AVAILABLE ABC BRIDGES SYSTEMS FOR SHORT SPAN BRIDGES - COURSE MODULE

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Acknowledgments

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CHAPTER 1. INTRODUCTION TO ABC – OUTLINE OF THE COURSE

1.1. Abstract

With the use of prefabricated bridge elements and systems, Accelerated Bridge Construction (ABC) promises significant reduction in on-site construction time and traffic interruptions. It also improves the life cycle cost by better control over schedule, and normally by the higher quality of elements resulting in better life-cycle performance. ABC is especially beneficial for short-span bridges that are more receptive of standardized prefabricated elements. In most such cases, the entire span of the bridge can be covered using prefabricated deck elements, modular decks, or systems encompassing the entire bridge width. Furthermore, the substructures in these bridges could avoid special treatment and can be accommodated by prefabricated elements. For shorter spans, prefabrication of the entire bridge consisting of substructure and superstructure is also an option. Various construction methods ranging from installation using customary cranes to the use of Self-Propelled Modular Transport (SPMT) units for moving the entire superstructure, or the use of slide-in methods can be employed for construction of the short span ABC bridges. There are various definitions as what span length constitutes short span. Some define bridges with a span of 20-45 ft. as short-span (FDOT), others span of up to 70 ft., and some attribute spans as long as 100 ft. The proposed course module will introduce the ABC concept and review its applications to short-span bridge construction. It will categorize and describe short-span bridges based on various factors such as access, topographic and geographic conditions, roadway functional category, span length, elements and systems, time constraints, and construction methods. Design and detailing of the bridge and joints will also be discussed in the course. Performance of these bridges will be reviewed based on the information available in the literature. Decision-making on the use of ABC in general and type of elements, systems, and construction method will be briefly discussed in this course. Further, the course will cover new and ongoing developments that can affect the future of ABC for short-span bridges. Inspection of short-span bridges will also be one of topics discussed in this course.

This report subscribes to a definition of short span bridges which will help to distinguish better the limitation in selection of ABC components as well as a better explanation for the scope of work by parties performing the project.

1.2. Background

The main goal of ABC is to use the advantages of prefabrication to the extent possible for reducing on-site construction activities and impact on mobility. In this, short-span bridges represent an ideal case basically allowing implementation of a wide variety of ABC solutions and methods. There are various definitions as what span length constitutes short span. Some define bridges with a span of 20-45 ft. as short-span (FDOT), others span of up to 70 ft., and some attribute spans as long as 100 ft. Solutions ranging from prefabrication at element and member level to pre-construction of the entire bridge can be employed for short-span bridges. Structures over 20 ft. in span are normally called “bridges”, while structures with a span less than 20 ft. in span are called culverts even if they directly support the traffic. It should however be noted that some structures with spans of longer than 20 ft. are designed hydraulically and structurally as culverts [1]. Often, culverts with span longer than 20 ft. are designed accounting for the support from surrounding soil. Such structures for which the need for static soil-structure interaction is identified, are called "buried bridges." Span in such structures can reach up to 100-ft spans requiring safety and design considerations as conventional bridges [2]. Many of the culverts and buried structures are constructed using ABC methods and as such, these types of bridges are covered among ABC short-span bridges in this report. Some examples culverts and buried structures are shown in Figure 1.1. Figure 1.2 shows other ABC elements and methods.

Figure 1. 1 Examples of culverts and buried bridges

Figure 1. 2 Other elements and methods for short-span bridges

The type of elements and construction method will depend on many parameters such as access, topographic and geographic conditions, roadway functional category, span length, elements and systems, and the time constraints. Accordingly, it is essential to make available to the users all element types, subsystems and systems available to choose for a short-span ABC bridge. Identifying the components and defining clearly their advantages, applications and limitations will help the selection. In most instances, span length is the most significant factor in determining the form and cost of a bridge. Design and detailing of the bridge, and especially the establishment of integrity between elements at the site using cast-in-place closure and other in-situ joints represents some challenges. Accordingly, ABC connections and joints play an important role and their application and limitations need to be understood. The prevalent defects observed in bridge decks using ABC have been cracks (Figure 1.3) accompanied usually with efflorescence and leakage. This type of defect has persisted for an specific type of ABC construction that uses side-by-side box precast concrete beams. Based on the reported survey, most of these problems were observed in the connections between deck panels and between deck panels and piers or abutments. Therefore, inspection and performance evaluation of joints, particularly closure joints, should be emphasized for short-span bridges.

Figure 1. 3 Other elements and methods for short-span bridges

Decision-making on the use of ABC in general and the type of elements, systems and construction methods in specific is essential for an effective project initiation, management and contractual aspects.

A concerted review of the application of ABC methods including important aspects of construction, detailing, performance and inspection, and decision making need to be communicated to stakeholders in the form of educational course modules. This project attempts to generate and compile materials for a course module material in relation with short-span ABC bridges.

1.3. Objectives of the Course

The primary objective of development of this course is to provide a general knowledge about the application of ABC for short-span bridges covering various aspects of decision-making, construction methods, available elements and systems, performance and inspection, design, detailing and connections.

1.4. ABC – Definitions and descriptions

Accelerated Bridge Construction (ABC) is a construction type that reduces the onsite construction time. To achieve the ABC mission, new and innovative materials, design, and construction methods are implemented in designing and construction of new bridges as well as in the replacement and rehabilitation of existing bridges. To reduce the onsite construction time, the prefabricated bridge elements and systems (PBES) is using in the construction of bridges. The prefabricated bridge elements are constructed offsite. In preparing the prefabricated elements, the construction, reinforcement placement, concrete placement, and concrete curing are conducted offsite. In this case, the construction of bridge components is in a high control condition which leads to improving the quality, safety, and durability of bridge elements. More specific, the offsite elements construction are not weather related to cause a delay in the bridge construction and also have no or little impact on traffic flow in comparing with conventional construction methods [3].

Conventional bridge construction is an onsite construction method which is highly dependent on weather condition that makes bridge construction time-consuming. The most disadvantage of this construction method is its effect on reducing traffic flow. To provide enough location for construction, a detour or temporary structure may be needed to reduce the impact of construction on traffic flow. Also, a remote site location is needed as a supporting location for the onsite construction. In fact, the onsite construction may reduce the transportation network mobility and safety. Therefore, the ABC method is more economical and safer than conventional construction method [3].

Conventional construction methods involve onsite activities that are time consuming and weather dependent [4]. An example could be Cast-in-place (CIP) deck which increases construction times and on-site labor activities [5]. For the case of ABC any cast-in-place concrete or overlay placement operation should be performed in a manner that reduces the impacts to mobility. This may require work that is performed under “Fast Track Contracting” methods with incentive/disincentive clauses, nighttime or off-peak hour timeframes, or work done entirely off line. Innovative materials may be needed to expedite placement times such as the use of rapid-set/early-strength-gain materials or ultra-high-performance concrete (UHPC) in closure pours [4].

Moreover, with ABC technology it is common that small closure pours will be required to complete some connections.

One of the key features of precast concrete construction, when compared to cast-in-place construction is the lack of restraint during curing. Individual elements are allowed to cure in a relatively unrestrained condition. The only restraint is the friction between the elements and the forms. In cast-in-place concrete construction, the casting of fresh concrete against previously placed elements leads to a build-up of internal stresses during curing, which often leads to cracking in the concrete. The most common form of this type of cracking is transverse cracking in bridge decks caused by restraint of the girders. Prefabricated concrete elements are placed after shrinkage has occurred; therefore, the potential for shrinkage cracking is eliminated. This will have a significant impact on the long-term durability of the elements [4].

A benefit of precast concrete is that the elements are cast in an un-restrained condition. In cast-in-place construction, concrete is often placed against previously cast concrete. Precast elements and precast bridge deck panels in particular are allowed to cure and shrink in an unrestrained condition, thereby reducing, and in most cases, eliminating shrinkage cracking. The reduction in cracking eliminates one avenue for water infiltration and long-term deterioration of the concrete [4].

1.4.1. Benefits of ABC

ABC technology has strived to create an advantage over the conventional construction methods. Even though traveling public are impacted by any methods of construction, the impact is significantly reduced due to the reduced onsite construction activities from ABC methods. Furthermore, during planning stage, any potential limitation can be accounted for to avoid the inactivity and assure quick progress. The most common benefits are categorized as followed:

- Reducing disruption to traffic and avoiding congestion
- Better safety for public and workers
- Achieving higher quality control for precast elements
- Reducing life-cycle costs and maintenance
- Decreasing environmental impacts
- Better control over cost and schedule (reduce weather dependency)
- Better constructability

1.4.2. Applications:

ABC can be applied to different types of bridge projects:

- Construction of new bridge

Even though the application of ABC appears to be more reasonable for existing bridges it can also offer a variety of benefits when it comes to new construction. A significant advantage for the new bridge construction is that designers have the facility to decide from a pool of options and choose the best suitable system for execution of the project. Common applicability of ABC for new construction can refer where existing construction limitations are forced by regulatory agencies for environmentally sensitive habitats. For this case ABC can be implemented and can decrease the impact to the sensitive habitat by significantly reducing the amount of construction time.

Moreover, if the bridge is a new structure over an existing roadway, the impacts to the lower roadway may still warrant an ABC approach in order to minimize the impacts to the vehicles below [4]. ABC methods also increase the safety at work by reducing the construction time. Furthermore, weather variability will be much less of problem for construction of new bridges using ABC method when compared to conventional methods of construction.

- Repair-Rehabilitation

A common application of ABC is to reduce traffic impacts. The safety of the traveling public and the flow of the transportation network are directly impacted by on-site construction-related activities, therefore reducing construction time will provide for better safety [6]. The national bridge inventory is aging; therefore, many of the bridges in the United States have significant deterioration [4]. ABC can be used for rehabilitation projects by doing the following:

  - Deck Replacement

Conventional construction method for bridge deck is time consuming and labor intensive as it requires extensive on-site activities. For example, for concrete bridges, a temporary formwork is required to hold the reinforcement and wet concrete until a specific strength is reached. By applying ABC approaches and using prefabricated precast deck elements these limitations can be avoided. There are three main types of ABC deck replacement strategies that have been used. Two main types are: partial depth and full-depth. Both types of concrete deck panels can be manufactured off site in a casting yard, allowed to cure, and transported to the site when needed [7]. Some other examples of prefabricated deck panels are open grid deck, concrete/steel hybrid deck, fiber-reinforced polymer deck, and timber deck panels.

Another main type of ABC deck replacement strategy is by using stay-in-place deck forms. These forms consist of corrugated metal panels that are designed to support the reinforcing steel and the wet concrete of the deck. The benefit to this method of deck construction is that it eliminates the need to strip the forms after the concrete is cured. The disadvantage to this system is that it still requires the placement of reinforcing steel, casting of concrete and curing of concrete, which does not result in a significant time savings during construction. Also, future visual inspection of the underside of the deck is not possible [4].

  - Superstructure Replacement

The use of a prefabricated superstructure reduces the time it takes to construct or replace a bridge's superstructure. This provides for a faster process than using cast-in-place concrete and faster than using girders with slabs placed on top (FHWA, 2011). ABC techniques are particularly well suited for superstructure replacement projects, since the normally time-consuming process of building foundations and substructures is not required [4]. SPMT and skidding/sliding technologies can be used to removed and install entire superstructures, they can be built offsite and placed into new position in a reduced time frame. Other ways are to construct the modular bridge segments or by using a combinations of different prefabricated bridge elements.

  - Substructure Replacement

While prefabricated superstructure elements reduce overall project construction time, there are significant opportunities to reduce construction time through the use of prefabricated substructure elements and application of ABC methods. In most cases, prefabricated substructure elements are designed to emulate cast-in-place concrete [6]. Selection of the type of elements will depend on time constraints, risks and costs to the project, environmental and geometric considerations, site conditions and accessibility, design constraints, and more importantly, compatibility with the superstructure and foundation. An example is the possibility to remove old pier columns and caps and replace them with prefabricated pier elements if the footings and foundations are in sound condition and structurally adequate. Closure pours at the base of the columns can be used to connect the old footings to the new pier elements. If an existing pier is supported on a spread footing, it is possible to build the new pier alongside the existing bridge on rails and jack it into place in a similar fashion to lateral superstructure [4].

- Replacement of existing bridges

Replacements of entire bridges and construction of new bridges differs from deck replacement and superstructure replacement projects in that there is also a need to replace the substructures and foundations, and more importantly, there is normally an existing traffic crossing the existing bridge. This adds a level of complexity to the project; however, ABC methods still offer advantageous options [4]. For the case of replacing an existing bridge most of the time traffic needs to be accommodated in order to proceed with the replacing. Application of ABC can help minimize impacts to the existing traffic by either building a bridge around the traffic or creating a detour for that purpose. ABC can help in several different replacement strategies and as many construction stages may be needed for the construction it can help reduce the time duration for each. Construction site safety also improves significantly with the use of ABC methods.

1.4.3. ABC Bridge Components

ABC components can be divided into superstructure, substructure, and foundation subsystems (Figure 1.4). Superstructure refers to deck and girders and everything above the decK [4]. The substructure refers to elements that hold the superstructure like piers, abutments, and wing walls, basically, everything below the superstructure bearing and above the foundation. Foundation is a part of substructure that transfers loads from the bridge to the earth and strata, it can be shallow or deep, and includes footings, pile caps, piles, etc. An overview of ABC bridge elements are shown in Figure 1.5. Culverts and buried bridges can be categorized as bridge systems or subsystems since they normally combine superstructure with substructure (3-sided box or arch) or represent the entire structure (box culverts). The ABC bridge elements and components are connected to each other using joints and connections which normally establishes in-situ [8], [9] (Figure 1.2). A more detailed definition, classification and uses of these components for short-span bridges will be covered in Chapter II.

1.5. Short Span Classification

This report covers ABC Bridge Systems for short span Bridges. In most instances, the span length is the most significant factor in determining the form and cost of a bridge. This report subscribes to a definition of short span bridges delimited with span lengths of up to 70 ft and maximum prefabricated bridge module weight equal to 90,000 lb. [10]. This definition helps to distinguish better the limitation in selection of ABC components as well as a better explanation for the scope of work for the project. Within this range of span length, structures with span of less than 20 ft are called culverts. Culverts, many of them surrounded with soil, are normally used for allowing water to flow under the road, rail, or similar, and are designed with hydraulic considerations. There are also "buried bridges" that are short-span bridges, span of greater than 20 ft, that are constructed with the use of box or three-sided culverts and prefabricated arches and are supported and interact with the surrounding soil. The course will cover briefly the culverts and will review culverts and arch structures classified as "buried bridges." However, the emphasis in this course will be on other type of bridge using prefabricated bridge elements and systems (PBES) that cover the upper range of the spans (closer to 70 ft), and include such superstructure elements as decked girders, modular superstructure, and similar.

Moreover, the number of spans, span range and weight should be such that it allows an easy transportation of entire elements. Lighter sections make shipping and erection easier. For instance, the longitudinal gantry frame method of installation is limited to relatively short span bridges because the size of the frame needs to be more than twice the length of the modules being installed [4]. Moreover, use of lower capacity smaller cranes become possible. Single short span bridges are more common than multiple or continuous spans.

When selecting types of prefabricated elements and systems the decision will be influenced by the span length of the bridge. Therefore, certain types and configuration of prefabricated elements will be more suitable for short span, along with the corresponding construction method. A more detailed approach for the type of bridge components based on span length is introduced in Chapter II.

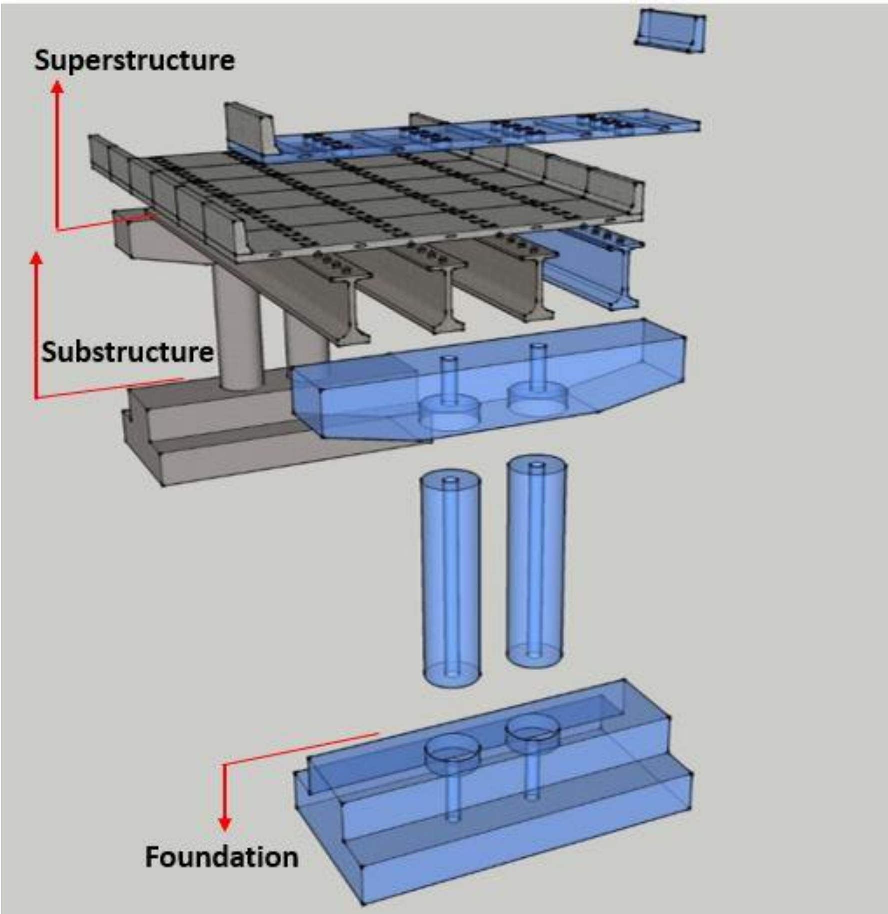


Figure 1. 4 ABC Bridge Components

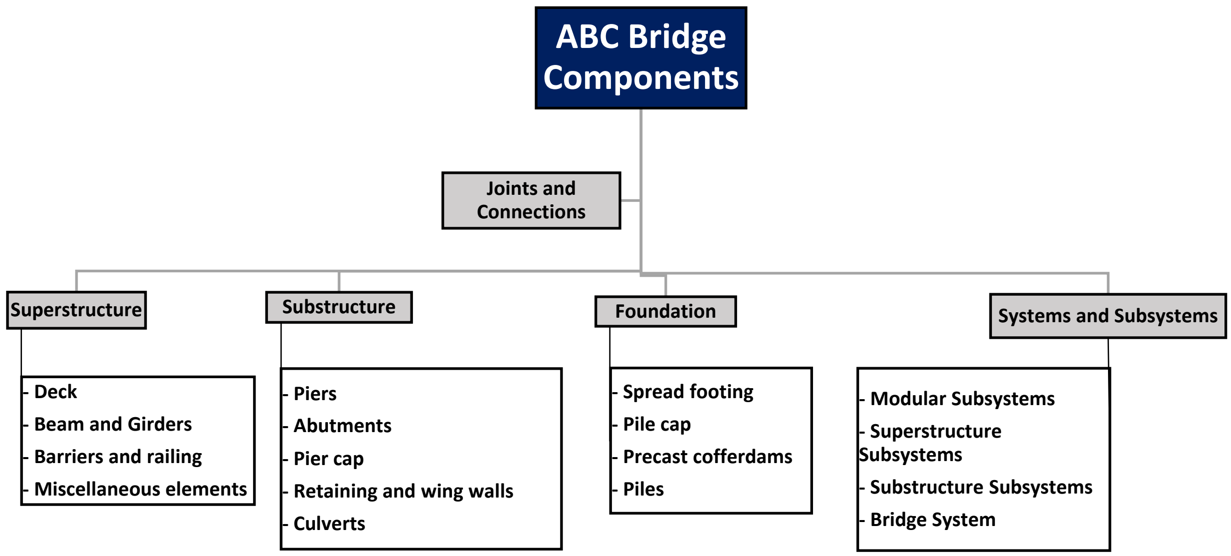


Figure 1. 5 ABC Bridge Elements

1.6. Outline of the course

It is envisioned that the course will be developed in several modules progressing from introduction and outline to various modules on specific topics. Each topic is presented here in this report as a chapter. The chapters corresponding to topics/modules are as follows:

- **Chapter 1 - Introduction to ABC for short-span bridges and Outline of the course**

This chapter, presented in the section above, introduces the motivation for the course, introduction to short-span ABC bridges and background, objectives, and breakdown and brief description of the chapters/modules of the course.

- **Chapter 2 - Types of elements and subsystems**

This report subscribes to a definition of short span bridges delimited with span lengths up to 70 ft and maximum prefabricated bridge module weight equal to 90,000 lb. [10].

Availability of different element types and subsystems are limitless, each fitting certain purpose and objective mostly dependent upon the construction method to be used for bridge erection. In addition to parameters influencing selection of the construction methods, e.g.; availability of space, accessibility, roadway functional category, and condition under the bridge, factors such as time constraint, risk and cost, environmental considerations, design constraint and compatibility among superstructure, substructure and foundation as well as availability will determine the type of elements and subsystems to be used for construction of an ABC bridge. This chapter will introduce and discuss the available elements and subsystems for short-span ABC bridges.

- **Chapter 3 - Joints and connections**

This chapter will deal with identifying the type of joints and connections between the superstructure, substructure, and foundation, and between their prefabricated elements as it applies to short-span bridges. Regardless of the type of prefabricated elements to be used in construction of ABC bridges, the elements, systems and subsystems need to be made integral with the use of joints and connections established in situ. ABC connections and joints play an important role and their application and limitations need to be understood. To effectively design a bridge system that resists design loads the components must be connected successfully. These connections are expected to perform equally to a conventional connection as they are planned to be emulative. Commonly, Ultra-High-Performance Concrete (UHPC), Self-consolidating Concrete (SCC), and other high- and normal-strength, fast-setting, early strength concrete mixes are used within the joints to accelerate the casting and curing process, and to decrease the potential defects. However, precautionary measures should be taken to minimize maintenance problems and improve durability.

- **Chapter 4 - Construction methods**

Main benefit of application of ABC technologies is to have the possibility of prefabricating the elements and systems of the bridge under controlled weather conditions and to install them onsite in less time that conventional construction.

In order for taking advantage of this method, the use of innovative structural placement and construction methods should be considered for all ABC bridge projects. Using any of the construction methods, the elements or systems could be moved in minutes or hours which will implicitly lessen the traffic disruption, increase work safety, constructability and improve contractor options to move new prefabricated bridges into position.

This is considered an important feature of ABC as using innovative structural placement and construction methods will improve safety, quality, and reduce the construction time. In this chapter construction methods applicable to short span bridges will be discussed.

- **Chapter 5 - Inspection and performance**

Prefabricated elements and systems are expected to have better quality and performance due to their construction in controlled environment and under stricter quality control than cast-in-place elements. Therefore, most performance issues in relation with ABC bridges will focus on the joints and connections that are established in situ. Cast-in-place joints may introduce a potential for weak link within Accelerated Bridge Construction (ABC) structures. The quality of the joints, expected to become serviceable quickly, depends on the concrete mix design, reinforcement and enclosure details, and is influenced by placement and curing procedure [11]. Despite the efforts to prevent weaknesses in these critical elements, potential exists that defects or anomalies are left in the joints during construction or develop later during the life of the structure [11].

In this module, a review of performance of ABC short-span bridges with an emphasis on joints will be carried out. Moreover, information on performance of general ABC construction and summary of deterioration patterns will be discussed. Additionally, inspection methods and means applicable to ABC short-span bridges will be explored. Based on the reported surveys, most of these problems have been observed in the connections between deck panels and between deck panels and piers or abutments. Therefore, inspection and performance evaluation of joints, particularly closure joints, should be emphasized for short-span bridges.

- **Chapter 6 - Decision making process**

Decision-making on the use of ABC in general and the type of elements, systems and construction methods in specific is essential for an effective project initiation, management and contractual aspects.

After a decision has been made to use ABC in construction of a new bridge or replacement/rehabilitation of an existing bridge, a decision as to what ABC technology is appropriate for a site need to be taken. Several ABC technologies can be found to be appropriate at a site. This will mean that the project planners need to decide which technique fit better into particular project for which multiple methods are identified. Moreover, further investigation for each option and major contributing factors will affect in the final decision. In some cases, however, one method of ABC will stand up as the most appropriate for a project site which will make the decision-making process easier.

This module will introduce available decision-making methods applicable to ABC short-span bridges. This will include decisions on the use of ABC as an alternative to conventional method, selection of construction method most applicable, and determination of type of elements and subsystems, as well as selection of the type of inspection required.

- **Chapter 7 - New developments**

For this module new and ongoing developments that can affect the future of Accelerated Bridge Construction will be discussed with a focus on short-span bridges.

CHAPTER 2. TYPES OF ELEMENTS AND SUBSYSTEMS

2.1 Abstract

As the choice of bridge structure is affected by many contextual factors it is important to provide a proper guidance to designers and bridge owners on the selection of type of elements and subsystems. Accordingly, it is essential to make available to the users all element types, subsystems and systems for a short-span ABC bridge. Identifying the components and defining clearly their advantages, applications and limitations will help the selection.

Often, the span length is the most significant factor in determining the type, design and details of a bridge. Traditionally, structures crossing span length of less than 20 ft have been called culverts that are often used for hydraulic crossings. This report subscribes to a definition of short span bridges delimited with span lengths up to 70 ft and maximum prefabricated bridge module weight equal to 90,000 lb. [12]. Hence, information of available components shall first consider their use for the range of span length identified.

Many element types and subsystems are available, each fitting certain purpose and objective mostly dependent upon the construction method to be used for the bridge erection. In addition to parameters influencing selection of the construction methods, e.g.; availability of space, accessibility, roadway functional category, and condition under the bridge, factors such as time constraint, risk and cost, environmental considerations, design constraint and compatibility among superstructure, substructure and foundation as well as availability will determine the type of elements and subsystems to be used for construction of an ABC bridge.

As an alternative to traditional bridges, buried bridges can sometime offer economic solution, especially for hydraulic and minor road crossings. A buried bridge is a buried structure supporting a roadway that relies on the support from the soil-structure-interaction. The design and installation of buried bridges have evolved over the years to accommodate longer spans inclusive of the range for short-span bridges. Since major segments, sometimes the entire superstructure and substructure, are prefabricated away from site and installed in place, they certainly qualify as ABC bridges.

This chapter identifies elements, subsystems and systems available for the use in short-span ABC bridges and includes information for facilitating their selection for a specific bridge project. The process of decision making is the subject of a later chapter. This chapter includes both PBES for traditional bridges and buried bridges alternatives. For completeness, culverts are also reviewed briefly.

2.2 Prefabricated Bridge Elements and Systems (PBES) for Conventional Bridges

Prefabricated bridge elements and systems (PBES) are structural components of a bridge that are built either off-site or adjacent to the site, in a manner to reduce the on-site construction time and mobility impact that can adversely affect the traveling public. Because of their versatility, PBES can be used to address many common site and constructability issues. Use of PBES has demonstrated proven benefits to agency owners, contractors, and the traveling public [10].

2.2.1 Elements:

Prefabricated elements consist of a single structural component of a bridge and are one category in PBES. Their use reduces the onsite construction time that is needed to build a similar structural component using conventional construction methods. An element is typically built in a prefabrication shop and in a repeatable manner to reduce the costs. Because of a controlled environment in the prefabrication plant, the influence of weather-related impacts can be eliminated and improvements in quality and durability can be better accomplished [13].

2.2.2 Systems:

Prefabricated Systems are another category for PBES that comprise of an entire superstructure, superstructure and substructure, or a total bridge that is built in a modular manner such to allow traffic operations to resume after placement. Prefabricated systems can be rolled, launched, slid, lifted, or otherwise transported into place, having the deck and preferably the parapets in place such that minimal construction phase is required after placement [13].

2.2.2.1 Superstructure Systems

Superstructure Systems include deck and primary supporting members integrated. In this case, mobility disruptions occur only during placement. These systems are normally rolled, launched, slid, lifted, or transported in place, onto existing or new substructures (abutments and/or piers) [13].

2.2.2.2 Superstructure/Substructure Systems

Superstructure/Substructure Systems may include the interior piers or abutments, and are normally slid, lifted, or transported into place onto new or existing substructures [13].

2.2.2.3 Total Bridge Systems

Total Bridge Systems include the entire superstructure and substructures (both abutments and piers) that are made integral. Total bridge systems typically require unique designs, high-performance materials, and well-designed placement methods [13].

2.2.3 Superstructure Elements and Systems

The superstructure refers to all parts above the bridge bearing and provide horizontal span and rideable surface. These elements carry loads from the deck span and provide the riding surface [9]. Superstructure includes girder and deck slab, miscellaneous elements, barriers, and railing.

2.2.3.1 Deck Panels

The deck elements contain road lanes, walkway, and sideways. The conventional construction method requires deck forming and curing of concrete. This method can provide a smooth riding surface. However, this type of bridge deck construction is quite time-consuming. Therefore, the prefabrication of deck elements can significantly reduce the bridge construction time. The deck panel systems consist full-depth precast concrete deck, partial-depth precast concrete deck, open grid deck, concrete/steel hybrid deck, fiber reinforced polymer (FRP) deck, and timber deck panel. (**Error! Reference source not found.**) summarizes different prefabricated deck systems and their installation times according to the Florida Department of Transportation [7]. Alternatives to the full and partial-depth concrete deck panel systems, i.e., open grid panels, fiber reinforced polymer (FRP) panel, timber deck, and steel/concrete hybrid deck panel systems are lightweight and can facilitate the shipping of the panels and are appropriate for moveable bridges. **Error! Reference source not found.** describes some deck panel systems as alternative to concrete deck panels that can be applicable to short span bridges alternative to the full-depth or partial-depth concrete deck panels.

Table 2. 1 Types of ABC deck panel systems alternative to concrete deck panels

Deck Panel Systems	Description
Prefabricated Timber installed as adjacent-deck-slab	Timber deck panels have been used as installed as adjacent-deck-slab superstructure for short span bridges.
Orthotropic Steel Deck Bridge	Orthotropic construction has tremendous potential for use in short- to medium-span girder bridges.
Aluminum Orthotropic Decks	The use of aluminum provides a corrosion resistance advantage that can result in lower maintenance costs, as it does not need periodic painting.
Fiber Reinforced Polymer (FRP) Bridge Decks	FRP decks have been used for short-span bridges and for deck replacement on bridges. The principal advantages of FRP as a material are that it does not corrode under the same conditions as steel materials and it is lightweight.

2.2.3.1.1 Concrete Deck Panels

Cast-in-place concrete decks that use stay-in-place forms can also be categorized within the ABC methods because it reduces the construction time by eliminating time for form removal and, depending on the form support type, reduces the need for scaffolding and form installation.

Table 2. 2 Prefabricated Deck panel systems [7].

Deck panel system	Installation time (days/span)
Full-depth precast concrete deck panel	2
Partial-depth precast concrete deck panel	7
Open grid deck panel	1
Concrete/steel hybrid deck panel	2
FRP deck panel	2
Timber deck panel	1

In full-depth precast deck panel application, the construction time of the bridge reduces more significantly [13] than the partial-deck or stay-in-place forms (Figure 2.1). In this case, however, the shipping of panels may introduce issues that can be addressed by constructing the panels near the bridge site., Restressing or post-tensioning may be needed in the full-depth deck construction. The deck panels are designed as one-way slabs, and longitudinal post-tensioned bars may be used to integrate them. Also, blockout connections are used to attach the beam to the deck panel. Application of the blockouts is for establishing composite action between slab and girders [13].

The partial-depth precast concrete panels that are also used as "concrete framework" have 3.5 to 4-inches thickness. After placement of the partial deck panels on the top of the beams, a layer of concrete is cast on top of the panels to build the full depth of the deck [14].

2.2.3.1.2 Open Grid Decks

In open grid decks, the grid is filled partially with concrete (Figure 2.2). However, there is a concern about the durability of this system [7].

2.2.3.1.3 Prefabricated Timber

Prefabricated timber beams and panels are normally fabricated using glue laminating process that involves gluing nominal dimension lumber side-by-side to create a solid panel. The elements are normally pressure treated before being laminated together, or pressure treatment can be applied after fabrication. The glue used for bridge application should be water proof [13]. In timber deck systems, bolting or post-tensioning is used to connect the glue-laminated deck panels to each other and provide deck span (Figure 2.3). Most timber bridges are used on low volume roadways, but they could be applicable to higher volume roads too [13]. Figure 2.3 shows an example of timber deck panels.

Timber deck panels have been used in two ways:

• Installed on top of beams (glue laminated wood beams or steel beams) by the way of installing laminated timber decks on top of timber or steel beams. The panels span transversely from beam to beam [13].

• Installed as adjacent-deck-slab superstructure for short span bridges by the way of laying laminated deck spans comprised of adjacent timber elements side to form a solid panel. They can be used to span the entire length of the bridge [13].

The design of some of the deck systems described here is covered in AASHTO LRFD structural specification [6].

2.2.3.1.4 Hybrid Decks

Hybrid decks can be made of partially filled grid decks or exodermic decks. In the former, the upper portion of the steel grid is filled with concrete (Figure 2.4).

2.2.3.1.5 Exodermic Decks

These are similar to steel grid, but the concrete is placed over the grid with a connection of concrete to the steel grid that is similar to a full-depth precast concrete deck.

Figure 2. 1 Lightweight precast deck panel [13].

Figure 2. 2 Open grid deck panel [13].

Figure 2. 3 Timber deck panels [7].

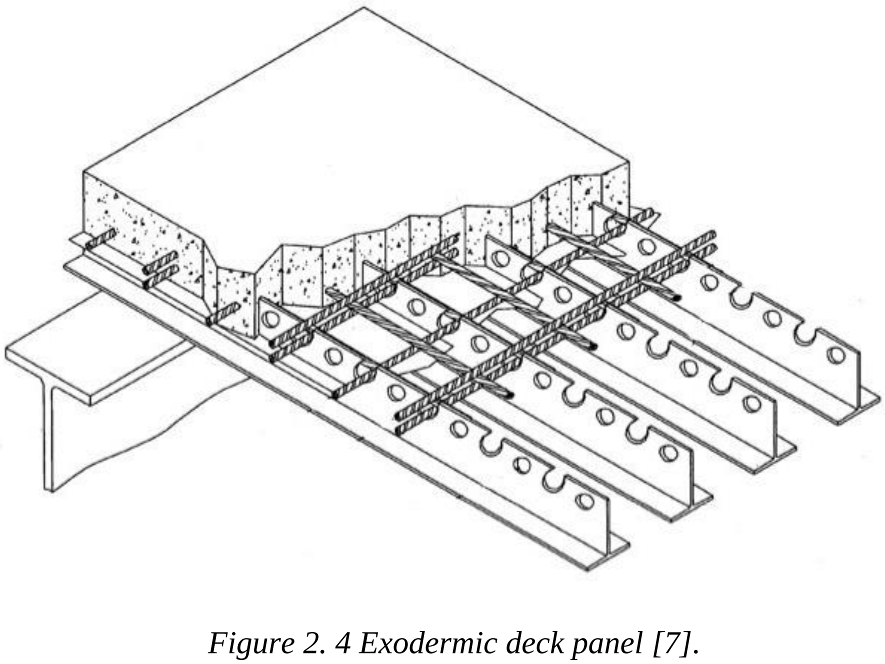


Figure 2. 4 Exodermic deck panel [7].

2.2.3.1.6 Steel Orthotropic Decks

Orthotropic steel plate can be utilized for distribution of deck traffic loads and for stiffening the supporting slender plate elements in compression. This system (Figure 2.5) consists generally of a flat, thin steel plate, stiffened by a series of closely-spaced longitudinal ribs at right angles or orthogonal to intermediate floor beams, and are typically made integral with the supporting bridge superstructure as a common top flange to beams and girders. This results in cost savings in the deck structure. The orthotropic steel bridge normally results in a nearly all-steel superstructure [15].

