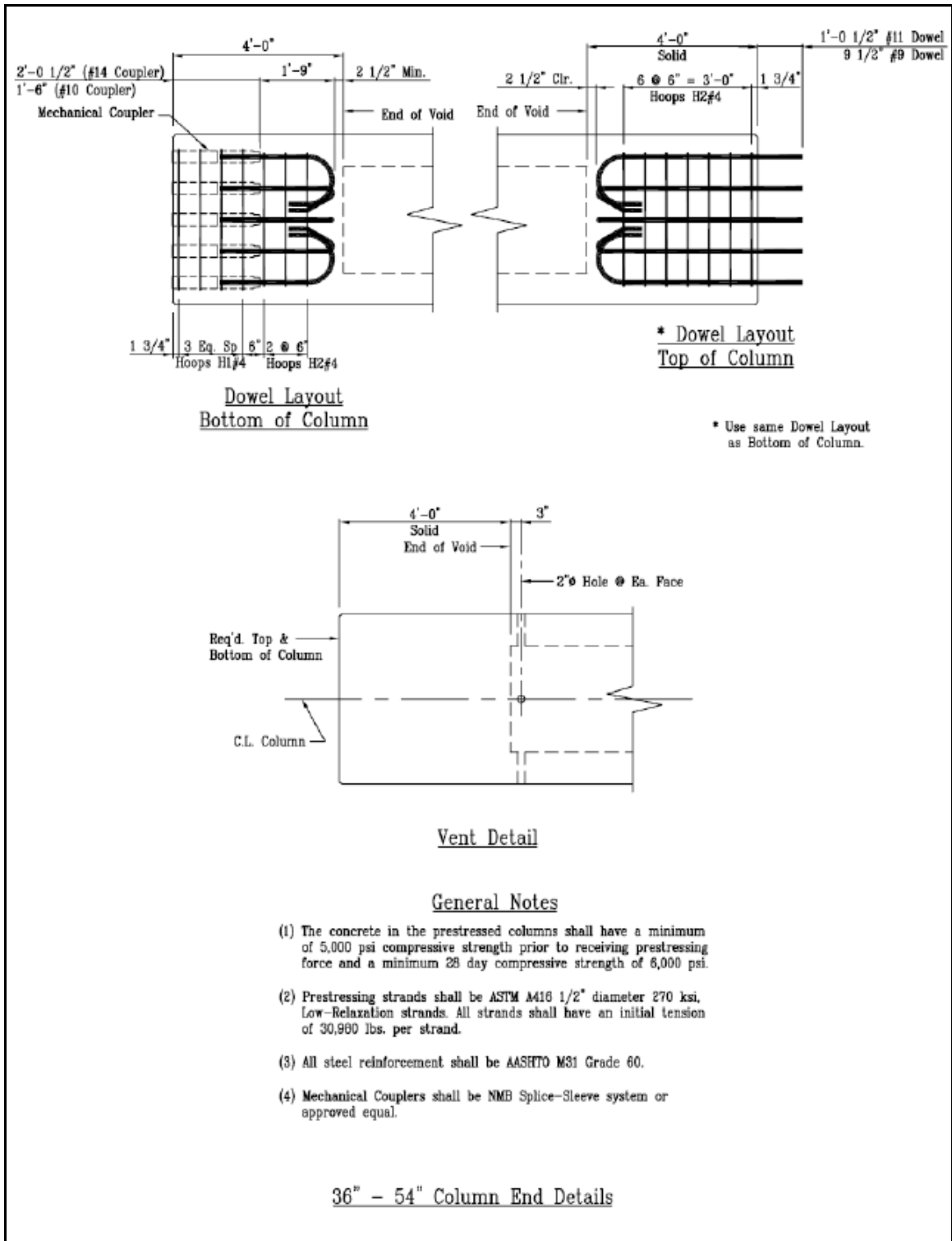


Figure 53. Precast Column Details for Prefabricated Alabama Bridge. (Fouad et al. 2006.)

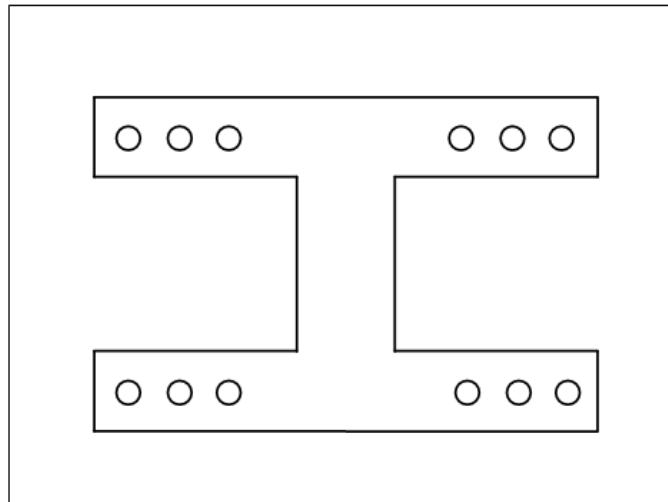


Figure 54. I-Shaped Column Cross-Section.

Other column cross-section shapes have been used in practice, such as those depicted in Figure 55. These standard voided shapes were developed by researchers at the University of Texas at Austin for TxDOT for use in precast segmental columns (Billington et al. 1998). The column system uses longitudinal PT for flexural reinforcement and segments are match-cast with shear keys at joint surfaces. Shown in Figure 55 is a table of segment weights based on an 8-ft segment height. To speed construction, taller segments could be fabricated and could serve as full-height column components. For example, standard section “P24” (shown in Figure 55)—roughly a 4 ft by 8 ft section—could be cast as a 32-ft-long segment with a resulting total weight of 92 kips. Longitudinal prestressing steel would likely be required in such a component to prevent damage during transport and erection.

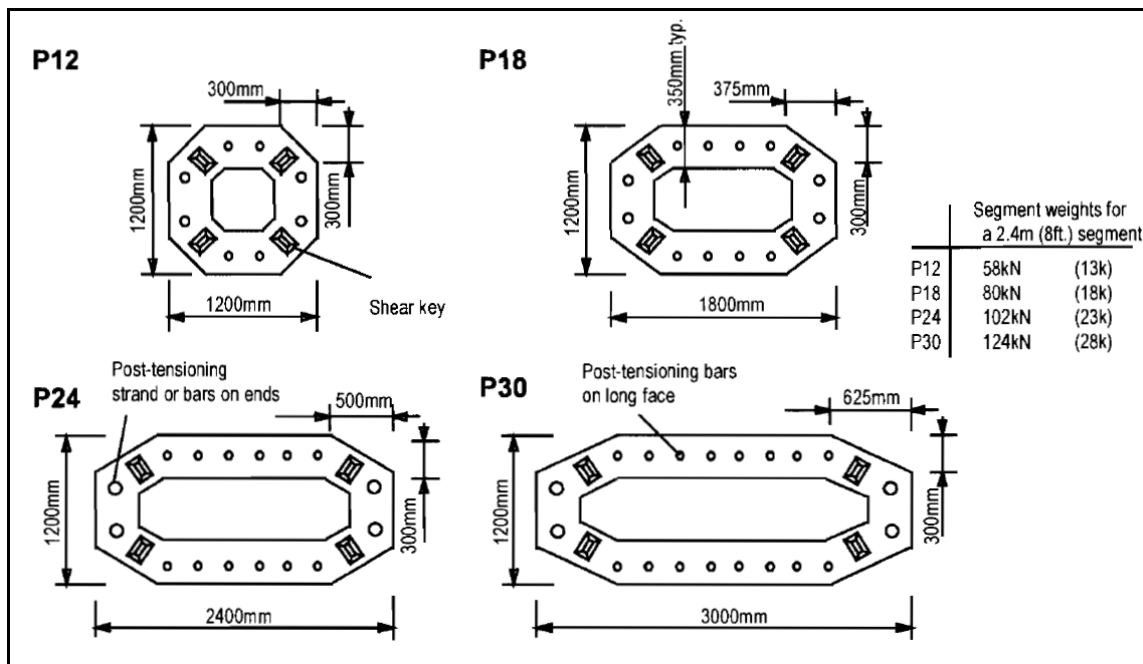


Figure 55. UT – Austin Precast Segmental Column Cross-Sections. (Billington et al. 1998.)

CONNECTIONS BETWEEN COLUMN SEGMENTS

Segmented columns will be required for very tall bridges in order to limit individual components based on weight and length for travel considerations (although the weight limit is likely to govern for columns of typical aspect ratios). Several issues must be considered when a segmented column design is needed, including the type of joint between column segments—match cast versus grouted—and connections between segments—spliced mild steel rebar or post-tensioning across joints.

Match-Cast and Grouted Segment Joints

There are benefits and drawbacks to both match-cast segment joints and grouted joints. Match-cast procedures involve using the joint surface of one segment as the formwork for the adjacent segment. Assuming the fabrication process was performed accurately, match-cast joint designs result in quicker construction in the field than a grouted joint connection, since the segment joint surfaces make a “perfect” fit and should not require adjustments for plumb in the field. Match-cast joints can be “dry” joints, in which case segments are simply placed one on top of the other without an epoxy layer at the joint. However, dry joints can result in stress concentrations and crushing at the segment edges, and are not appropriate for regions where temperatures below freezing occur. Epoxied joints are thus preferred for match-cast connections. Also, the epoxy layer allows the upper segment being lowered into position to move more easily into alignment as the epoxy “lubricates” the surfaces being mated. Epoxied match-cast joints have resulted in both efficient assembly performance and good durability (Billington et al. 1998).

The alternative to a match-cast joint is a “loose-fit” joint, which requires mortar or CIP concrete to be used between the segments. Whereas match-cast joint construction requires using a previously cast segment as part of the formwork for the next segment, loose-fit does not. Because segment surfaces are not a “perfect fit” as in match-cast construction, each segment being lowered into place requires alignment and a CIP pour to achieve a uniform bearing between the two segment surfaces. Formwork around the joint will need to be placed, and time will be required for grout curing. Thus, the loose-fit method requires significantly more effort in the field for erection and will not provide for as rapid construction as match-cast joints.

Although match-cast joints result in quicker field erection than grouted joints, fabrication of components can be more labor and time intensive. Because one segment serves as partial formwork for another segment, the production rate is low, since time is required for the newly cast segment to cure before it can be moved and serve as formwork to the next segment.

On the other hand, grouted joint construction allows for rapid segment production at the precast facility, because multiple segments can be cast simultaneously, rather than one at a time as for match-casting.

However, for typical bridges in Arizona, column heights will be such that only a few segments are required. This should allow for reasonable production rates at the precast facility. For this and the other reasons presented above, match-cast joints should be used between column segments.

Longitudinal Reinforcement Connection

There are two main types of longitudinal reinforcement typically used in precast concrete columns—mild steel deformed bars, and post-tensioning steel. Either of these systems allows for reasonably simple connections between segments, and both have been used successfully. If a column is reinforced with conventional mild steel reinforcement, the grouted splice sleeve connectors discussed previously can be used. One issue with using the grouted splice connection in columns is the slight loss in depth of rebar within the section due to the physical dimensions of the grout splice sleeve and the requirements for cover. Because the coupler is larger in diameter than the reinforcing bar, in order to provide a void region for grout, the center of the reinforcing bars must move further into the section, away from the edges, which reduces the effectiveness of the reinforcement. This movement toward the center is on the order of an inch, and the slight loss in effective section depth is not expected to dramatically increase required column sizes. Tolerances will be critical with this type of connection. One option suggested in the FHWA *Connection Details for Prefabricated Bridge Elements and Systems* manual (FHWA 2009) is to require the fabricator to perform a dry fit-up of each connection in the shop before shipping the connections to the construction site.

Figure 56 illustrates the column segment-to-segment connection made with grouted splice connectors as shown in the UDOT standard drawing (UDOT 2010d). This detail has not actually been used in practice for connections between bridge column segments, but the authors of *Connection Details for Prefabricated Bridge Elements and Systems* (FHWA 2009) state that, because of the successful usage of the grouted splice connector between other components, this connection type should produce a durable and rapid construction connection. Moreover, the previous successful use of this connection type between precast bridge columns and both concrete footings and precast cap beams would indicate that the connection could adequately connect column segments.

A post-tensioned connection can be made with either prestressing bars or strand. If bars are used, connections can be made with couplers at the joints between segments. Temporary bracing can hold precast column segments in place until the column post-tensioning operation is complete. A few of the PT bars may terminate at the top of the column and can be post-tensioned prior to placement of the cap beam (either CIP or precast). The remainder can be anchored in the cap beam and post-tensioned after cap placement. Prestressing strands can be used for PT reinforcement with a U-shape duct within the footing or dead-end anchors embedded in the foundation.