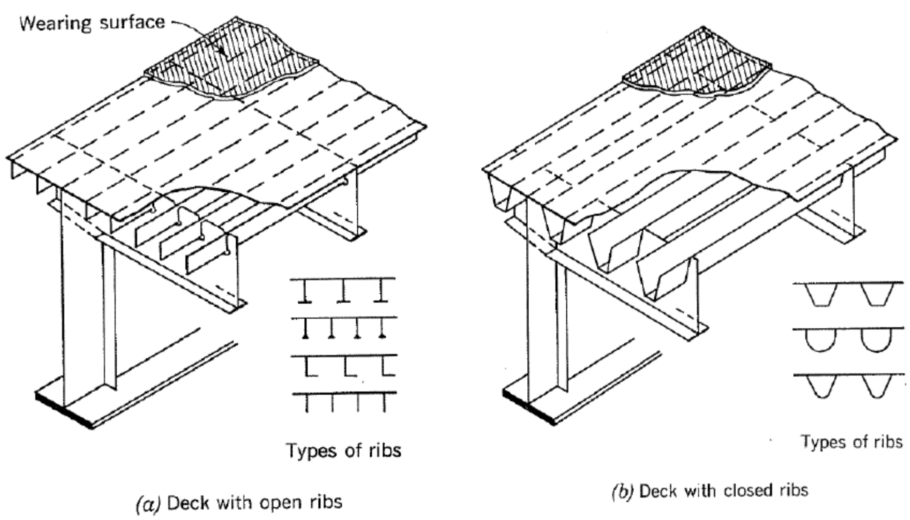


Figure 2. 5 Orthotropic Steel Deck Bridge [15].

Orthotropic construction has good potential for use in short- to medium-span girder bridges. Although the system has not been used more extensively for economic reasons, its light weight makes becomes beneficial for improving load rating during a deck replacement and for instances where replacement of the bridge may have been the only other alternative [15]. Orthotropic steel deck systems have been known to include details that are sensitive to fatigue damages.

2.2.3.1.7 Aluminum Orthotropic Decks

The aluminum orthotropic deck system (Figure 2.6) configuration is similar to the steel orthotropic deck described above, where the use of aluminum instead of steel provides a corrosion resistance advantage resulting in lower maintenance costs since it does not need periodic painting. The additional cost associated with aluminum has often deterred its use in the United States. Other factors to consider include differences in thermal expansion coefficients, reactions with dissimilar materials, lower modulus of elasticity and lower fatigue strength of the material, and difference in welding processes and characteristics [15].

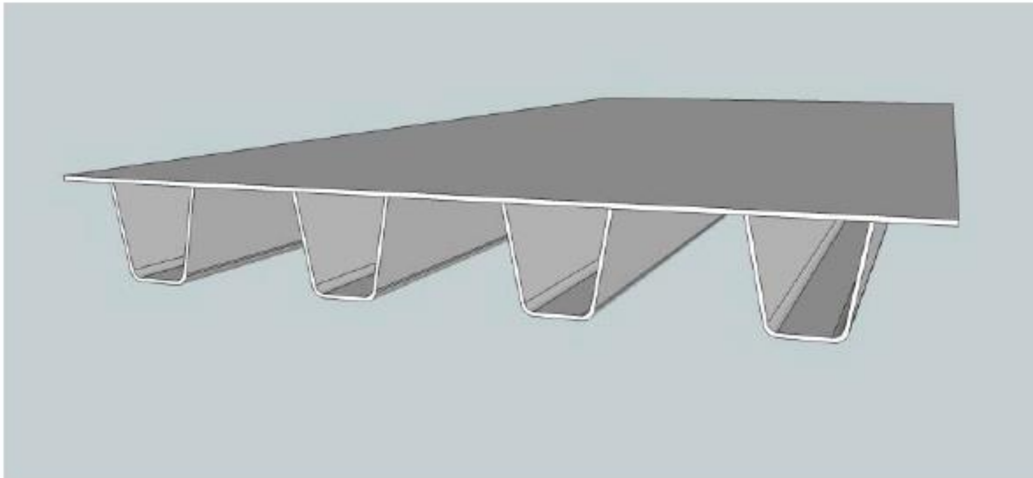


Figure 2. 6 Orthotropic deck [13].

2.2.3.1.8 Fiber Reinforced Polymer (FRP) Bridge Decks

Fiber reinforced polymer (FRP) bridge decks and superstructure systems present newer technology. FRP which can be constructed using different types of fibers (Figure 2.7) [7]. FRP decks have been used successfully for short-span bridges and for deck replacement. The principal advantages of FRP are resistance to corrosion under the same conditions as steel materials and its light weight. Its potential has shown promise for deck replacement (Figure 2.8), especially if total load capacity is relatively low [15].

Figure 2. 7 FRP deck panel [7].

Figure 2. 8 FRP bridge deck and superstructure applications (Aboutaha 2001) [15].

2.2.3.2 Girders:

The girders carry the slab loads and transfer loads to the substructure and foundation. The term girder sometimes is used interchangeably with beam. Girders can be constructed from different materials, most commonly from steel or concrete.

Steel girders are configured in different shapes (Figure 2.9). Their main advantage is in their light weight that is advantageous for shipping when compared to concrete. The long-term maintenance and corrosion resistance of steel girders can however be an issue. To address corrosion issue, weathering steel girders introduce that require no painting and therefore less maintenance [13]. The steel beam pre-topped with concrete slab can be used as modular superstructure for replacement and construction of superstructure.

Precast prestressed concrete beam is another type of girder element. The AASHTO and precast/prestressed concrete institute (PCI) have developed standardized precast girders shape [16]. These girders include I-beam, U-beam, Single and Double-tee beam, rectangular beam, voided slab beam, and box-shape beam (Figure 2.10). Among others, the box girders and decked girders are the two shapes of girders commonly used in the ABC bridge construction [13].

Figure 2. 9 Steel girder [17].

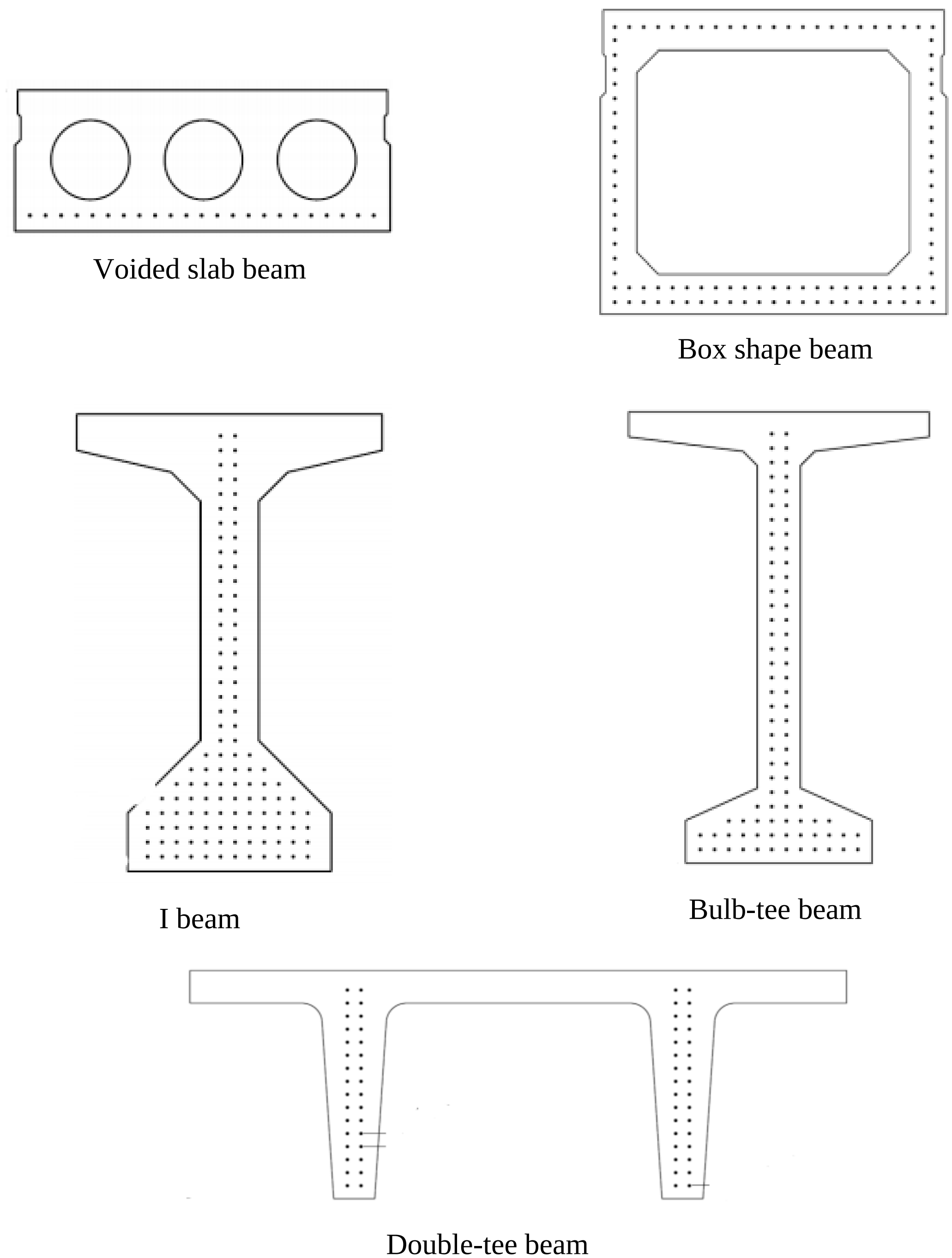


Figure 2. 10 Different shape of precast girders [16].

Table 2. 3 Summarizes different types of girders with potential for use in ABC short span bridges. For completeness we included the result to up to 100 ft.

Girders	Description	Span Length (Feet)							
		30	40	50	60	70	80	90	100
Decked Slab Girder (DS)	The decked slab girder is a very shallow section suitable for short spans. These girders are simple to fabricate and are well-suited to GRS-IBS systems.	■	■	■	■				
Decked U Girder (DU)	The decked U-girder is a shallow and efficient structure suitable for short- to medium-length spans up to 144 feet.	■	■	■	■	■	■	■	■
Rolled beam using W-shapes	W-shapes are used in shorter spans up to about 100 ft for simple spans and up to about 120 ft for continuous spans.	■	■	■	■	■	■	■	■
Steel Folded Plate	The beams are made of a single folded steel plate. This system could be very useful for short span bridges.	■	■	■	■				
Inverted-T Precast Slab	Inverted-T precast slab, which also provides a platform for the construction and formwork for the cast-in-place concrete deck, is suitable for short-span bridges with under clearance issues.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Box Beams	Box beams, distinguished by a square or rectangular shape, usually have a beam depth greater than 17 inches. Box beams can be adjacent or spread, athey are typically used for short and medium span bridges.	■	■	■	■	■	■	■	■
Prestressed concrete single-cell and multi-cell box beams	Prestressed concrete single-cell and multi-cell box-beams, which are used in the side-by-side box-beam bridge, are one of the first-generation prefabricated girders used in short-span (20 ft to 60 ft) bridges.	■	■	■	■				
Double Tee Beams	Standard double-tee sections require a cast-in-place concrete deck. Hence, the use of these girders is limited to short-span bridges with low-traffic volume.		■	■	■	■	■	■	
Bulb-tee Beams	Bulb-tee beams are distinguished by their "T" shapes, with a bulb-shaped section (similar to the bottom flange of an I-beam) at the bottom of the vertical leg of the tee. This type of beam can be used for spans as long as 200 feet	■	■	■	■	■	■	■	■
Next F Beam	The NEXT F beam system requires an 8 in. thick cast-in-place concrete deck on the typical 4.5 in. thick flange. Both the NEXT F and D beams are suitable for short and up to short-to-medium span bridges with a cast-in-place deck	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
The next D beam	The NEXT D beam is intended for use on short-span bridges on low-volume roads where there is not a durability concern with the longitudinal joint.	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Channel Beams	This particular shape can be precast or cast-in-place. Channel beams are formed in the shape of a "C" and placed legs down when erected. They function as both superstructure and deck and are typically sed for shorter span bridges	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
I-Beams	I-beams, distinguished by their "I" shape, function as superstructure members and support the deck. This type of beam can be used for spans as long as 150 feet.	■	■	■	■	■	■	■	■
Voided Slabs	Voided slabs, distinguished by their rectangular shape and their interior voids, are generally precast units supported by the substructure. The interior voids are used to reduce the dead load. Voided slabs can be used for spans up to 60 feet.	■	■	■	■				
Trapezoidal box (closed)	The trapezoidal box girder was developed for bridges up to short-to-medium spans. Trapezoidal box (totally closed) spans up to 95 ft	■	■	■	■	■	■	■	■
Trapezoidal box (open)	The trapezoidal box girder was developed for bridges up to short-to-medium spans. Trapezoidal box (open top) spans up to 86 ft	■	■	■	■	■	■	■	
Modular Steel Folded Girder	This consists of modular steel inverted tub girder elements topped with a precast concrete deck. The beams are made of a single folded steel plate. This system could be very useful for short span bridges.	■	■	■	■				
Modular Steel Deck Beams with an Integral Concrete Deck	The modular superstructure elements and systems, except the segmental box-beam section, are suitable for short-span bridges (i.e., 20 ft to 60 ft).	■	■	■	■				

2.2.3.2.1 Decked slab girder (DS)

A variety of decked slab girders have been developed. For example, the Colorado Department of Transportation (CDOT) has developed a decked slab girder with a very shallow section suitable for short spans. These girders are simple to fabricate and are well-suited to GRS-IBS (Geosynthetic Reinforced Soil-Integrated System) systems. The girder lengths are limited by factors such as ultimate strength of concrete and deflection under service load. When compared to deeper girder types, these girders may be expensive to construct due to the volume of materials required for the deeper spans. Simple spans up to 56 feet are feasible. Longer non-standard spans become feasible if the stiffness contribution of rails is accounted for [18]. Figure 2.11 shows the decked slab girder for the 15-foot width.

Figure 2. 11 Decked slab girder [18].

2.2.3.2.2 Decked U-girder (DU)

Decked U-girder is another type of girder the Colorado Department of Transportation (CDOT) has developed with a shallow that offers an efficient structure suitable for short- to medium-length spans of up to 144 feet (Figure 2.12). Their standard section has 5-inch thick web. A thicker 7 1/2-inch web is used when increasing shear capacity for longer spans or shallow sections is required [18]. The useable span length is limited by section weight. More efficiency if provided by this system for span lengths from 30 feet to 96 feet. Fabrication of this system is likely to be more labor intensive and time consuming than the other recommended types [18].

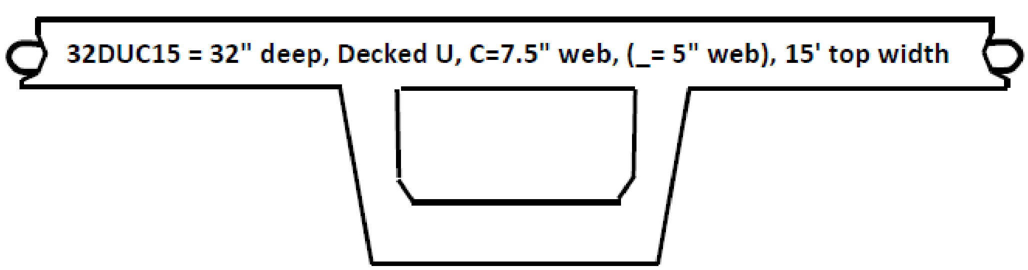


Figure 2. 12 A sample decked U girder: top widths 15 feet 0 inch, 9 feet 10 inches, or 7 feet 3 inches [18].

2.2.3.2.3 Precast slab/deck beams

Other states also have their standards for Precast slab/deck beams. These are defined as adjacent slab beam bridges, a common superstructure type for short-span bridges applicable to 30- to 60-ft span lengths. Alabama's prestressed slab units is one example which uses post-tensioning after the beams are placed side by side. Another example is Florida Department of Transportation's (FDOT's) Prestressed Slab Units (PSUs) that are joined with longitudinal shear keys and require no post-tensioning and [7]. The Florida Slab Beam (FSB) initially were limited to off-system bridges with low average daily traffic (ADT) and low average daily truck traffic (ADTT). Three FSB section depths are currently available (12, 15, and 18 inches) for spans ranging from 30 feet to 60 feet [5]. Typical Florida Slab Beam (FSB) section details are shown in Figure 2.13

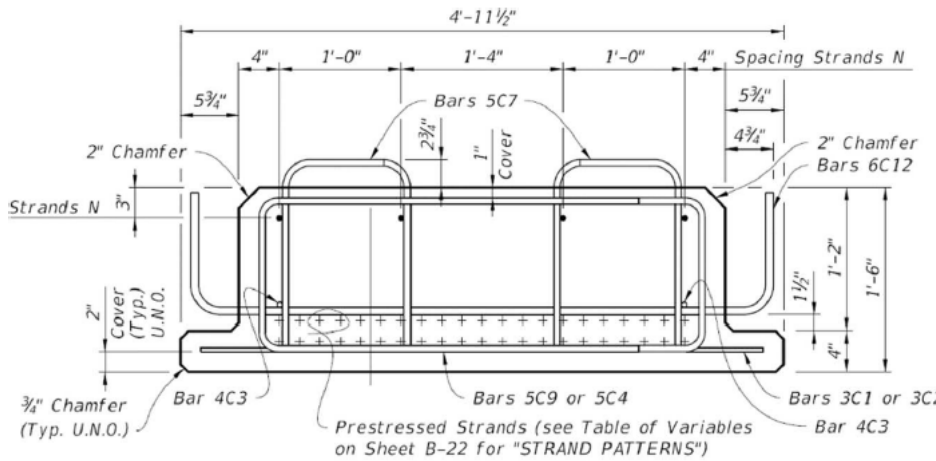


Figure 2. 13 Typical Florida Slab Beam (FSB) Section [5].

2.2.3.2.4 Rolled Beam using W-shapes

Currently, composite multi-girder subsystems, plate girders or tub girders, that use rolled beams are the most common steel bridge superstructures (Figure 2.14). These systems can be single or multi span, straight or curved, or can also be skewed. For shorter spans up to about 100 ft. for simple spans and up to about 120 ft. for continuous spans, rolled beam superstructures using W-shapes can be utilized [15].

Figure 2. 14 Axtel UT rolled-beam bridge (https://www.shortspansteelbridges.org/gallery/images/rolled-beam-bridge)

2.2.3.2.5 Inverted-T Precast Slab

Inverted-T precast slab (Figure 2.15) that provides a formwork for the cast-in-place concrete deck, is also suitable for short-span bridges where there are clearance issues. Additional time required to place and cure the cast-in-place concrete deck can be seen as an issue with this system. Reflective deck cracking is also a concern similar to that observed for adjacent box-beam bridge decks [9].

Figure 2. 15 Inverted-tee Beams (www.fhwa.dot.gov/bridge/prefab/slab.cfm) [7].

Decked bulb tee is another standardized section from the inverted-tee family that is intended to behave like a series of adjacent box beams, while attempting to avoid the difficulties associated with precasting voided sections and issues with the inspection. The adjacent box beam and pre-topped inverted tee systems are compared in Figure 2.16 [5].

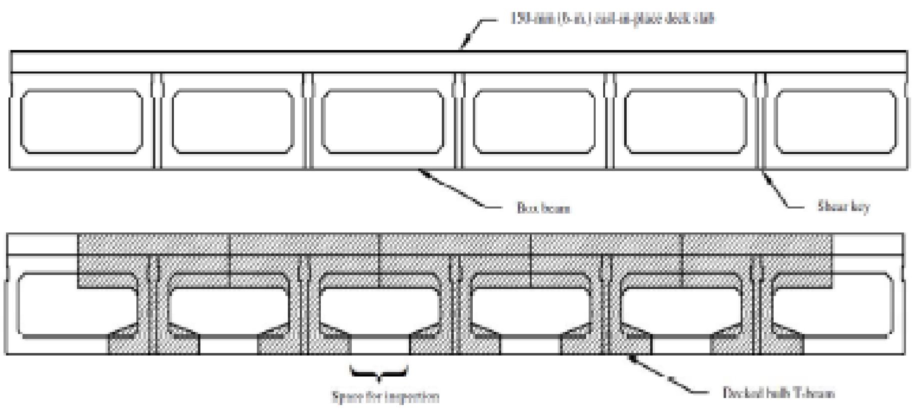


Figure 2. 16 Decked bulb-tee shape compared to adjacent box beam configuration Grace et al [5].

2.2.3.2.6 Box Beam

Box beams with either a square or rectangular shape, usually come with depth greater than 17 inches. They can be arranged as adjacent or spread, used typically for short and medium span bridges. Adjacent box beams have practical span lengths that range 40 to 130 feet and spread box beams have practical span lengths that range up to 130 feet [1].

State of Texas has developed a set of standards for prefabricated prestressed concrete box beam that are appropriate for off-system bridges. They are placed adjacent to each other to achieve the desired roadway width [7]. Figure 2.17 shows an example of Texas Adjacent Box Beam

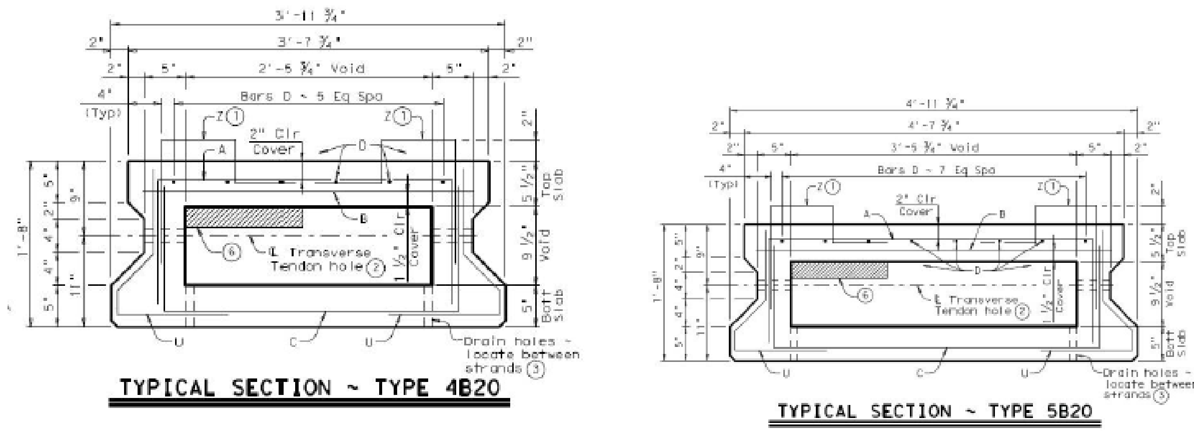


Figure 2. 17 Texas Adjacent Box Beam [7].

One of the disadvantages attributed to this system is the longitudinal joints between the boxes where leakage and durability becomes a concern. To address these issues, post-tensioning can be used to connect the boxes transversely and provide compression across the joints [7]. However, it has been shown that reflective cracking can develop even under post-tensioning [9]. Adjacent box beams (Figure 2.18 a) have practical span lengths in the range from 40 to 130 feet, where spread box beams (Figure 2.18 b) have practical span lengths that ranges up to 130 feet [1].

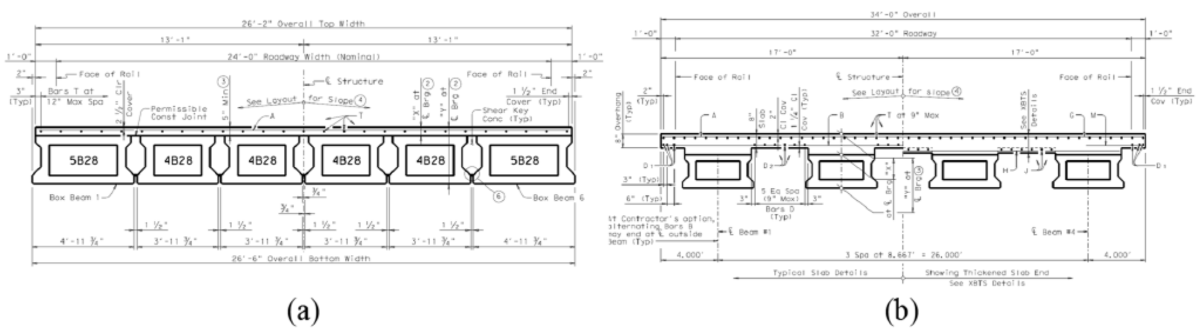


Figure 2. 18 Traditional (a) adjacent and (b) spread configuration for 28-inch depth box beams [19].

2.2.3.2.7 Double-Tee and Decked Bulb-Tee Girders

The standard double-tee girder system (Figure 2.19), originally developed for building and parking structure, has been available for a long time (PCI committee 1983). The limiting factor in the prestressed girder design is the web thickness. Further, due to limited flange thickness, developing a moment connection detail at the flange with two layers of reinforcement has been difficult. Standard double-tee sections require a cast-in-place concrete deck. The use of these girders is limited to short-span bridges with low-traffic volume (Bergeron et al. 2005; Chung et al. 2008; Li 2010) [7].

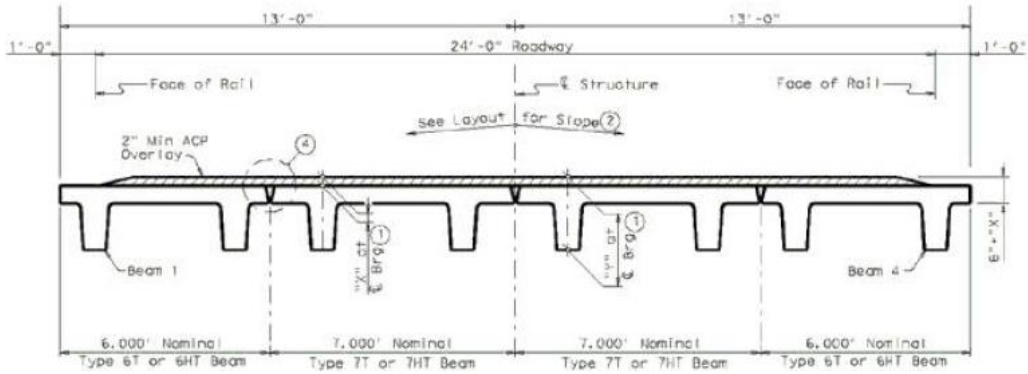


Figure 2. 19 Double-tee Bridge Profile Typical Transverse Section [9].

Decked bulb-tee sections (Figure 2.20) were developed (Shah et al. 2006; PCI 2011) to address the limitations of double-tee system. Larger web thickness of decked bulb-tee sections accommodates post-tensioning to develop continuity details over the supports. This system is suitable for short-to-medium span bridges. As for any other system, durability performance is a concern. The increased flange thickness of the decked bulb-tee section is also suitable for developing durable flexure-shear transfer connection details (Graybeal 2010a; UDOT 2010b; CPMP 2011; Culmo 2011) [7].

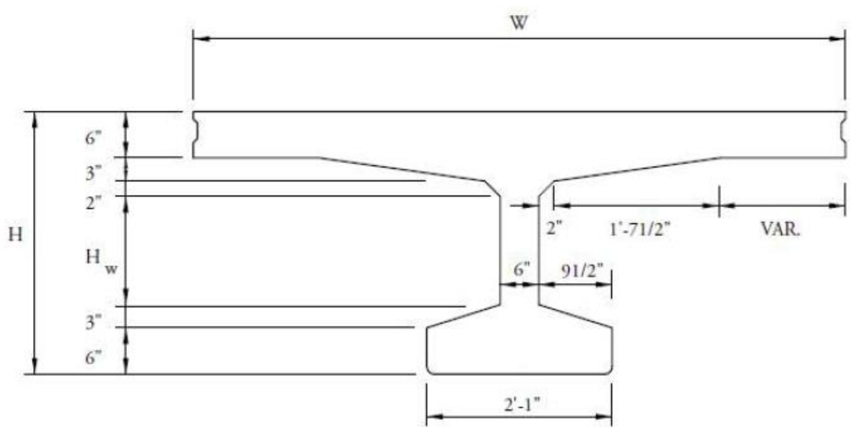


Figure 2. 20 Decked Bulb-tee Cross Section [9].

Bulb-tee beams can be distinguished by their "T" shapes, with a bulb-shaped section (similar to the bottom flange of an I-beam) at the bottom of the vertical leg of the tee. This girder-deck system can be used for spans as long as 200 feet [1].

2.2.3.2.8 NEXT F Beam

The NEXT F beam system requires an 8 in. thick cast-in-place concrete deck on the typical 4.5 in. thick flange. As with any prefabricated system, joint durability is a concern. However, durability may improve by the use of flexure-shear transfer connections [9].

2.2.3.2.9 NEXT D Beam

The NEXT D beam (Figure 2.21) is appropriate for use in short-span bridges on low-volume roads where there is a less durability concern with the longitudinal joint. Because the top flange is intended to act as a structural deck, a closure pour between members is require as the longitudinal connection in the form of a shear key and headed reinforcing bars that extend from the flanges. To contain the concrete for the closure pour, removable formwork has to be used, and it has to also accommodate differential camber of the beams. The parapets have to be either precast onto the beam during fabrication or must be cast-in-place on site after installation because the top flange is being used as a riding surface. The use of lightweight concrete on the full-depth, top flange section can significantly reduce the self-weight of the beam, and thus reducing the shipping costs [7]. Both the NEXT F and D beams are suitable for short and up to short-to-medium span bridges with a cast-in-place deck.

These beams are available in four different depths (28-inch, 32-inch, 36-inch, and 40-inch), two different widths (96-inch and 120-inch) and are recommended for spans between 20 feet and 80 feet. Because it is a standardized bridge girder, Precast/Prestressed Concrete Institute Northeast (PCINE) has predesigned sections depending on the span length for each beam group, as shown in Figure 2.22 [5].

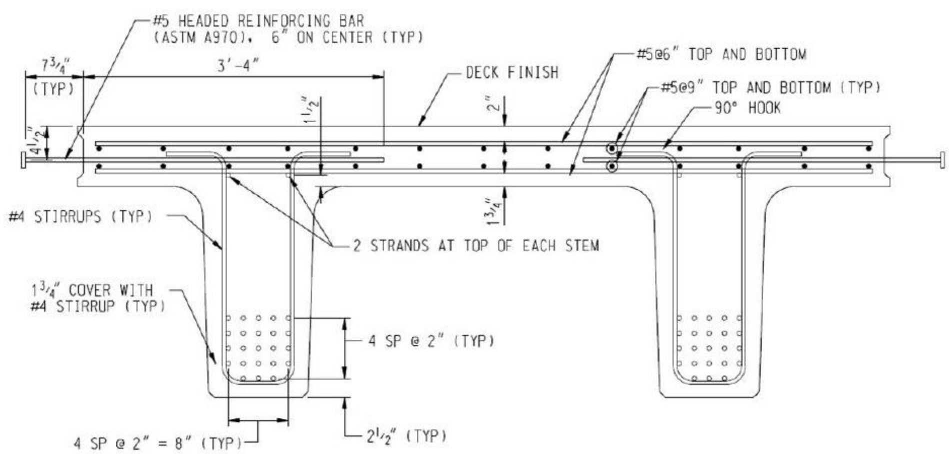


Figure 2. 21 Full-depth Top Flange NEXT Beam [7].

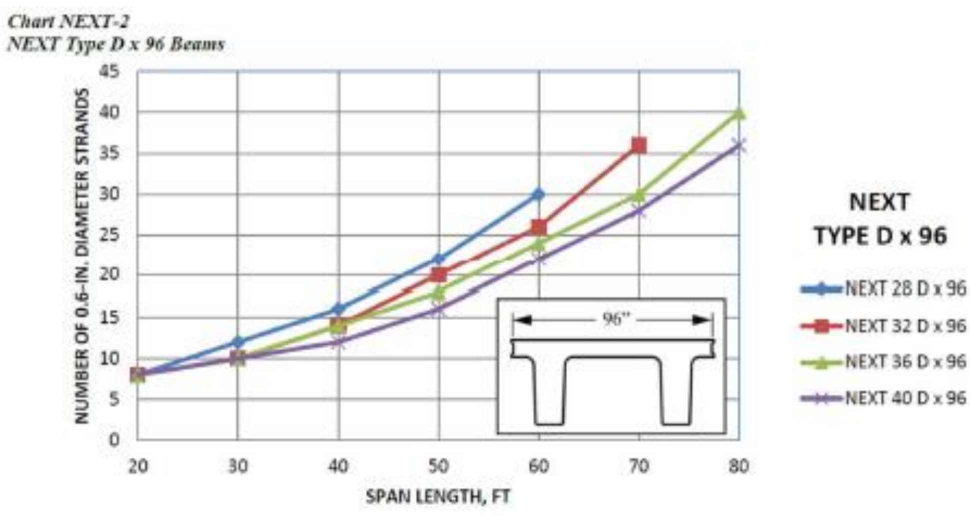


Figure 2. 22 NEXT D beam span lengths [5].

2.2.3.2.10 Channel beams

Channel beams can be precast or cast-in-place. These (Figure 2.23) are formed in the shape of a "C" and placed legs down when erected. They function as both superstructure and deck and are typically used for shorter span bridges [1].

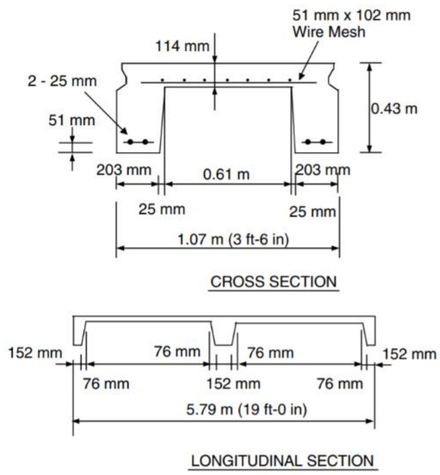


Figure 2. 23 Precast channel beam cross section and longitudinal section [20].

2.2.3.2.11 I-beams

Distinguished by their "I" shape, I-beams function as superstructure members and support the deck. This type of beam can be used for spans as long as 150 feet [1]. Figure 2.9 has an example of I beams.

2.2.3.2.12 Voided slabs

Distinguished by their rectangular shape and their interior voids, voided slabs (Figure 2.24), are generally precast units supported by the substructure. The interior voids are used to reduce the dead load. Voided slabs can be used for spans up to 60 feet [1].

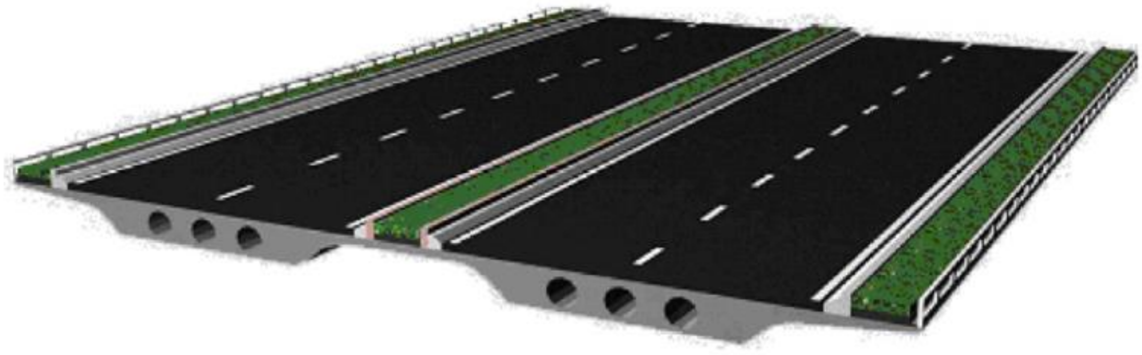


Figure 2. 24 Voided Slab Bridge Deck (https://www.sciencedirect.com/science/article/pii/S0965997810000505)

2.2.3.2.13 Trapezoidal Box Girder

This system was developed in 1998 for bridges up to short-to-medium spans. The girder was developed in two cross-sections: (1) a closed trapezoidal box and (2) an open section requiring a cast-in-place concrete deck.

Considering the difficulty in the casting of a closed trapezoidal box section, an open-top is preferred (Badie et al. 1999). The features of an open-top trapezoidal box girder are shown in (Table 2.4). Based on the data currently available, this section has not been specified for any project [9].

Table 2. 4 Attributes of Trapezoidal Box Girders (Source: Badie et al. 1999) [9].

	Depth range (in.)	Spans up to (ft)	28 day concrete strength (psi)
Trapezoidal box (totally closed)	23.5 – 31.5	~95	7,500
Trapezoidal box (open-top)	20 – 28	~86	9,000

2.2.3.3 Modular Superstructure System

The modular superstructure system is created when deck panels, girders, and their connections together are fabricated integrally. In this system, the panels can be connected to each other at the edges using grouted shear connector pockets (shear keys) [13]., A low shrinkage pour should be used to prevent transverse cracking. The limitation in the dimension of the modular systems is controlled by their heavy weight affecting their shipping. Therefore, the modular steel system is more preferable than their counterpart modular precast concrete systems due to its lightweight.

2.2.3.3.1 Modular Steel Girder Superstructure systems

Modular Steel systems can be made of topped multi-beams unit, modular steel folded plate girder system, or orthotropic steel deck system. Steel modules offer advantages over other modular systems as it reduces shipping weight of the modules [13]. The modular superstructure elements and systems are suitable for short-span bridges (i.e., 20 ft. to 60 ft.) [9].

2.2.3.3.1.1 Modular Steel Beams with an Integral Concrete Deck:

Modular Steel Decked Beams (e.g., using steel I-beams) are made by casting the concrete onto beams at an off-site location typically with two beams in order to facilitate shipping and handling (Figure 2.25). A single beam decked element is also an option [21]. These prefabricated modular steel beam elements are then shipped to the site and lifted into place (Figure 2.26). After placement, the joints between the deck portions of the modular steel beam elements are established with closure pours. Feasibility of pre-cambering the beams offers advantage for steel beams through which the vertical profile required by the roadway can be achieved easier. Doing this with precast concrete beams is more difficult. Steel decked beam elements are relatively wide and can lead to increased shipping and handling weight. This can limit their practical use for short and moderate span bridges [21].

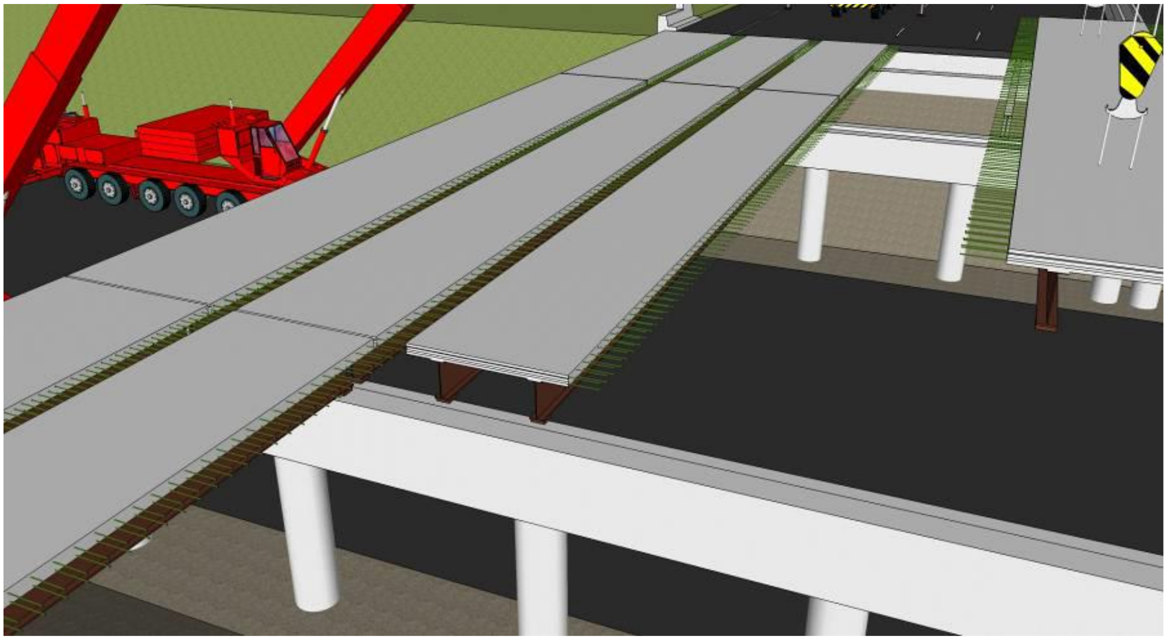


Figure 2. 25 Modular steel superstructure system [13].

Figure 2. 26 Modular Beams with Decks [13].

2.2.3.3.1.2 Steel beam with orthotropic steel deck system

Another modular steel system is the steel T beam with orthotropic steel deck system that can be single span orthotropic with the running of ribs on the deck span or orthotropic T beam. In orthotropic T beam system, steel girders and a portion of the orthotropic deck are using together as shown in Figure 2.27. The disadvantage of the orthotropic system is its high cost. A standardized method and technique in the construction of the modular orthotropic system is being developed by the FHWA to reduce its cost [13].

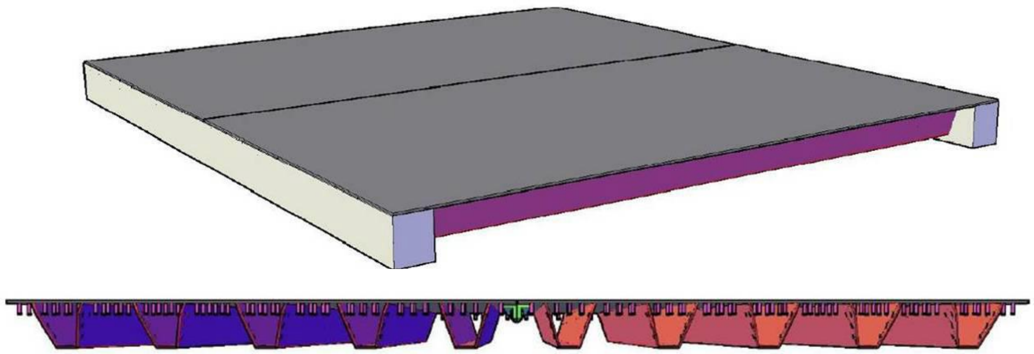


Figure 2. 27 Modular orthotropic superstructure system [13].

2.2.3.3.1.3 Modular Folded Plate Girder Bridge System (FPGBS)

The modular steel folded plate girder can used for short span bridges with a maximum span of 60 feet (Figure 2.28). This system has a tub section that is built by bending a flat plate. The advantage of this system is its stability that doesn’t require the external or local frames against lateral bucking and similar [22].

Figure 2. 28 Modular steel folded plate girder [22].

Folded Plate Girder Bridge System (FPGBS), offers an economical solution for many of the nation's bridges with maximum span lengths up to 60 ft. The system consists of a series of standard shapes that are built by bending flat plates into inverted tub sections using a press break. Figure 2.29 shows a fabrication process for a typical folded plate girder [22].

Figure 2. 29 Fabrication of folded plate girder using a press break machine [22].

FPGBS have many advantages for both steel fabricators and bridge owners. Folded plate girders suitable for different span lengths differ only by their cross-sectional dimensions [22]. The Folded Plate Girder Bridge Systems (FPGBS) can be constructed using conventional construction techniques as well as using principles of Accelerated Bridge Construction (ABC) [22]. FPGBS is constructed by using prefabricated, pre-topped elements, where each unit consists of a folded plate girder with deck cast on the top. Several (usually four) of these units (pre-topped folded plate girder) could then be transported to the field, placed side by side and joined together to complete the bridge construction [22]. Figure 2.28 is a Pre-topped folded plate girder unit.

2.2.3.3.1.4 Press-Brake-Formed Tub Girders

The press-brake-formed tub girder system consists of modular shallow trapezoidal boxes fabricated from cold bent structural steel plate (Figure 2.30). Steel shapes are available in either hot-dipped galvanized or weathering steel options [23]. The fabrication of a composite folded plate girder module starts with a single steel plate of the desired thickness that is strategically bent into a structural shape. The plate is then cold formed into a U shape with a press brake, with each bend occurring along the plate's longitudinal axis [24]. Once the plate has been formed, shear studs are then welded to the top flanges. A reinforced concrete deck is then cast on the girder in the fabrication shop and allowed to cure, becoming a composite modular unit. Modules are then longitudinally joined using Ultra-High-Performance Concrete (UHPC) [23].

Figure 2. 30 Conceptual view of modular press-brake-formed tub girder system [23], [25]

Press-brake-formed tub girders are versatile for multiple-deck options. They can be used for both tangent and skewed configurations, as well as simple and continuous spans. They are recommended for single spans up to 60 feet or less [26].

2.2.3.3.2 Modular Precast Concrete Superstructure Systems

Double tees and decked bulb tees comprise the modular precast concrete superstructure systems. Double tee modular system includes two girders connected with a deck slab as shown in Figure 2.31., The adjacent beams connect to each other using the shear key connection for the double tee modular superstructure. Bulb tee system consists of a girder with an extended top flange. In this system, the connection of two adjacent bulb tees is established using the welded tab connection. This type of connection limits the use of this system to low volume roads due to the low durability of the connection [13].

Figure 2. 31 Modular double tee superstructure system [13].

2.2.3.3.3 Timber Element Systems

Modular timber elements system is another type of modular superstructure system (Figure 2.32). In this system, all the elements are prefabricated, and laminated girder deck system is installed on the top of timber or steel beam. The laminated deck spans are basically comprised of adjacent timber elements that are laid side by side to form a solid wood panel. These panels can be used to span the entire length of the bridge. The laminations can be made with sawn lumber laid on edge, or glue laminated wood panels. The connection between laminations can be made with spikes, bolts or transverse post-tensioning [13].

Figure 2. 32 Laminated timber deck system [13].

2.2.3.4 Barriers and railing

The barriers for ABC bridges can be designed and constructed with prefabricated deck, cast in place, or attached to the deck using fasteners such as bolts (Figure 2.33). The FHWA provided a manual that defines the barrier and railing requirements for bridges [27]. This manual requires crash testing for barriers. To this date, there is no crash tested prefabricated barrier available [13]. A prefabricated railing system has been developed recently by Iowa State University researchers as part of ABC-UTC projects that are verified with static/push-over testing. Next phase of this research project aims at verification through crash testing (Figure 2.34) [28].

Figure 2. 33 Prefabricated deck panel with a barrier (Utah DOT) [13].

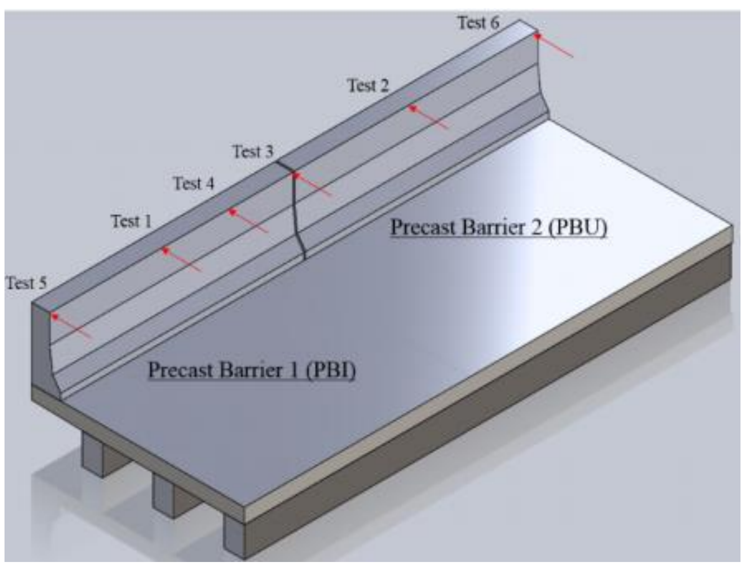


Figure 2. 34 3D model of prefabricated deck panel with barrier lab set-up at Iowa State University [28].

2.2.3.5 Miscellaneous elements

Miscellaneous elements of the superstructure include the drainage assembly, lightning, expansion joints, bridge bearing, and deck overlay or riding surface of the bridge. The deck overlay or wearing surface can be surface of the bridge without any overlay or can be overlaid with asphalt pavement. The drainage assembly can be preinstalled on the prefabricated deck elements or established the same way as conventional bridges [29].

In the ABC bridges using prefabricated girders and deck, bridge bearing is placed between girder and cap beam to adjust the elevation of girder and deck, and to provide proper, durable and uniform seating for the girders (Figure 2.35). This is normally not the case for conventional bridges for which the gap between the top of girder and the deck (deck haunch) is used to elevation adjustment [13].

For accommodating changes due to temperature variation and preventing the premature deterioration or overloading of the bridge, deck expansion joints are necessary [11]. Expansion joints are not used for the case of integral abutments where super- and substructure become monolithic [12]. Expansion joints can be categorized into two groups [12]. One includes joints within the deck overlay and consists asphaltic plug material and epoxy header with glands or seals. The other includes the embedded joints into the deck. The embedded joints experience large movements and contain modular expansion joints, armored seals, or finger joints. The concern about the expansion joints is that they deteriorate rapidly and need high maintenance requirements. To address this issue, link slab has been introduced to eliminate the use of expansion joints in the ABC projects [30]. The practical recommendation and guideline to use the link slab in the ABC projects is in development and will be available shortly through ABC-UTC.

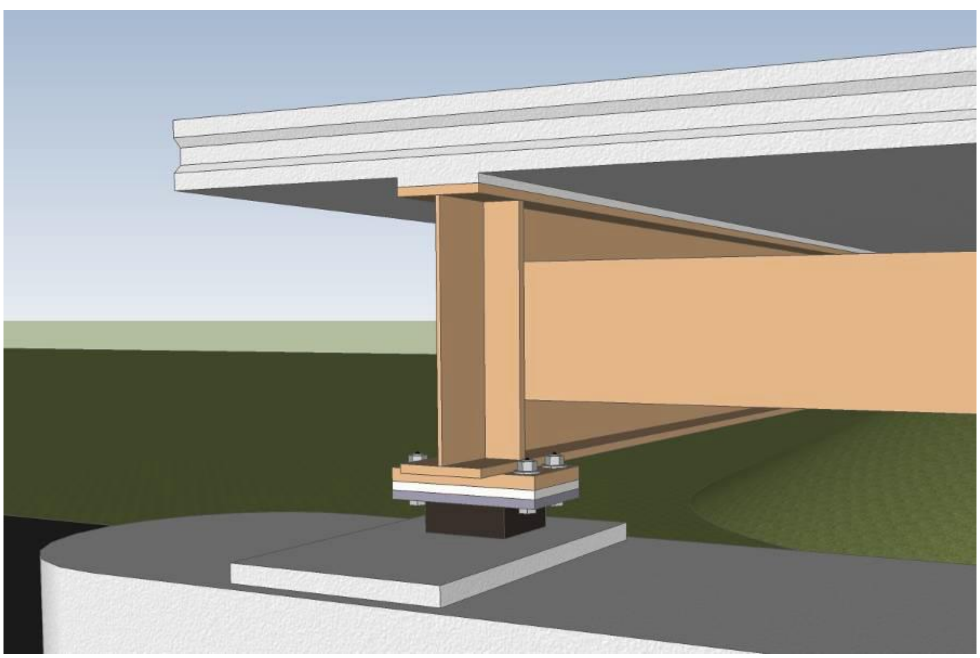


Figure 2. 35 Bridge bearing [13].

2.2.4 Substructure

Substructure elements transfer vertical and horizontal loads from superstructure into the foundation. Piers, pier cap, abutments, culvert, wing walls, and retaining walls are the substructure elements (Figure 2.36) [13].

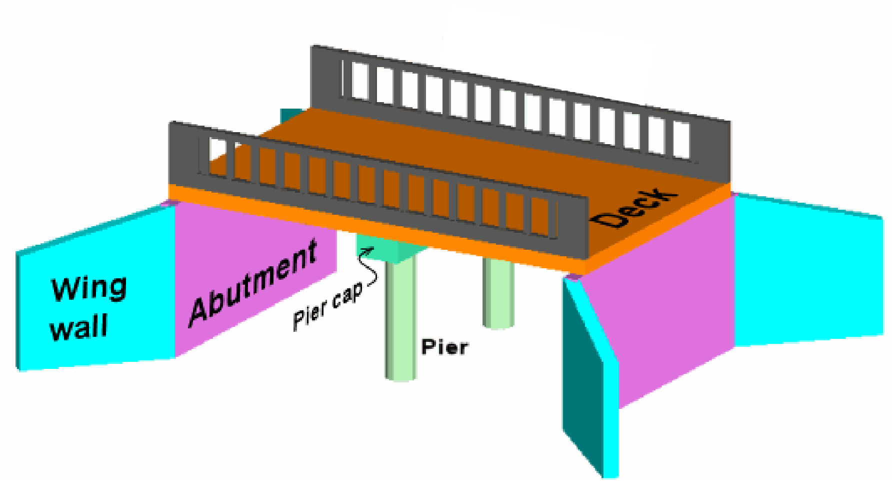


Figure 2. 36 Substructure elements

2.2.4.1 Piers

Piers are vertical elements that support deck span at intermediate points and typically consist of pier columns and pier caps. This element transfers loads to the foundation and resists horizontal loads using its shear resistance mechanism. Piers that consist of more than one column are called pier bent (Figure 2.37) [13]. To connect pier cap and column, various types of connections are used, one is grouted splice reinforcing bar couplers. When the pier is affected by the errant vehicles or is adjacent to the railroad, the wall piers may be used instead of the pier (Figure 2.38) [13]. The integrity of piers connection to the pier cap and footing is very essential, especially in the seismic region because they should resist the majority of shear and seismic loads.

Figure 2. 37 Prefabricated pier bent [13].

Figure 2. 38 Wall Pier [13].

2.2.4.2 Abutments

Abutments are elements that sustain the superstructure live and dead load, retain the earth or embankment lateral pressure, and resist sliding and overturning due to the embankment. Abutments consist of walls, wing-walls, and abutment cap. In fact, abutments play both pier and retaining wall function. Abutments are constructed at the beginning or end of the bridge span where the superstructure rests on land [13]. Although the abutments can be constructed integrally or semi-integrally with the superstructure or built as a conventional free-standing abutment, integrally or semi-integrally construction of abutment is more popular.

Construction of abutments integrally with the superstructure has two significant advantages in comparing to the conventional free-standing abutment construction. Integrally and semi-integrally abutments have no deck joints and transfer embankment soil force to the superstructure [13]. In the fully integral abutment, the abutment connection to the superstructure is a full moment connection. However, in semi-integral abutment which a portion of the abutment is constructed with the superstructure, the pin connection is used to allow the rotation of superstructure in respect to the substructure (Figure 2.39) [13]. In this construction type, the abutment is supported on a row of column. An example of the integral abutment is shown in (Figure 2.40). This abutment configuration was constructed based on Utah DOT and several other states specification for the integral abutment. The corrugated void connection was used in this abutment. To create the voids in the abutment stem, the corrugated steel pipe was used. Recently, a research project as a part of ABC-UTC project has been introduced to investigate the constructability of abutment details and evaluate the strength and durability of abutment connections [31]. This project can facilitate the use of abutments in the ABC project by providing a detailed document for the construction of abutments.

Other types of prefabricated abutments are cantilever and spill-through abutments (Figure 2.41). These abutments constructed separately from superstructure and retain the soil pressure and superstructure loads. In the cantilever abutment, wall stem connects to the footing using different connections like grouted splice couplers. To attach the wall to the abutment cap, the reinforcing bar cage which is cast into the corrugated voids can be used [13]. The corrugated steel pipes can be used to create the voids and also reduce the abutment elements weight. When a large void is erected in the cantilever stem, it is called spill-through abutment. The erection of this void can reduce the soil pressure on the abutment significantly.

The retaining wall and wing wall are the abutment extension to maintain the earth pressure in the approach embankment (Figure 2.42). These walls are constructed at the abutment and are designed to resist earth pressure from backfill, surcharge from the live load, and hydrostatic load from saturated soil. If these walls are not constructed, the earth stays in natural angle response [13].

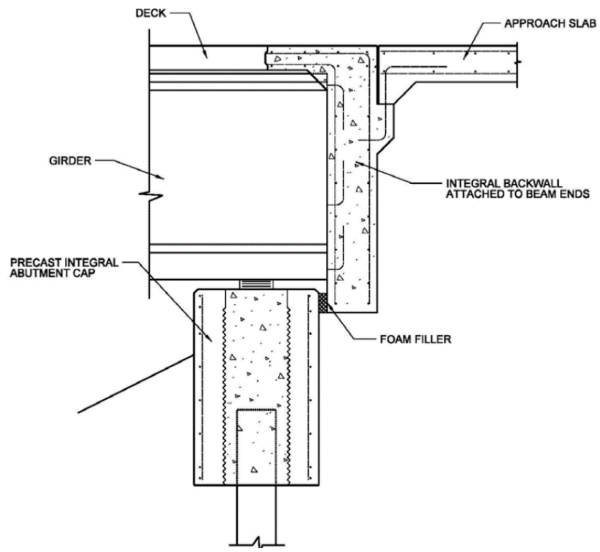


Figure 2. 39 Semi-integral abutment [13].

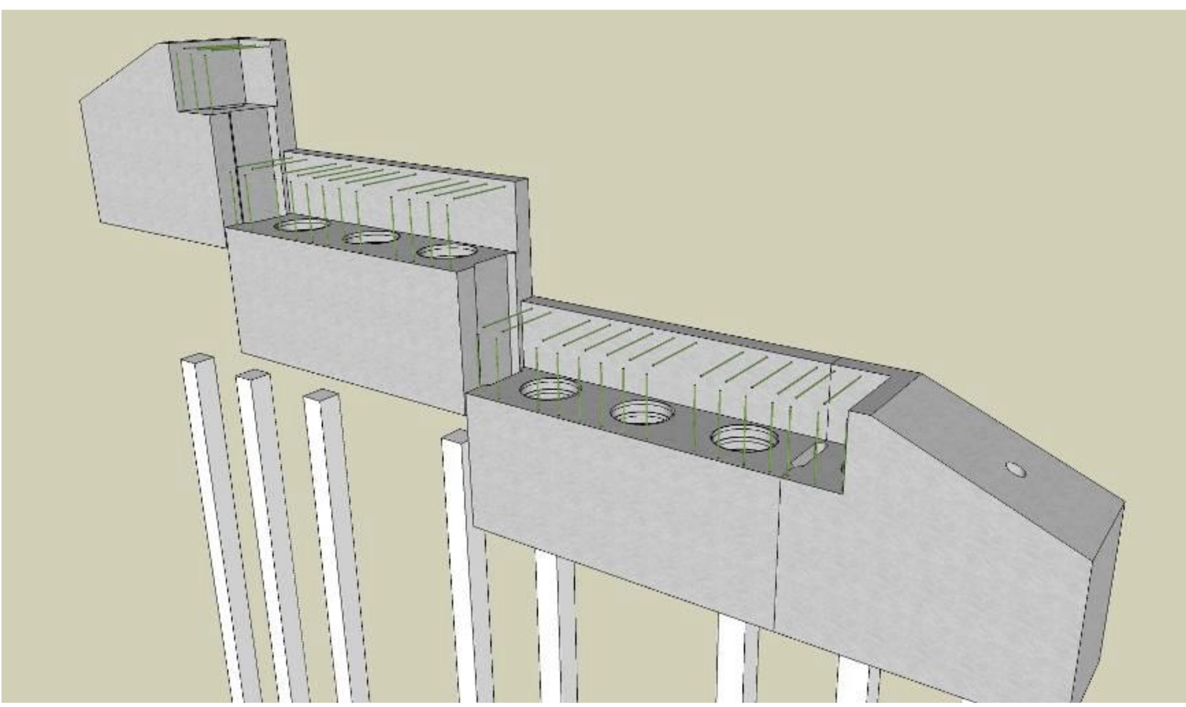


Figure 2. 40 Prefabricated integral abutment [13].

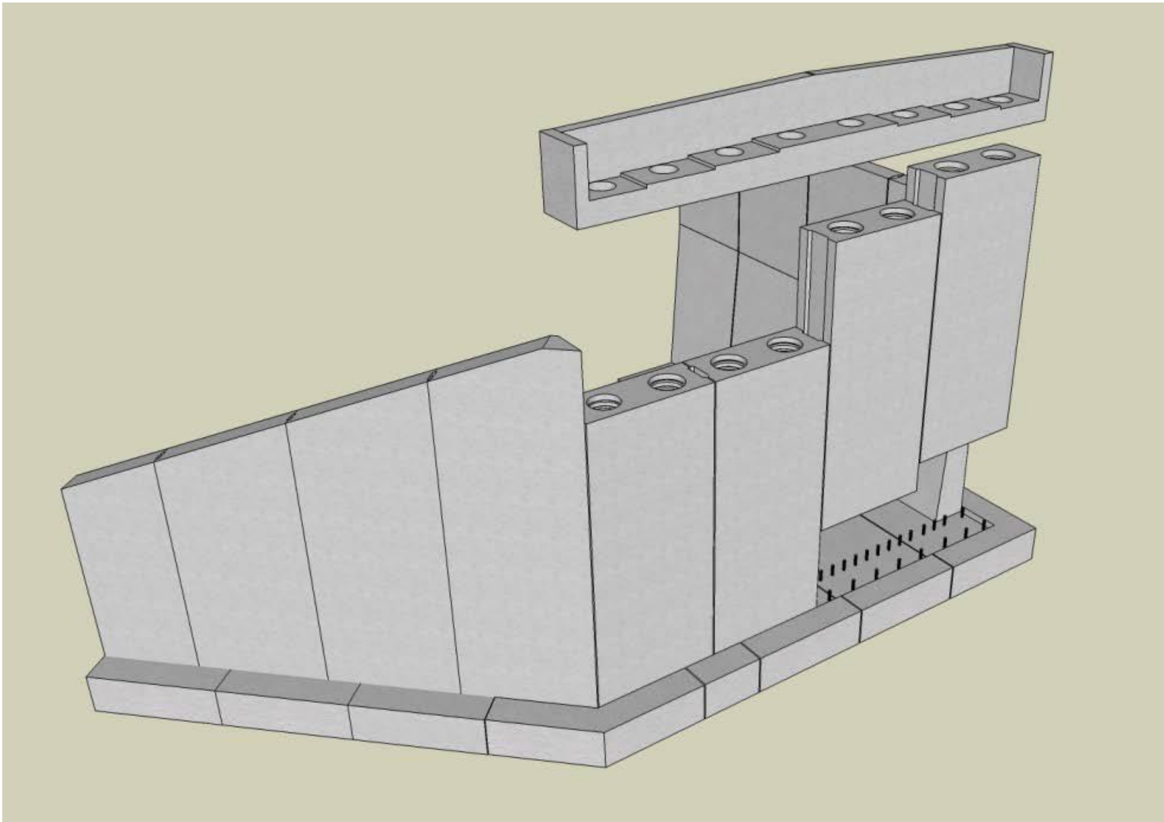


Figure 2. 41 Prefabricated cantilever abutment [13].

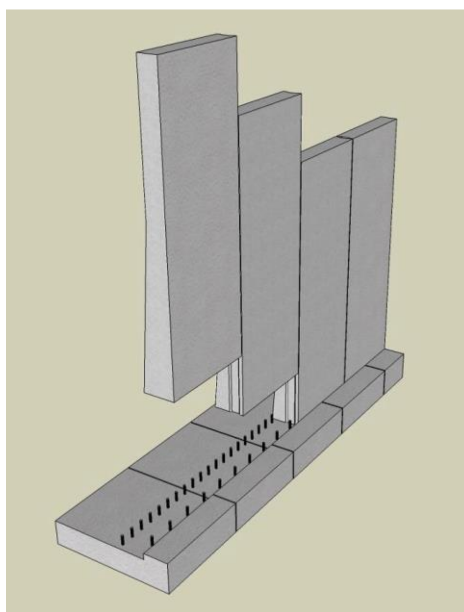


Figure 2. 42 Prefabricated cantilever wing wall [13].

2.2.4.3 Pier cap

Pier caps provide enough space for sitting of girders to transfer loads from superstructure to substructure and distribute the loads from bearing to piers (Figure 2.43) [13]. The cast-in-place and the precast pocket connections are typically used to connect the columns to the cap. Other connection types have also been used for this purpose. Cap beams can be designed according to the displacement-based or force-based method using AASTO LRFD bridge design specification. A linear elastic behavior for cap beams during the earthquake is necessary according to the specification [32].

Figure 2. 43 Precast Pier Cap [8].

There is two main types of pier cap including rectangular pier cap and inverted-tee pier cap. However, the precast rectangular pier cap is used widely [12]. Rectangular pier cap is typically used when there is a precast girder or steel girder that can sit directly on the top of the pier cap (Figure 2.44). The connection of pier cap to the pier can be fixed, pined, or isolated. The inverted-tee pier cap can be used when there are precast girders (Figure 2.45, 2.46). However, there is a challenge with the seismic behavior of the tee edges to satisfy the required demand that should be considered in the seismic regions [33].

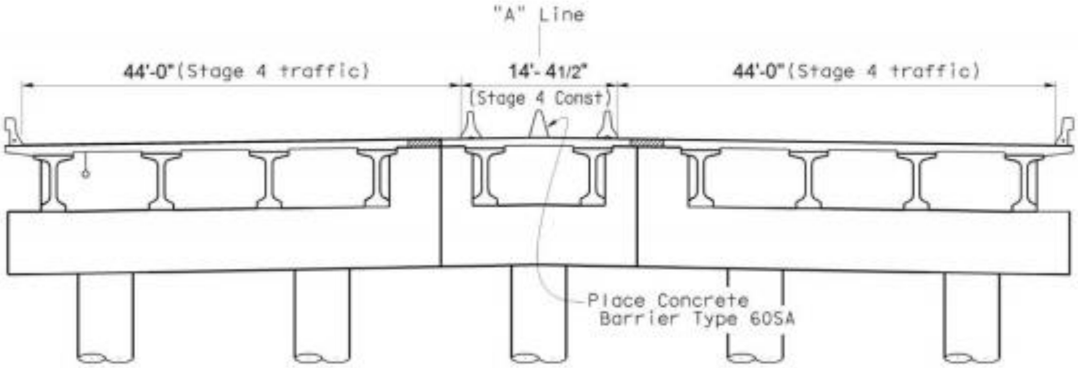
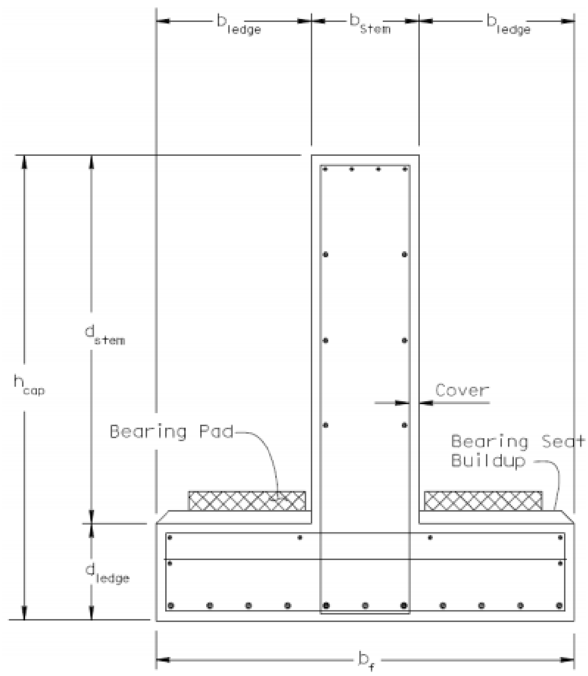


Figure 2. 44 Rectangular pier cap [33].



b_{ledge} =	ledge width	d_{ledge} =	ledge depth
b_{stem} =	stem width	d_{stem} =	stem depth
b_f =	flange width	h_{cap} =	bent cap depth

Figure 2. 45 Inverted-tee pier cap [33].

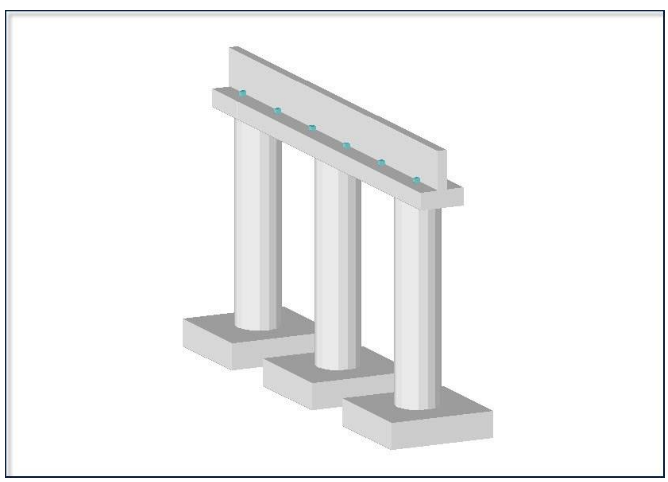


Figure 2. 46 Inverted-tee pier cap [34].

2.3 Buried Bridges (20 ft.< Span < 70ft)

A buried bridge is a buried structure supporting a roadway that relies its support from the soil-structure-interaction with a bridge length greater than 20 feet [2]. The design and analysis methods consider the static soil-structure interaction and that gives the reason of the use of the term buried. As these structures have a span length that exceed 20 ft. and in some cases approach 100-foot span therefore the term bridge is utilized. As the same case for conventional bridges, buried bridges can be used for new bridges, existing bridges and bridge reparation [2]. Buried bridges can be used for a variety of reasons, including but not limited to remote site access, aquatic crossings, pedestrian tunnels, temporary detours, and it can support heavy live loading for trucks, mine vehicles, etc. [2]

Implementation of Accelerated Bridge Construction is possible with buried bridges as installation can be done in a relatively short time (days) basis reducing onsite manpower and expertise for installation. Additionally, accelerated design and installation process can be also guaranteed with availability of many standard designs, rapid shop fabrication and minimum material shipment needed. This type of bridge can improve environmental characteristics and sustainability as onsite material can be used for backfilling. Maintenance decreases as there is no bridge deck and no expansion joint. Reuse of existing foundations are possible and foundation settlement tolerance is increased.

In order to select buried bridge geometry, evaluation of durability, and adequate soil-structure interaction parameters are considered through the evaluation of the function and site constraints for the design. Size of the structure can be defined by rise and span (Figure 2.47) and different types can be determined by the hydraulic opening or clearance envelope. Length on the other hand, can be determined by the roadway width, end treatments or waterway placement [2]. These different types of geometry can be classified into reinforced concrete and corrugated metal geometry as they are in Table 2.6.

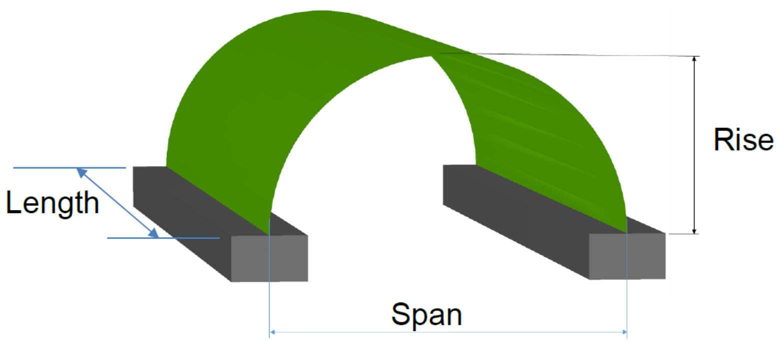


Figure 2. 47 Buried Bridge Structure Geometry [35].

Table 2. 5 Buried Bridge Geometry [35].

SHAPE	RANGE OF SIZES	COMMON USES
REINFORCED CONCRETE		
RECTANGULAR (BOX)	Span 8 ft to 48 ft	Culverts and Short-span bridges.
THREE-SIDED	Span 8 ft to 48 ft	Culverts and Short-span bridges.
ARCH	Span 15 ft to 102 ft	Culverts and Short-span bridges For low, wide waterway enclosures, aesthetic bridges

SHAPE	RANGE OF SIZES	COMMON USES
CORRUGATED METAL		
ARCH	Span x Rise 5 ft x 1 ft 9.5 in. to 82 ft x 42 ft	Culverts and Short-span bridges, Low clearance waterway, aesthetic bridges
HIGH PROFILE ARCH	Span 20 ft To 83 ft	Culverts and Short-span bridges, Grade separations, Ammunition magazines, earth covered storage
BOX	Span 10 ft To 53 ft	Culverts and Short-span bridges

2.3.1 Reinforced Concrete

Use of plant precasting of standardized sections is another way in which accelerated bridge construction can be implemented. Several manufacturers have developed precast concrete box, three-sided, and arch systems. These systems can be filled with onsite or granular backfill. Sometimes, these structures can be slid under existing bridges without interrupting existing roadway. Voids between both structures can then be filled with or without removal of existing bridges [13].

2.3.1.1 Rectangular (Box):

- Span range of 8 ft. to 48 ft.,
- Common uses: culverts and short span bridges

A variety of sizes, depths and for different live loads are offered in precast concrete box buried bridges. The speed of construction is one of the major advantages when using a precast concrete box [1]. An example of a rectangular (box) buried bridge can be seen in Figure 2.48.

Figure 2. 48 Rectangular (box) buried bridge [35].

2.3.1.2 Three-Sided:

- Span range of 8 ft. to 48 ft.,
- Common uses: culverts and short span bridges

Three-sided structure was created by a change in the design of the box culvert by removing the floor slab, this was done so it could comply with some environmental restrictions. Therefore, this type of design is used when there is limitation with hydraulic and environmental challenges in some states [36]. Figure 2.49 is an example of three-sided buried bridges.

Figure 2. 49 Three-sided buried bridge [35].