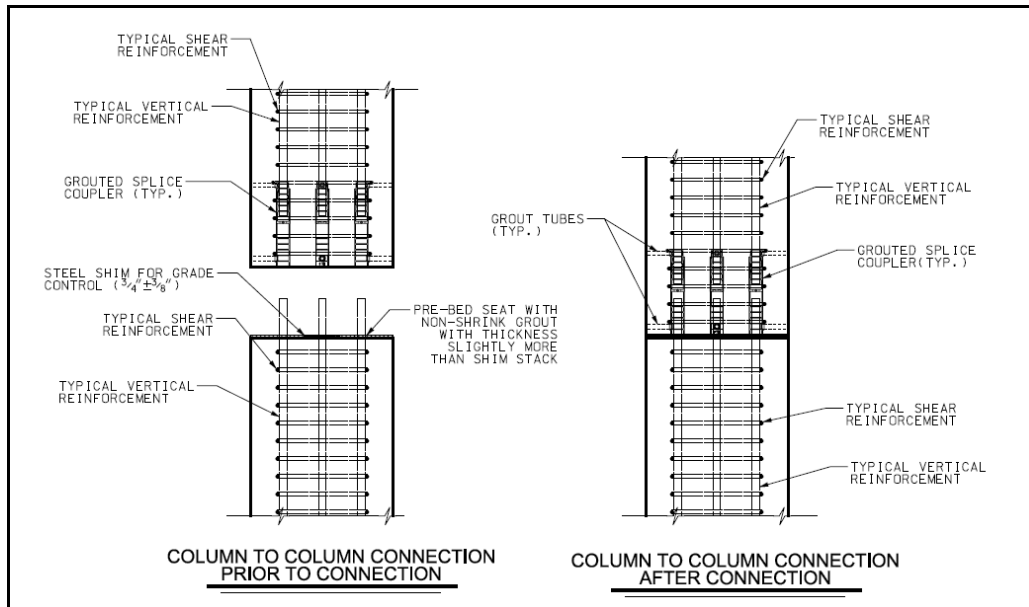


Figure 56. Column Segment-to-Segment Connection via Grouted Splice Sleeve Couplers. (UDOT 2010d.)

CONNECTIONS BETWEEN COLUMNS AND FOUNDATIONS

A number of different methods have been used to connect precast columns to foundations, and each presents challenges and opportunities. The footing may be CIP or a precast footing; the applicability of the connection schemes described below will depend on this variable.

Grouted Splice Coupler Connection

The grouted splice connector described previously for column segment connections has been successfully used to connect a precast concrete column to a CIP footing supported on driven piles. For the Edison Bridge in Fort Myers, Florida, grouted splice couplers were used to connect precast columns to both the foundation and precast cap beam. The bridge has been in use for over 18 years with no serviceability issues associated with the connections. The 55-ft-high, full-height precast columns were erected at a rate of six per day. Another, more recent, project in Troop County, Georgia, on I-85 also successfully used the grouted splice coupler to connect precast columns to CIP footings and precast bent caps. The grouted splice coupler connection can also be used to join a precast concrete footing and precast column, and in theory to join a precast column and large-diameter drilled shaft.

The main issue with using the grouted splice coupler connection at the footing-column joint is the tight tolerances required in order to get proper alignment of the precast substructure system with respect to the overall layout of the bridge. However, templates can be used to locate the footing dowel bars prior to casting of the footing concrete. Once a column is erected, its precise location can be surveyed and a template can be used to record the locations of protruding longitudinal steel or coupler pockets. If a precast cap beam is to be used, the template can then be used to set locations of rebar and couplers in the cap beam prior to its casting. Temporary supports will be required to secure the precast column while the grout in the couplers cures.

Grade control can be accommodated in this connection type with shim packs between the top of foundation and bottom of the precast column. Polymer shim materials should be used over metallic as the latter will create hard points that can significantly alter the response and performance of the precast column. A grout bed can be used to provide uniform bearing at the joint. Figures 57 and 58 illustrate the grouted splice coupler connection between a footing and precast column.

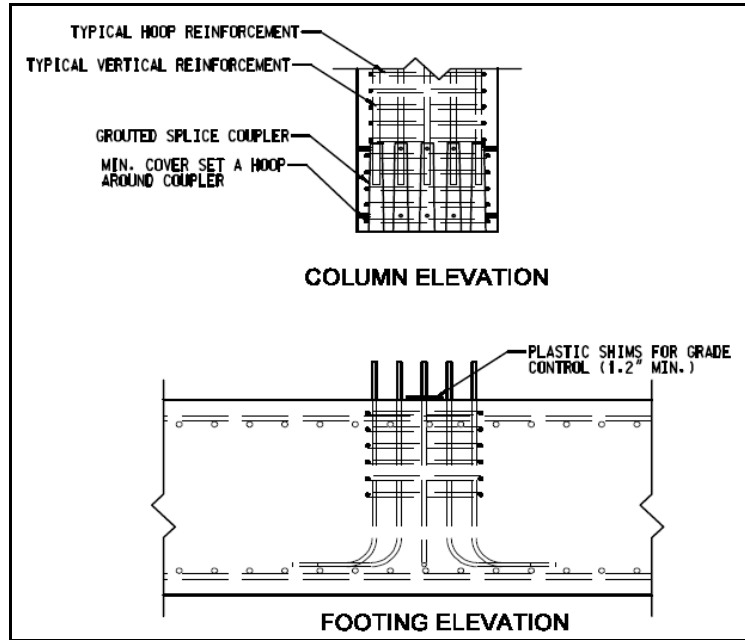


Figure 57. Column/Footing Grout Splice Coupler Connection. (FHWA 2009.)

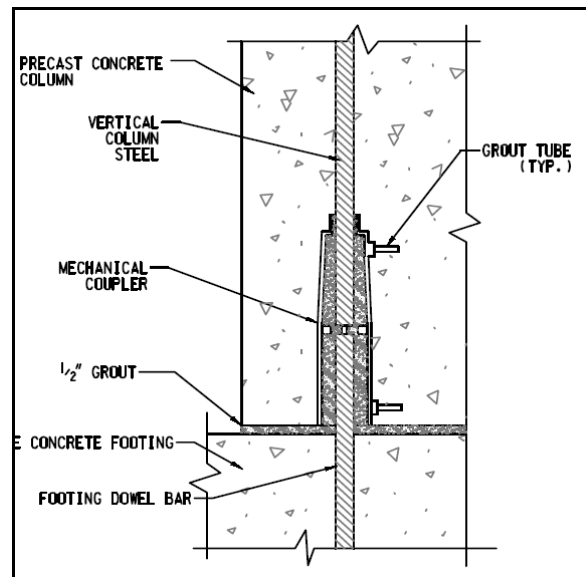


Figure 58. Detail of Grout Splice Coupler Connection. (FHWA 2009.)

Column with Support Leg Connection

This connection has been used in Bellevue, Washington, on the Direct Access project. The design of this connection is based on research conducted at the University of Washington on the development of precast concrete bridge piers for rapid construction (Hieber et al. 2005a). The basic concept consists of casting a support leg into the bottom of the precast column component, with column longitudinal steel protruding from the bottom of the column as shown in Figures 59 and 60. The support leg can be any convenient steel shape, such as an angle or channel section. Because the support leg protrudes a larger distance from the bottom of the column than the longitudinal steel, the system allows for placement of the precast column prior to making the CIP connection. If a CIP footing is being used, a leveling pad is cast against the earth with grade set at the proper elevation. The column is then lifted into position with the support leg bearing against the pad carrying the weight of the column. The column must be secured against horizontal movement with temporary supports. Footing reinforcement is arranged around the column longitudinal reinforcement and concrete is then poured, thereby encasing the protruding column steel and making the connection. This connection should provide for an essentially identical response to a conventionally constructed CIP footing and column connection.

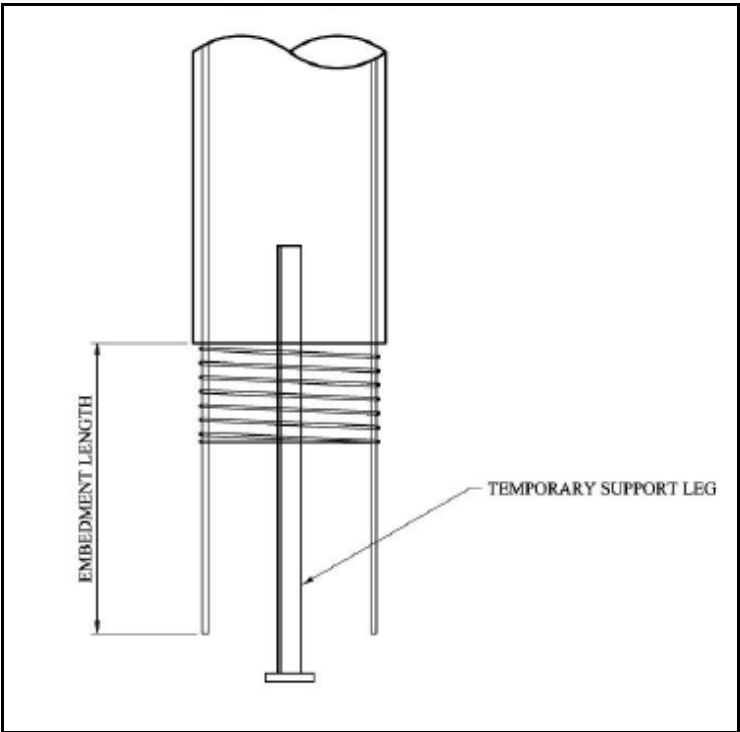


Figure 59. Precast Column Support Leg Detail for Mild Steel Rebar. (Hieber et al. 2005a.)

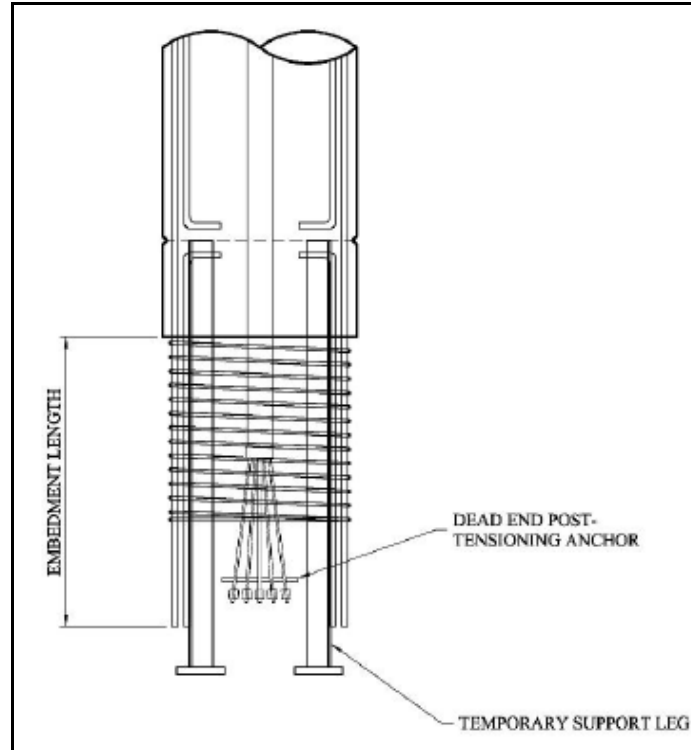


Figure 60. Precast Column Support Leg for Post-Tensioned Rebar. (Hieber et al. 2005a.)

This system can also be used with drilled shaft foundations. In this case, the shaft concrete is not poured to the final height, but rather a given distance below it. The column is then lowered into position with the support leg bearing on the top of the shaft concrete. Once secured, the remaining shaft concrete is poured around the precast column, thereby completing the connection. If desired, a leveling screw can be added to the support leg in order to provide for final vertical alignment of the column. Figure 61 depicts the precast column-to-drilled shaft connection.

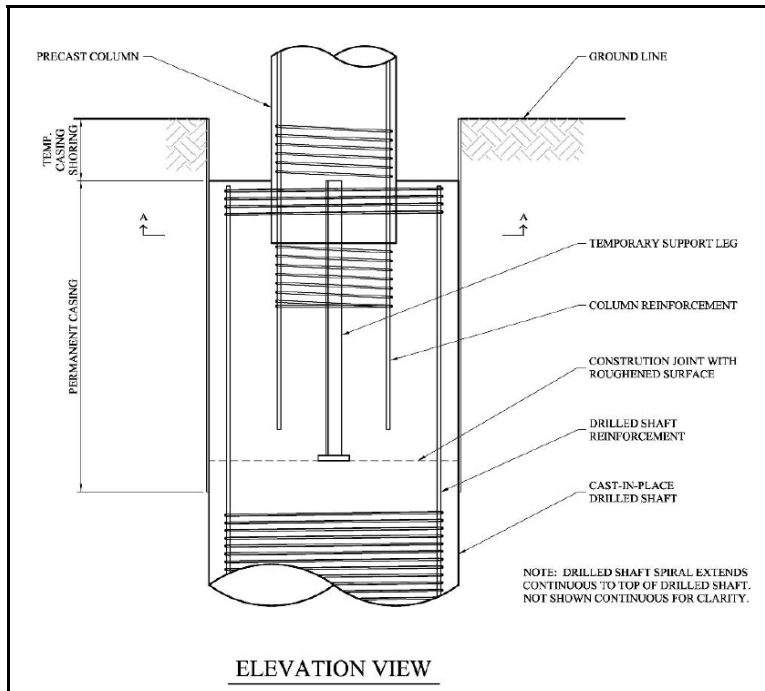


Figure 61. Precast Column Support Leg Connection to Drilled Shaft. (Hieber et al. 2005a.)