2.3.1.3 Arch:

- Span range of 15 ft. to 102 ft.,
- common uses: culverts and short span bridges. For low, wide waterway enclosures, aesthetic bridges

Another environmentally friendly, bottomless option is the arch. Depending on the span length arches can come in one or two pieces. As is the case in Figure 2.50 where a longer span is needed the tow piece arch rebar from each element is tied together at midspan [36].

Figure 2. 50 Arch System [35].

Figure 2. 51 Arch buried bridge [35].

2.3.2 Corrugated Metal

Several corrugated metal plates are bolted together to form these bridge systems [36]. Corrugated Metal Buried bridges are defined below:

2.3.2.1 Arch:

An Arch is a curved-shape structure that works in compression primarily and does not have a floor slab. This type can be effectively used where natural aquatic organism passage is necessary [1]. Figure 2.52 have different examples of arch buried bridge usage.

Figure 2. 52 Corrugated Metal Arch buried bridges [35].

2.3.2.2 High Profile Arch:

The difference between a regular arch and a high-profile arch is that its high-rise dimensions are for larger flow volumes or where there are not clearance restrictions that could govern a specific structure selection. This type of structure is available in steel and aluminum and has an elliptical shape [36]. Figure 2.53 possesses many examples of high-profile arch buried bridges.

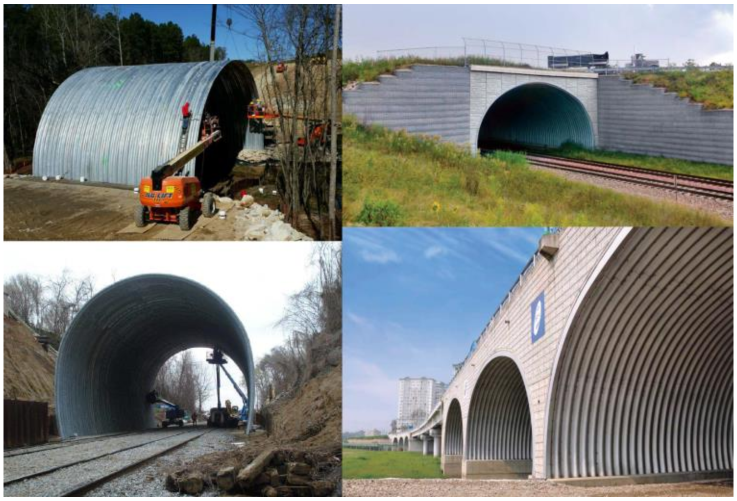


Figure 2. 53 High Profile Arch buried bridges [35].

2.3.2.3 Box Shapes

Figure 2.54 is an example of box shapes. It can be observed that is neither arch shaped nor rectangular, but uses a flat top with rounded corners, allowing the metal plates to make the geometric transition [36].

Figure 2. 54 Example of metal corrugated box [35].

2.4 Culverts (Span<20ft)

The NBIS bridge length definition included in the *FHWA Recording and Coding Guide for the Structure Inventory and Appraisal of the Nation's Bridges* states: "A structure including supports erected over a depression or an obstruction, such as water, highway, or railway, and having a track or passageway for carrying traffic or other moving loads, and having an opening measured along the center of the roadway of more than 20 feet between undercopings of abutments or spring lines of arches, or extreme ends of openings for multiple boxes.". Therefore, by understanding, those structures that have a span less than 20 feet may be classified as culverts [1]. A brief summary of culverts classification will be covered next, the will be subdivided into Precast Concrete Sections and Metal Culverts Sections

2.4.1 Circular Shape or Round Arch:

The most common section shape for pipe culverts is the circular. The pipe generally causes some reduction in the stream during low flows volume. This type of culvert is very common and possible drawbacks can be that they are prone to clogging more than any other shapes [1]. Figure 2.55 is an example of a precast circular culvert structure and Figure 2.56 is an example of a round arch culvert

Figure 2. 55 Twin Concrete Pipe Culvert [1].

Figure 2. 56 Round Arch Culvert [1].

2.4.2 Pipe arch and elliptical shapes:

These are often used when the clearance distance is limited or whether due to flow volume a wider section is needed. They are also prone to clogging as the circular shapes, however they are not as structurally efficient as the circular shape [1]. Figure 2.57 is an example of a pipe arch culvert.

Figure 2. 57 Pipe Arch Culvert [1].

2.4.3 Arch Culverts:

When a natural stream bottom is needed, arch culverts offer a better option to avoid an obstruction in the waterway compared to pipe arches [1]. Figure 2.58 is an example of a pipe arch culvert.

Figure 2. 58 Pipe Arch Culvert [1].

2.4.4 Rectangular cross-section culverts:

This is one of the most common culverts where there is no environmental restriction as the box culvert has a floor slab that supports the whole structure. Dimensions of the box can vary and are determined by structural, hydraulic and geotechnical design criteria [1]. Figure 2.59 is an example of a concrete box culvert and Figure 2.60 is an example of a metal box culvert.

Figure 2. 59 Concrete Box Culvert [1].

Figure 2. 60 Metal Box Culvert [1].

2.4.5 Multiple barrels:

For cases where low embankments or wide waterways are needed to obtain an adequate hydraulic capacity the use of multiple barrels (Figure 2.61) substitute the box culvert [1].

Figure 2. 61 Multiple Cell Concrete Culvert [1].

2.4.6 Three-sided Frame Culverts:

This type of culverts can be made of precast reinforced concrete. The shape is generally similar to a box culvert with the difference of not having a floor slab. These are commonly used where there is the need to provide a passage for the aquatic organism [1]. Figure 2.62 is an example of a three-sided frame culvert.

Figure 2. 62 Three-sided frame culvert [1].

2.5 Foundation

The function of a foundation is to transfer load from the abutment, pier, and wing wall to the earth strata [13]. It acts as an interfacing element between the superstructure/substructure and the underlying soil or rock. Selection of proper foundation is important to transfer load to the underlying soil without causing shear failure of soil or damaging settlement of the superstructure [37]. Therefore, it is essential to systematically consider various foundation types and to select the optimum alternative based on the superstructure requirements and the subsurface conditions. When the soil near the surface is adequately stable and can provide enough bearing for the bridge load, spread footings can be used as the bridge foundation. However, when the top soil is not stable enough, deep foundation such as piles should be considered under the footing to transfer the load into the hard strata and thereby provide enough support to the bridge structure. Also, in case of bridge construction in water, the bridge foundations should be deep enough to prevent scouring due to water current. To reduce the amount of construction time and impact on traffic flow, different precast prefabricated elements can be used in the foundation [13]. Different elements of foundation for accelerated construction include, but are not limited to the following:

- Deep foundations
- Prefabricated Spread Footings
- Prefabricated Caps for Caisson or Pile foundation
- Sheet Piling (Steel or Precast Concrete)
- Precast Pier Box Cofferdams

Additionally, embankment systems that may be used for ABC bridges include;

- Geofoam Rapid Embankment
- Geosynthetic Reinforced Soil
- Mechanically Stabilized Earth Retaining Walls

Details of the foundation elements are presented in the following section.

2.5.1 Precast Spread Footing

Spread footing should be considered as bridge foundation if competent soils are available within shallow depth. The width of spread footing is expected to be small and depth of footing should be economically feasible [37]. Shallow spread footings require significantly less time to excavate and place than deep foundations such as drilled or driven piles. If necessary, ground improvement methods can be used to improve the subsurface conditions for shallow spread footing [37]. Generally, spread footings are constructed using cast-in-place methods. However, precast spread footings are also available for bridge foundation. These footings are precast off-site, transported to the construction site and placed on a prepared subgrade and then grouted in place [38]. However, transporting precast concrete footings may be challenging as the size of footings can get quite large for bridge loads [13]. A new hybrid system can be applied which allows the installation of the footing at the speed of precast with the economy of cast-in-place. In such cases, a precast concrete footing is used only under the columns. A continuous footing is then obtained by using a cast-in-place closure pour on extended reinforcing bars from precast concrete footing during the erection of the remaining portions of the bridge [13]. The completed continuous footing is designed to support all other loads. Figure 2.63 presents a schematic of precast spread footing as bridge foundation.

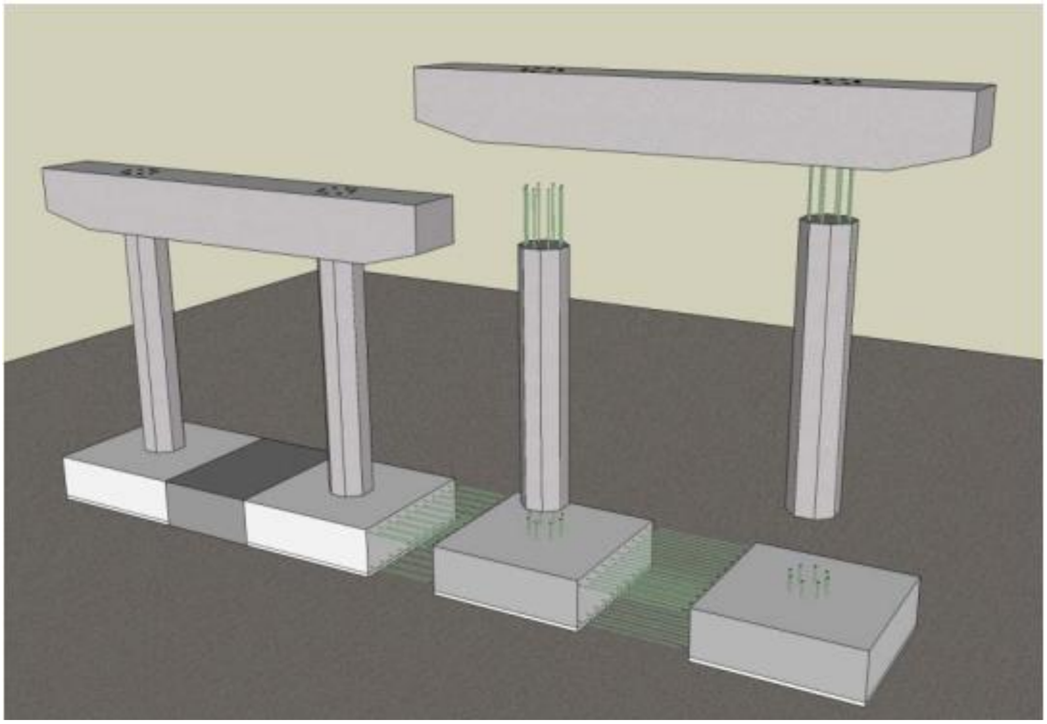


Figure 2. 63 Precast spread footing as bridge foundation [13].

2.5.2 Deep Foundations

Deep foundations are selected when competent soils or rocks cannot be found on the top stratum or if there is a possibility of extensive scour, liquefaction or lateral spread [39]. Deep foundations are one of the most commonly used foundations for bridges by many state agencies [39] - [40].

Different types of deep foundations such as driven piles, micropiles, continuous flight auger (CFA) piles, or drilled shafts are frequently used as bridge foundation [13], [37], [39] - [42]. Generally, a cap is built with the pile foundation to provide a stable platform for supporting substructure. Also, piles can be directly connected to the bent cap for short span bridges. Pile bents are cost effective and can be built quickly since there is no need for a footing. Most pile bents are constructed with precast concrete piles [13].

Driven piles are the most commonly used deep foundation system for bridge projects. These precast prefabricated foundation elements are installed in the ground using a pile driving hammer. Driven piles such as steel H, pipe, and prestressed concrete piles (Figure 2.64) with various section properties are available to support bridge structures [37].

Drilled shafts (Figure 2.65) are favorable and cost-effective for constructing foundation on cohesive soils, especially with deep groundwater. Large axial and lateral resistance can be obtained from drilled shaft when founded on a firm bearing stratum within 100 ft. of the surface. Also, drill shaft foundation can be constructed at places with restricted access, low overhead and with a small footprint. The need for a concrete footing can be eliminated by using large diameter drilled shafts to support individual concrete pier columns [42].

The advantage of using CFA piles is that these piles are drilled and cast in place rather than driven into the ground. The CFA piles are formed by screwing a continuous auger into the ground and then grouting or concreting through the hollow center of the auger. The CFA is suitable for a wide range of cohesive and cohesionless soil conditions. Also, CFA does not produce shocks, vibrations, noise which makes it suitable for construction in urban areas [[13], [42]].

Micropiles are another type of drilled pile that are generally smaller in diameter (less than 12 inch), reinforced and grouted deep foundation element. Micropiles are typically used for underpinning, seismic retrofitting, and projects with difficult drilling conditions. These types of piles are suitable for places where small size and lightweight is advantageous or required because of the site constrains [[37], [42]].

Figure 2. 64 Driven pile (prestressed concrete) as bridge foundation [37].

Figure 2. 65 Drilled shaft piles as bridge foundation [42].

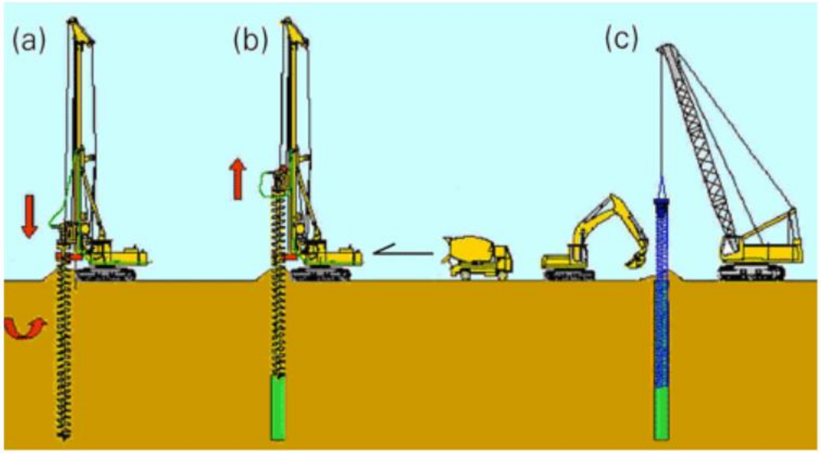


Figure 2. 66 Continuous flight Auger pile as bridge foundation [13].

2.5.3 Pile Cap Footings

Precast concrete pile caps can be used when steel or concrete piles are left projecting above the ground line to support the superstructure/substructure. Generally, a pile cap is cast-in-place by pouring concrete around the projecting piles to provide support for the superstructure. However, a precast cap with grouted pocket connection can also be used instead of a cast-in-place pile cap. The connection between the cap and the piles is achieved by filling the grout pockets with an epoxy grout [[13], [38]]. A number of different pile cap connections are detailed in the FHWA Connections Manual [8] to ensure punching shear and moment resistance at the connections. Figure 2.67 presents a sketch of precast concrete pile cap placed on precast concrete piles.

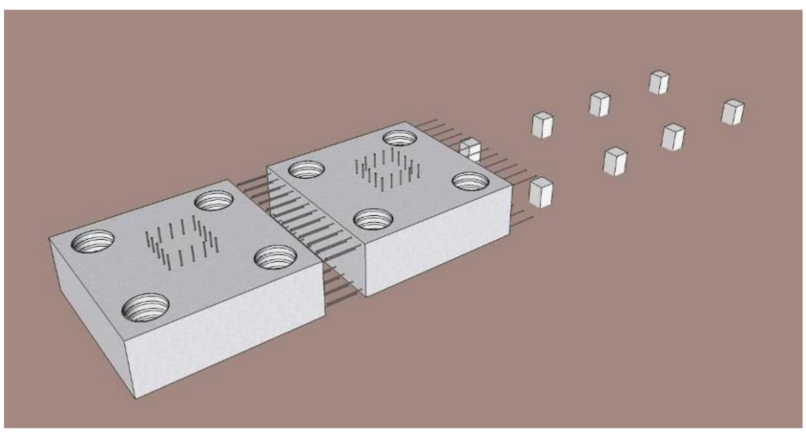


Figure 2. 67 Prefabricated pile cap footing [13].

2.5.4 Precast Pier Box Cofferdams

In case of bridge construction in water, a precast concrete pier box is used to dewater the area where deep foundation connects to substructure. This structure can sit over the shaft and be sealed to provide a dry condition during construction of footing. Also, the precast pier box systems can eliminate the need for complicated cofferdams and dewatering systems. This prefabricating system can be floated downstream from the place of cast and set into place to block off water flow for the installation of the pile caps. Also, these can be used as an additional corrosion protection system for the new pier footing when built with high performance concrete. Additionally, significant savings in time and money in the construction of the foundations can be achieved by using the precast concrete pier boxes [13], [38]]. Figure 2.68 presents a precast concrete pier box that allows construction of footings in a dry environment.

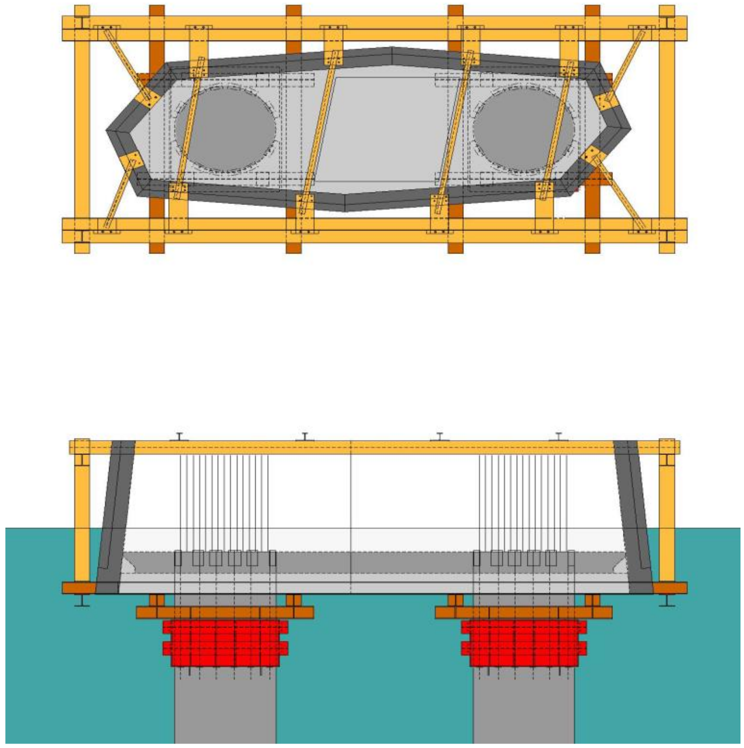


Figure 2. 68 Precast concrete pier box cofferdam [13].

2.5.5 Precast Sheet Piling

Precast concrete sheet pile and cellular steel sheet piles are most commonly used sheet piling systems for foundation construction and excavation support. Standards for precast concrete sheet piling was developed by Florida DOT. Typically, two types of cellular sheet piles are available, namely closed cell sheeting and open cell sheeting [13]. These precast prefabricated elements can be used to accelerate construction of bridge piers and abutments.

A geotechnical engineering scan tour of Europe was organized by FHWA and AAASHTO in June 2002 to evaluate the use of different accelerated bridge construction technologies. Based on the findings from that scan tour, Dumas et al. [43] presented a comparison (Table 2.7) between bridge foundation systems, equipment, and ground improvement methods for poor subgrade. According to Dumas et al. [41], the standard of practice for bridge foundation construction in the U.S. is driven piles or drilled shafts as CFA piles were found to have problem with quality control/quality assurance. An alternative for rapid construction could be the use of CFA piles with automated computer control and automated QC/QA. Another alternate accelerated method suggested by the scan team was bored cased secant (CSP) piles which can be used for both bridge support and excavation support involving cut situations. Accelerated bridge construction technologies such as Hydro-Mill and vibro-jet sheet pile driving method were found to be useful for rapid construction of bridge foundation.

Table 2. 6 Bridge Foundation Systems, Equipment, and Ground Improvement Methods for Accelerated Construction on Poor Subgrades

Technology or process	**Anticipated accelerated Construction Performance**	**Related Potential for Accelerated Construction**	**Applicable conditions for Accelerated Construction**	**Relative Cost**	**Improvement in Quality**	**Comments**
Continuous Flight Auger Piles (CFA)	Rapid pile installation for vertical or batter piles	High	Best in weak to medium soil	Medium	Low	Automated control, Not suitable for difficult drilling
Bored Piling-Cased Secant Pile (CSP)	Rapid Pile installation for vertical piles	High	Cut situations, temporary excavations	Medium	Medium	Casing assists in some soil conditions
Self-Drilling Hollow Bar Nailing and Miro piling	Self-drilling and grouting for one-step installation	High	Difficult ground for drilling/driving	Low	High	Confined condition with difficult ground for drilling
Vibro-Jet of Sheet pile Driving	Speeds driving of sheet piles through layered soils	Medium	Same as conventional	Low	Low	Bridge abutments with grouting through vibro-jet pipes
Hydro-Mill	Rapid excavation of wall with no mess	Medium	Difficult drilling condition, large loads	Medium	High	Difficult drilling conditions, large loads and tight spaces
Screw piling	Requires 1/3 the time of auger cast piles	Low	Relatively weak soil conditions	Medium	Low	Auto control Depth<100ft Non-artesian

2.5.6 Geofoam Rapid Embankment System

The Geofoam Embankment System (Figure 2.69) constitutes an embankment formed by expanded polystyrene blocks [13]. Given their light weight property they are used for weak sub soils.

Typically, a load distribution slab is built on top of the geofoam and covered with soil [44]. It usage is not predestined for a structural support system; the expanded polystyrene geofoam can also be placed around piles of an integral abutment or behind a conventional abutment [13].

Application of this technology is mainly for but not limited to reducing swell pressure of swell-type soils, reduce lateral earth pressure and reduction of settlement in embankments [44]. Moreover, benefits of this system include the elimination of pre-load settlement times, extremely lightweight material and fast construction [13].

The design considerations for this system is straightforward. Site is leveled, and layer of bedding sand needs to be placed. Geofoam are then placed with bedding sand that will fill the gap between backslope and geofoam. A load distribution slab is placed on top of the geofoam and then a layer of fill over the slab, and finally covered by the pavement [45].

Figure 2. 69 EPS Geofoam Embankment (Source ACH Foam Technologies)

2.5.7 Geosynthetic Reinforced Soil (GRS) Integrated Bridge System

GRS refers to an innovative geotechnical system that combines properties of granular soil and geosynthetic material to improve strength and stiffness of a soil mass. GRS systems are somewhat analogous to reinforced concrete. Both plain concrete and soil perform adequately in compression and shear, but lack strength and ductility in tension. The addition of rebar in concrete and geosynthetics in soil improves performance of both materials. GRS systems were shown to have a beneficial application to short-span bridges in recent years [36]. The GRS needs to be finished with a beam seat or cap to receive the superstructure. Figure 2.70 shows an example of GRS/IBS Bridge abutment.

A recent form of abutment system is the Geosynthetic Reinforced Soil Integrated Bridge System (GRSIBS), which is described in FHWA publication *FHWA-HRT-11-027* (Adams et al. 2011). This is a relatively new abutment system that has been used for accelerated bridge construction, and typically for short spans up to about 140 feet. The abutment uses alternating thin layers of compacted fill and geosynthetic reinforcement sheets that combine to form a reinforced soil mass foundation that directly supports the bridge superstructure without the need for piles. The geosynthetic reinforcement is connected into layers of precast facing blocks that are placed with the reinforcement and soil backfill. Once completed, the reinforced soil mass is ready to support the bridge. Traditional abutments are typically concrete construction. When deep foundations are required to support the bent caps, they normally consist of timber, prestressed concrete square, solid round or hollow cylinder piles, CIP concrete drilled shafts, or steel HP or pipe pile sections [15].

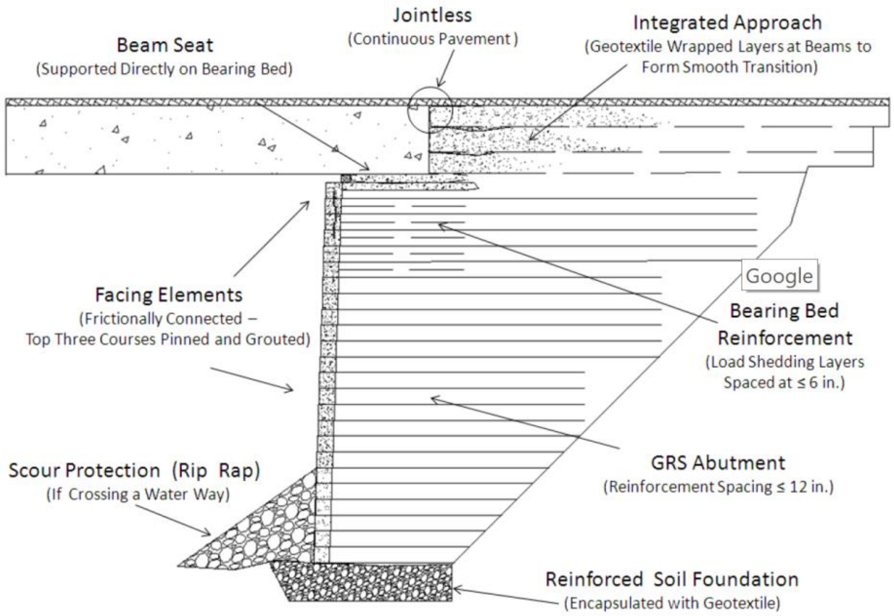


Figure 2. 70 Typical Section of a GRS/IBS Bridge abutment [13].

2.5.8 Mechanically stabilized earth retaining walls

Mechanically Stabilized Earth (MSE) retaining walls are very common in the U.S. They are comprised of precast concrete panels connected to reinforcing strips that are embedded into the backfill soils. Figure 2.71 shows a cross section of a typical MSE wall. The use of MSE accelerates the construction of walls since the curing of concrete is minimized (footing only) and backfilling and erection of the wall occur in parallel. MSE walls function by engaging the soil mass behind the wall face to form an earth gravity wall system [6].

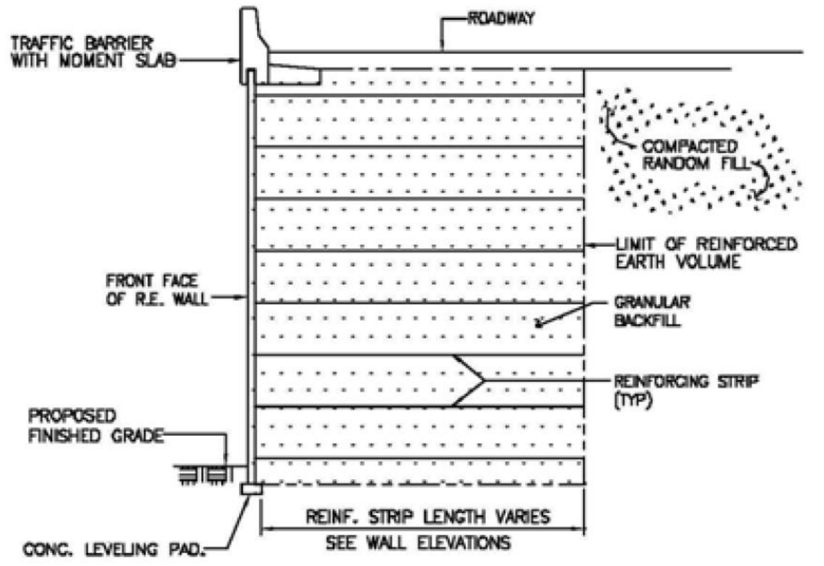


Figure 2. 71 Typical Mechanically Stabilized Earth Systems (MSE) Wall Details [13].

There are also wall systems that use GRS fabric, wire mesh or natural vegetation in place of the wall panel facings. The construction of these walls can progress rapidly because the system is built while the soil is being placed behind the wall; thereby combining two processes into one [13].

Many states also use MSE walls for abutments; however, the walls typically do not support the bridge. Piles or drilled shafts are installed prior to wall construction. The MSE wall is then typically built in front of the piles with the reinforcing strips placed between the piles. Once complete, a concrete footing is installed on top of the piles, creating two separate structures [6].

2.6 Survey: FDOT Superstructure Types for Short and Medium Spans

This section provides a summary of survey conducted in the state of Florida by the Florida Department of Transportation (FDOT). The purpose of this survey was to assist them in choosing an optimal superstructure section type to serve as an efficient superstructure for bridges with spans between 50 and 80 feet and to evaluate different structural shapes for off-system bridges with spans between 30 and 60 feet. Even though this survey was not done specifically for ABC bridges the compiled information can be useful when applying ABC technologies.

The superstructures types considered for the survey are: Solid Slab with P-T, Double T (FLET), FDOT PSU, Type II Box Beam, Texas Box Beam, Minnesota Flat Slab, Truncated FIB, Super T Beam and AASHTO Type II Beam. Figure 2.72, Figure 2.73, and Figure 2.74 represent the drawings showing the nine superstructure typical sections considered in the survey. This information will provide a practical and useful set of inputs indicating the preference of the end users for the type of elements works best for them.

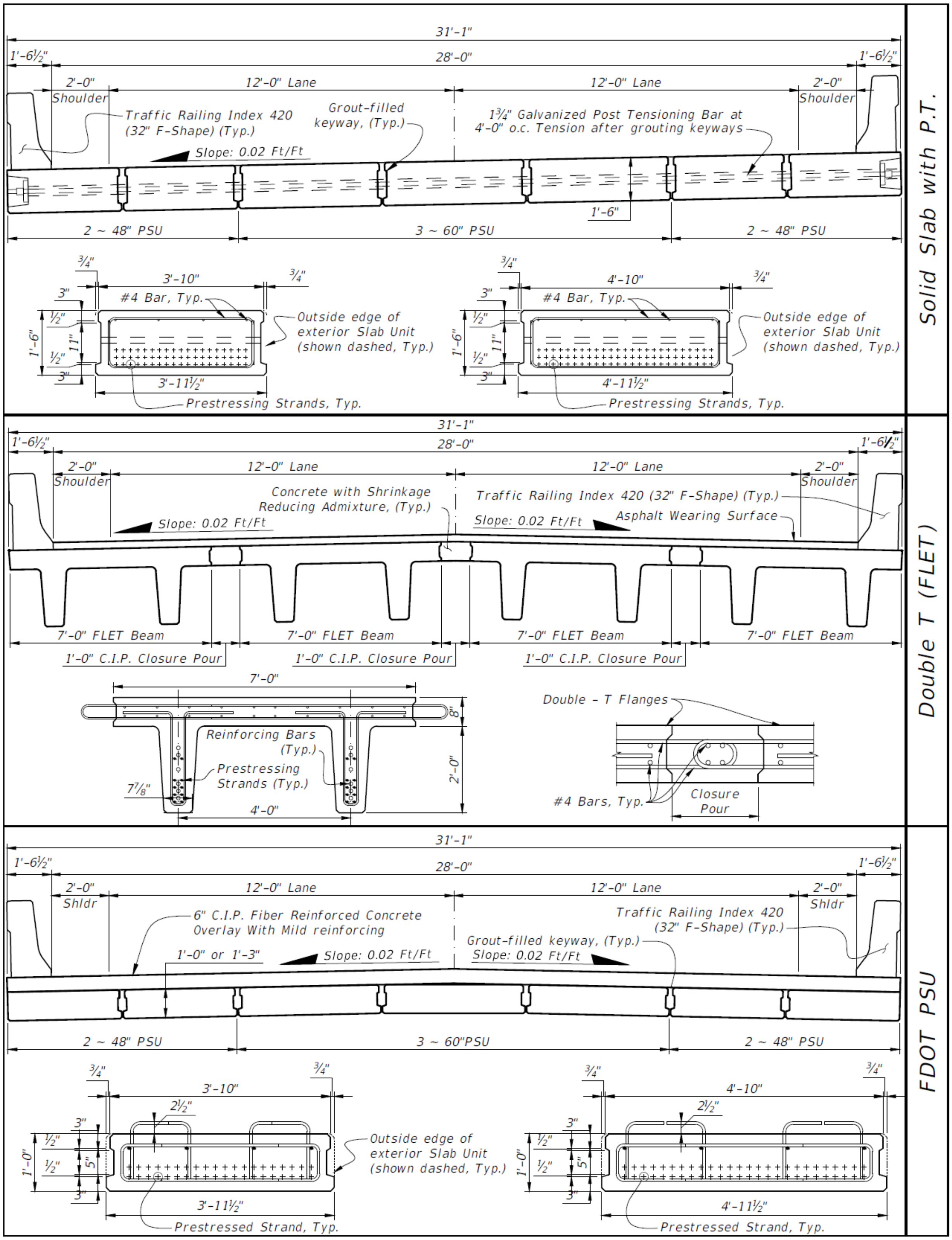


Figure 2. 72 Drawings for Solid Slab with P.T, Double T (FLET), and FDOT PSU [46].

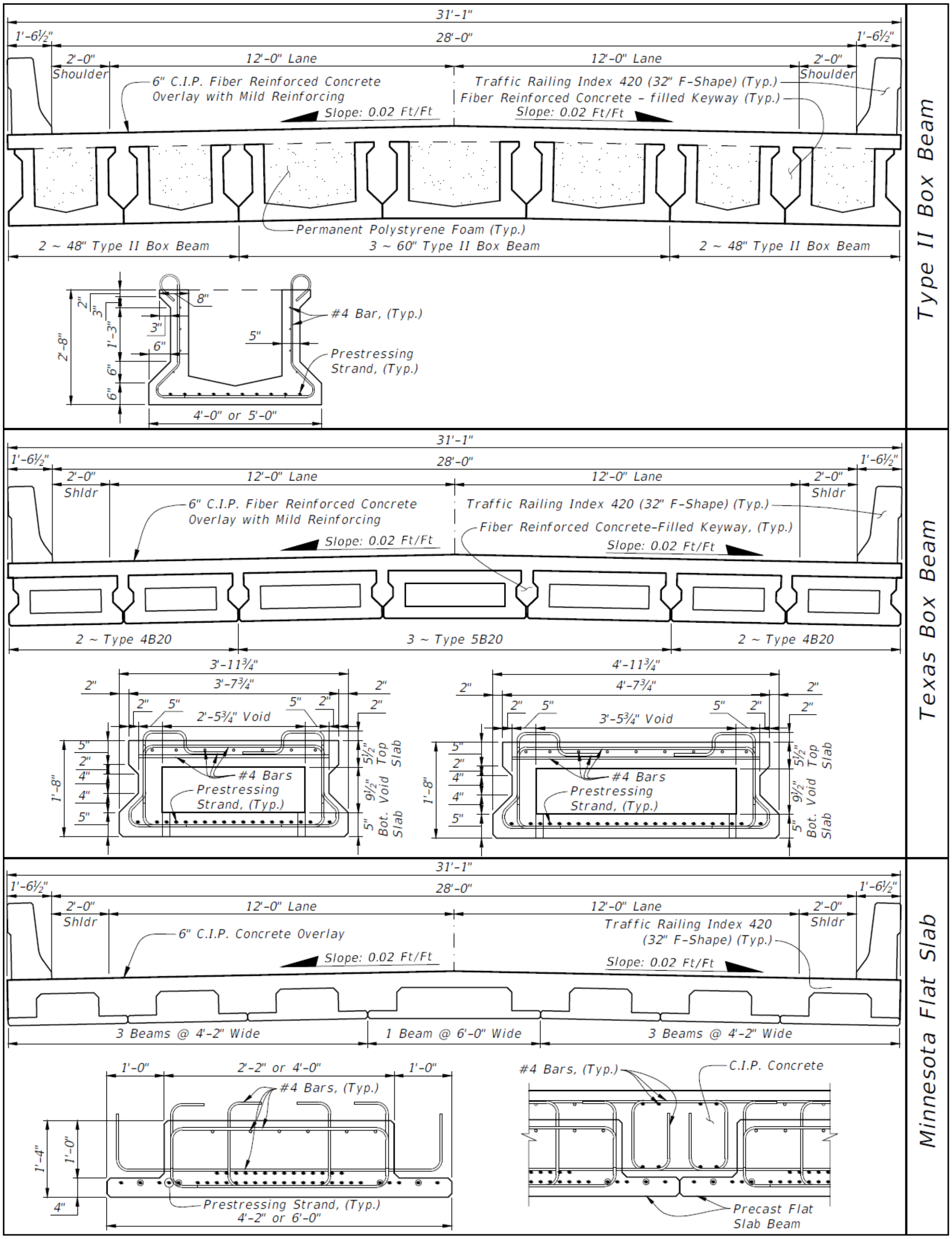


Figure 2. 73 Drawings for Type II Box Beam, Texas Box Beam, and Minnesota Flat Slab [46].

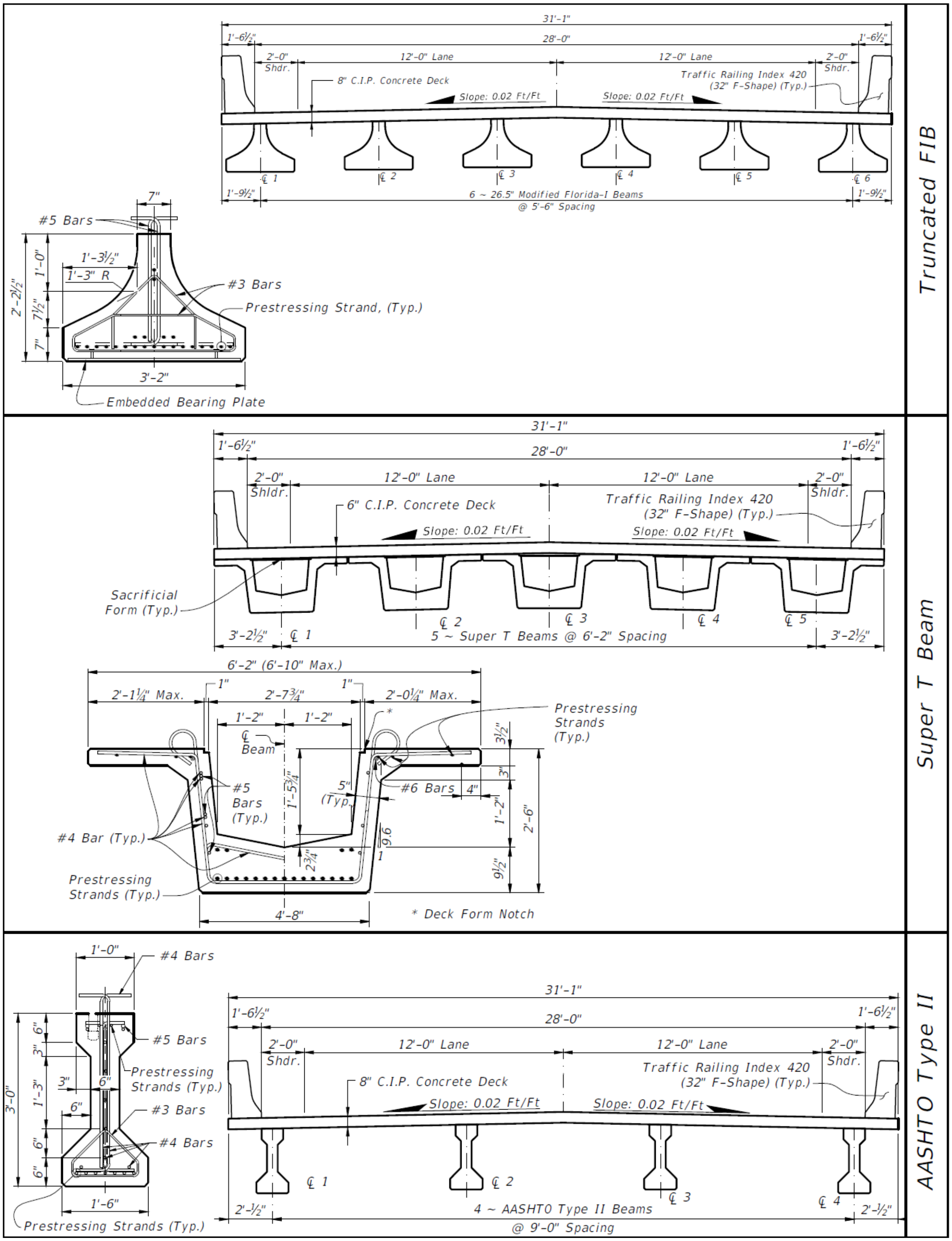


Figure 2. 74 Truncated FIB, Super T Beam, and AASHTO Type II [46].

The following terms were defined for rating purposes:

Definitions of Terms:

Urban Area: Congested project site, limited site access and minimal road closures allowed

Rural Area: Remote project site, located far from precast plants and concrete plants

Constructability: Can the proposed superstructure be easily constructed? Consider fit-up, tolerances, access, equipment needed, etc.

Speed of Construction: How quickly can the superstructure be constructed?

Material Information:

Precast Concrete Beams: Concrete Class VI

Cast-in-Place Concrete: Concrete Class II (Bridge Deck)

Post-Tensioning Bar: ASTM A722 CAN/CSA (G279-M1982) alloy steel

Grout: Non-Shrink Grout

Fiber Reinforced Concrete: Concrete Class II (Bridge Deck) with basalt or steel fibers per project specifications

Figure 2. 75 Definitions of Terms for Survey [46].

The survey intended to determine what type of superstructures are commonly selected for short and medium spans bridges. The span range was specified for each of the options. The subject was focused on evaluating different types of superstructures by rating each superstructure type from 1=poor to 10=ideal. Table 2.8 shows each response to the survey, top three responses for each reviewer were highlighted in green. Survey was subdivided into evaluation of each superstructure for constructability in Urban and Rural area, and speed of construction. Same rating values for different types of superstructures can be observed, the reason is that the survey was not developed as a ranking. Moreover, each column represents responses for each company that participated in the survey.

Table 2. 7 Survey results [46].

Superstructure Type	Maximum Span (ft)	Constructability																						Speed of Construction											
		Urban Area												Rural Area																					
Solid Slab with P-T	50	6	8	4	1	9		8	6	7	1	4	10	8	8	5	4	8	8	7	1	6	9	7	8		5	5	5	8	10	7	1	8	10
Double T (FLET)	60	5	8	4	7	8	3	7	7	2	8	6	8	8	8	4	8	7	7	2	8	6	6	6	8		6	3	8	7	8	5	8	7	7
FDOT PSU	50	10	8	5	10	10		7	7	9	7	6	10	8	8	5	9	7	7	9	7	6	7	7	7	8	6	8	9	7	8	8	7	7	8
Type II Box Beam	86	5	8	6	8		3	6	4	6		6	7	3	8	5	9	6	4	6		6	7	2	7		5	?	9	6	4	5		6	7
Texas Box Beam	60 (for 20" ht)	5	9	5	8		3	6	7	7		6	8	4	9	6	7	5	7	7		6	7	5	7		5	4	9	7	8	7		7	6
Minnesota Flat Slab	53	7	9	4	9			4	6	8		6	8	4	9	4	7	4	6	8		6	8	6	8		4	4	7	4	6	8		7	7
Truncated FIB	63	6	6	5	5		10	4	3	9		6	6	7	6	5	10	6	3	9		6	5	5	6		5	?	6	5	5	8		6	5
Super T Beam	79 (for 30" ht)	6	7	5	8		5	8	7	4		6	7	6	7	5	9	8	7	4		6	6	5	8		7	?	10	7	6	4		6	7
AASHTO Type II Bea	70	7	6	6	5	9	10	5	6	8	6	6	9	7	6	6	10	5	6	8	6	6	5	6	6		6	10	6	5	5	8	6	6	5

Of the survey's recipients some provided feedback. A summary of the responses is provided in Table 2.9.

Table 2. 8 Survey average results for rating of various systems.

Superstructure Type	Maximum Span (ft.)	Constructability		Speed of Construction	Overall Average
		Urban Area	Rural Area		
Solid Slab with P-T	50	5.40	6.11	6.40	6.0
Double T (FLET)	60	5.91	6.44	6.60	6.3
FDOT PSU	50	7.90	7.33	7.45	7.6
Type II Box Beam	86	5.78	5.88	5.50	5.7
Texas Box Beam	60 (for 20" ht)	6.22	6.38	6.56	6.4
Minnesota Flat Slab	53	6.63	6.00	6.00	6.2
Truncated FIB	63	6.00	6.50	5.75	6.1
Super T Beam	79 (for 30" ht)	6.22	6.50	6.63	6.4
AASHTO Type II Beam	70	6.73	6.67	6.40	6.6

In addition, a few comments were provided for each of the superstructure types. A total of 11 individuals contributed with additional comments from the rating process. A summary of their responses is provided. For **Solid Slab with P.T** (Figure 2.72) some indicated that they had used solid slab with P.T with a topping, and the benefit was that they were able to drive on the slabs immediately after being set. Others found that The PT does help with live load distribution between the slab units, but it complicates future widening and phase construction. Moreover, it has been found that on many of the solid slab with P.T the transverse connections between the slabs beams have failed. The result is the beams are not deflecting equally under traffic load and continual maintenance of the wearing course due to reflective cracking is necessary. Other issue was that Solid Slab with P.T with void slabs produced problems with differential camber between the units. Some suggestions for considering a Solid Slab option is to use closure pours b/w slabs, similar to those shown for Double Tee, and eliminate the P/T. Comments for **Double T (FLET)** (Figure 2.72) is that some had never used them and other stated that the sections are very heavy and only one piece at a time can be transported. However; they were easy to handle. **FDOT PSU** (Figure 2.72) advantage is that the FDOT PSU could be driven on, so keyway grout could be poured right out of the ready-mix truck. Some had also used the FDOT PSU beams on several county projects. They typically use 2 layers of steel which requires a little thicker CIP section. This design has successfully locked the individual slab units together and has prevented any cracking from reflecting up to the deck surface. One disadvantage is that they generally had longitudinal cracks through the topping above the shear keys and live load distribution could be questionable in some cases. For **Type II Box Beam** (Figure 2.73)**,** the recommendation was to use sacrificial form. As for Urban Area, ability to widen in future is needed; which would be the reason why transverse p/t is not preferred. For the **Texas Box Beam** (Figure 2.73) only one individual mentioned that they generally had longitudinal cracks through the topping above the shear keys. Also live load distribution could be questionable in some cases. **Minnesota Flat Slab** (Figure 2.73)**:** for this one they had more confidence in live load distribution due to the stirrups in the blockouts between units. Minnesota flat slab only requires one concrete placement without PT or placement of key or closure concrete which should make it very fast when construction duration is critical. The units are also lighter than the other systems, so they have excellent constructability. **Truncated FIB** (Figure 2.74) it was used on a widening project where vertical clearance was an issue. At the time of the response it was early in the project, but they had run some preliminary analysis and had found that the release stresses can easily control the design and were likely going to need to add some steel near the top of the Tee. Moreover, a few never built any of these because of the need for SIP forms and greater superstructure depth which usually make them less attractive than a flat slab system for shorter spans. For **Super T Beam** (Figure 2.74) recommendation to use sacrificial form. As for Urban Area, ability to widen in future is needed; that's why transverse p/t is not preferred. Some claimed to have longitudinal crack concerns for Super T. A comparison was made between Super T Beam with the Florida U-beam which is typically only used if there are aesthetic criteria to be met, not because it is economical. They expected this would be similar behavior. For **AASHTO Type II Beam** (Figure 2.74) only one comment was made to express that they had built a lot of these and they had worked [46].

CHAPTER 3. JOINTS AND CONNECTIONS

3.1. Abstract

Regardless of the type of prefabricated elements to be used in construction of ABC (Accelerated Bridge Construction) bridges, the elements, systems and subsystems need to be made integral with the use of joints and connections established in situ. To effectively design a bridge system that resists design loads the components must be connected successfully. These connections are commonly supposed to perform equally to a conventional connection as they are planned to be emulative. Commonly, Ultra-High-Performance Concrete (UHPC), Self-consolidating Concrete (SCC), and other high- and normal-strength, fast-setting, early strength concrete mixes are used to decrease the potential defects. However, precautionary measures should be taken to minimize maintenance problems and improve durability.

Closure pours (joints) can be defined as joints for connecting the bridge deck elements to each other, connecting the bridge deck elements to the substructure, connecting superstructure to substructure as well as substructure elements to each other, and to foundations. Therefore, selection and design of the type of closure joints may depend on type of prefabricated elements.

In some literature, Closure Joint has been defined as joints in the bridge deck, connecting deck slab elements to each other and to the pier or abutment cap. Categorization of closure joints have been established in various ways depending on the application, geometrical features, or structural details.

ABC connections and joints play an important role and their application and limitations need to be understood. This module will deal with identifying the type of joints and connections between the superstructure, substructure, and foundation, and between their prefabricated elements as it applies to short-span bridges.

3.2. Joints and Connections

In an ABC bridge construction, joints and connections are needed to attach the prefabricated elements to each other as well as using between foundation, substructure, and superstructure (Figure 3.1 and Figure 3.2). The design and details of joints and connections in bridges that use prefabricated elements should at a minimum satisfy the same conditions as connections in cast-in-place bridges to provide enough durability and integrity for the structure [47]. Also, performance such as ductility, energy dissipation, strength, stiffness and failure modes need to be comparable to cast-in-place system in seismic region. The main characteristic of emulation design is to provide a substitute connection that emulates the standard lap splice of cast-in-place concrete structures [8]. In other words, "Emulating connection detailing" and design is used to make the precast structural elements behave as they are monolithic [48]. Accordingly, various connection types have been developed and validated for prefabricated elements including welded ties, mechanical couplers, small closure pours, closure joints, socket and pockets, and grouted tubes with reinforcing dowels.

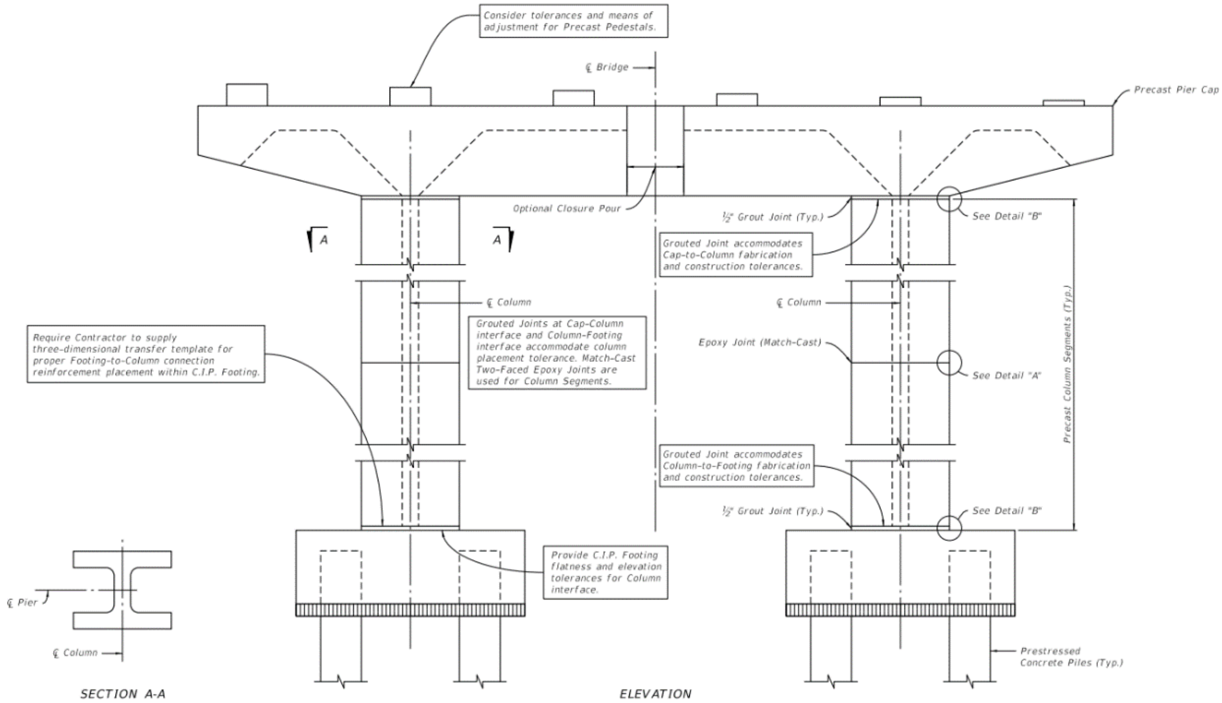


Figure 3. 1 Prefabricated Bridge Connections Example [8].

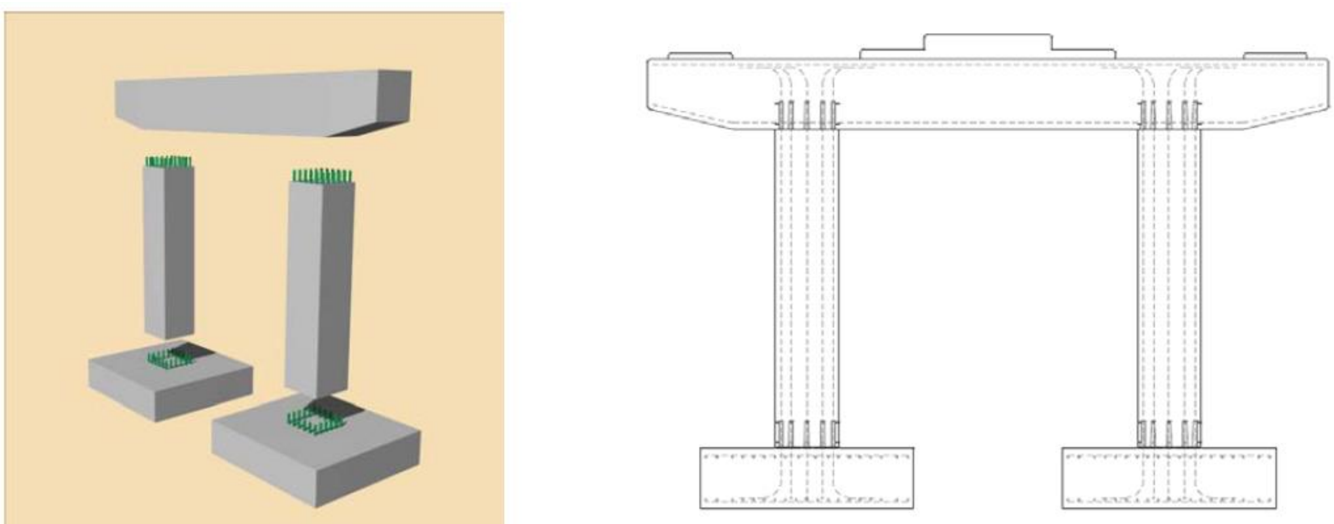


Figure 3. 2 Prefabricated Bridge Connections [8].

3.2.1. Typical ABC Connection Types:

Prefabricated connections can be categorized into different common types and groups. Depending on what type of elements (material) they connect, ABC joints can be divided into those connecting steel elements and others connecting concrete elements [8]:

3.2.1.1. Steel Elements:

3.2.1.1.1. Bolted:

This process have been used for many years to connect prefabricated bridge elements. It can be used for transverse connection of modular double tee units and also adjacent units diaphragms plates that are joined together by bolt connections [8]. Depending on the type of connection, the process of bolting can be fast or slow. For example, due to a larger number of bolts required, girder splices are slow connections [8]. Figure 3.3 shows and example of a bolted girder [49].

Figure 3. 3 Example of bolted connections from Ohio's Muskingum County Bridge [50].

3.2.1.1.2. Welded:

Lately, many states have expanded the use of welding and have developed procedures that take into consideration the factors that affect the use of field welding. These factors include lack of certified field welders, concerns with quiality of field welds, and time and difficulties with welding in colder environments [8]. This type of connection is preferable for ABC application as connections can be completed quickly. It can be used to connect steel girders to panels, for which, first steel plate is positioned in a specified place on the panel, and then the girder and the panel are welded together.

3.2.1.1.3. Cast-in-Place Diaphragms to Connect Steel Girders:

One of the means to connect steel girders or modular superstructure elements with steel girders at the pier location is the use of cast-in-place closure pours (diaphragms). This configuration, as it pallies to ABC construction, normally creates simple span for dead load and contious span for live load (SDCL). The connection can be established in different ways. Inclusion of top reinforcement in the deck level for transfering negative moments between two girdes, and shear studs welded to the top and/or bottom flange of the steel girders are performed in some cases. The use of steel bearing blocks between the bottom flanges of the steel girders over pier has been used as one means for transfering compressive forces in the bottom flanges from negative moment at the pier. Closure pour assures the live load continuity connection and goes to steel member by bearing plates or welded stud shear connectors [8]. Recently, a SDCL joint that in addition to the details discussed above includes horizontal steel ties at the bottom flange level to assure that the joint would perform properly in the seismic application. This system is discussed in more details later in relation with superstructure to substructure connections. These connecctions have shown to perform excellent in seismic regions and offer good constructability under bi-axial horizontal seismic loading [51]. Figure 3.4 shows an example of the construction sequence for simple for dead load and continuous for live load (SDCL)

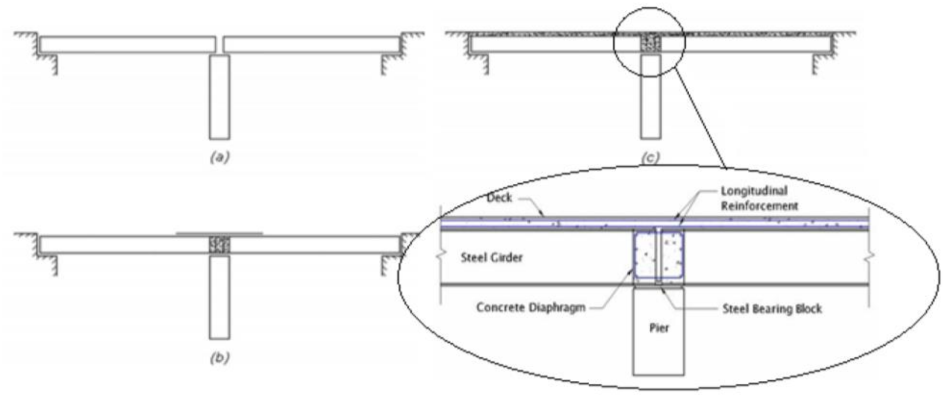


Figure 3. 4 Construction sequence for SDCL Bridge Systems [52].

3.2.1.2. Concrete Elements:

In the following, some of the common types of connection between concrete elements are discussed.

3.2.1.2.1. Grouted Reinforcing Splice Couplers:

Couplers have been developed by various manufacturers that can splice reinforcing steel bars within precast elements. These couplers are in the form of a pipe. Elements are connected by the couplers and then grout is cast in the joint cavities and pumped into couplers to establish the connection. This connection is desirable for substructure as large diameter bars can be spliced in less distance than conventional development lengths. These types of connections can develop 125%, 150% and up to 160% of yield strength of the connected bars [8]. Figure 3.5 shows a grouted Reinforcing Splice Coupler.

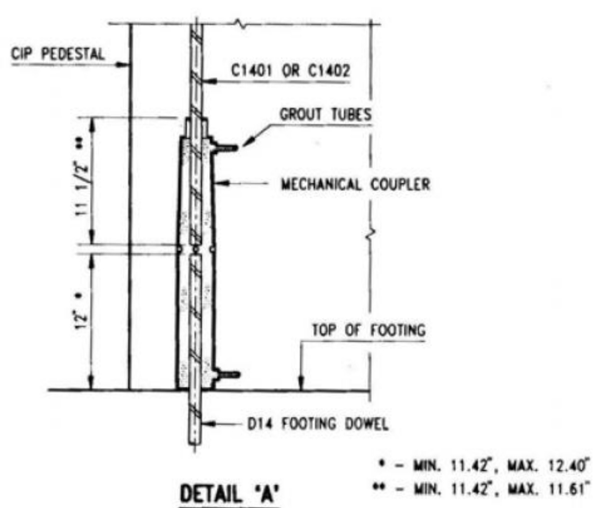


Figure 3. 5 Grouted Reinforcing Splice Coupler [8].

3.2.1.2.2. Using Grouted Post-Tensioning (PT) Ducts:

These connections are similar to the grouted reinforcing splice couplers with the difference that the reinforcing bars from one element are inserted into non-structural ducts (post-tensioning duct segments) cast in the receiving element. Because the ducts are non-structural, normally, confinement reinforcement will be required to develop the connection. For seismic areas that require plastic hinging connections, these types of connections are not recommended as they do not have the required ductility to perform in a high seismic zone [8]. Figure 3.6 shows a grouted reinforcement PT duct layout [8].

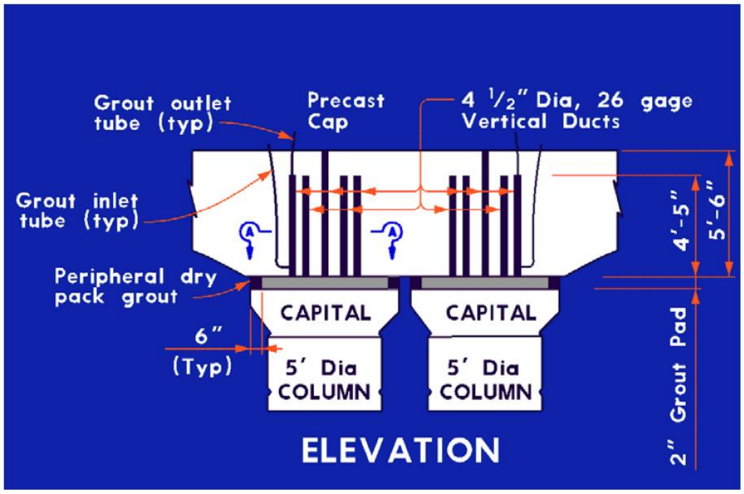


Figure 3. 6 Grouted Reinforcement PT Duct Layout [8].

3.2.1.2.3. Grouted Voids:

These types of connections are used in connections that transfer little moment between elements, such as pin connections. In contrast to grouted reinforcing splice couplers, the coupler is substituted with a void cast in the element [8]. Figure 3.7 shows an example of grouted placement [8].

Figure 3. 7 Grouted Placement [8].

3.2.1.2.4. Traditional Post-tensioning (PT):

Post-tensioning connections between pieces in a segmental box girder bridge is considered the most common type. It can also be used in pier caps, pier columns, and precast concrete bridge decks. Connection of deck elements using post-tensioning combined with grouted shear key is also common [8]. Figure 3.8 shows typical post-tensioning details [8].

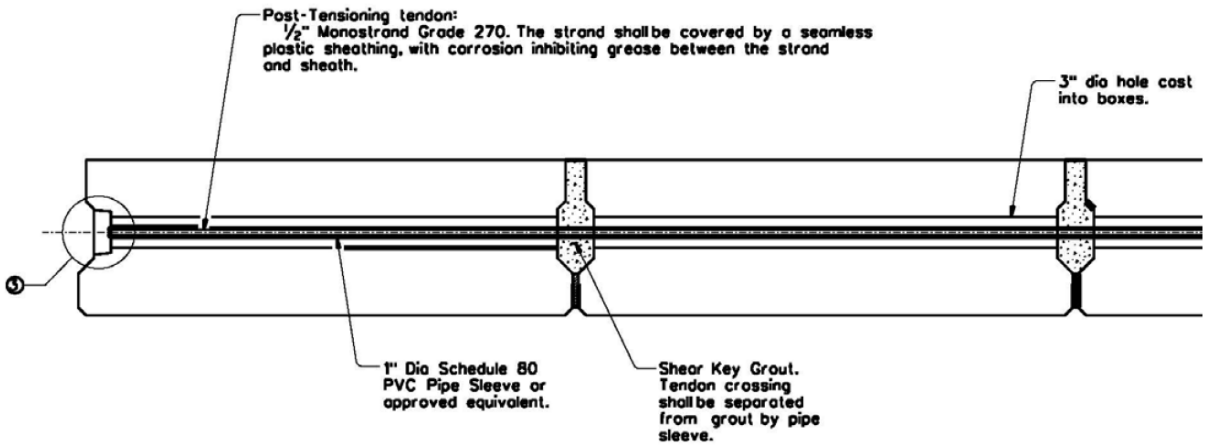


Figure 3. 8 Lateral Post-Tensioning Details [8].

3.2.1.2.5. Welded connections:

As stated above, welding can be used to connect precast elements. Normally, welded connection is made after erection using the steel plates that are embedded in the elements [8]. Figure 3.9 Shows details of welded plate connection.

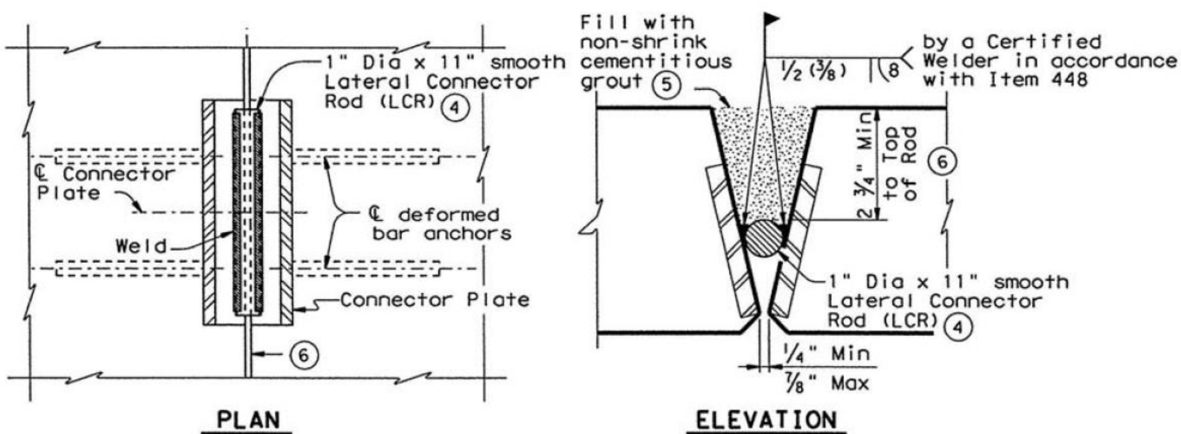


Figure 3. 9 Lateral Welded Plate Beam Connection Details [8].

3.2.1.2.6. Cast-in-place Concrete Closure Pours:

This type of joint is considered one of the simplest connections as only an area is left to pour concrete to allow an effective connection between two precast concrete elements [8]. Figure 3.10 shows examples of various types where cast-in-place concrete closure pours is performed.

3.2.2. Superstructure element connections

Joints for connecting the bridge deck elements to each other and to the substructure are generally called closure joints. Selection of the type of closure joints is subject to many different factors. It may depend on functional requirements, type of substructure, environmental conditions, type of material selected for closure joints, type of deck elements, time constraint, necessity for continuity for shear and bending transfer, etc. Figure 3.10 has examples of various types of ABC closure joints. Additionally, use of proper concrete with characteristics such as high- and normal-strength, early strength, fast-setting, Self-Consolidating Concrete (SCC), and Ultra-High-Performance Concrete (UHPC), assure the closure joints are less vulnerable to defects and discontinuities [11].

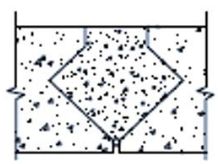
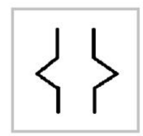
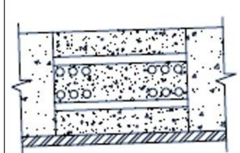
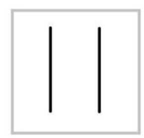
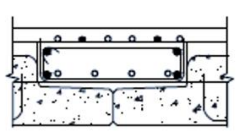
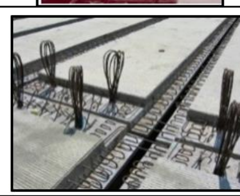
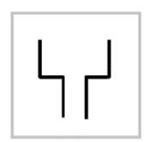
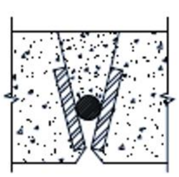
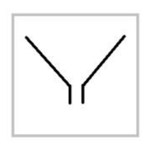
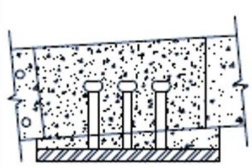
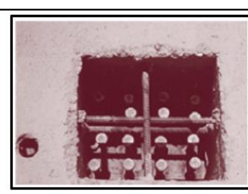
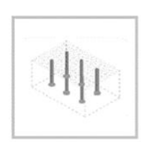
Figure 3. 10 Examples of various types of ABC closure joints [8], [53], [54], [55]

3.2.2.1. Deck Connections

Deck connections are defined as connections joining the deck slab segments to each other and to the girders and diaphragms. Deck connections can be categorized in different ways. Definitions may vary based on the purpose of categorization. Hence, the following descriptions and definitions adopted from different sources may overlap and, in some cases, disagree. However, for completeness, these definitions are covered in the following with reference to the specific approach adopted for such categorization.

Categorization based on geometric features: According to Mehrabi and Farhangdoust (2019) closure joints can be subdivided into five different types when considering the geometric features and type of anomalies influencing the use of NDT methods for evaluation of these joints [11]. These five groups of closure joints are represented in Table 3.1. The first four joint types in this table are linear joints which are used for connecting deck panels to girders, deck panel to each other, and to abutment/piers longitudinally and transversely (Figure 3.11). Longitudinal joints will be required only where multiple panels are needed across the bridge width. Joints should all be detailed and designed as full moment connections [56]. Finally, the last joint type (Type 5) is mostly used for connecting deck panels to the girders through pocket-type joints called blockouts [11].

Table 3. 1 Different types of closure joints [57].

Group	Sample		Symbol
Type 1			
Type 2			
Type 3			
Type 4			
Type 5			

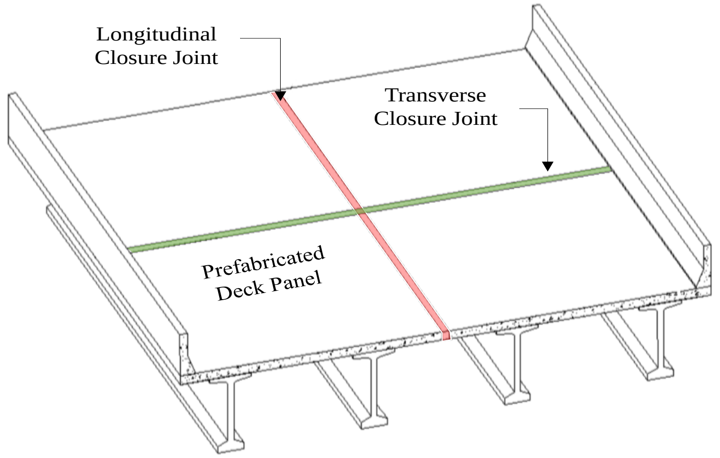


Figure 3. 11 Schematic view of linear closure joints [58].

The most common closure joints are categorized in the above table are described below [57].

3.2.2.1.1. Closure Joint: Type 1

This type of closure joint is normally used to connect Full-Depth Precast Desks and sometimes for connecting precast beams [8]. This joint may come in different shapes, such as rectangle and diamond-like in order to provide shear transfer. These joints are also known as shear-key or keyway joints and depending on the application are used longitudinally and/or transversely. The shape is prone to debonding, voids and porous grout formed in the corners. Also, sharp corners may contribute onset and propagation of cracks [59]. Figure 3.12 shows an example of Type 1 joint.

Figure 3. 12 Type 1 joint [11].

3.2.2.1.2. Closure Joint: Type 2

This type of joint is used to connect precast desks to precast concrete beams and Full-Depth Precast Desk to each other. This type of connection is differentiated from others by its near straight sides which allows smoother placement of concrete and decrease the possibilities of creation of voids [8]. For the case when this connection is used to connect the slabs to the girders, shear reinforcement is extended into the joint channel to transfer the horizontal shear. This type of joint is usually cast with self-consolidating non-shrink grout and can also be used to provide negative moment and continuity at the piers [8]. Figure 3.13 shows an example of Type 2 joint.

Figure 3. 13 Type 2 joint [11].

3.2.2.1.3. Closure Joint: Type 3

This linear joint is normally used to join butted decked precast girders, partial depth precast deck panels and sometimes to join steel girder superstructure with P/C Slab longitudinal connections [8]. This joint usually contains longitudinal and transverse reinforcement and may be used in both directions of longitudinal and transverse. Also, for unreinforced joint, post-tensioning can be used [8]. Moreover, where projecting tie bars of panels were bent and used as reinforcement in the connection this type of joint can be used to connect precast PT tub girders to precast deck slabs. Also, it can be used as a partial-depth link slab or transverse joint to provide negative moment and continuity at the piers [8]. Figure 3.14 shows an example of Type 3 Cross Section.

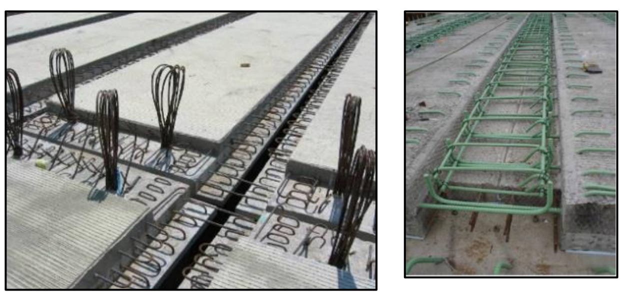


Figure 3. 14 Type 3 Sample Cross Section [11].