Post-Tensioned Connection

Precast columns and walls can be connected to foundations using post-tensioning strands or bars anchored in the foundation. Either a grout bed can be used between the top of footing and bottom of the precast column, or a CIP closure pour can be used. The main issue with the PT connection is that tight tolerances are required for alignment and splicing of the PT ducts and reinforcement. Use of a grout bed will be more efficient than a CIP closure pour, but this method will not provide the flexibility of adjusting clear column height that the CIP closure pour will. The I-287 Cross Westchester Expressway Viaduct project in Westchester County (10 miles north of New York City) used precast voided segmental piers connected to a CIP footing using PT bars. The column segments were match cast and piers were erected at the rate of one per day (FHWA 2009). Figure 62 shows details of the column segments used on the project.

Another connection detail for prestressing strand is a 180-degree turn of PT duct embedded in a footing. With this arrangement, strand can be pushed through the ducts from the top of the erected column, and both ends of the tendon are anchored at the top of the substructure in a recess in the cap beam.

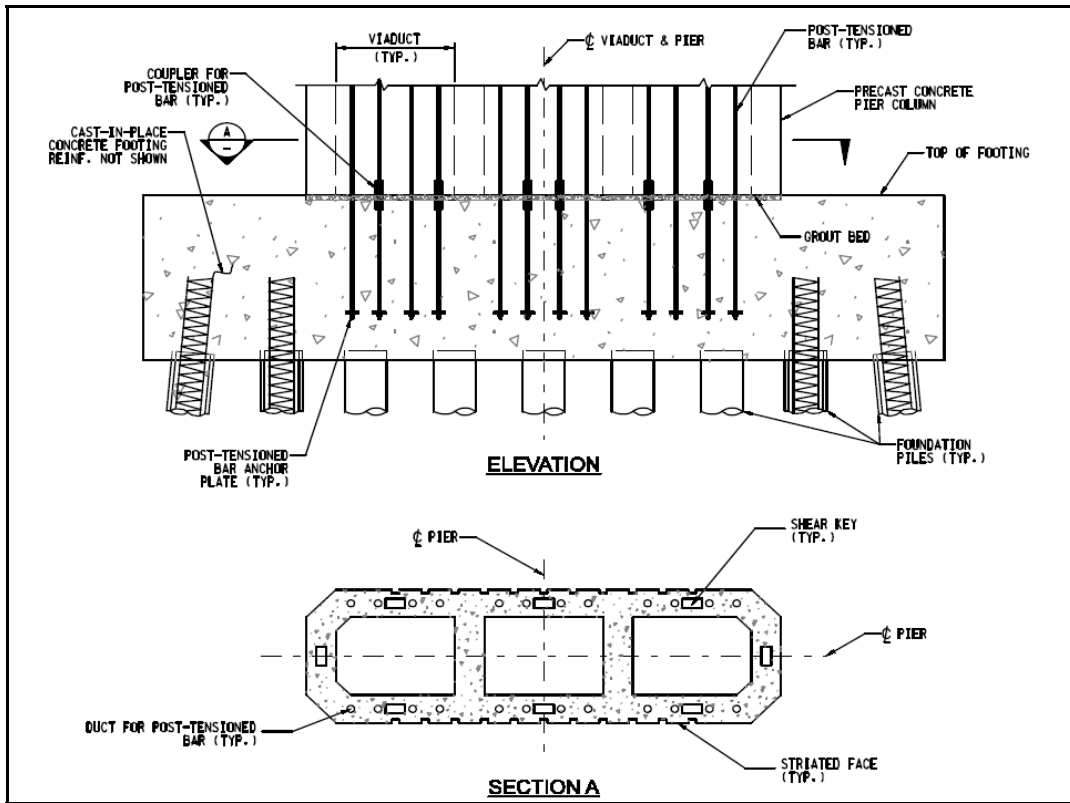


Figure 62. Precast Column with Post-Tensioned Connection to Footing. (FHWA 2009.)

CHAPTER 5. PRECAST FOOTINGS

The use of precast concrete footing components in bridge construction is much less common than bridge designs incorporating precast bent cap beams and columns. However, there are instances of successful use of precast concrete footings in the United States. Furthermore, several DOTs have either already used or plan on implementing precast footing technology. Some technical documents provide guidance on the use of precast footings, including the FHWA's 2009 *Connections Details for Prefabricated Bridge Elements and Systems* and the PCI Northeast Bridge Technical Committee's *Guidelines for Accelerated Bridge Construction Using Precast/Prestressed Concrete Components* (PCINE 2006).

This chapter covers the following topics:

- Issues to consider in relation to implementing precast concrete footings on bridges in Arizona.
- Precast spread footings and footings supported by deep foundations.
- Connections between precast footing segments, and between precast footings and piles and drilled shafts. (For a discussion of connections between precast footings and columns, see Chapter 4.)

ISSUES WITH PRECAST CONCRETE SPREAD FOOTINGS

Precast concrete spread footings have been used successfully on bridge projects in the United States. The major issue with precast footings is the need to ensure that a uniform bearing between the bottom of the footing and subgrade is achieved. Typically, this is done by pouring a flowable concrete or grout under the footing once it has been set into its final position. Figure 63 provides a schematic drawing of a precast footing on subgrade (UDOT 2010d). A precast concrete footing could be used with either a conventional CIP RC column or a precast column.

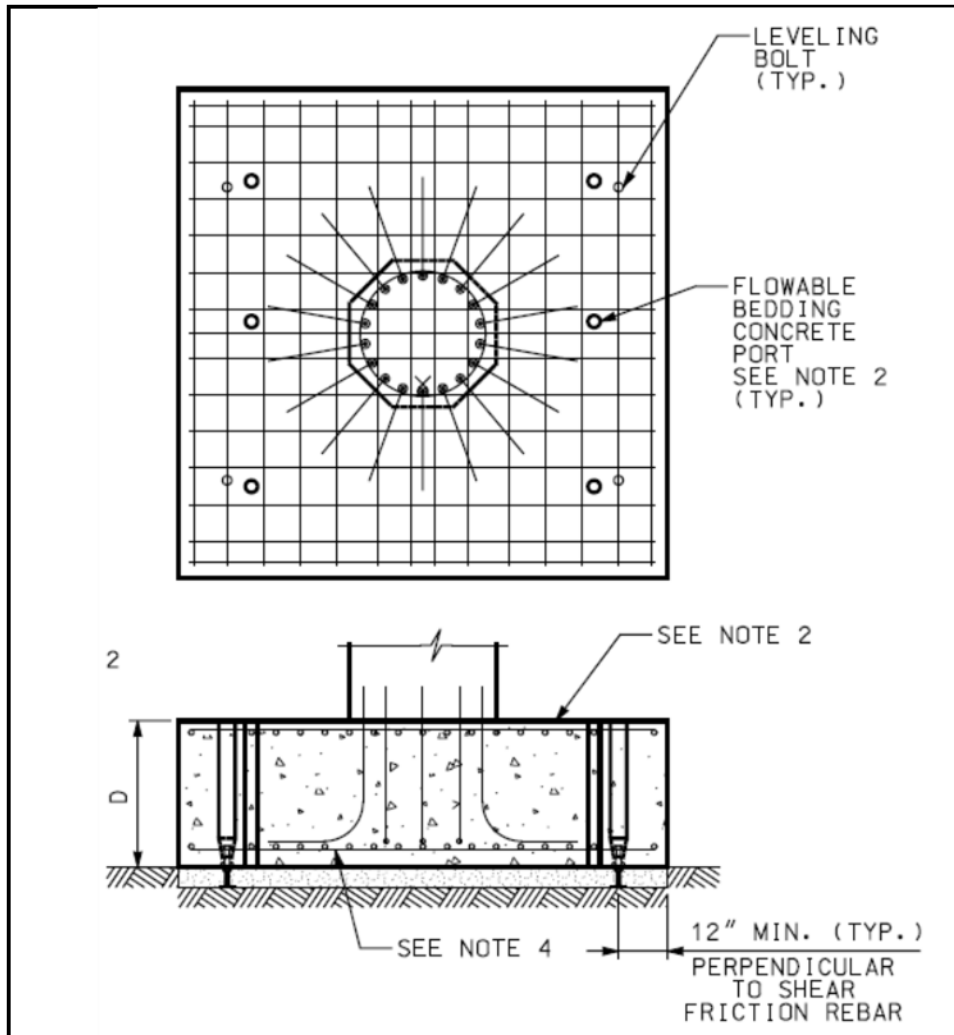


Figure 63. UDOT Precast Spread Footing. (UDOT 2010d.)

Preparation of the ground for precast footing installation is similar to that for conventional CIP footing construction, with a few minor changes. If rock is present at the site, it will be critical to have a good understanding of the variations in rock elevation across the region where footings will be placed, and thus a more extensive boring program may be required. Over-blasting of rock by approximately one foot may also be warranted in order to provide for pouring of a concrete and/or grout under the footing (PCINE 2006). When footings will be located in regions with soil, the normal excavation done for conventional footing construction is used.

Two common methods are used for providing a level surface for footing placement. The first entails pouring a low-strength concrete sub-footing on the subgrade to a height a few inches below the intended bottom of footing elevation. Then, leveling screws embedded in the footing can be used to adjust footing elevation to the desired level. The sub-footing concrete need not be formed, and can be cast directly against the sides of the excavation. The other option is to locate small leveling pads under the locations of the leveling devices, as shown in the right hand drawing in Figure 64. A minimum of four leveling devices should be used, and the leveling bolts should be well-greased to ensure they can easily

be turned during the footing installation and leveling process. The PCI-Northeast *Guidelines for Accelerated Bridge Construction Using Precast/Prestressed Concrete Components* manual suggests designing each leveling device so that it can support one-half of the precast footing weight (PCINE 2006). To facilitate turning the leveling bolt, the full weight of the footing should not be released from the crane until the footing is level.

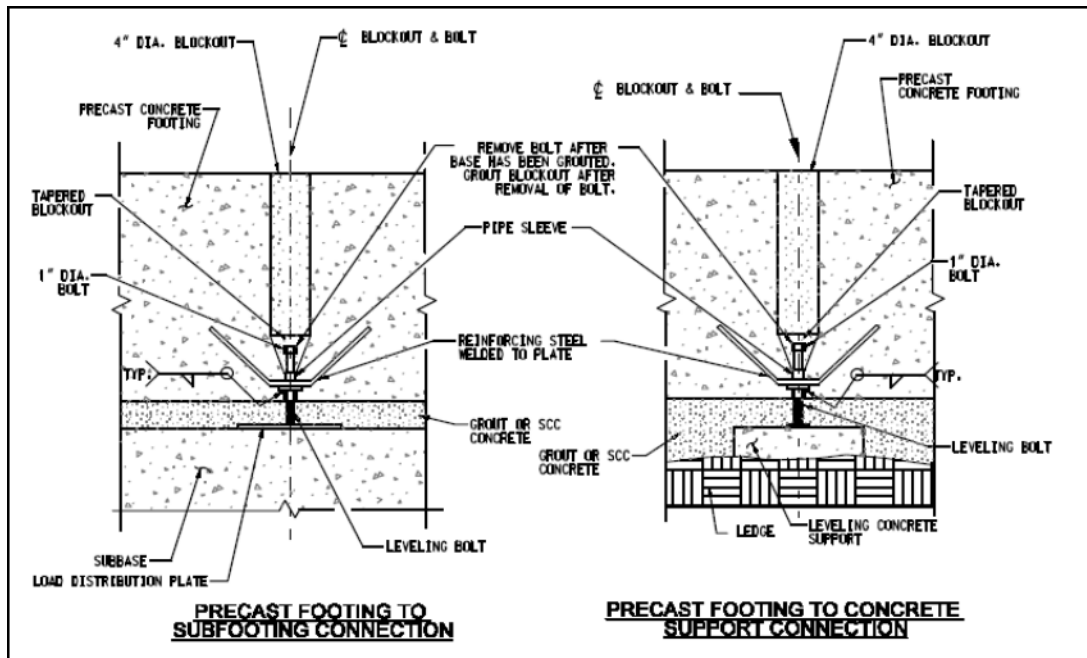


Figure 64. Precast Footing Leveling Mechanism Detail. (FHWA 2009.)

Once the footing has been installed, a flowable grout is poured underneath the footing through grout ports in the top of the footing. The grout should not be poured from the sides of the footing as it is likely that air pockets will remain underneath the footing and uniform bearing won't be achieved. After the grout has set, the leveling bolts should be backed out and the leveling device blockouts should be filled with grout. In order to enhance the sliding resistance of the footing, the bottom of the footing should be roughened to an amplitude of 0.25 inch during fabrication (PCINE 2006).

The *Connection Details for Prefabricated Bridge Elements and Systems* manual (FHWA 2009) suggests an approximate time for installation of a precast footing as one to two days. This estimate includes the leveling and grouting underneath the footing. The New Hampshire State Department of Transportation used the precast concrete footing design on the Mill Street crossing in Epping, New Hampshire. The precast footings had a total width of 39 ft and were fabricated and shipped in three segments (Stamnas and Whittemore 2005). Shear keys between footing segments with dimensions of 3.5 inches by 9 inches were used; the footing installation is shown in Figure 65. As seen in the figure, a keyway at the top of the footing was used at the connection between the footing and the precast abutment stem. Grouted sleeve splice couplers were used to provide a moment connection between the top of the footing and the abutment stem wall.



Figure 65. Precast Concrete Footing Being Lowered into Position on Native Subgrade. Mill Street Bridge over Lamprey River, New Hampshire. (FHWA 2009.)

Similar to other precast concrete components intended for use on bridge structures, the weight and size of precast concrete footings can become excessive and prohibit their economic use. Typical bridge widths are such that fabrication of a whole-width precast spread footing is not practical from a handling and shipping perspective. However, as discussed in Chapter 4 (under “Connections Between Column Segments”), footings can be cast easily in segments, thus reducing sizes to more reasonable values. Fabricating precast footings in segments will not necessarily increase construction effort in the field a great deal, since many footings are designed for one-way action and structural connections at transverse joints thus can be simple, such as a grouted key (no reinforcement across the joint). If desired, however, a CIP closure pour with rebar extensions from segments on each side of the joint can be used to provide structural continuity.

Another option for reducing the dimensions and weight of precast footings is to use partial precast footings as detailed by the UDOT and shown in Figure 66. The precast footing section could be designed to carry only those loads acting during erection and CIP concrete extensions could be poured when convenient during construction and before the final load condition is applied.

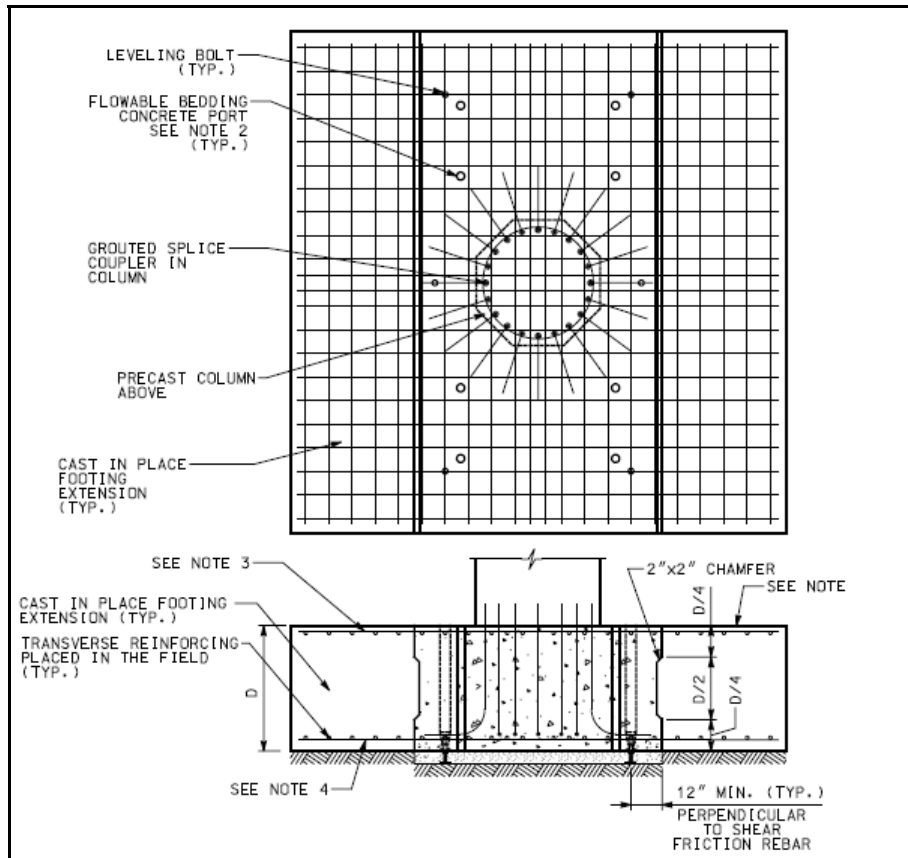


Figure 66. UDOT Partial Precast Spread Footing. (UDOT 2010d.)

PRECAST FOOTINGS ON DEEP FOUNDATIONS

A precast concrete footing could be used where deep foundations are called for. This is not unlike the use of precast concrete pile caps, which have been used on many bridge projects. Some of the same issues that must be addressed on precast spread footings also apply to those on piles or drilled shafts.

Installation of precast footings on piles or shafts follows that for spread footings. A sub-footing should be poured, or leveling pads should be located at leveling devices. Several different connection details between the piles/shafts and footing are possible. These different details depend on the type of pile—concrete versus steel—and whether uplift capacity is needed at the connection. In general, generous tolerances at the pile-to-footing connection should be used. The pile/shaft should extend a given distance into blockouts in the bottom of the footing, and the distance will depend on whether a moment connection is required. The PCI Northeast Bridge Technical Committee suggests 6 inches of minimum clearance around the pile to account for variations in pile/shaft location.

Figures 67 and 68 depict precast concrete footings on drilled shafts or pipe piles and steel H-piles, respectively. For drilled shafts and pipe piles, longitudinal rebar is extended from the pile or shaft into the breakout region within the footing. The blockouts are formed with corrugated metal pipe and are filled with concrete to complete the connection. Where H-piles are used, either shear studs or rebar placed through holes in the web help to transmit tensile forces from the pile to the footing. Figure 69 shows another potential detail for precast concrete piles and footings with uplift (PCINE 2006). A large

recess is formed in the bottom of the footing that encompasses the entire pile group. Thus, rather than providing individual pile blockouts, which will need to be large to accommodate pile driving tolerances, the recess will simply fit over the pile group, and the region can be filled with concrete. At each pile location, rebar extensions fit into smaller blockouts just large enough to accept the rebar (with appropriate clearances), and the tapered blockout region is grouted. Figure 70 shows a connection detail where the foundation does not experience uplift forces (PCINE 2006).

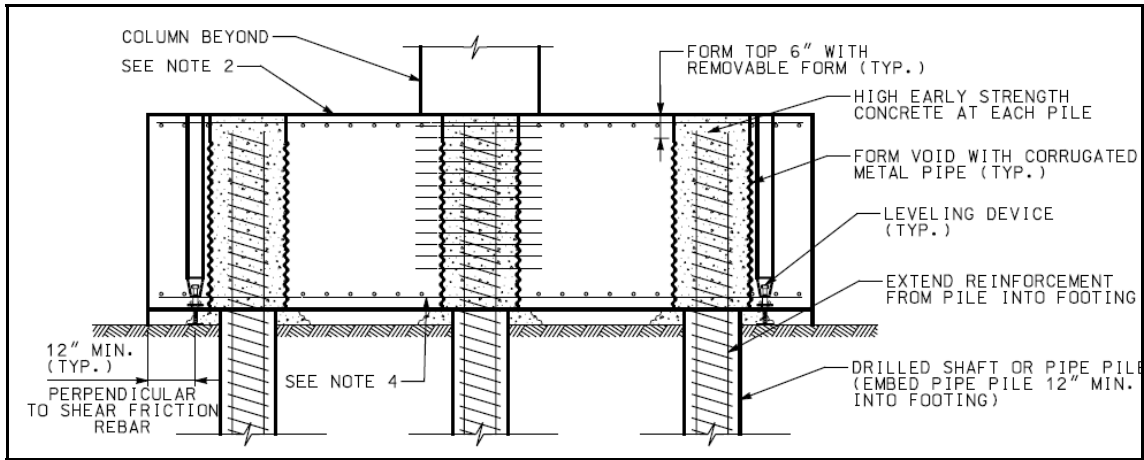


Figure 67. UDOT Precast Footing on Drilled Shaft or Pipe Piles. (UDOT 2010d.)

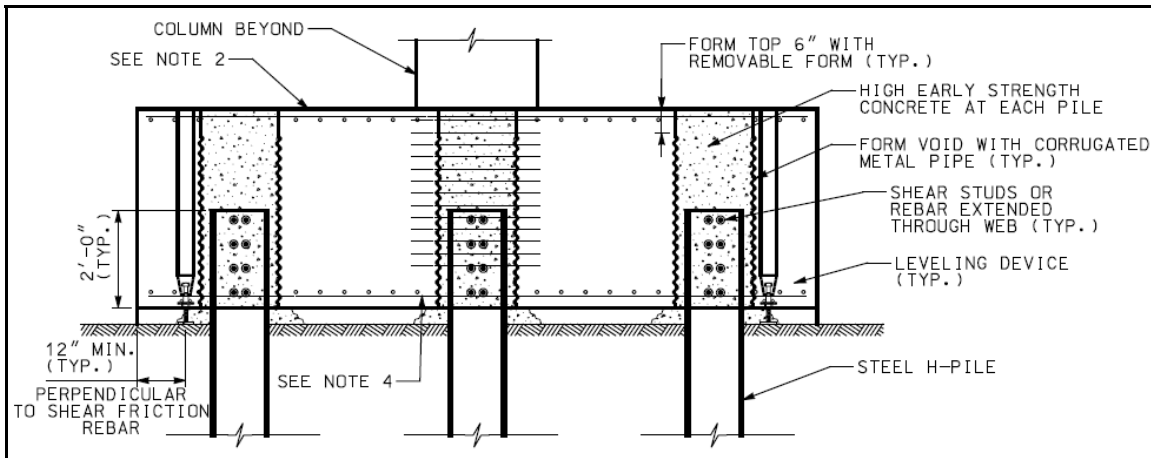


Figure 68. UDOT Precast Footing on Steel H-Pile. (UDOT 2010d.)

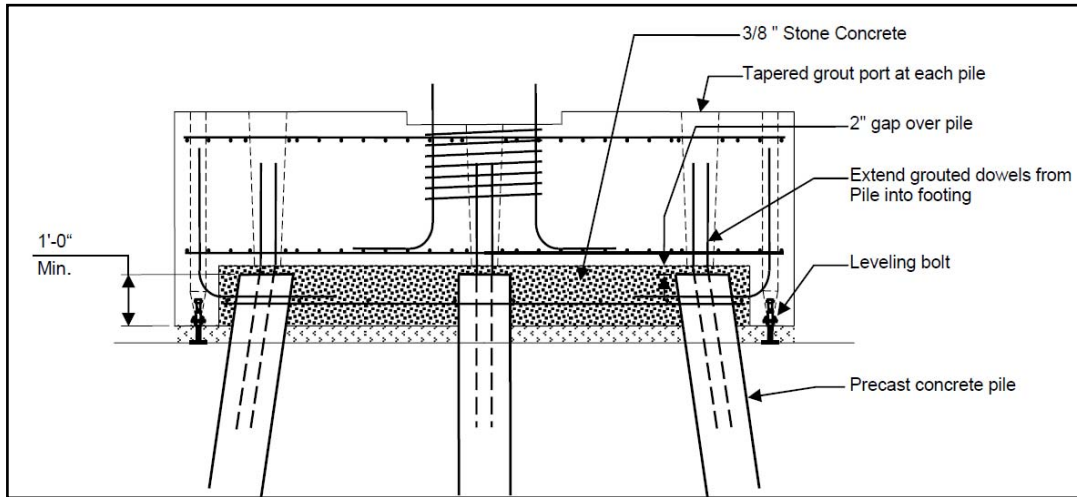


Figure 69. PCI Northeast Precast Footing on Piles with Uplift. (PCINE 2006.)