3.2.2.1.4. Closure Joint: Type 4

The last linear joint of Table 3.1 is only casted in the longitudinal direction and it refers to those that connect double beams or two prestressed tee beams, and sometimes partial or full depth deck panels. To fill this type of joint a non-shrink cementitious grout is what is normally used. Additionally, a layer of leveling surface is expected to be cast over the deck including this type of joint [11]. Figure 3.15 shows an example of Type 4 Cross Section.

Figure 3. 15 Type 4 joint [11].

3.2.2.1.5. Closure Joint: Type 5

This type of joint refers to blockouts which are box/rectangular shaped joints. They usually connect steel girders or concrete I-beams to precast full depth decks and are spaced throughout the decking. Usually shear connectors are extended into the blockout void and void is cast using high-early strength concrete. If necessary, adhesive tape can be used to prevent leaking by sealing the bottom of the joint [8]. A layer of leveling surface is expected to be cast over the deck. Care should be taken in installation of jointed elements since deck reinforcement may need to be adjusted for cases where steel reinforcement crosses the joint. Moreover, sometimes the joint can be used in combination with grouted linear shear key joint [11]. Additionally, UHPC joints and grout-filled deck pocket connections between adjacent deck panels are capable of providing structural integrity under earthquake loading [51]. Figure 3.16 shows an example of Type 5 joint.

Figure 3. 16 Type 5 joint [11].

Categorization based on mechanical and material aspects: Another way to classify the different types of closure joints is following categorization suggested by Garber and Shahrokhinasab (2019) for several common joints used in practice for joining precast full-depth deck panels. The joints were subdivided into different categories: post-tensioned, mechanical, ultra-high-performance concrete and conventional concrete as shown in Figure 3.17. These types of joints are described in the following.

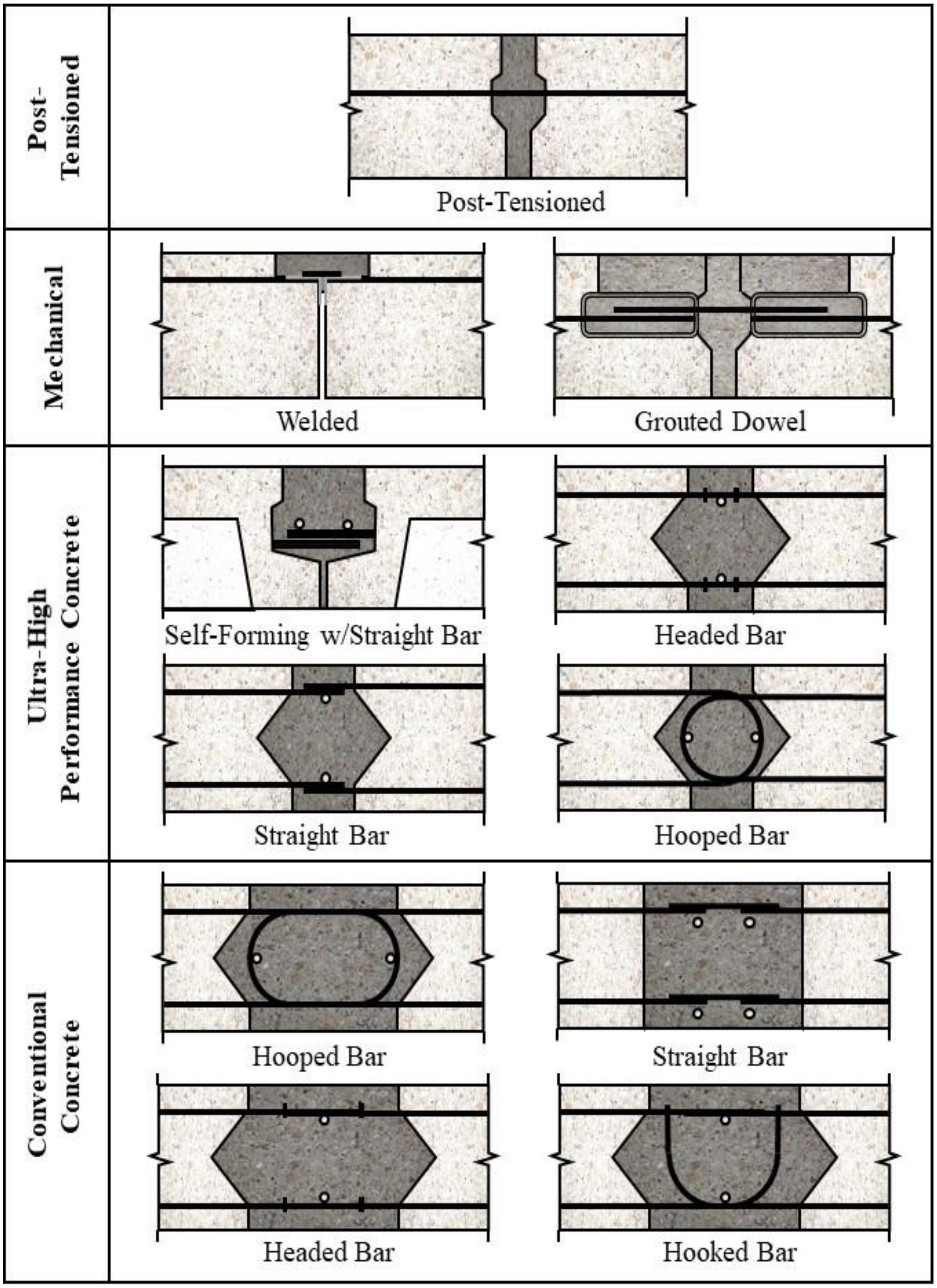


Figure 3. 17 Common types of longitudinal and transverse joints in FDPC Deck Panel Database [60].

3.2.2.1.6. Longitudinal Post Tensioning with Grouted Shear Key:

Use of non-strands, flat multi-strand tendons and high strength threaded rods is typical for longitudinal post tensioning. Post tensioning usually runs along entire length of the bridge and is located at the mid depth of the panels. This type of connection is the most common transverse joint detail that has been used as it is considered a good way to improve durability of the system. Male-to-female (Figure 3.18 b) match-cast joint with epoxy or grout, or female-to-female (Figure 3.18 a) joint with a small grouted section between panels can be used for post tensioned joints [60].

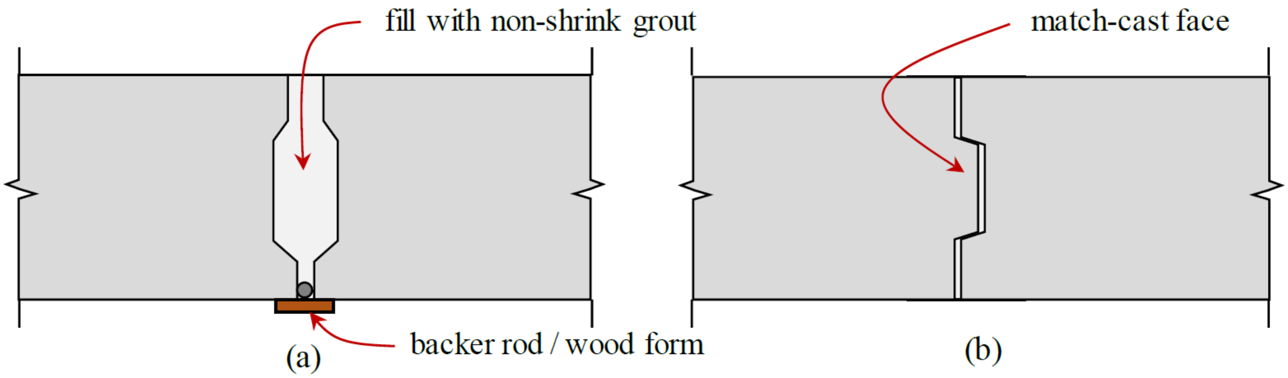


Figure 3. 18 Typical longitudinal PT joints: (a) female-to-female and (b) male-to-female match cast [60].

Blockout joints which are pockets cast in the slab produce the composite behavior between girders and deck panels. Shear studs are extended from the beam into the grouted pockets as seen in Figure 3.19 [58].

Figure 3. 19 Shear pocket used to create composite action between beam and deck [8].

3.2.2.1.7. Mechanical Connections:

The grouted reinforcing dowels placed in slotted connection is one of the options to connect precast deck panels [58]. Results from investigation related to NCHRP project 12-65 showed that development length could be shorter thanks to the confinement given by the steel box containing the connection. The use of this connection in Live Oak Creek Bridge in Texas is shown in Figure 3.20 [58].

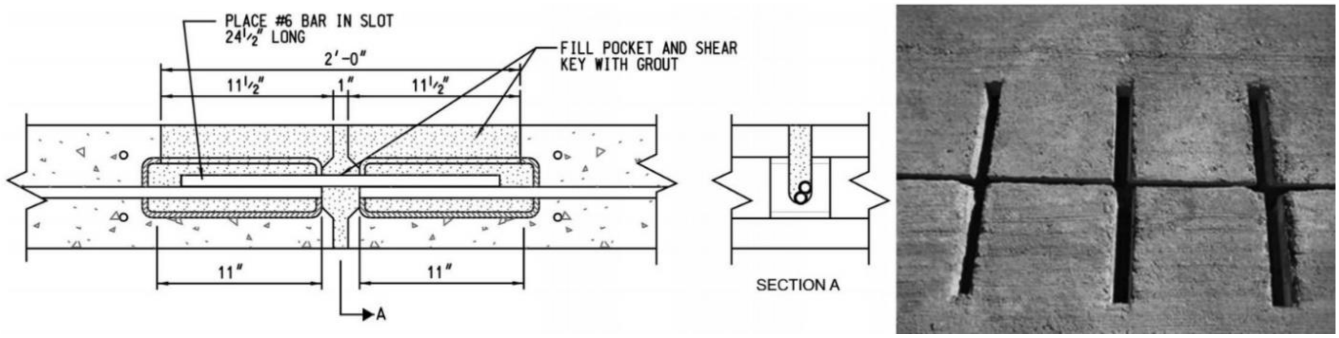


Figure 3. 20 Transverse connection at Live Oak Creek Bridge, Texas [8].

The other option is the use of welded or bar coupler. However, due to corrosion affecting the long-term performance, this type of connection is not used anymore as bridges with welded tie connections can experience leakage between deck panels [58].

3.2.2.1.8. UHPC with Straight Bar:

This type of connection can also be used in longitudinal and transverse joints [60]. Many experimental tests have been conducted investigating the bond behavior reinforcing steel encased in UHPC. These investigations have concluded that UHPC can meet the development requirement generally in shorter lengths when compared with normal strength concrete [58]. Therefore, width of closure joints can be reduced in this case. Additionally, durability and long-term performance makes UHPC a supreme alternative for closure joints [61]. An example of closure joint using UHPC is shown in Figure 3.21

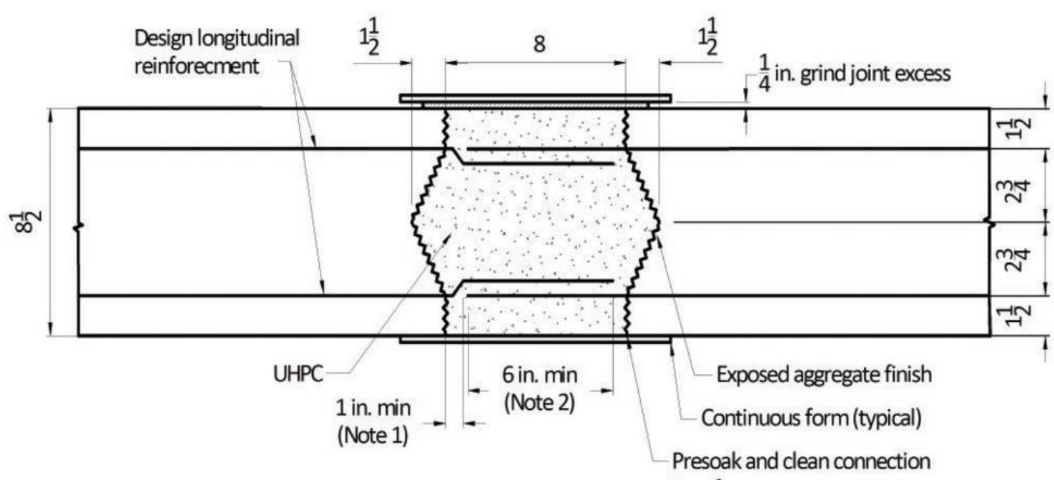


Figure 3. 21 Closure joints detail using UHPC [61].

3.2.2.1.9. Conventional Concrete with Hooped or Straight Bars:

This type of connection whether with straight or hooped bars can be used for longitudinal and transverse joints. However, it is mostly used in the longitudinal direction as it requires a wide closure pour. As it has a wider width, the shear studs and reinforcement are easily placed, and the top of girder can be used as base form for the joint. Figure 3.22 shows an example [60].

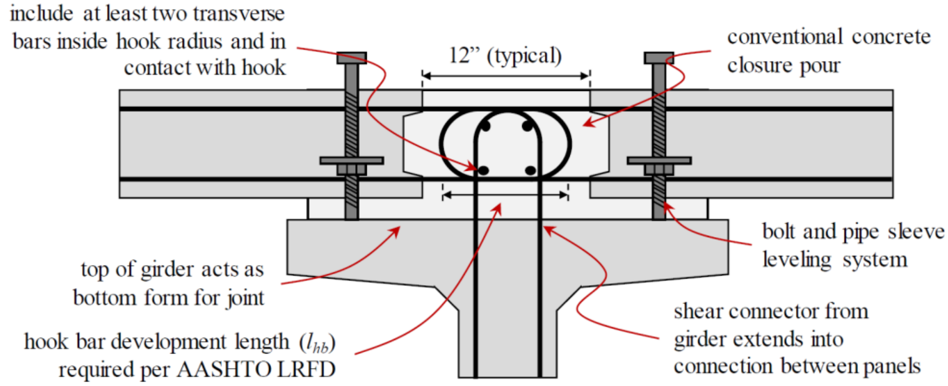


Figure 3. 22 Schematic of conventional concrete longitudinal joint over girder [60].

Some other definitions for superstructure joints are included in the following.

Linear joints can be divided into two types, non-grouted male-female (Figure 3.23) and grouted female-to-female joint (Figure 3.24) [8]. For non-grouted joints, in order to connect the panel and keep them together, a longitudinal post-tensioning bar is used. Before post-tensioning is applied, sealant or epoxy is applied at the interface. For the case of grouted female joints, non-shrink grout is typically used as filler. The performance of this type of connection is considered acceptable if shrinkage or service loads do not produce cracks and leakage does not occur through the joint [62]. Moreover, to resist shear and bending moment and to distribute traffic live load, the longitudinal reinforcement (Figure 3.25) in panels can be doweled or spliced within the joints [8].

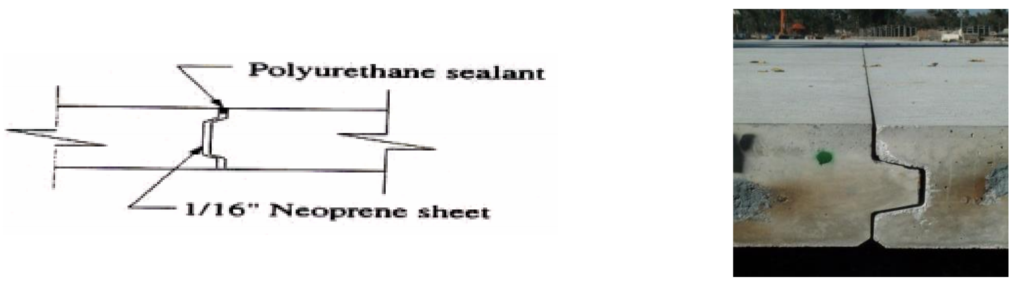


Figure 3. 23 Non-grouted panel to panel (male-to-female) joint [[56], [58]]

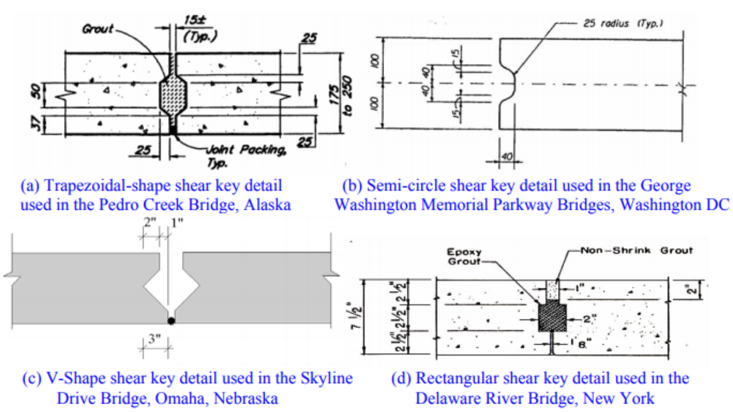


Figure 3. 24 Various types of female-to-female joint [62].

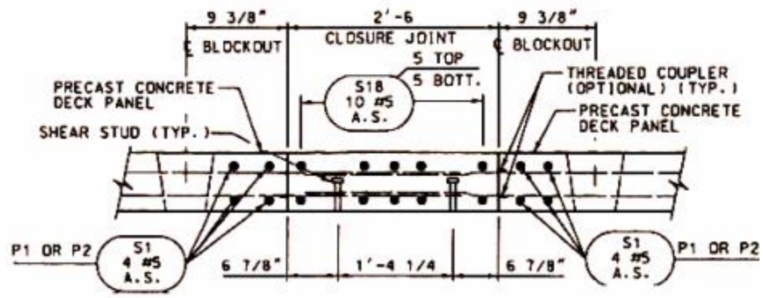


Figure 3. 25 Longitudinal reinforcement [62].

Blockouts are pockets left in the precast panels, and they are used to connect the precast panel to concrete girders. Shear studs and/or reinforcement embedded into the pockets transfer shear between two connected elements (Figure 3.26). Composite action between deck and supporting girders can be achieved by the use of shear pockets and shear studs (Figure 3.27) preventing any vertical or horizontal movement [60]. This type of connection is easily accessible, has little deformation and can experience high shear and bending moment. Also, linear closure joints with headed steel studs can establish the connection of precast deck panels to girders and piers [62].

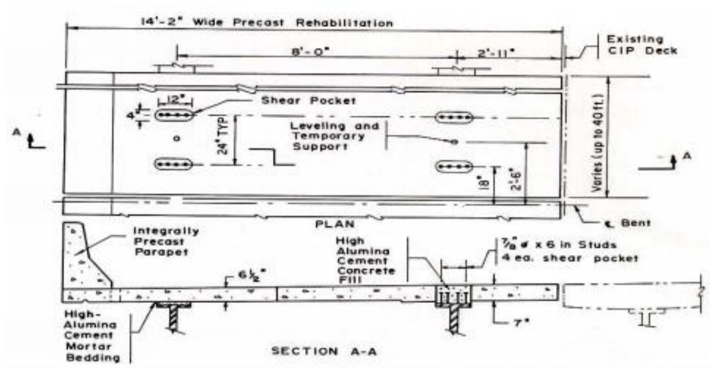


Figure 3. 26 Panel to girder connection detail [62].

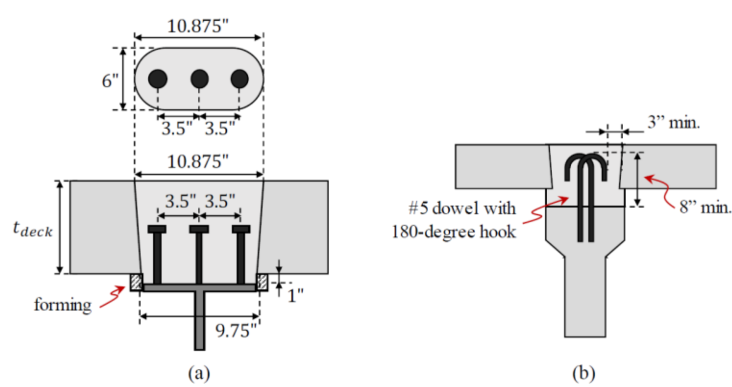


Figure 3. 27 Examples of shear pocket and connector details for (a) steel plate girders and (b) prestressed concrete girders [60].

It is also important to mention the use of a leveling device (Figure 3.28) when there is an irregularity due to inconsistency in the panels or supporting members. Leveling is done by colocating a threaded socket in each panel corner. A bolt is then threaded and wrenched to adjust the elevation [62].

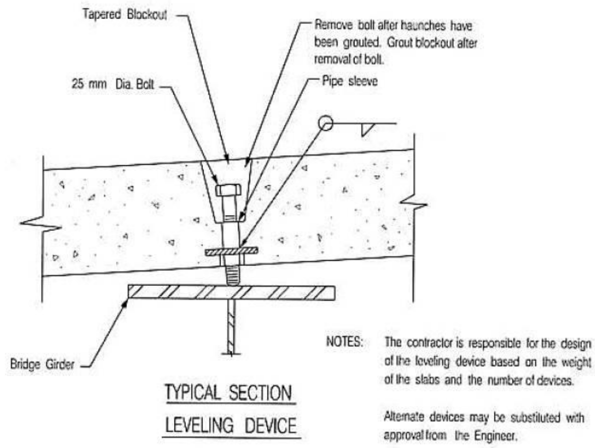


Figure 3. 28 Leveling bolt [12].

It is also important to mention that proper material selection is critical for these connections for the long-term performance of the system. For example, high early strength concrete can develop shrinkage and excessive cracking can occur which will result in gradual deterioration [6]. Also, strength is gained at different rates in different materials. This has to be considered when the connection design anticipates load carrying during material curing time. For example, UHPC requires several days to finally obtain the ultimate strength anticipated for the connection [6]. Fast-setting concrete, high and normal-strength concrete, Ultra-high Performance concrete and Self-Consolidating concrete (SCC) are mixes normally used to fill closure joints [11].

3.2.2.2. Expansion Joints and Link Slabs

Another important component to mention for the superstructure is the expansion joint. Expansion joints are considered one of the most problematic components of simple span bridges. They are known for providing a gap for the deck system and bridge girder to expand, contract, and rotate. These joints can cause durability problems due to the gap as it allows the entrance of corrosive materials and resulting in faster deterioration of the underlying structure. For this problem, one solution is the application of link slabs. They can create a continuous bridge deck system by replacing the expansion joints over the piers and maintaining a simply-supported conditions under the deck. This will effectively eliminate the ingress of corrosion but will be subjected to axial forces and high moments by the service and thermal loading of the supporting girders. Therefore, link slabs must be designed so they can withstand the tensile loads and maintain crack resistance properties to avoid penetration of corrosive materials [63]. Moreover, UHPC joints cast over the piers can be designed to have adequate structural integrity to bear severe earthquake loading [51].

3.2.2.3. Connection between deck/superstructure and substructure

Superstructure can simply sit on the pier or abutment using rollers, rockers, neoprene pads and similar for non-integral pier or abutment type. On the other hand, connections can be established between superstructure and substructure to accommodate integrity (semi or full). Some of such connections are presented in the following with more covered later in the substructure connection sections.

3.2.2.3.1. Simple for Dead Load Continuous for Live Load (SDCL)

SDCL joint was introduced earlier in this report in relation with superstructure connection. Here, SDCL joint is described in relevance to superstructure to substructure connection. This system is suitable for short and medium span bridges [52]. In SDCL system, girders span from abutment to pier, or from pier to pier. For the superstructure consisting of steel girder and cast-in-place deck, spans are simply-supported when deck is cast. After the deck is cast and cured, the deck reinforcing steel provides continuity for live load and superimposed dead loads. For the case of ABC bridges where modular girder systems consist of steel girder pre-topped with deck slab, the slab dead load is transferred to the modular system as simply supported. After the continuity joint (SDCL) is established between two adjacent spans, the remaining future superimposed dead load and live load are carried by continuous spans. Compressive forces are transferred between the bottom flange through devices such as steel bearing blocks, shear studs, ties and concrete providing continuity for carrying negative moment at the pier location. An example of SDCL joint can be seen in Figure 3.29 [52].

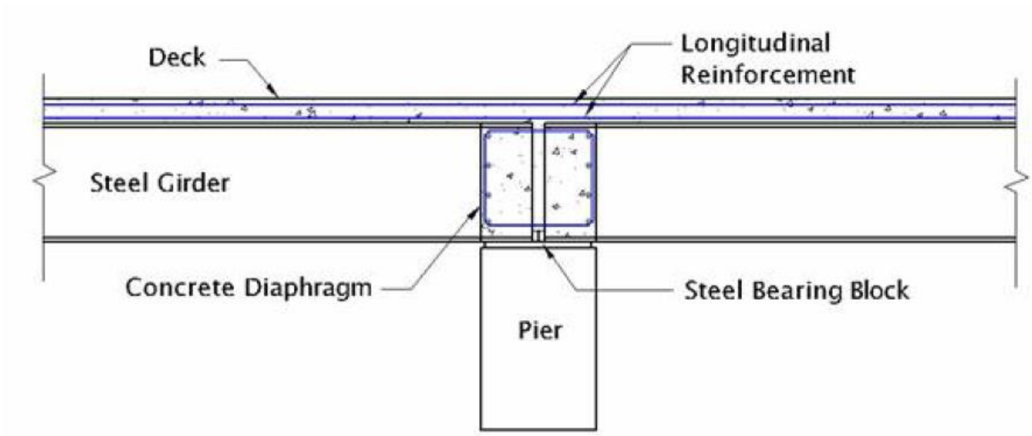


Figure 3. 29 Simple for Dead and Continuous for Live connection detail [52].

This system is appropriate for ABC technologies as individual spans can be built off-site and can be joined over the piers after being transported to the site [52]. This system can have a higher service life as there is no expansion joint or bolts in the connection. The construction process follows the simply supported spans located over the piers, then connected through concrete diaphragm and finally deck becomes continuous for live loads [52].

This system has been proven to be economical for non-seismic application (Figure 3.30). However, new research from Florida International University proposes a connection (Figure 3.31) that performs adequately under seismic forces as well. Experimental work was performed on truncated system in the lab as well as complete two-span bridge specimen on shake tables. After the experimental phase culminated, connection behaved as designed and sufficient ductility was noticed, therefore, connection was proven to perform effectively under high levels of displacements [64].

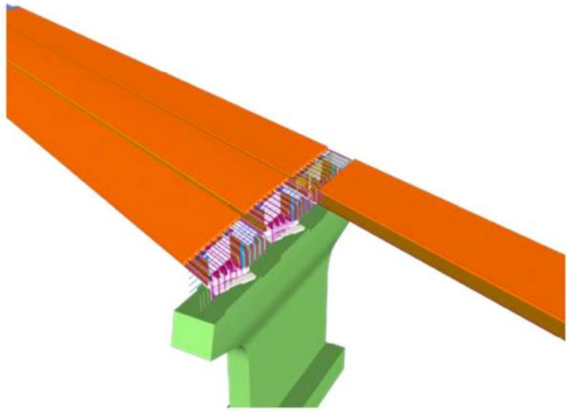


Figure 3. 30 ABC Application of SDCL in non-seismic areas [64].

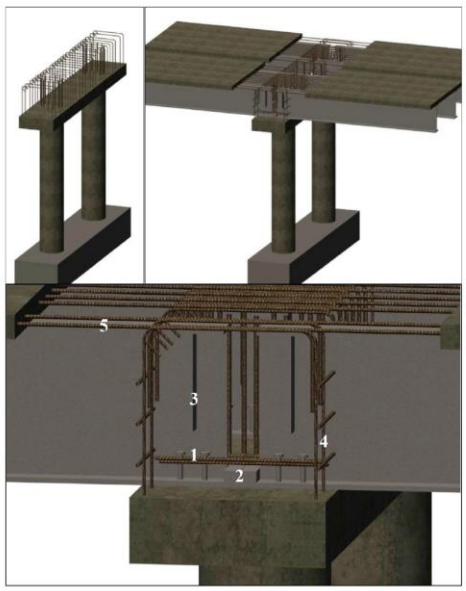


Figure 3. 31 Schematic view of developed SDCL connection details for seismic areas [64].

3.2.2.3.2. Integral and semi-integral abutment

Construction of abutments integrally with the superstructure has two significant advantages when comparing to the conventional free-standing abutment construction. Integral and semi-integral abutments have no deck joints and transfer embankment soil force to the superstructure [4]. In the fully integral abutment, the abutment connection to the superstructure is a full moment connection. However, in semi-integral abutment which a portion of the abutment is constructed with the superstructure, a system comparable to pin connection is used to allow the rotation of superstructure in respect to the substructure [4]. Figure 3.32 shows an example of Semi-integral abutment used by the New York State DOT. Moreover, figure 3.33 is an example of a precast integral abutment from Utah DOT. It shows interaction between a variety of elements in the colure pour. Details shows a separate backwall element that can possibly be made integral with the stem if beam depths are not excessive [6].

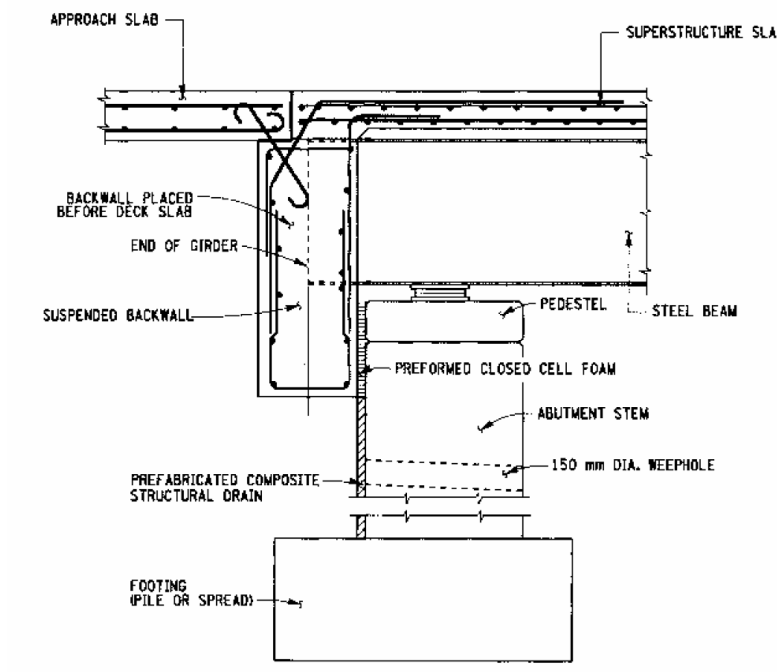


Figure 3. 32 Semi-integral abutment [65].

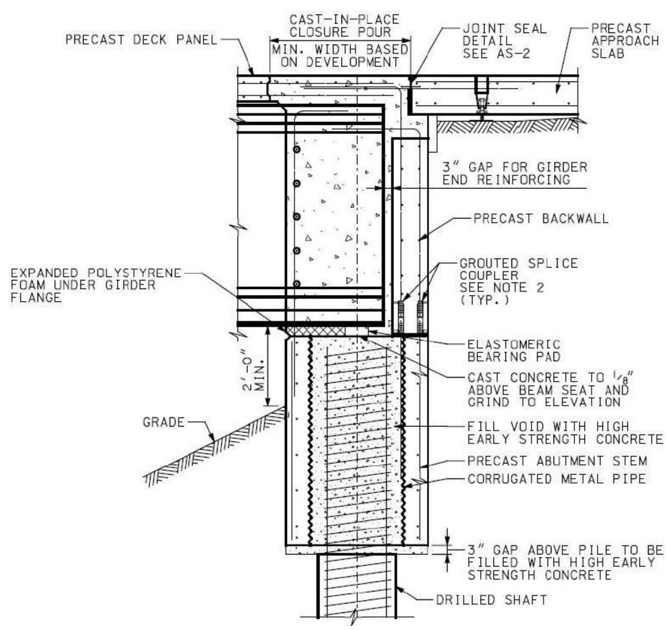


Figure 3. 33 Prefabricated integral abutment [6].

Recently, a research project was completed as a part of ABC-UTC program that investigated the constructability of abutment details and evaluated the strength and durability of abutment connections [66]. This project has produced a guideline to facilitate the use of integral abutments in the ABC projects. Design details of two integral abutments was provided. Figure 3.34 shows UHPC connection of the specimens tested in this study, and Figure 3.35 shows schematic of UHPC-joint connection of the integral abutment systems proposed for ABC projects. According to Hosteng and Shafei (2019), the integral abutment connection with the use of UHPC was designed to be used with slide-in-construction. UHPC was chosen due to its high strength, good flowability, and impermeability. For this type of connection, the design would include a mechanical coupler, specifically Dayton Superior D310 Taper-Lock Standard Couplers [67]. The second type of connection can be seen in Figure 3.36 which shows the Grouted reinforcing bar coupler (GRBC) connection tested in the study and Figure 3.37 is a schematic GRBC proposed in the Guideline [67]. The design of this connection includes typical cast-in-place integral abutment and insertion of grouted reinforcing bar couplers. For this type of connection, a slide-in construction is not possible. However, any other alternative as crane or SPMT's is feasible [67].

Figure 3. 34 Integral Connection: UHPC Connection [66].

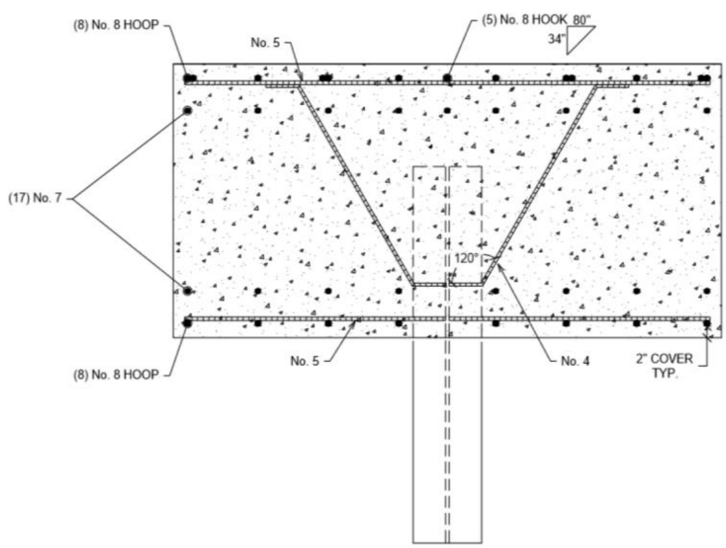


Figure 3. 35 Plan View of UHPC-Joint specimen [67].

Figure 3. 36 GRBC integral diaphragm completed [66].

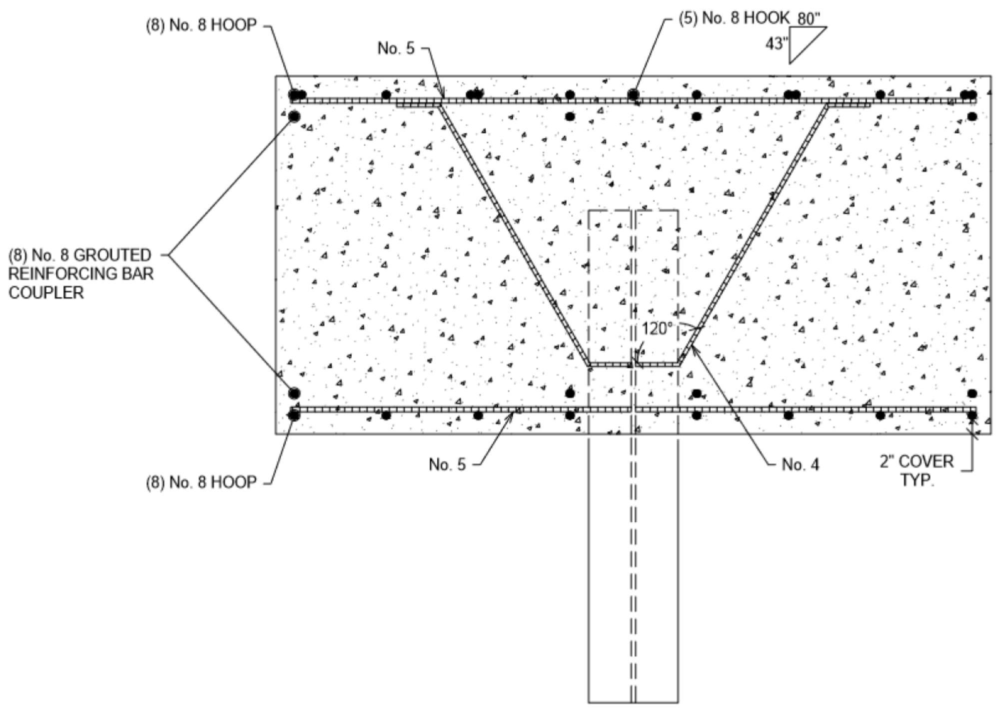


Figure 3. 37 Plan view of GRCB specimen connection [67].