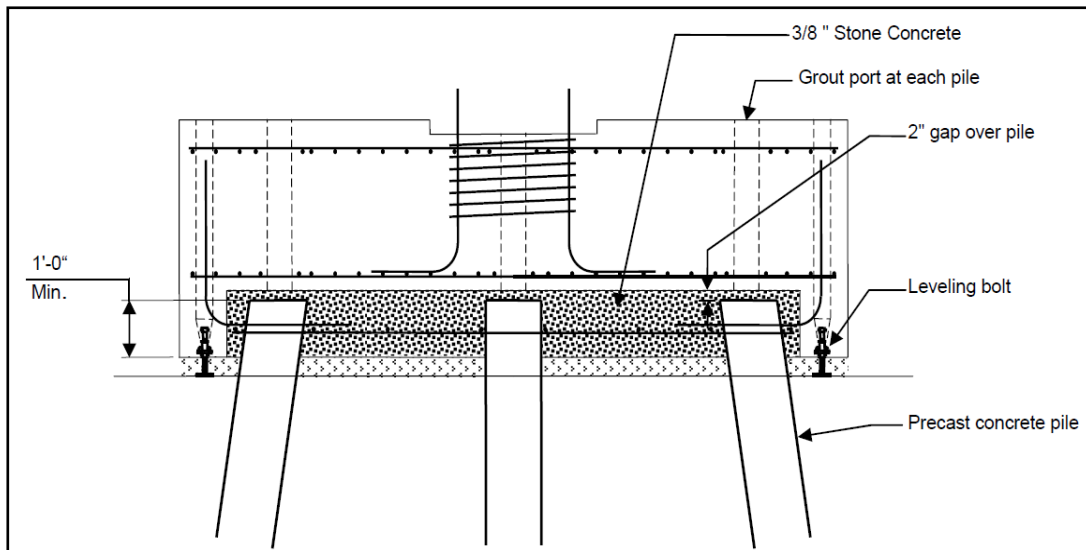


Figure 70. PCI Northeast Precast Footing on Piles without Uplift. (PCINE 2006.)

DESIGN OF PRECAST FOOTINGS

To the author's knowledge, no specific guidelines for design of precast concrete footings are available in published form. For precast spread footings, there should be no appreciable differences in behavior as compared to a conventional CIP footing as long as sufficient uniform contact between the bottom of the footing and the earth is achieved. If a precast spread footing is used along with CIP footing extensions, existing principles of force transfer across the joint can be used in the analysis and design process. For precast footings on deep foundations, the major unknown variable is the connection between the piles/shafts and the precast cap.

CHAPTER 6. RECOMMENDATIONS FOR IMPLEMENTATION

Implementing technologies and policies to reduce the duration of construction of bridges within Arizona will help to fulfill the AASHTO Subcommittee on Bridges and Structures' (SCOBS) "Grand Challenge #3": Accelerating Bridge Construction. This research effort focused on investigating the practices of other state DOTs, and the general the state of the art, related to the use of precast bridge substructure components. Beyond considering just prefabricating substructures, however, there is vast potential for other strategies for speeding bridge construction. With this in mind, the first section of these recommendations, "ABC Implementation," addresses the broad topic of "accelerated bridge construction." Following that section is a discussion of implementing specific precast substructure technologies for Arizona bridges.

ABC IMPLEMENTATION

The recommendation is that ADOT develop a strategic plan for how ABC practices might be developed and adopted for design and construction of future bridge projects. Other states, such as California and Washington, have already published their own versions of how to fulfill the ABC goal espoused by AASHTO. Shown in Figure 71 are steps that outline the philosophy adopted by UDOT for implementing accelerated project delivery; this philosophy includes ABC. The UDOT approach arises out of the realization that successfully implementing new technology requires a certain degree of risk taking—trying new ideas and learning from less than ideal outcomes—and thus is not an overnight process.

As ADOT looks to establish ABC as a goal for delivery of bridge projects in Arizona, a strategic plan should be created and should:

- Establish an ABC advisory committee.
- Review what is being done in other states to achieve ABC.
- Develop a decision-making process to evaluate whether ABC is the correct choice for a particular project.
- Engage the industry.
- Develop technical standards.
- Perform technical research as necessary.
- Use a phased implementation.
- Develop a feedback process as ABC is implemented.

Keys to Successful Program Implementation

UDOT has a successful program to accelerate project delivery. Some keys to its success include:

- ❖ Gaining upper level management support – without this type of support the goals and objectives of program acceleration will not be achieved.
- ❖ Having enabling processes in place – UDOT had developed mature processes related to alternative project delivery, contracting, and partnering.
- ❖ Recognizing that implementing new processes requires cultural changes within the organization – a need is recognized and efforts are made to enlist the support of UDOT staff.
- ❖ Being willing to try new technologies – UDOT has aggressively implemented some new technologies in the area of bridge design and construction and has the patience to wait for the benefits of new technologies to outweigh the costs.
- ❖ Engaging industry in improvement processes – hearing the voice of industry through input, discussion, and collaboration is critical.
- ❖ Measuring performance is critical – UDOT is tracking the results from project and program acceleration and can point to successes.
- ❖ Learning from the past – changes to improve the acceleration process have been made based on past experiences.
- ❖ Maintaining a vision for the future – UDOT is constantly looking for new and better ways to accelerate project and program delivery.

UDOT has embarked on an ambitious program of project acceleration while focusing on lowest project cost. While UDOT has been successful thus far, it continues to look forward to find ways to further reduce delivery times while minimizing the impact on road users.

Figure 71. UDOT Approach to Speeding Delivery of Bridge Projects in Utah. (UDOT 2010b.)

ABC Advisory Committee

To gain the highest possible degree of agreement from all parties with an interest in bridge construction within Arizona, the recommendation is that ADOT establish a panel or committee that will help to develop ADOT goals and practices for ABC use on Arizona bridges. This panel should include ADOT management and technical personnel, FHWA representatives, industry design professionals, and representatives from precast fabricator and bridge contractor companies. To facilitate meeting organization, the committee membership should be kept to eight to 12 individuals. If this committee is created, an initial “ABC kick-off meeting” should be held as soon as practical. The ABC advisory committee should develop an ABC implementation plan and set specific, reasonable milestones. In addition to creating the ABC advisory committee, ADOT should identify an internal ADOT “champion” who can lead the ABC practice development.

Survey of ABC Practice

Essentially, a survey of ABC practice entails looking at the broad category of accelerated bridge construction, and at what other DOTs have been successful in adopting to speed bridge construction. Again, although this report is focused on one specific means of achieving ABC—prefabrication of bridge substructures—there are many additional methods that other transportation agencies are using, such as precasting bridge decks, whole bridge moves via SPMTs, etc. Ideally, ADOT should consider how to

achieve the greatest time savings, balanced with considerations of economy. There exists a large volume of documentation on how, nationally, ABC is being achieved, and this task simply would be to collect the data and decide what makes sense for Arizona.

ABC Decision-Making

It is well understood that speeding up construction while maintaining quality is generally a positive for all parties affected by or involved with the construction of transportation facilities. There are real societal and economic negative impacts associated with construction, but it is often difficult to determine quantitatively the value of aspects such as user traffic delays, safety improvement, environmental risk reduction, etc. Thus, although there may be benefits from using ABC methods on a particular project, decision makers often do not have hard data that can be used to decide whether, for example, an increase in cost of an ABC alternative is justified by other “savings” or enhancements. The above challenges are being addressed by those making the push toward ABC as a standard practice, and ADOT has guidance on how to evaluate the appropriateness of ABC on a project-by-project basis.

The FHWA has developed a decision-making framework, which was described in Chapter 2 of this report (FHWA 2006a). This document could provide ADOT with the necessary framework for evaluating ABC alternatives, although it does not provide any specific quantitative measures for the various project variables that influence whether ABC is “the right choice.”

Also described briefly in Chapter 2 is the state pooled funds research project (Doolen et al. 2011) that was headed by researchers at Oregon State University. The result of this project was a project-level tool that quantitatively measures whether ABC methods are more economical than conventional construction procedures.

The recommendation is that ADOT become familiar with the FHWA document and consider the results of the state pooled funds study to develop an internal policy and practice for ABC decision-making.

Industry Involvement

Successfully implementing ABC in Arizona will be difficult without input from precast fabrication and bridge construction companies. As with implementing any new technology, it can be difficult to learn how to use it properly, and there can be general resistance to it. Industry professionals who are comfortable with CIP construction methods for bridge substructures initially may not see the benefits associated with ABC that they can enjoy. It will be paramount to educate those involved on the construction side on why ABC is being implemented and how it can improve their operations. Moreover, it will be critical for the ADOT Bridge Group to communicate their commitment to ABC methods so that contractors clearly understand that the new technologies and methods will become more commonplace rather than “one-off” occurrences. Some necessary re-tooling will be required, and contractors will need to see that their investments will pay off in the long term. Workshops describing the new ABC technologies being implemented should be offered in order to educate the construction industry and thus potentially alleviate some of the concerns and hesitation that may initially be present.

The additional aspect of industry engagement is to gather industry input on the most effective means and methods of ABC construction, with the goal of developing a practice that is both practical and economical and saves time. Consulting engineers, fabricators, erectors, shipping personnel, and general

contractors should all be included in the process of developing ABC procedures for Arizona bridges. This involvement should, in the early phase of ABC practice development, be through the ABC advisory committee (described previously under “ABC Advisory Committee).”

Technical Standards Development

Development of design, construction, and maintenance standards and procedures will be required in order to successfully implement ABC. A significant amount of information is available on technical requirements for various ABC technologies; ADOT should build its practice based on the existing practices of other state DOTs, adjusting where appropriate. For prefabrication ABC technologies specifically, one of the biggest concerns has been connection behavior and design. Sufficient research in the last decade has shown proven methods for joining prefabricated components. As described in Chapters 3 and 4, several different connections between precast bent cap beams and columns have been developed, tested under realistic (simulated) loading, and implemented on actual bridge projects. Additionally, the *Connection Details for Prefabricated Bridge Elements and Systems* (FHWA 2009) is a comprehensive resource on various methods for mating prefabricated bridge components.

Technical Research

Where there exist gaps in knowledge related to ABC technologies that ADOT chooses to implement, ADOT should consider funding research projects to provide a basis for practice development. The three public universities within Arizona have sufficient capacity to perform this type of applied research, and consulting engineers from industry should also be engaged in these activities.

Phased Implementation and Continuous Improvement Process

When ADOT and its ABC advisory committee (once the committee is formed) have identified ABC methods to consider implementing, ADOT should develop a phased implementation plan. This plan would likely include implementing one specific ABC technology for a project in a pilot phase. Based on the pilot project and assuming positive results, that particular technology could be used on a more regular basis for other projects, thus moving that technology from pilot status to regular practice. Part of the initial ABC implementation should include a feedback or continuous improvement process where “lessons learned” are recorded and used to improve ADOT’s ABC practice. The feedback process should include representatives from all parties involved with the specific project and its specific ABC aspect.

PRECAST SUBSTRUCTURE IMPLEMENTATION

This section discusses specific precast technologies that can be relatively easily implemented for accelerating the construction of bridge substructures in Arizona. Based on the literature surveyed and evaluation of what other states are already doing to speed construction using precast components, there now exists both sufficient technical knowledge and successful previous use of precast substructure systems to justify using any of the precast components described in this report. However, rather than going “all-in” and implementing an all-precast substructure design from the beginning, it is likely prudent to choose specific components that can have the highest impact in terms of accelerating construction and alleviating its deleterious impacts to the public. Also, some of the technologies described in this report have a more established track record of use, and thus could be adopted with more confidence for use in Arizona.

Based on these considerations, a possible approach to a phased implementation of precast substructures would be to implement precast substructure components in this order:

1. Bent cap beams.
2. Columns and pier walls.
3. Footings and abutments.

The above ranking is based primarily on the fact that there is more precedent for using precast bent cap beams than columns, spread footings, and abutments. Numerous projects have been constructed using precast cap beams, and they all have shown the promise of the technology for reducing construction time and also addressing other issues, such as limited vertical clearance for falsework over existing traveled way and eliminating the environmental threat posed by pouring concrete in place over water ways. Furthermore, there is a greater body of technical knowledge related to the design and performance of precast concrete bent cap beams.

Chapter 2 of this report provides a review of two documents that contain a significant amount of information on the use of precast concrete substructure components: the FHWA *Connection Details for Prefabricated Bridge Elements and Systems* (FHWA 2009) and the PCINE *Guidelines for Accelerated Bridge Construction Using Precast/Prestressed Concrete Components* (PCINE 2006). These documents provide comprehensive guidance on the range of issues related to the use of precast concrete bridge substructures, and should be referenced as ADOT develops its ABC practice.

Bent Cap Beams

Based on the review of literature and practice of other state DOTs, there are two viable alternatives for precast cap beams: a precast cap beam connected to columns via the grouted splice sleeve connectors (see the section in Chapter 3 titled “Grout-Filled Splice Sleeve Couplers”), or by extended longitudinal column steel grouted into vertical ducts embedded within the cap (see the sections in Chapter 3 titled “Connection Types” and “Washington DOT Precast Bent Cap System”). Both connection schemes have been used in practice, but only the vertical grout duct with extended column longitudinal bars has been tested experimentally on a large scale. The grouted vertical ducts with extended column steel connection system has been tested both at the University of Texas and the University of Washington, and has been implemented on actual bridge projects in both states. The column-to-cap connection using the grouted sleeve mechanical coupler has not been tested in a connection subassembly, but has been implemented on a variety of different bridge projects, including one in the state of Georgia (see the section titled “Georgia” in Chapter 2). If ADOT selects the grouted sleeve connection system for use on Arizona bridges, the recommendation is that ADOT experimentally test a column-beam subassembly.

For either connection system, bent cap beams can be analyzed and designed by essentially the same methods currently used for conventional CIP RC construction. Detailing is also essentially the same as for conventional construction, except that additional transverse reinforcement may be required within the joint region for the grouted vertical duct connection. An additional recommendation is to review *Development of a Precast Bent Cap System for Seismic Regions* (Restrepo et al. 2011).

Columns and Pier Walls

As detailed in Chapter 4, a significant amount of research has been aimed at developing precast concrete column systems for bridges. Much of this research has focused on the benefits of such systems for seismic loading, where the presence of column PT provides re-centering capabilities. However, concepts for accelerating the construction of bridge bents using column prefabrication have been developed, tested, and put into practice. Two prominent concepts should be considered for use on bridges in Arizona: the precast column with longitudinal rebar extensions that are grouted into adjoining components, and the precast column with grouted sleeve couplers for connections to foundation and cap beam.

In Washington state, precast columns with a support leg have been tested experimentally under realistic loading and used in practice on actual bridge projects (see the section titled “Column with Support Leg Connection” in Chapter 4). This column system could be adaptable to “typical” Arizona grade separations where column heights are not excessive. The concept is simple and only requires that a grout pad be cast at the proper elevation and location (centered on column) before the footing steel is fabricated. The precast column with support leg will need to be braced before the foundation concrete is poured and hardens, but this done for column formwork in conventional CIP construction as well. Because the connection between the column and foundation is essentially the same as a CIP connection, just with order reversed, analysis and design of the column should follow the same principles and requirements as for CIP RC columns.

The precast column system that relies on grouted sleeve couplers to mate with other components has not been tested experimentally, but has been used in practice (see “Georgia” in Chapter 2). Assuming the connection is capable of transferring forces between columns and adjoining elements, analysis and design should follow the same practices as used for conventional CIP RC column construction. However, as noted for precast cap beams above, the recommendation is that a column-to-foundation and column-to-cap beam connection be constructed and tested experimentally to verify that the connection provides for adequate force transfer between components.

Although not specifically discussed in Chapter 4, precast bridge supports that are more wall-like could be adopted in Arizona with the same provisions as described for columns.

Footings

Precast spread footings have been used to speed bridge construction on at least one bridge project in the United States—the Mill Street Crossing in New Hampshire (see “New Hampshire” in Chapter 2 and “Issues with Precast Concrete Spread Footing” in Chapter 5). The precast footing in that project used the grouted sleeve splice coupler to connect the precast footing and abutment stem wall. Precast footings could be used for Arizona bridges, although there are no published design guidelines to date. Using grouted sleeve couplers to mate a precast footing and adjoining component should be verified by large-scale experimental testing of the connection.

SUMMARY

Presented in this report is a review and evaluation of the current technologies that have been used or proposed to accelerate the construction of concrete bridge substructures within the United States. The

review found a large body of literature specifically related to prefabrication of bridge substructure components in the form of precast concrete elements. However, in an overall sense, developing precast substructures and actually implementing them are still in their infancy. Nevertheless, there are areas where ADOT could reasonably adopt methods for speeding construction without taking on high levels of risk. Precast cap beams on conventional CIP RC columns or on piles could immediately be implemented in order to speed construction. Other technologies, such as precast columns, should also be evaluated and considered for use on Arizona bridges.

Recommendations for future work in this area include following up on the research projects described in this report. These projects can provide critical and missing knowledge that will facilitate use of precast concrete substructures in Arizona. Additionally, due to the high promise of the grouted sleeve splice coupler for making quick and structurally sound connections between precast components, and due to the lack of experimental testing of the couplers in connection sub-assemblages, experimental testing of connections made with the couplers should be pursued in order to provide the confidence needed for adoption in practice.

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APPENDIX A

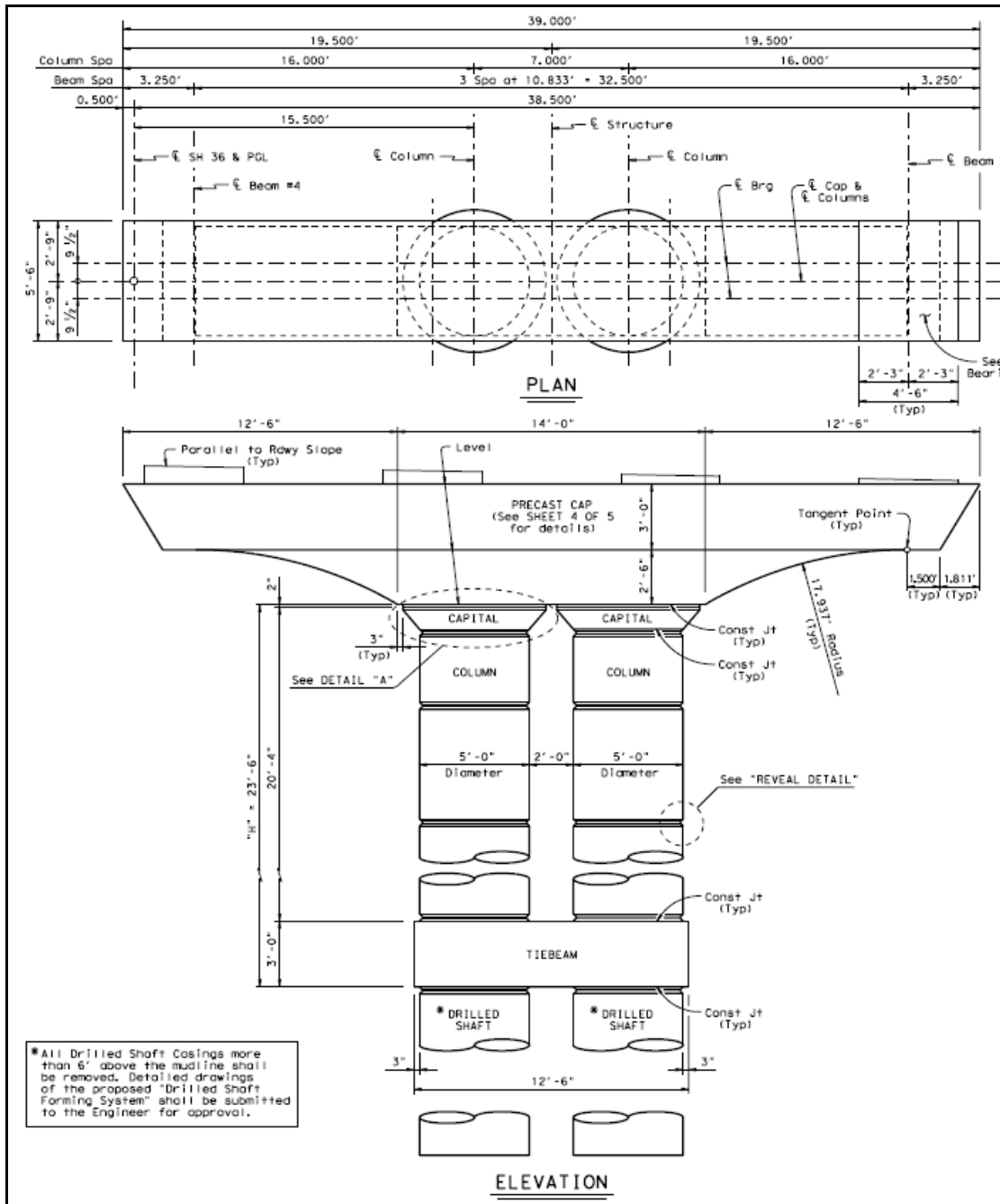


Figure A-1. Precast Cap Layout on Lake Belton Bridge, Texas. (FHWA 2011a.)

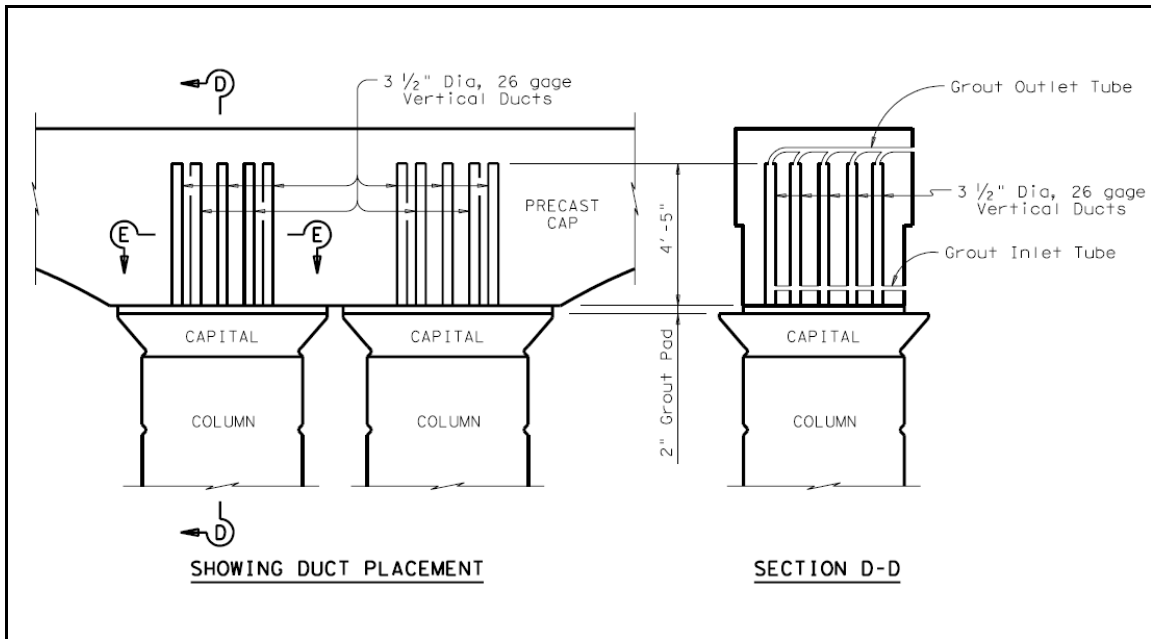


Figure A-3. Precast Cap Details on Lake Belton Bridge, Texas. (FHWA 2011c.)

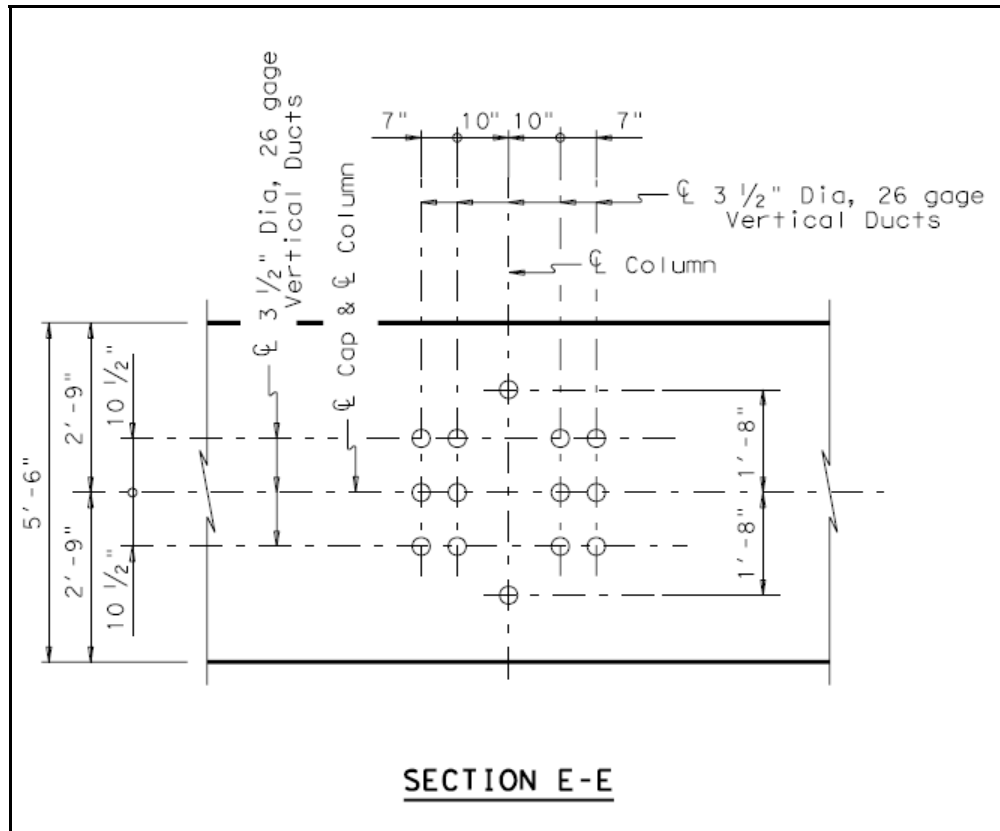


Figure A-4. Precast Cap Details, Lake Belton Bridge, SH 36, Bell County, Texas.
(FHWA 2011c.)