3.2.2.4. Precast Concrete Bridge Barriers Connections:

Bridge barrier is an important safety component as its purpose is to shield, redirect and contain vehicles in case of a bridge accident. Iowa State University performed a research to present two connection alternatives between the precast barriers and the deck as part of research performed at ABC-UTC [68]. The literature review they completed showed the following types of connections:

There are three commonly used concrete bridge barrier shapes [68]. Profiles shapes can be seen in Figure 3.38

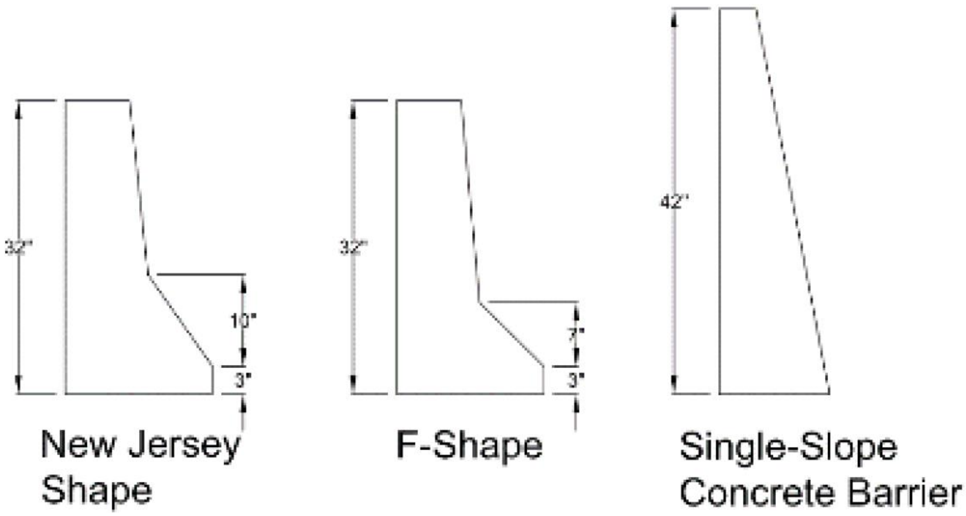
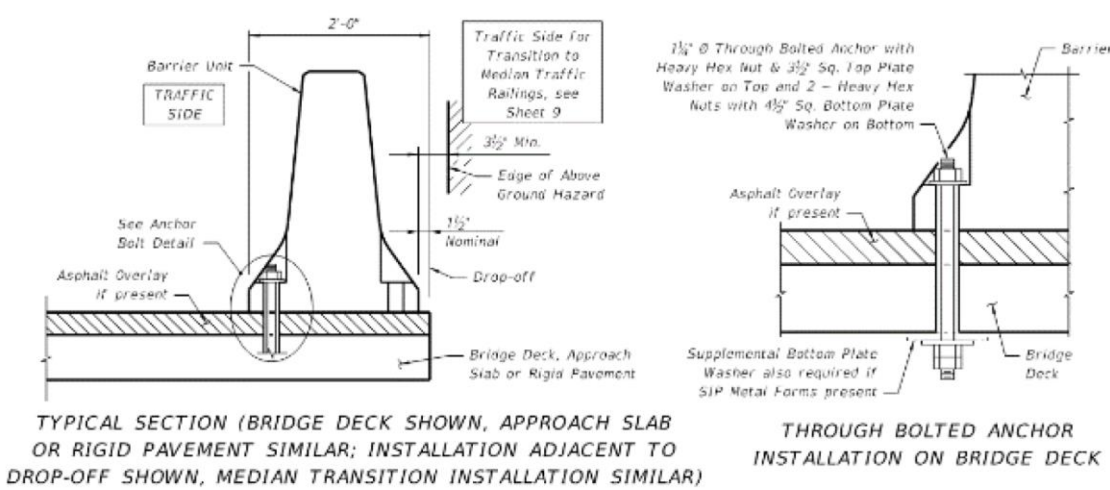


Figure 3. 38 Commonly used concrete bridge barrier profile shapes [68].

3.2.2.4.1. Florida DOT Precast Concrete Bridge Barriers Connections:

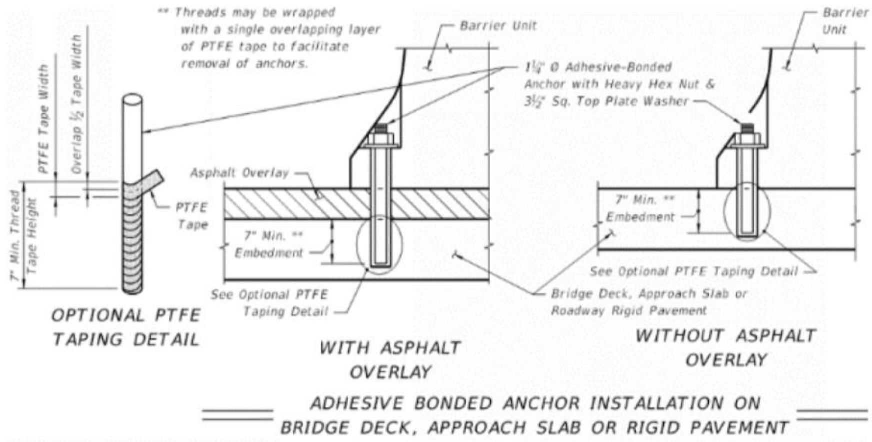
Florida has two types of methods for anchoring barriers to deck. One is the through-deck bolts which is applied in the Type K temporary concrete barrier system. The shape is similar to a F-shape profile and has sloped faces on both sides. Figure 3.39 shows a detail of the Florida DOT configuration [68].

The other technique used is the adhesive-bonded anchor (Figure 3.40). This method consists of drilling a hole into the deck and inserting a threaded bolt. Adhesive is used to secure the bolt [68].



FDOT 2012

Figure 3. 39 Through-deck bolting detail developed by Florida DOT [68].

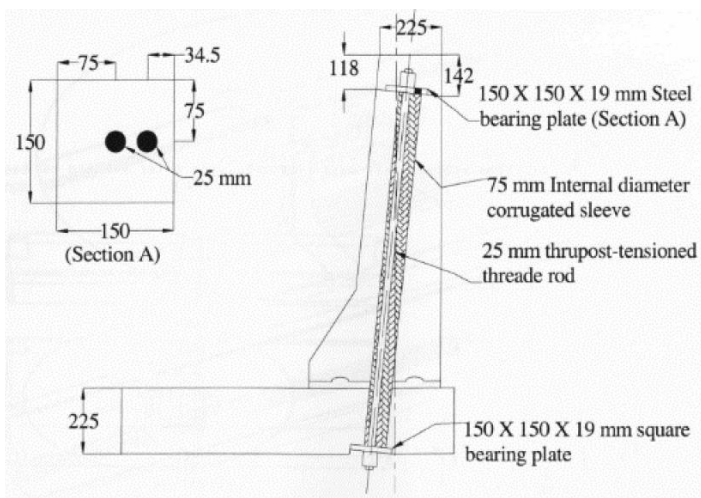


FDOT 2012

Figure 3. 40 Adhesive-bonded anchor detail [68].

3.2.2.4.2. Ryerson University Precast Concrete Bridge Barriers Connection:

Using post-tensioned rods inserted through the wall and deck slab is another way for connecting barriers utilizing the previous mentioned through-deck method. In the test conducted by Ryerson University the post-tension rods were anchored by the end plates, nuts and washers. Corrosion and access to exposed hardware is a challenge for this connection. Figure 3.41 shows a detail of the Ryerson University system [68].

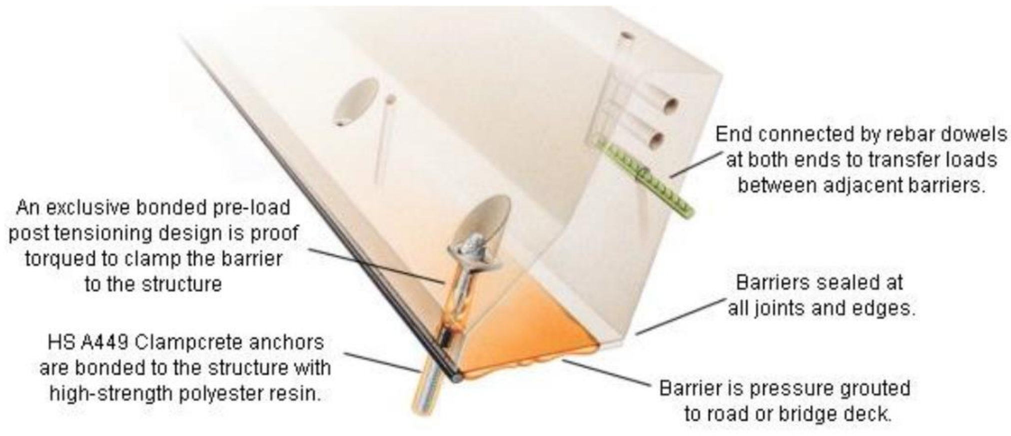


All dimensions are in mm; 1 mm = 0.0394 in.
Patel 2008

Figure 3. 41 Ryerson barrier-to-deck slab connection details [68].

3.2.2.4.3. Clampcrete Precast Concrete Bridge Barriers Connection:

Connection of this type of precast barrier is similar to adhesive-anchored connections. It consists of the barrier connected to the deck by polyester resin anchors that are drilled in. The connection consists of three deformed reinforcement dowels at a minimum. This system can be used for temporary and permanent barriers and it is shown in Figure 3.42 [68].

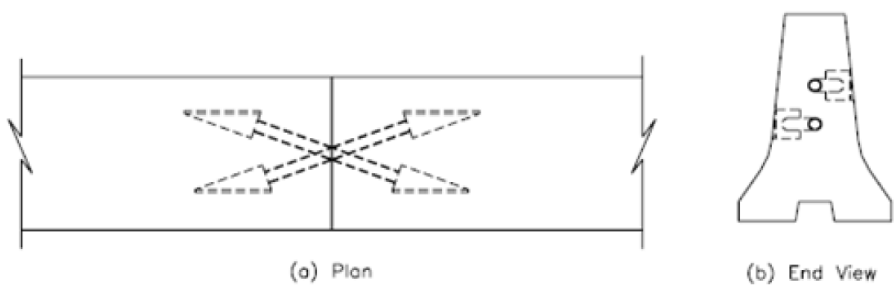


www.clampcrete.com/html/featuresindex.htm

Figure 3. 42 Clampcrete barrier system [68].

3.2.2.4.4. Texas Transportation Institute Precast Concrete Bridge Barriers Connections:

Texas transportation performed a study to design a portable concrete traffic barrier. The connection used two threaded rods across the joints and has a profile similar to an F-shape. The connection is called an X-bolt connection and is used for temporary concrete barriers. Figure 3.43 shows a drawing of the X-bolt connection [68].



Bligh et al. 2005b

Figure 3. 43 X-bolt connection concept [68].

3.2.2.4.5. Iowa State University ABC Railing Connection

In their research, Iowa State University proposed two new railing systems for Accelerated Bridge Construction. Additionally, a new connection was also introduced between two adjacent prefabricated barriers. All connection details were designed considering factors such as ease of replacement, minimal damage to deck, durability, constructability and cost effectiveness. Structural performance, force distribution and load carrying capacity were examined under different loading options [68].

3.2.2.4.5.1 Barrier-to-deck connection using inclined reinforcing bars:

This system consists of connecting the barrier to the bridge deck with the use of inclined reinforcing steel. A special threaded bar sleeve hardware is used to anchor the bars into the deck. However, this custom made hardware may render the joint less cost effective. The barrier system is designed to fail at the barrier-to-deck connection interface which will guarantee an easier repair. Figure 3.44 is a schematic illustrating details of this connection [68].

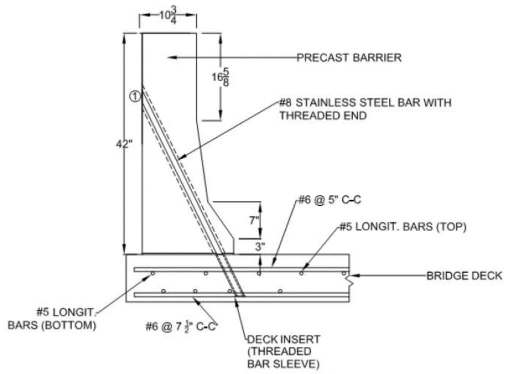


Figure 3. 44 Inclined bar connection between precast barrier and deck [68].

3.2.2.4.5.2 Barrier-to-deck connection using a U-shaped reinforcing bars:

This system consists of connection of barrier to bridge deck using a stainless-steel U-shape reinforcing bar. The U-shaped bar is inserted into the precast barrier through the bridge deck under the bridge overhang and then it is grouted. This type of connection was designed to ensure durability and minimize cost. Stainless-steel U-shape is considered to make the connection more durable. Compared to the inclined bar connection, this concept is more cost effective. However, the connection with the U-shape bars is considered more labor intensive, and its potential repair may require replacing a portion of the deck. Figure 3.45 is a schematic illustrating details of this connection [68].

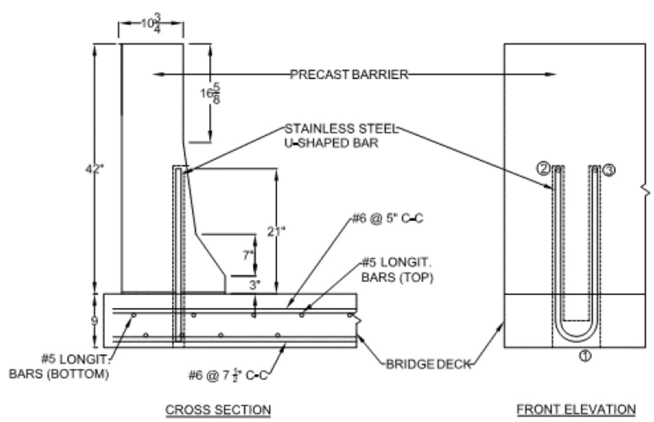


Figure 3. 45 U-bar connection between precast barrier and deck [68].

3.2.2.4.5.3 Barrier to Barrier connection

This type of connection utilized headed reinforcement in transverse and longitudinal directions, and it was designed to produce continuity such that the load will be distributed between barriers. It included four double headed ties between barriers and transverse reinforcement utilized to guarantee the confinement in the perpendicular direction. This type of connection did not have any exposed reinforcement to assure that its durability. Figure 3.46 shows a drawing of this connection detail [68].

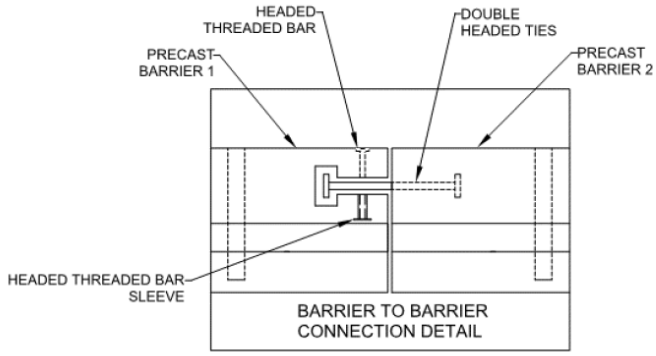


Figure 3. 46 Plan view of the barrier-to-barrier connection [68].

3.2.3. Substructure element connections

Within a substructure, joints are used to connect columns, piers, or walls to a cap beam as well as to the footing [8]. While it is easy to access the connections to the pier cap beam for inspection, the connections to the footing can be covered. These connections can experience high shear and bending moment, especially from lateral loading due to the earthquake. Additionally, in the longitudinal direction, it may undergo considerable lateral loading due to high deformation from thermal expansion of the deck slab [8].

3.2.3.1. Cap beam connection to column

Precast cap beam may connect to the cast-in-place column, a precast concrete column, steel pile, or precast concrete pile. There are different methods to join the column to cap beam. The connection of column to cap beam can form in the cap beam or along the column. In another method, the cap beam can be welded to the column. The summary of different methods to connect cap beam and columns are listed in Table 3.2. Moreover, according to NCHRP Project 20-68A three types of ABC columns were identified to perform well under seismic events, natural or man-made events, blasts, loading and other larger forces. First type included column embedded into pockets/sockets cast in an adjacent member such as, footing, cap beam or pile shaft [48]. The second type included grouted couplers connected to footing dowels, embedded into a precast column and subsequently grouted. The third connection type is grouted (corrugated) ducts forming oversized holes in the cap or footing that receives longitudinal bars protruded from a precast column and then filled with grout [48].

3.2.3.1.1. Connection inside the Pier Cap- Grouted Sleeve:

One of the methods for connecting precast pier columns to the prefabricated pier caps are with the use of grouted sleeve (Figure 3.47). In this method, slots or sleeves in the cap receives the extended reinforcing bars from the column.

Table 3. 2 Different connections of cap beam and column

Type	Connection method	Usage
Formed in cap beam	Grouted sleeve	-Connect precast cap beam to cast-in-place or precast concrete column
	Grouted pocket	-Connect precast cap beam and precast or cast-in-place concrete column -Connect precast cap beam and steel pile or column
Formed along the Columns	UHPC column segment	-Connect precast cap beam and precast concrete column
	Grouted sleeve	-Connect precast cap beam and precast concrete column
	Mechanical couplers	-Connect precast column to cap beam
Other types	Welding	-Connect precast cap beam and steel pile or column
Cap beam segments	Closure pour	-Connect precast cap beam segments
	Mechanical couplers	-Connect precast cap beam segments to create moment connection

Figure 3. 47 Column to cap beam connection using grouted sleeve method [62].

Moreover, the study developed by the University of Nevada also evaluated the seismic performance of a precast bent with a pocket connection and advanced materials such as ECC (Engineered cementitious composited) and UHPC (Ultra-high-performance concrete). The two columns were connected to a precast cap beam and a precast footing. Shake table results showed the effectiveness of this detail in limiting damage and a good overall performance of the pocket connection [69]. Figure 3.48 shows the construction sequences of the bent model.

Figure 3. 48 (a) precast footing with two circular pockets; (b) cap beam pocket construction; (c) cap beam pocket-view from underneath; (d) inserting the columns into the footing pockets; (e) placing cap beam on the columns [69].

3.2.3.1.2. Connection inside the Pier Cap- Grouted Pocket:

In another method that can be used to connect precast cap beam and the cast-in-place concrete columns or steel piles and columns, a large oversized pocket in the pier cap is left to receive the column or pile. The pocket is intended to receive the longitudinal bars extended out of column (Figure 3.49) or the entire column section [62].

In this method, after installation of column or pile, the column or pile is inserted into the cap beam pocket and leveled on its position. Then, the grout is poured from the holes on the top of the cap beam. When the pocket is used to insert the entire column section, a thin layer of grout may be used between the cap beam and column to provide a uniform bearing [70]. This method was used by MnDOT to connect cast-in-place pile and precast cap beam as shown in Figure 3.49. This connection also can be used to connect the pier column to pier cap integrally constructed with superstructure, integral abutments, or semi-integral abutments [8]. This technique can also be used to connect driven steel piles and precast cap beam.

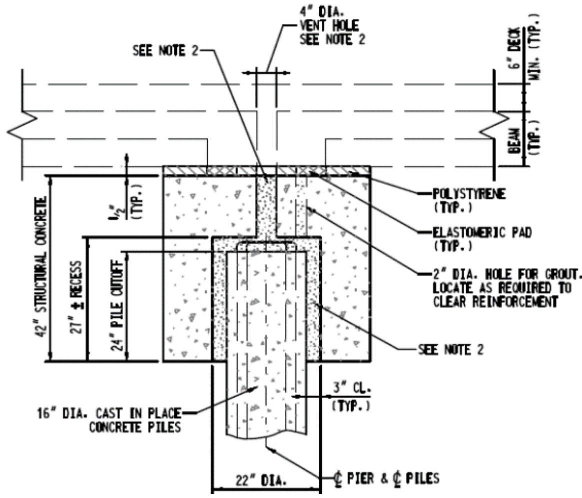


Figure 3. 49 Precast cap beam and cast-in-place column using grouted pocket [8].

3.2.3.1.3. Connection along the Columns- UHPC Column Segments:

Another type of connection between the precast column and precast cap beam where connection is formed along the columns has been recently developed under an ABC-UTC project using UHPC at Florida International University. The details of this connection for the seismic and non-seismic region are depicted in Figure 3.50 [71]. In the proposed connection for the seismic region, two layers of UHPC is used. The second layer near the cap beam is used because of the potential for significant stresses in this area. In the none-seismic connection, the two members are joined simply with a layer of UHPC.

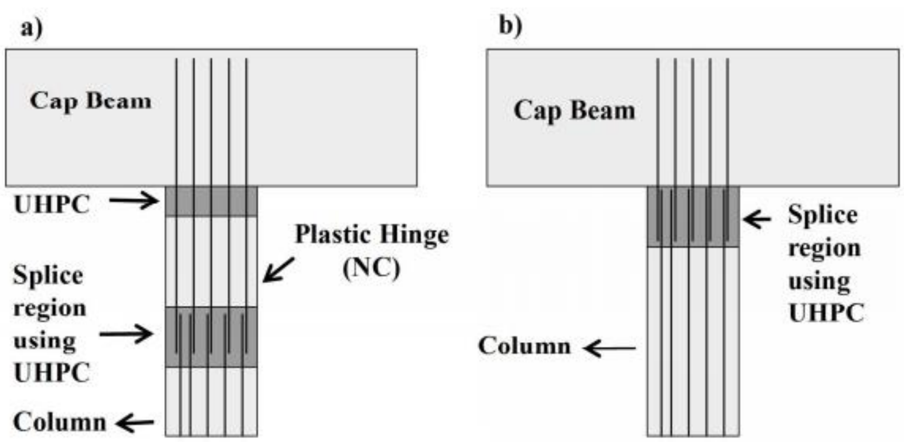


Figure 3. 50 a) Seismic and b) non-seismic detail of UHPC connection of precast column and precast cap beam [71].

3.2.3.1.4. Connection along the Column- Grouted Sleeve:

Sleeves can be also left at the top end of precast or cast-in-place columns to receive reinforcing bars projected downward from the cap beam. The connection zone and inside the coupler is then grouted to establish the connection. Figure 3.51 shows an example of grouted splice sleeve.

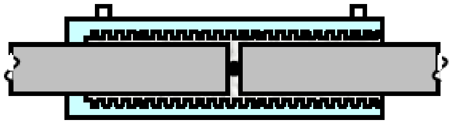


Figure 3. 51 Grouted Splice Sleeve [47].

3.2.3.1.5. Welding:

Connections between column or pile and cap beam can also be established by welding. In this method, a steel plates embedded at the bottom of beam and the top of pile or column are welded to each other [8]. Figure 3.52 shows the welding procedure for a pile to cap connection.

Figure 3. 52 Pile to Cap Connection [8].

3.2.3.1.6. Connection of Cap Beam Segments:

When the width of the bridge deck is large, it is possible to have a cap with large dimension and massive weight that can make problem in their shipping. In this case, the cap beam segments can be constructed with a smaller dimension. Then, the cap beam segments can be connected in the field using cast-in-place closure pour method (Figure 3.53) [8].

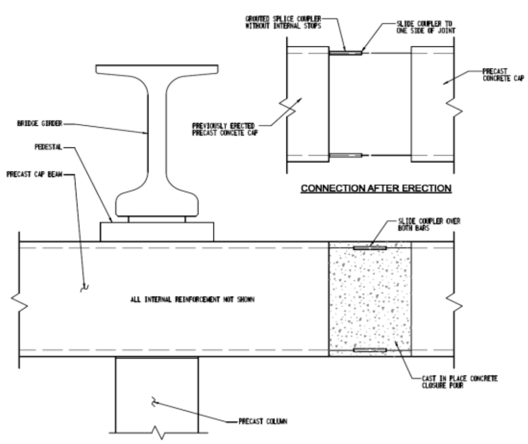


Figure 3. 53 Connection Details of Cap Beam Segments [8].

3.2.3.1.7. CFST Column-to-Precast Cap Beam Connections

Concrete-filled steel tubes (CFSTs) can provide stiffness and strength and allow fast construction. They can be used as piles, piers, and drilled shaft foundations. The use of self-consolidating concrete (SCC) can expedite the concrete placement as it does not require vibration. Stephens et al (2016) proposed three connections types that minimizes damage in the cap beam and provides excellent ductility under reversed-cyclic loading. Only one of the three proposed connection is further discussed as it was considered the only connection that could offer better benefit for the accelerated construction [72].

3.2.3.1.7.1 Embedded CFST annular ring (ER) connection

This type of connection develops full ductility and flexural capacity of the concrete filled steel tubes. Annular ring is the transfer mechanism which is welded to the tube ends. It is extended inside and outside providing shear and normal transfer from the tube to the cap beam [72]. Figure 3.54 shows an ER connection.

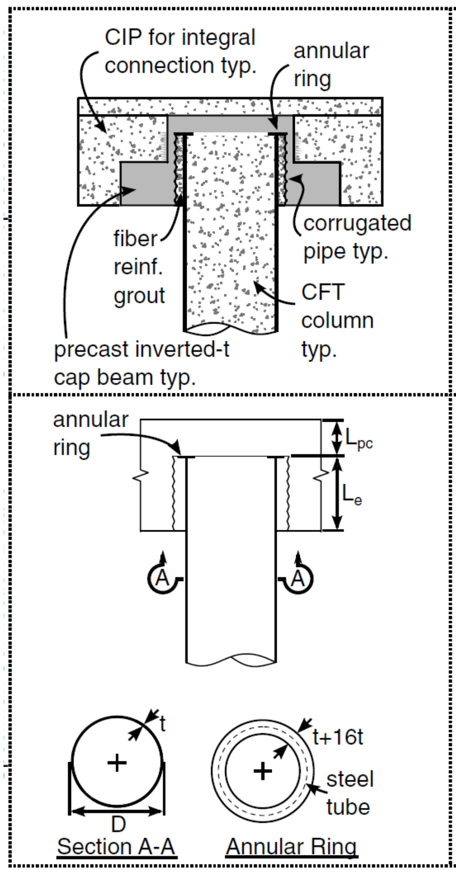


Figure 3. 54 Proposed ER Connection [72].

3.2.3.2. Footing connection to column:

Another connection in the bridge substructure is the connection between column and footing. A summary of the column to footing connection are listed in Table 3.3. The precast concrete column either may need to connect to the cast-in-place concrete footing or precast concrete footing [8]. To connect the precast concrete column to the cast-in-place footing, two methods can be used.

Table 3. 3 Different connections of column and footing

Type	Connection method	Usage
Formed along the column	Grouted sleeve	- Connect precast concrete column and cast-in-place footing - Connect precast column to precast footing
	Mechanical couplers	- Connect cast-in-place footing and precast column
Formed in footing	Grouted Pocket	- Connect precast column and precast or cast-in-place footing
Column segments connection	Closure pour Grouted sleeves mechanical couplers	-Connect precast column segments

3.2.3.2.1. Connection along the Column, Grouted Sleeve:

In one, the footing is cast with waiting reinforcing bars (dowels) projecting from the footing. Sleeves are incorporated at the lower end of the precast column to receive the bars projecting from the footing. The column is then braced in its position on the top of the footing using temporary supports. Then the grout is poured in the sleeves around the projecting reinforcing bars. This connection is formed in the column and called grouted sleeve connection method (Figure 3.55). Utah DOT used this connection to join the precast column to precast footing.

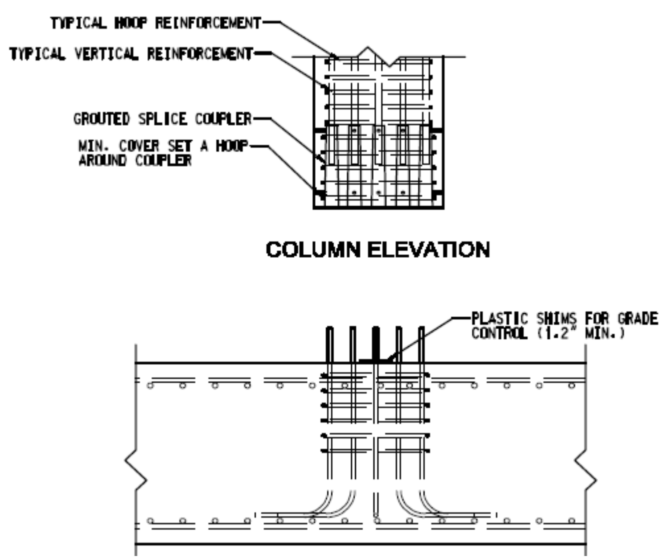


Figure 3. 55 Grouted sleeve connection between footing and column [8].

3.2.3.2.2. Connection along the Column, Mechanical Couplers:

In another method, mechanical couplers can be used to connect the cast-in-place footing to the precast column. The mechanical coupler details used by Florida DOT is shown in Figure 3.56. When the footing is also prefabricated, the grouted sleeve or splice connection method can be used.

An critical part of designing bridges with precast elements using mechanical connections is to assure adequate resistance to loads and development of at least 125% of yield strength of the connected bar [6]. Connection of prefabricated columns to cap beams or footing can be established by the use of mechanical bar splices [73].

An extensive parametric study was developed by Tazarv et al. (2015) to investigate seismic behavior of connections using mechanical couplers. In general, tension-compression couplers can be categorized as (1) shear screw couplers, (2) headed bar couplers, (3) grouted sleeve couplers, (4) threaded couplers, and (5) swaged couplers [73]. These five types of common mechanical bar splices can be seen in Figure 3.57.

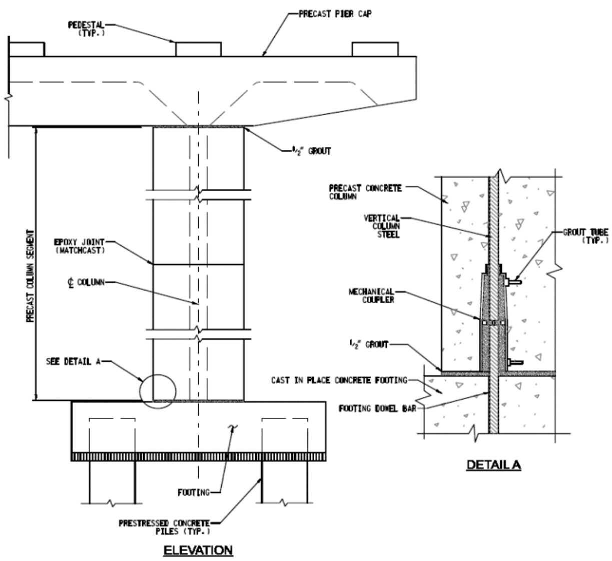


Figure 3. 56 Cast-in-place footing to precast column connection using mechanical couplers [8].

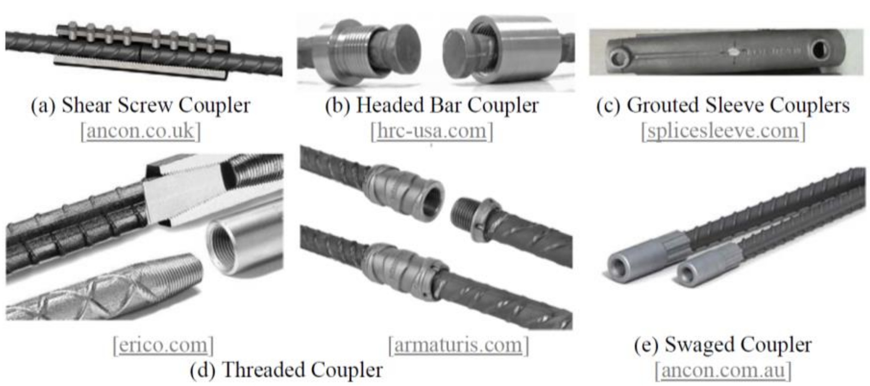


Figure 3. 57 Mechanical Reinforcing Bar Couplers [73].

3.2.3.2.3. Connection in the Footing, Grouted Pockets:

For this type of connection, the longitudinal reinforcement bars projecting from the precast column are embedded into the precast footing pocket and later grout is poured into the remaining space [74]. For this type of connection, a non-shrink or high strength grout is preferred [75]. It can be constructed with full or partial penetration (Figure 3.58) and connection should not experience any significant sliding for any of the options. For the case of the full penetration, axial strength depends on the shear resistance acting in the embedded portion and for partial penetration the side shear and tipping provide the axial load resistance [75].

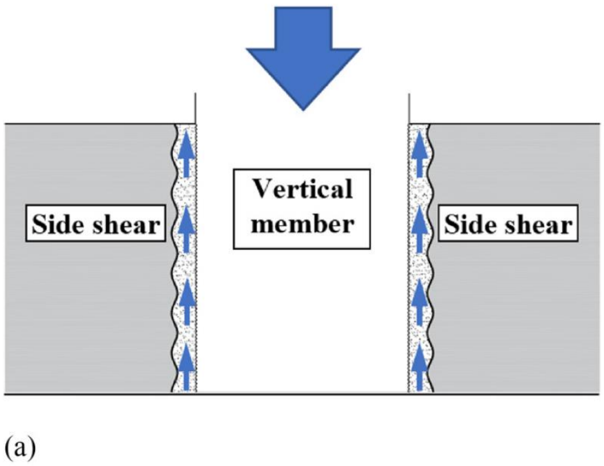


Figure 3. 58 (a) Fully penetrated pocket connection; (b) Partial penetrated pocket connection [75].

Kavianipour et al., (2013) tested precast columns inserted into precast footing with pocket connections and filled with High-strength grout (Figure 3.59). As column and footing were prefabricated, the method saved onsite construction. Embedment length of the column in the footing was 1.5 times the column diameter which according to the study was sufficient to develop full fixity at the base of the columns [69].

Figure 3-13: Pouring high strength grout in the gap between precast column and footing

Figure 3. 59 Pouring high strength grout in the gap between precast column and footing [76]

A study carried out by the University of Nevada evaluated the seismic performance of a precast column to precast footing with a square pocket connection. To eliminate permanent drifts, the column was post-tensioned with unbonded CFRP (Carbon fiber reinforced polymer) and in the plastic hinge zone UHPC (Ultra-high-performance Concrete) was used to mitigate the seismic damage. Shake table test and follow-up analysis showed that plastic hinge was formed successfully in the column with no damage to the pocket connection [69]. Figure 3.60 shows the construction sequences of the column model.

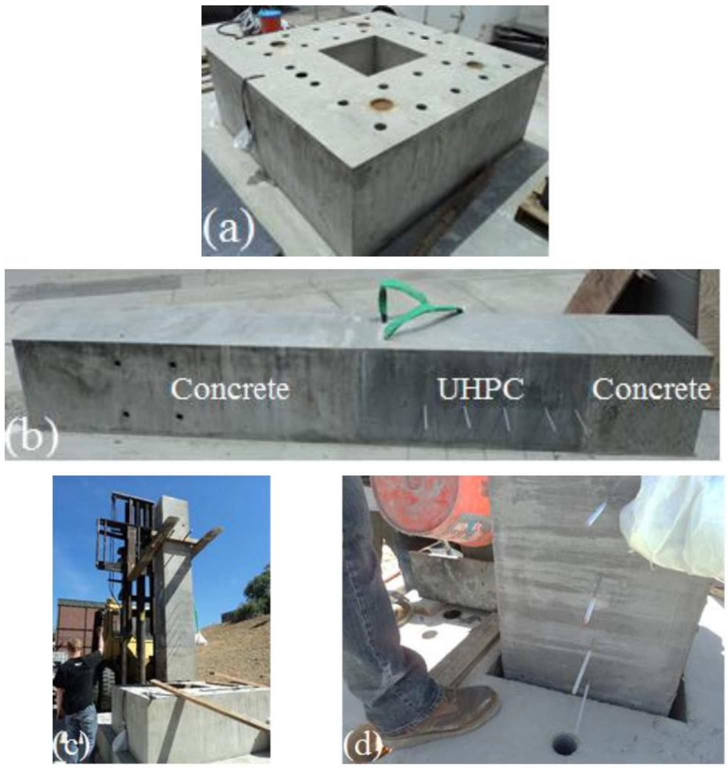


Figure 3. 60 (a) precast footing with central pocket; (b) precast column with UHPC in the plastic hinge; (c) inserting column into the pocket; (d) filling the gap by UHPC [69].

In another study, a synthesis about the behavior and performance of the pocket connection in the seismic region was conducted to define a standardized pocket connection detail. The results showed that full plastic moment occurs in the column. Also, the full precast column or partially prefabricated column (Figure 3.61) can be used to be inserted into the pocket [77].