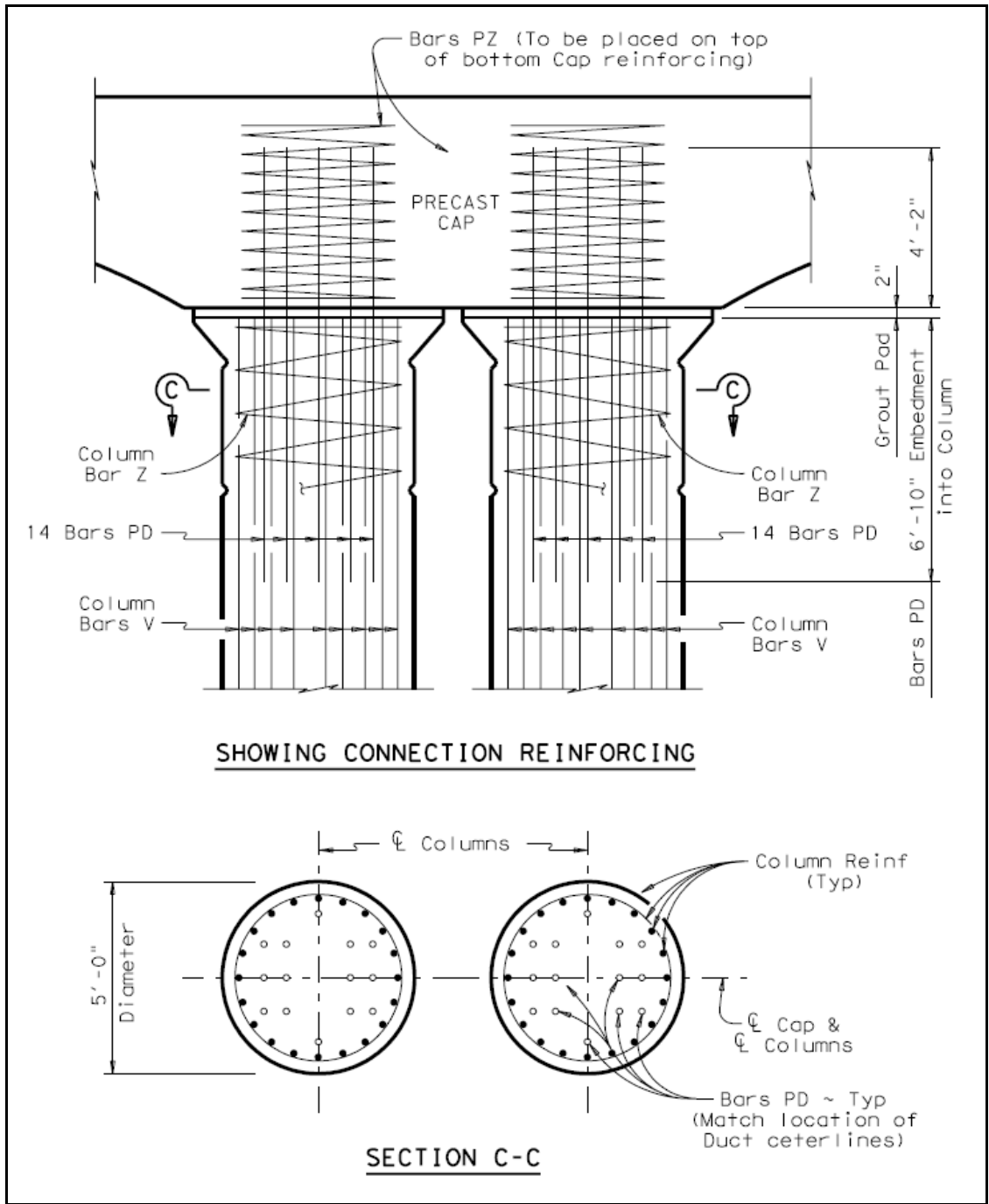


Figure A-5. Precast Cap-To-Column Connection Details on Lake Belton Bridge, Texas. (FHWA 2011c.)

PRECAST BENT CAP CONSTRUCTION NOTES

Construction shall be in accordance with the requirements of Item 420. Vertical Ducts shall be semi-rigid, spirally crimped, corrugated ducts of galvanized, cold rolled steel conforming to ASTM A527 and ASTM A619. Corrugations shall have an amplitude of 0.094 in. Ducts shall be placed in a manner to prevent intrusion of Bent concrete.

Precast Bent Caps shall be handled, moved, stored and placed in the structure in a manner to avoid chipping, cracking, fractures and excessive bending stresses or damage. Precast Caps shall not be stacked. They shall be supported on firm blocking until placed and shimmied into final position. Blocking shall be installed such that uneven settlement due to wet ground or inadequate material underneath the blocking will not occur.

The Contractor may alter mix design and/or move or place caps before completing the prescribed curing period in Item 420 provided all of the following conditions are met:

1. The concrete has reached a flexural strength of 425 psi or a compressive strength of 3000 psi.
2. The curing time is interrupted for no more than 2 hours.
3. The alternate plan meets the approval of the Engineer.

Place columns in accordance with Item 420. If the connection dowels (Bars PD) are inserted after the concrete has been placed, the concrete shall be re-vibrated. Dowel placement tolerance is $\pm 1/2$ " (plan and elevation).

Caps may be placed on columns, after the column concrete curing has been completed and after a flexural strength of 425 psi (or 3000 psi compressive strength) has been achieved. Use plastic shims to support the caps at the proper elevation prior to grouting. Total area of plastic shims used on top of each column may not exceed 6% of the column area.

Grout forms and tubes (input and vent tube type and location) shall be approved prior to grouting. Connection shall be grout tight such that fluid grout does not leak out before grout has achieved initial set.

All grout for precast connections shall consist of prepackaged, cementitious, non-shrink grout in accordance with ASTM C-1107 and the additional performance requirements listed in the Table of Grout Performance Specifications, including mechanical properties, compatibility, constructability and durability. Table requirements shall govern over ASTM C-1107 requirements. Grout using metallic formulations will not be allowed. Grout shall be free of chlorides. No additives shall be added to prepackaged grout. Fluid grout shall not exhibit frothing or foaming.

Two (2) 2" x 2" x 2" grout cube samples will be cast for each precast bent cap (one per precast cap-to-column connections) by the Contractor and given to TxDOT for testing to ensure that the grout meets the specified mechanical property criteria for compressive strength. Failure to meet strength criteria or evidence of frothing or foaming shall be cause for removal and recasting of the connection as deemed necessary by the Engineer. Grout selected shall meet the other criteria listed as well.

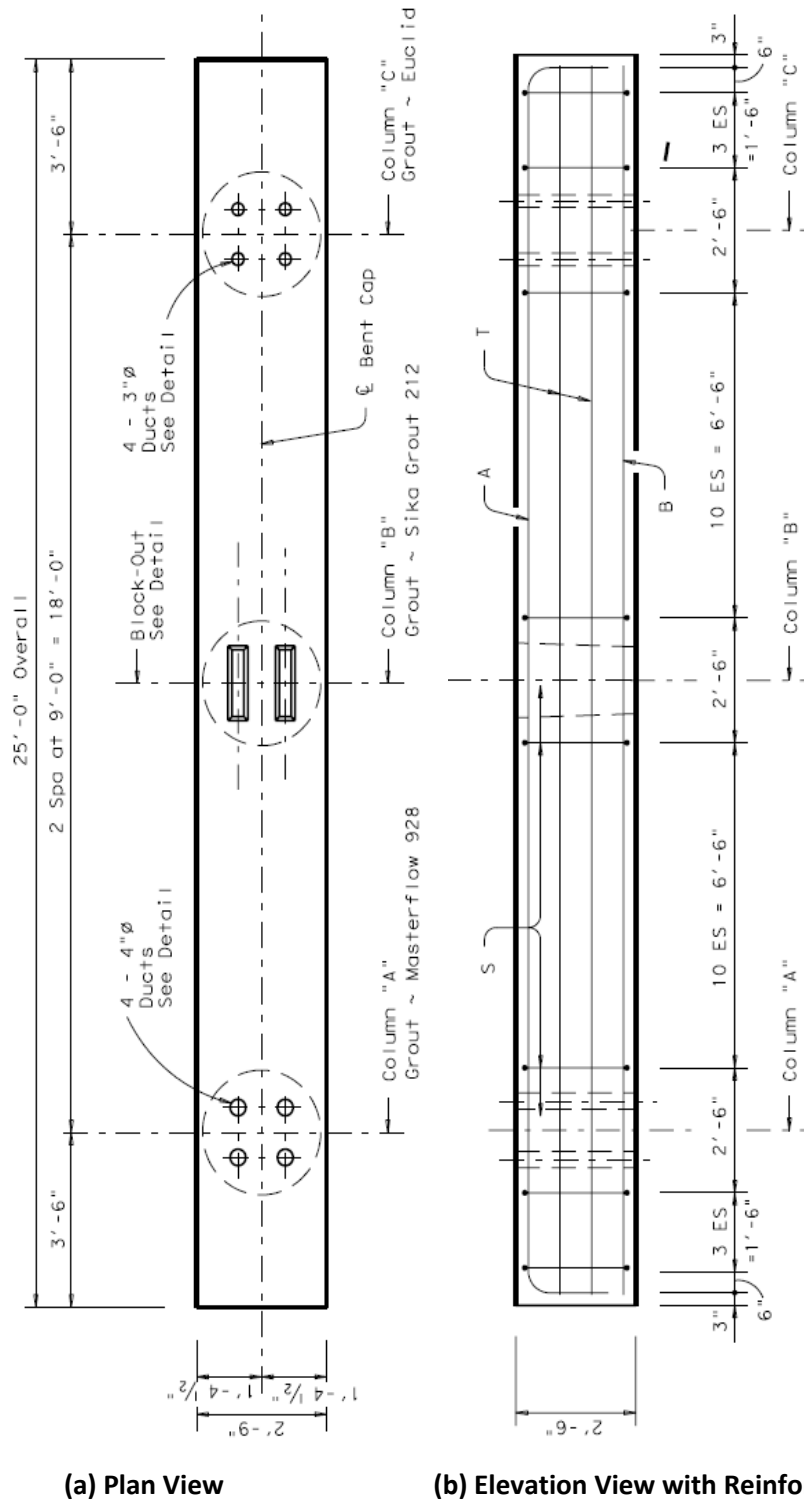
Prestressed beams may be placed on the caps after a grout compressive strength of 3000 psi has been achieved.

Figure A-6. Precast Cap Construction Notes on Lake Belton Bride, Texas. (FHWA 2011c.)

TABLE OF GROUT PERFORMANCE SPECIFICATIONS		
PROPERTY	VALUES	
MECHANICAL	AGE	COMPRESSIVE STRENGTH (psi)
Compressive strength (ASTM C-109, 2" cubes)	1 day	2500
	3 days	4000
	7 days	5000
	28 days	5800
COMPATIBILITY		
Expansion Requirements (ASTM C-827 & ASTM C-1090)	Grade B or C ~ expansion per ASTM C-1107	
Modulus of elasticity (ASTM C-469)	2.8 - 5.0 x 10 ⁶ psi	
Coefficient of thermal expansion (ASTM C-531)	3.0 - 10.0 x 10 ⁶ /deg F	
CONSTRUCTABILITY		
Flowability (ASTM C-939; CRD-C 611 Flow Cone)	fluid consistency efflux time: 20-30 seconds	
Set Time (ASTM C-191)		
Initial	2.5-5.0 hrs	
Final	4.0-8.0 hrs	
DURABILITY		
Freeze Thaw (ASTM C-666)	300 cycles, RDF 90%	

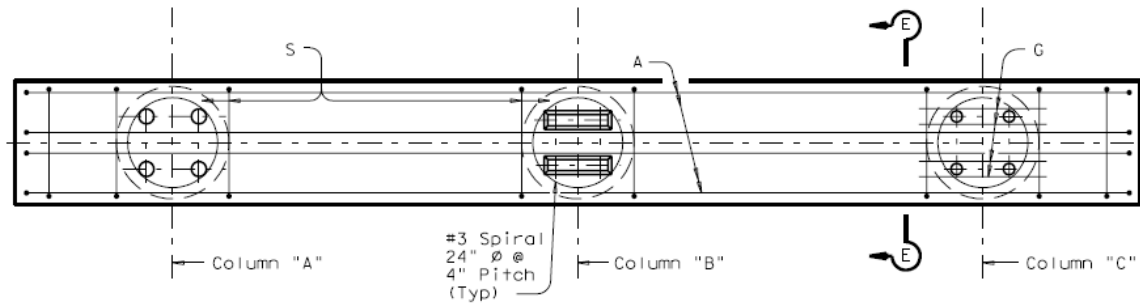
Figure A-7. Precast Cap Grout Specification on Lake Belton Bridge, Texas. (FHWA 2011c.)

APPENDIX B

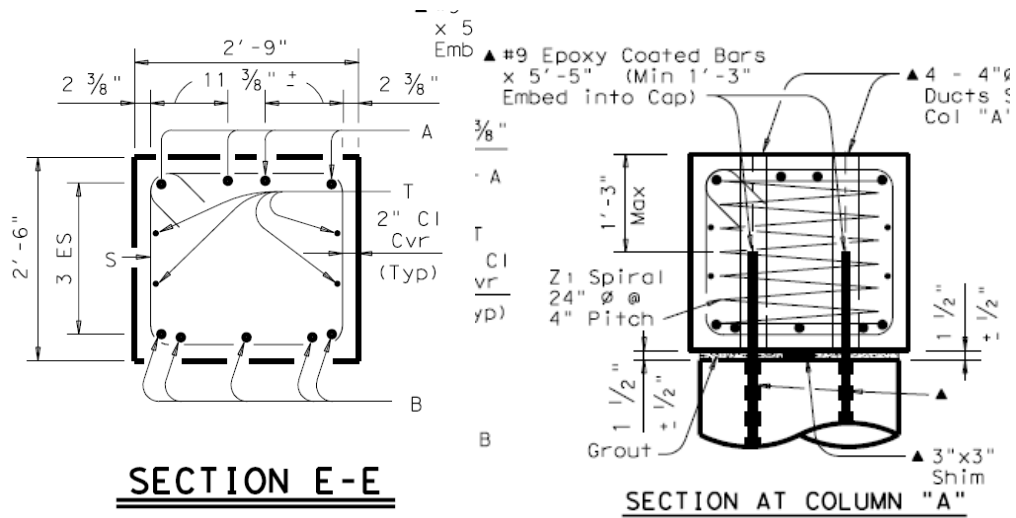


(a) Plan View (b) Elevation View with Reinforcement Layout

Figure B-1. Precast Cap on Lake Ray Hubbard Bridge, Texas. (FHWA 2011d.)



(a) Plan View with Reinforcement Layout



(b) Precast Cap Typical Section View

(c) Precast Cap Section View through Connection

Figure B-2. Precast Cap Details on Lake Ray Hubbard Bridge, Texas. (FHWA 2011d.)

APPENDIX C

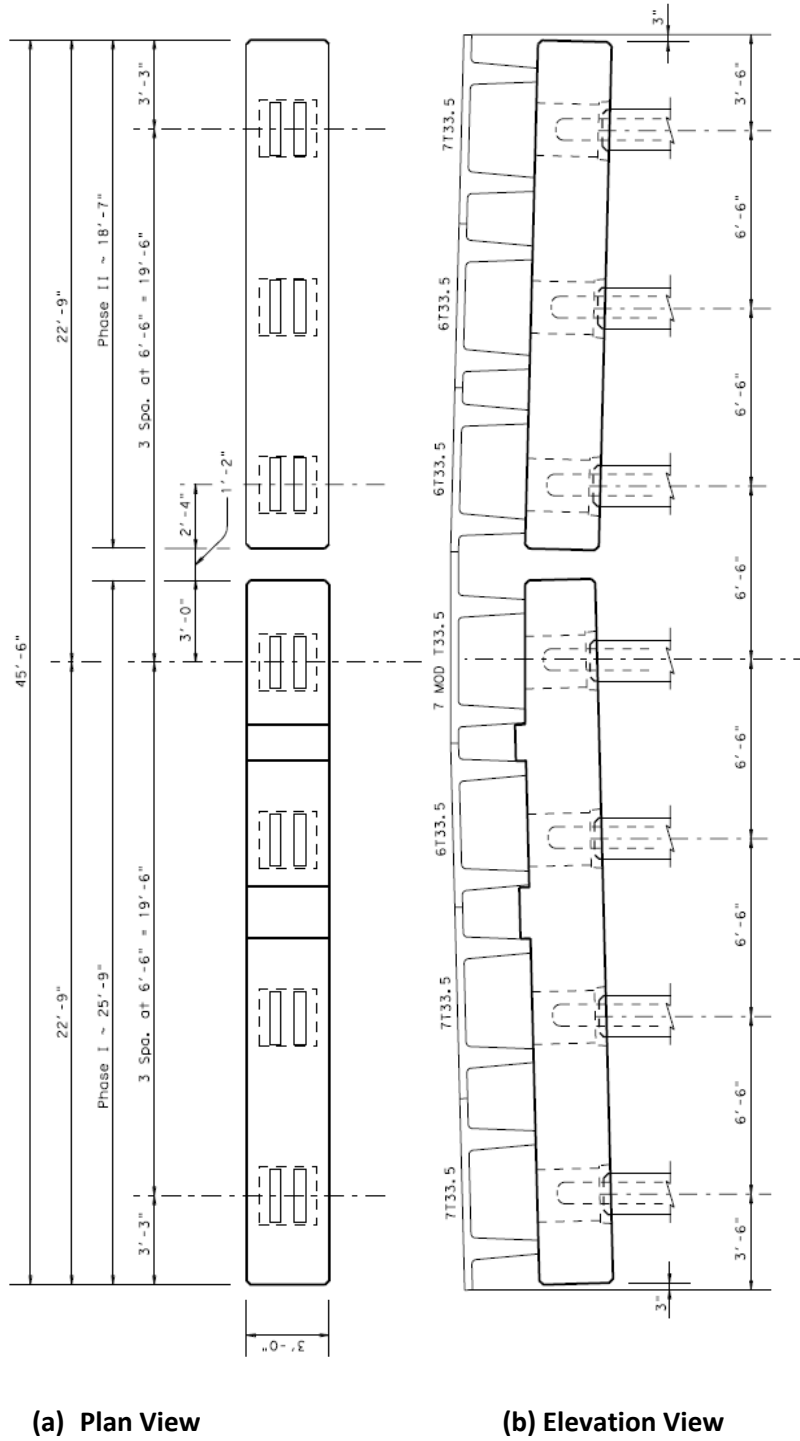
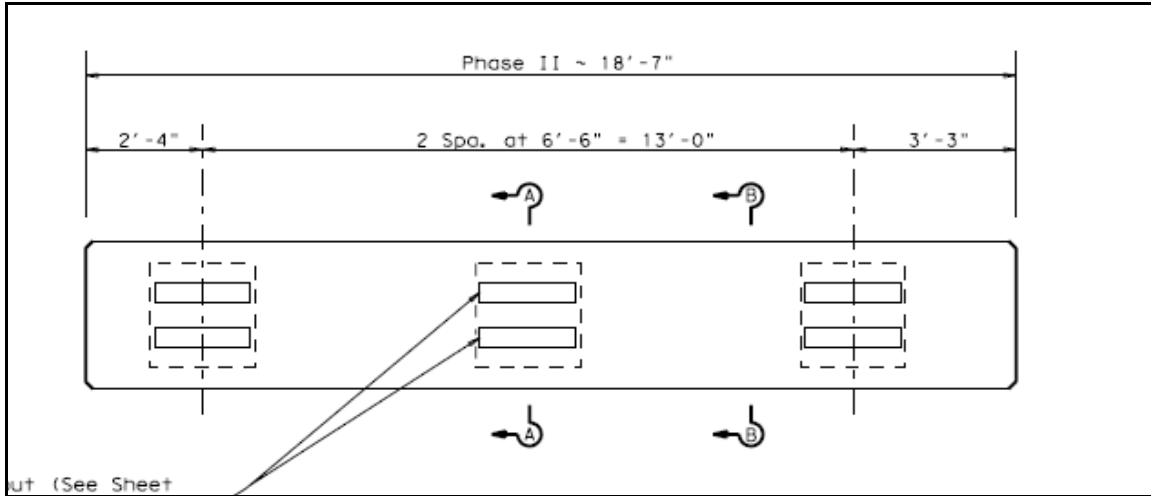
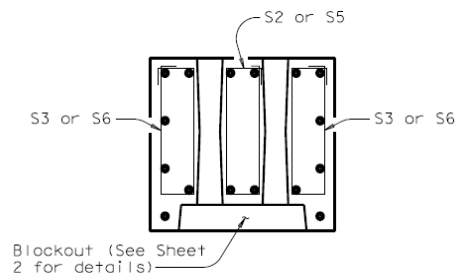


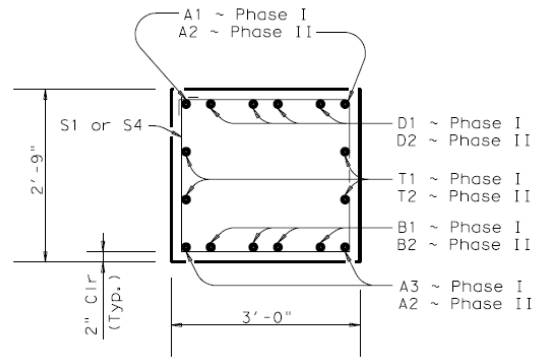
Figure C-1. Precast Cap Layout on Red Fish Bay Bridge, Texas. (FHWA 2011e.)



(a) Plan View



SECTION A-A



SECTION B-B

(b) Section at Column View

(c) Section between Columns

Figure C-2. Precast Cap Rebar Details on Red Fish Bay Bridge, Texas. (FHWA 2011f.)

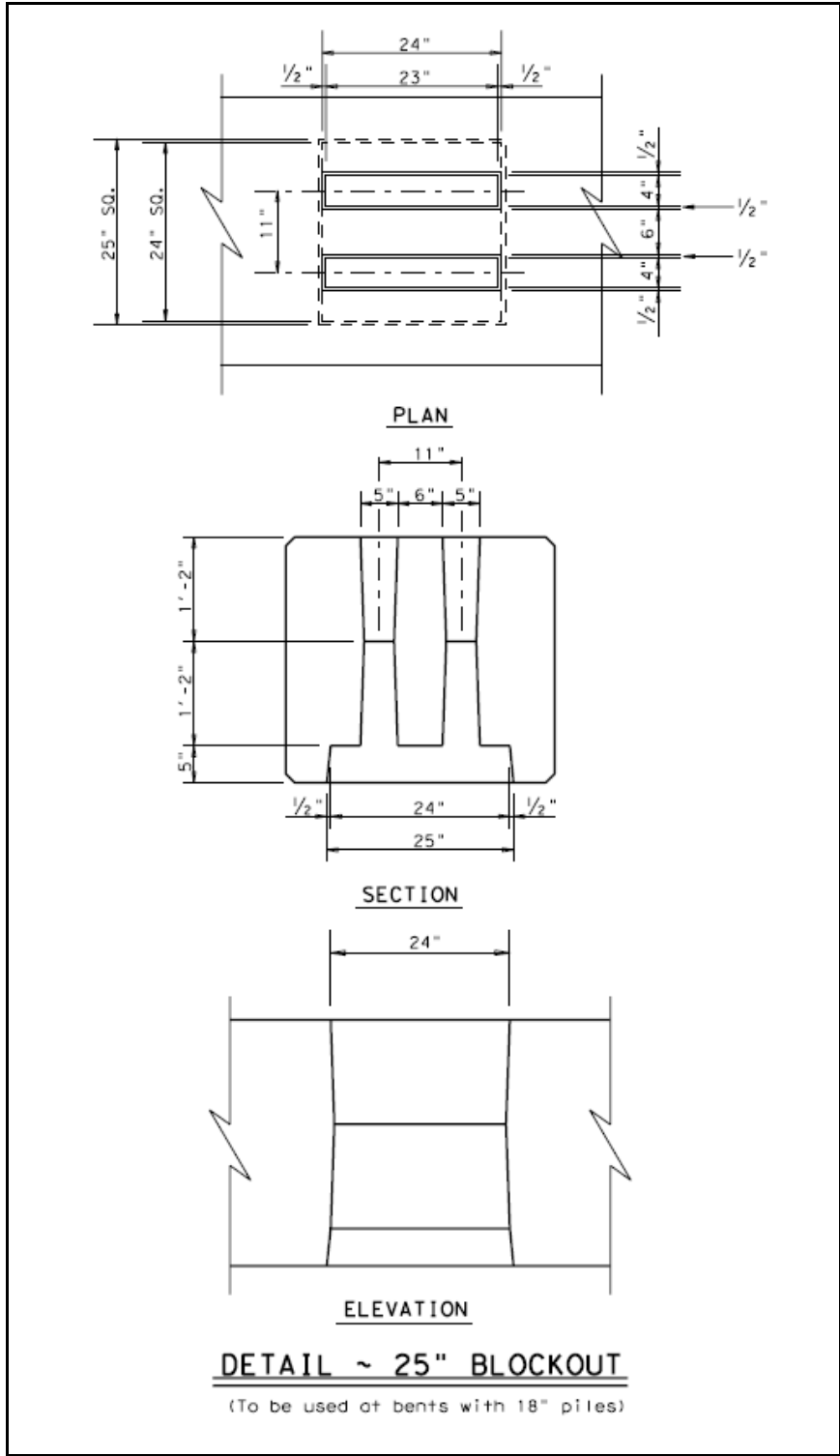


Figure C-3. Precast Cap Pile Blockout Details on Red Fish Bay Bridge, Texas. (FHWA 2011g.)