3.2.3.3. Connection between column segments:

In some cases where the height of the columns is long, column segments are prefabricated and connected to each other in the field to make the handling of the prefabricated columns easier. To establish continuity and the required strength, the segments are post-tensioned and grouted in the field (Figure 3.62) [8]. Grouted sleeves, mechanical couplers, and other types of connection can be used between column segments.

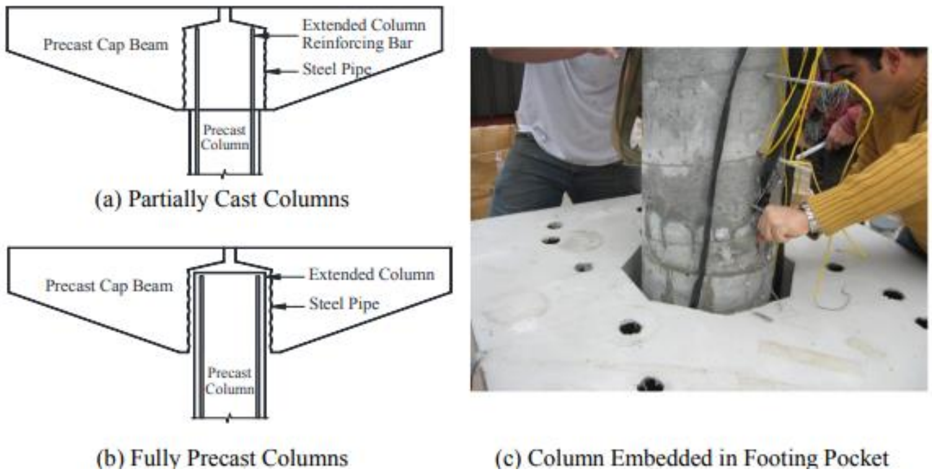


Figure 3. 61 Pocket connection of footing and column [77]

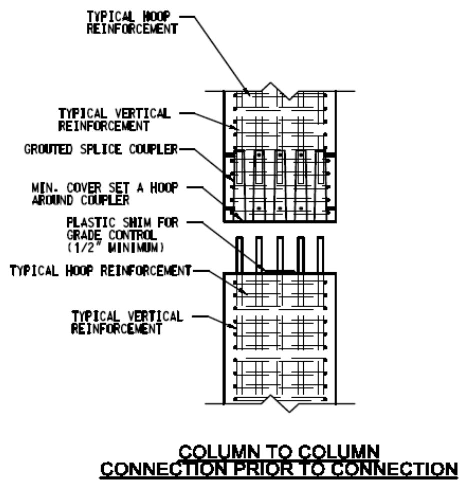


Figure 3. 62 Column to column connection [8].

3.2.3.4. Abutment and wall systems connections

Abutment systems including cantilever abutment, spill-through abutment, precast wall, integral and semi-integral abutments are other components of the bridge that can be constructed off-site and connected to each other in the field. The connections that can be used to join the abutment components together are summarized in Table 3.4.

3.2.3.4.1. Closure pour:

Cast-in-place closure pour is the connection method that can be used to connect the integral abutments elements and join abutment to superstructure. Figure 3.63 depict this connection details [78].

Table 3. 4 Abutment systems connections

Connection type	Comment
Closure pour, grouted pockets or sleeves	-Connect abutment elements -Connect abutment to superstructure
Grouted Sleeve/Splice couplers	-Connect all types of abutment elements
Grouted Pocket Connection	-Connect abutment stem or cap directly to steel piles or precast concrete piles
Welded Plate Connection	Connect steel piles to abutment
Steel bar dowels connection	-Connect pile cap and integral abutment
Small closure pour	-Connect abutment segments
simple grouted shear key	-Connect abutment cap segments

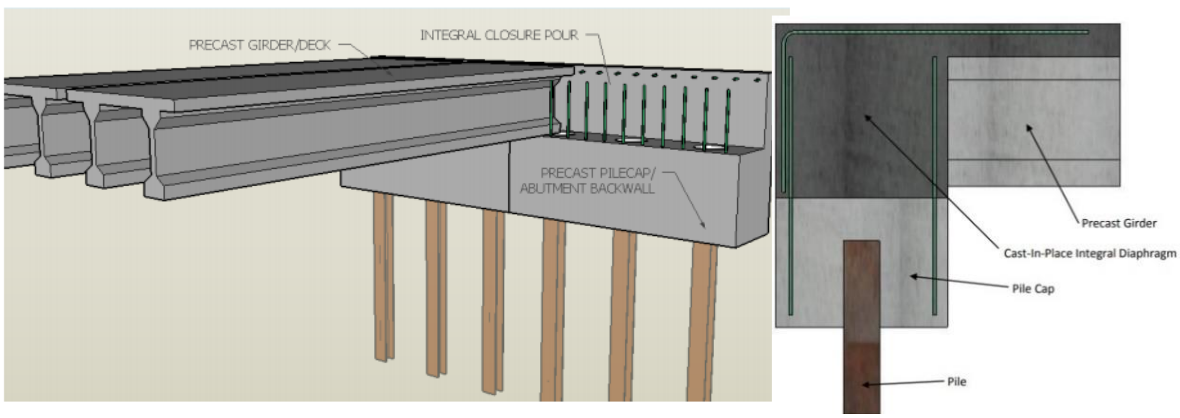


Figure 3. 63 Closure pour connection in abutment [78].

3.2.3.4.2. Grouted Sleeve/Splice couplers:

Grouted splice couplers can be used to connect precast elements like abutment stem and footing [8]. This connection type has been used by New Hampshire DOT to connect the abutment elements and is shown in Figure 3.64. In the cantilever abutment system, the connection of backwall to abutment stem is also needed (Figure 3.65, 3.66). Backwall is used to support the soil behind the beam ends. To connect backwall to abutment stem, the grouted splice couplers connection, same as abutment stem to footing connection, can be used. Also, other types of connections adapting to the existing conditions can be used. Another connection in the cantilever system is precast breastwall (checkwall) to abutment stem. Breastwall in this system is used as a decorative element at the corner of the abutment to connect the end of the beams. To attach precast breastwall to abutment stem, grouted splice couplers or other kind of connections based on the conditions can be used. In another type of abutment system, spill-through abutment, the same type of connections as that used for cantilever abutment can be used [8]. Other connecting methods of the precast wall to the precast footing include grouted shear key and using mechanical connectors. Recently, a study conducted by Iowa State University evaluated durability, strength, and application of grouted couplers in the integral abutments. The grouted reinforcing bar and pile couplers were evaluated, and this connection detail was established [[79], [78]].

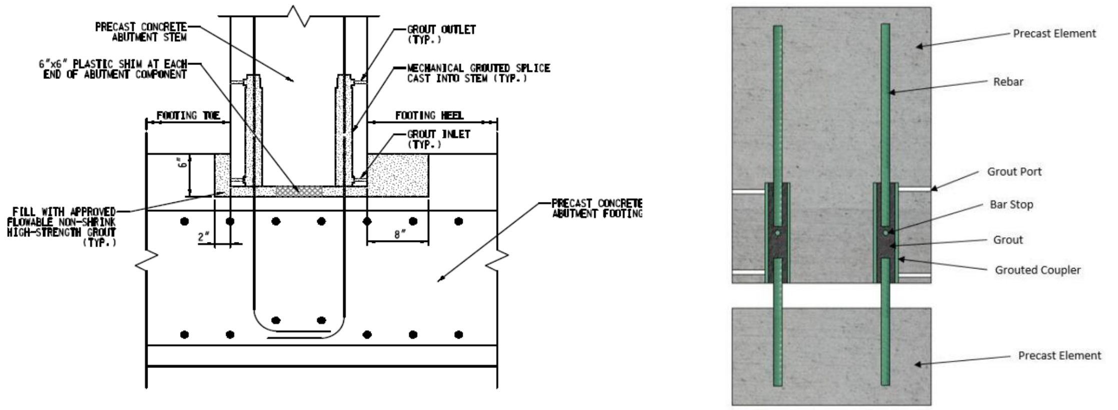


Figure 3. 64 Precast abutment stem to precast footing connection [[8], [79]]

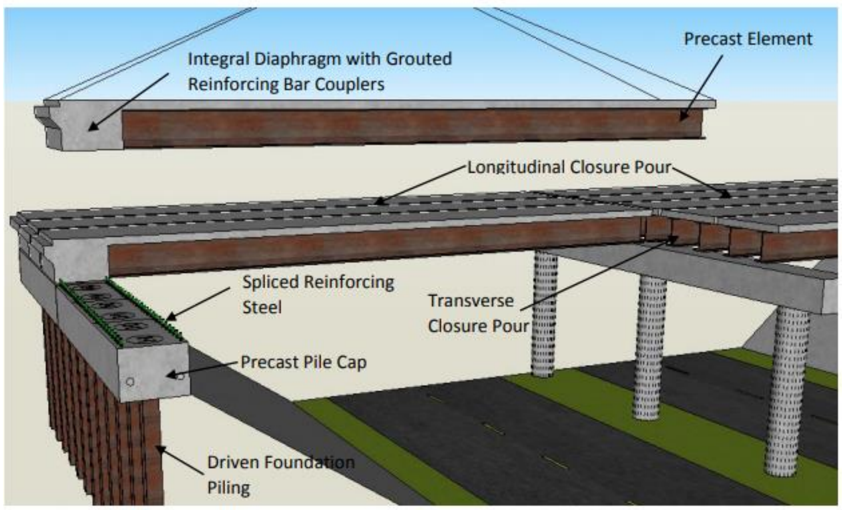


Figure 3. 65 Grouted couplers connection in prefabricated abutment [79].

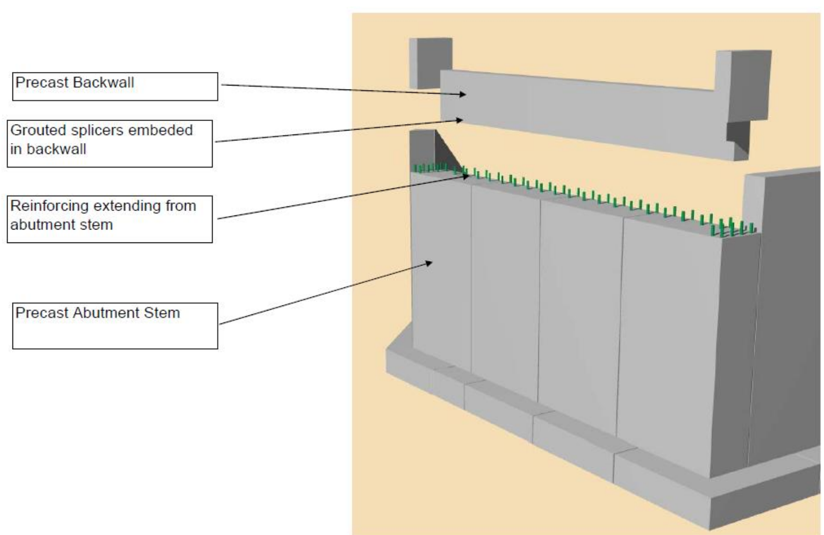


Figure 3. 66 Abutment connection [8].

3.2.3.4.3. Grouted Pocket Connection:

In some cases, the abutment stem or cap connect directly to steel piles or precast concrete piles. One way to establish this connection involves a large pocket prefabricated in the precast abutment stem, and the pile is embedded into the pocket and grouted (Figure 3.67, 3.68). This develops an integral abutment detail that transfers bending and shear.

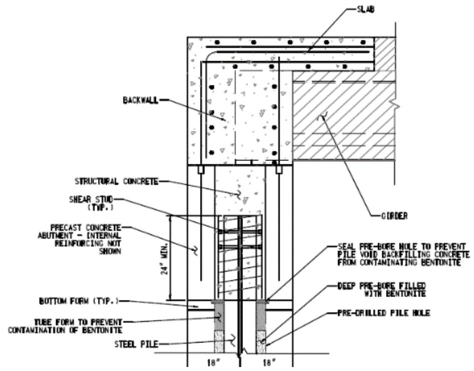


Figure 3. 67 Precast integral abutment connection to steel pile [8].

Figure 3. 68 Precast integral abutment connection to steel pile [8].

3.2.3.4.4. Welded Plate Connection:

To connect the steel piles directly to abutment, steel plates can be anchored in the abutment, and welded to the piles. Figure 3.69 shows a pile connection plate detail. Moreover, welded plate connection can be used for flying wingwalls. Normally, plates are anchored in the elements and then during installations plates are welded together [8].

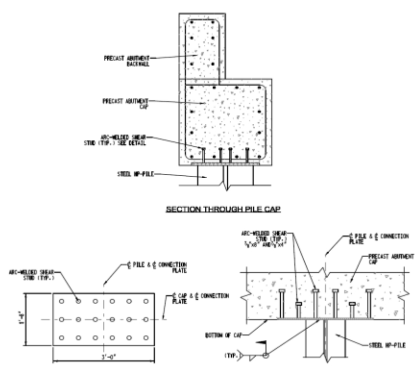


Figure 3. 69 Pile Connection Plate Detail [8].

3.2.3.4.5. Steel bar dowels connection:

To make the abutment integral with the superstructure, steel bar dowels can be used between the abutment stem and abutment cap that is made integral with the superstructure. Figure 3.70 shows a dowel connection.

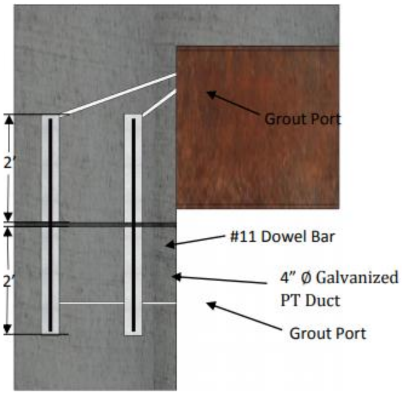


Figure 3. 70 Steel bar dowels connection in abutment [78].

3.2.3.4.6. Small closure pours:

In some cases, because of the abutment dimensions and shipping limitations, the abutment cap may be prefabricated in segments [8]. These segments can be attached to each other in the field. To connect them, the match cast and post-tensioning method which is used by Maine DOT or small closure pour technique can be used (Figure 3.71).

Figure 3. 71 Adjacent abutment segments connection [8].

3.2.3.5. Precast Arch Section connections

Connection between sections of bridge arches are normally designed as continuous connections. For large spans, sometimes a mid-span splice is made between two half-arch pieces at the crown. A temporary connection is established by first bolting the pieces together and a closure pour is made between the pieces to complete the joint. The arch soffit acts as a form for the pour [8]. Figure 3.72 shows an example of a precast arch connection.

Figure 3. 72 Precast Arch Connection [8].

3.2.3.5.1. Precast Arch Segment Connections for culverts and buried bridges:

Figure 3.73 shows a connection of adjacent precast arch units. This connection helps the spandrel walls to resist the lateral soil forces. On the exterior unit, a structural connection is used. However, the other joints are butted and sealed as mostly precast arch segments do not need a structural connection. They can be butted together and joints are stablished parallel to the roadway with a waterproofing strip placed over the gap in order to prevent any type of soil to fall through the joints and to guarantee corrosion protection [8].

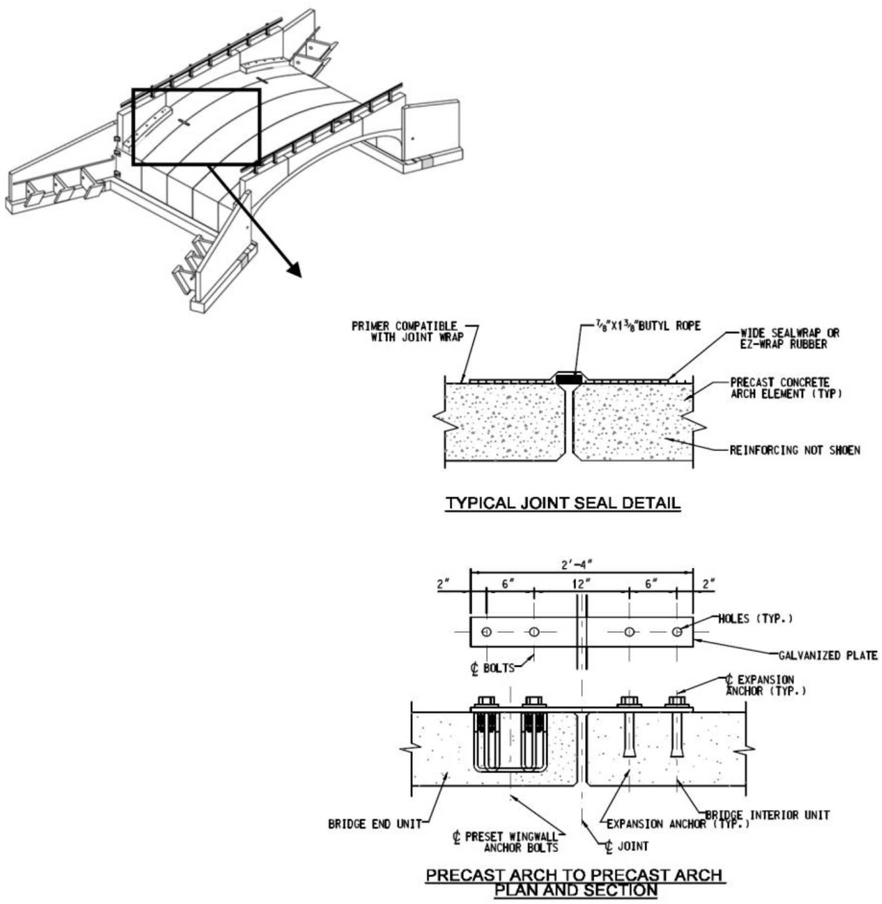


Figure 3. 73 Connection of Adjacent Precast Arch Units [8].

3.2.3.5.2. Precast Spandrel Wall to Precast Arch unit

This type of connection connects a precast arch unit to a precast spandrel wall. One type of connection consists of a spread footing bolted with stainless steel bolts. Another type of connection uses a cast-in place concrete bond beam that connects the spandrel wall to the precast arch. This connection also is used to resist vehicle impacts by resisting overturning [8]. Figure 3.74 shows an example of a bridge with spandrel walls in the corners.

Figure 3. 74 Example of spandrel wall to arch connection [8].

3.2.3.5.3. Precast arch to precast wingwall connection

Connection between precast arch and spandrel wall with a wingwall stem can be established using galvanized steel bots and plates. The connection is bolted and used during backfilling to guarantee alignment. Overturning forces are resisted by wall anchors cast into stem elements [8]. Figure 3.75 shows an example of a precast arch to a precast wingwall connection.

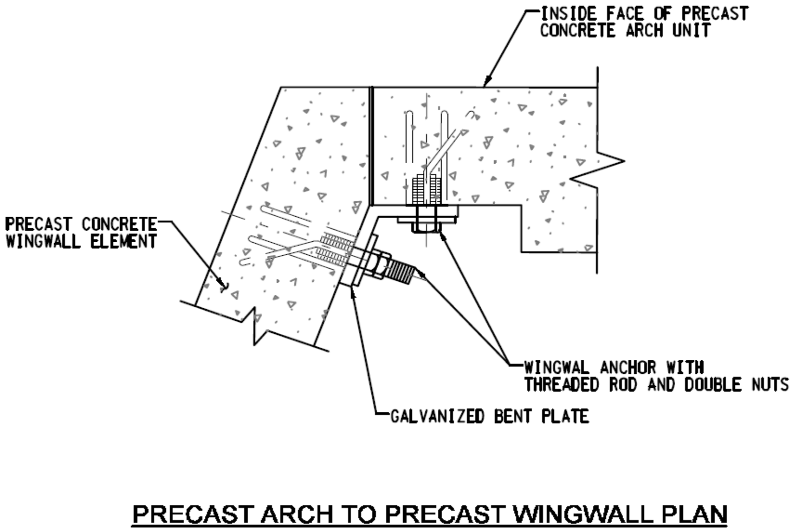


Figure 3. 75 Precast arch to precast wingwall connection [8].

3.2.3.5.4. Precast Arch Unit to Precast Footing Connection

Arch elements are designed to have pinned connection at the base. To resist lateral shear, the arch is installed into a shallow pocket. To adjust grade and to allow for grouting under the stem, the arch units are set on shims. Figure 3.76 is an example of precast footing to arch connection [8]. Moreover, footing joint is also used to connect wingwall footing to arch footing. Figure 3.77 shows an example of precast concrete footings connections.

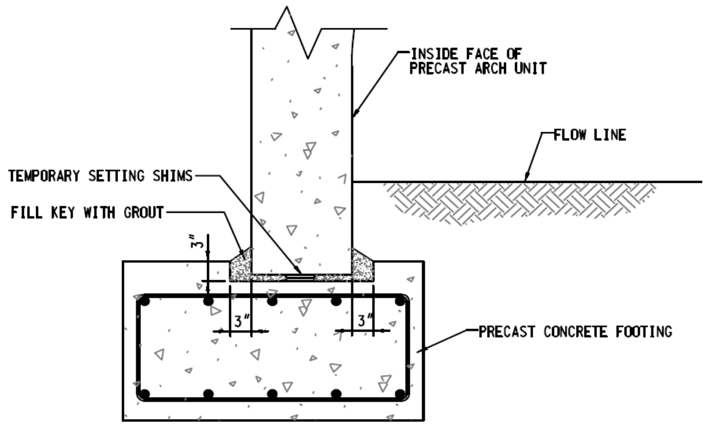


Figure 3. 76 Precast footing to arch connection [8].

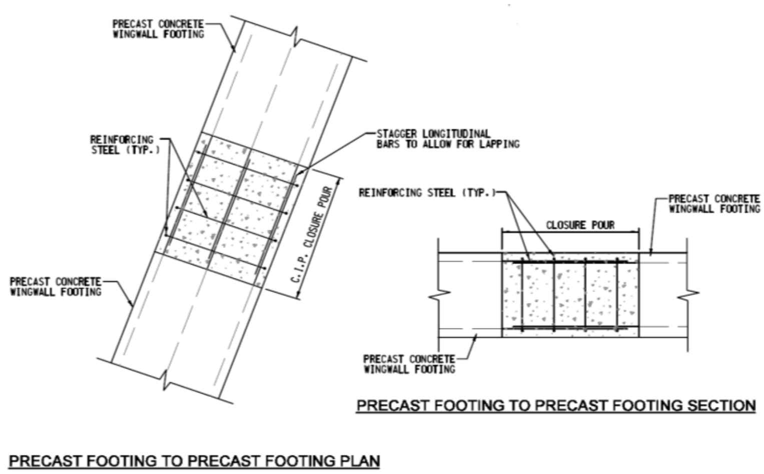


Figure 3. 77 Precast footing to precast footing connection [8].

3.2.4. Foundation connections

Proper connections are required between different precast foundation elements to successfully transfer the load to subgrade soil and resist failure. Connections are required to ensure sufficient joints between precast footing to steel and concrete pile, precast footing to precast footing. Details of different connections in foundation systems are discussed in the following sections.

3.2.4.1. Footing and Pile Systems:

Prefabricated piles are most commonly used for bridges by state DOTs whereas the concept of prefabricated footings is relatively new. The connection between the footing and pile system is important to transfer the load successfully.

3.2.4.1.1. Precast Footing to Subgrade Connections:

The primary problem with the use of precast concrete footing is to properly seat the footing on the subgrade. Settlement or rocking of the foundation may result from inadequate seating on the subgrade. It can be eliminated by placing a flowable concrete or grout under the footing or by using leveling bolts on the corners to lift the footing above the subgrade. In such cases, low grade concrete or flowable fill can be used as this is not a structural element. A sub-footing can also be used to create a level area for footings construction in bedrock [8]. Figure 3.78 presents the connections between precast footing and subgrade materials.

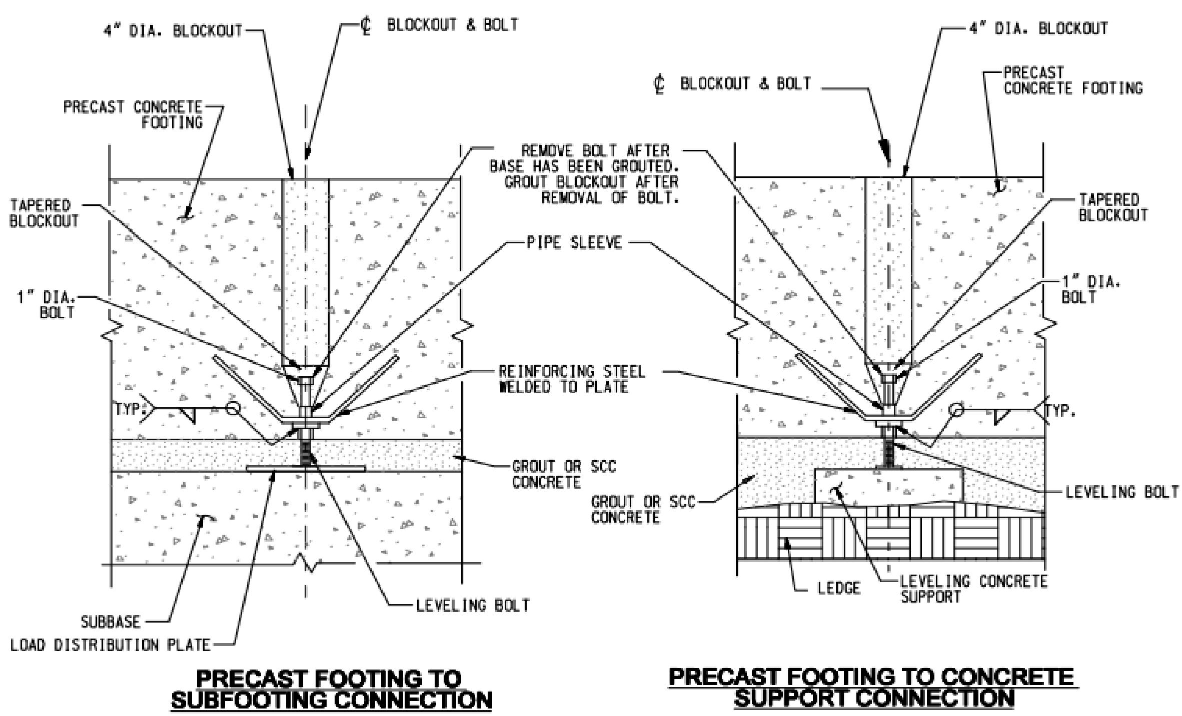


Figure 3. 78 Details of Precast footing to subgrade Connection [8].

3.2.4.1.2. Precast Footing to Precast Footing Connections:

The connection between adjacent footing elements may or may not need to be a structural connection, depending on the design. A simple grouted shear key can be used if there is no structural requirement for the connection. However, a small closure pour connection can be used if a moment connection is required (Figure 3.79). For this purpose, reinforcing bars are extended from footing elements and grout is poured in the formed area created by the two footing elements and the subgrade [8]. Figure 3.80 presents a photograph of installation of a precast concrete footing with grouted shear connection on concrete sub-footing.

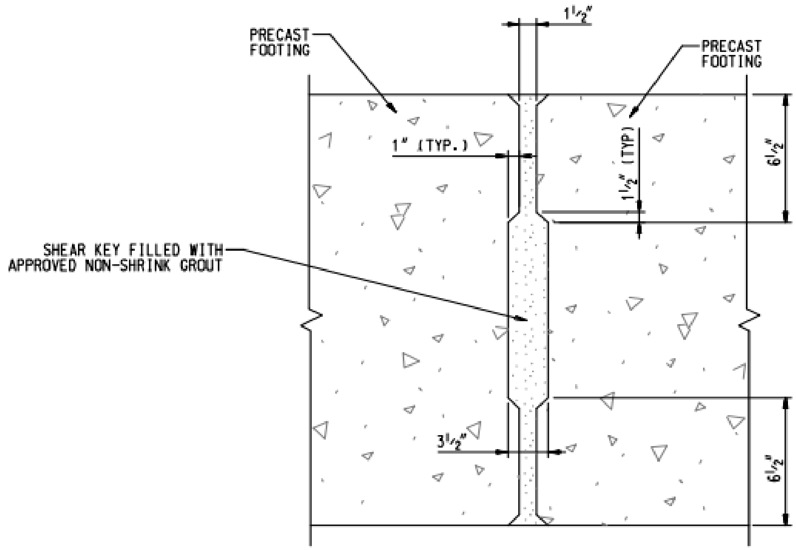


Figure 3. 79 Precast concrete footing to precast concrete footing connection [8].

Figure 3. 80 Installation of a precast concrete footing with grouted shear connection on concrete sub-footing [8].

3.2.4.1.3. Precast Footing to Steel Pile Connection:

The connection details for precast concrete pier caps to steel pile mentioned can be used for precast footing to steel pile connections. However, uplift on the piles or moment capacity requirement may create problems for such connections. The pile end reinforcing steel can be welded and embedded in a closure pour to provide enough uplift capacity for this connection (Figure 3.81). Also, embedment of the pile top by at least 12 inches into the footing will help to achieve adequate moment capacity for this connection [8].

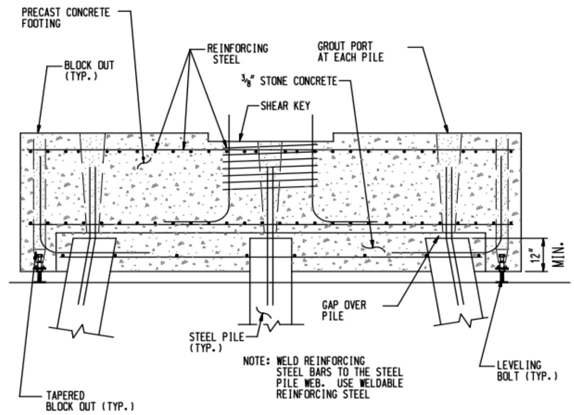


Figure 3. 81 Connection between precast concrete footing and steel pile with uplift [8].

3.2.4.1.4. Precast Footing/Caps to Precast Concrete Piles:

Similar to steel pile connections, several states have developed connection details for precast concrete piles connected to precast concrete pile caps/footing. There are also details developed for integral pile to pile cap connection. For example, Florida DOT has developed a connection for a hollow precast concrete pile to a precast footing to develop full moment capacity of the pile (Figure 3.82). The connection consists of a large blockout in the footing where a reinforcing steel cage is installed between the pile top and the blockout [8].

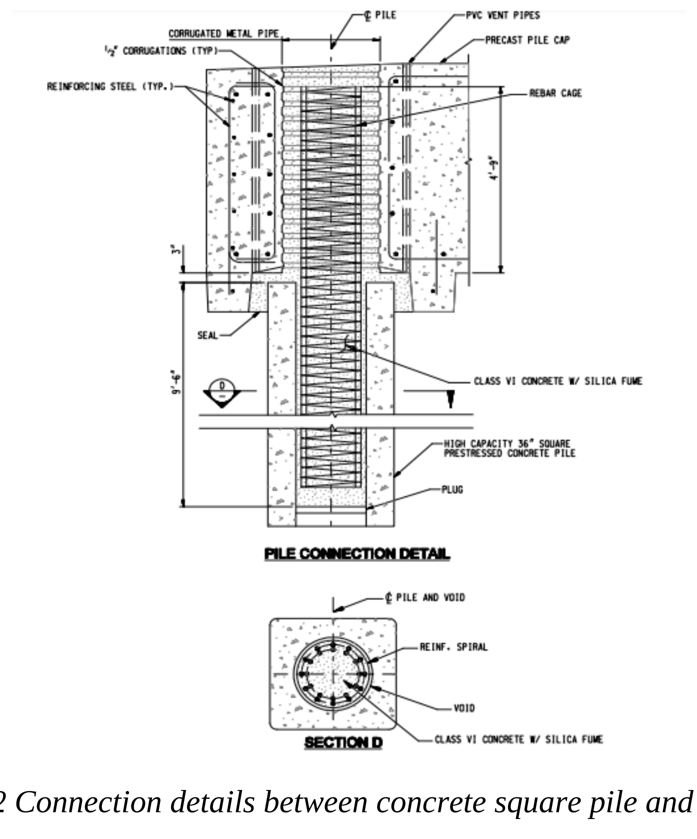


Figure 3. 82 Connection details between concrete square pile and pile cap [8].

Another option for the design of the pile cap connection is to project pile reinforcing into a void in the cap that will be filled with closure pour concrete. Figure 3.83 shows the detail used in Iowa.

Moreover, Figure 3.84 shows details that have been used in Minnesota and South Carolina, respectively, where the pile is embedded into a pile cap pocket. Depth of embedment follows the agencies' requirements for cast-in-place construction [6].

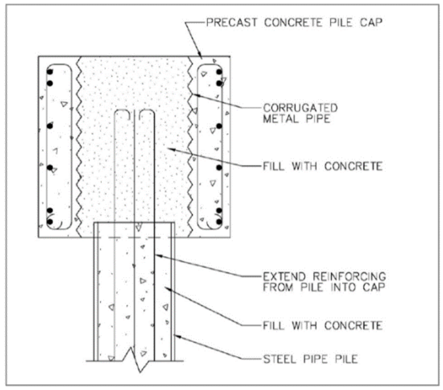


Figure 3. 83 Pile Cap Connection using Extended Reinforcing Steel [6].

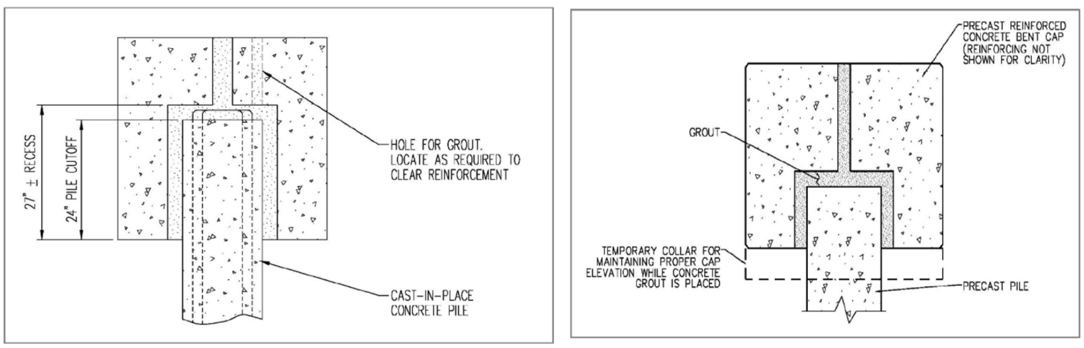


Figure 3. 84 Pile Cap Connection using Embedded Pile [6].

3.2.4.1.5. Precast Footing to Cast-in-place Pile or Drilled Shaft Connections:

Till now, no connections between precast footing to cast-in-place piles or drilled shafts connected to precast concrete footings have been developed by any state DOTs. However, the precast footing to concrete pile connection details could be adapted for use with cast-in-place concrete piles or drilled shafts.

3.2.4.2. Precast Columns to Drilled Shafts:

The concept with this connection as shown in Figure 3.85 is to have an oversized drilled shaft and after concrete in the drilled shaft is cast to a specific elevation, the column reinforcing is inserted in the shaft space near the shaft reinforcing, and finally connection is completed using a cast-in-place pour. Similar detail can also be adopted for precast concrete column [8].

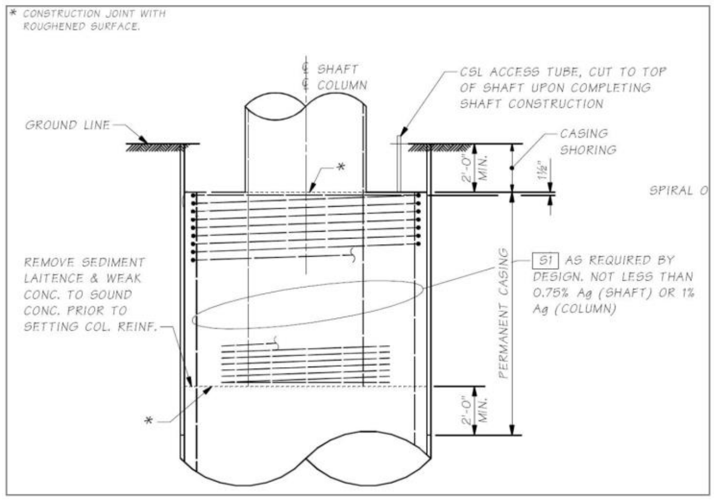


Figure 3. 85 Connection of Pier Column to Large Diameter Drilled Shaft (Source: Washington State DOT Bridge Design Manual) [8].

3.2.4.3. Precast Pile to Precast Pile Connection:

Splicing in precast piles is often required when there are length limits for shipping and transportation; limited headroom, and/or when required capacity is not achieved with existing lengths. Also, to accommodate variations in subsurface conditions, pile lengths for some pile types can be easily adjusted and spliced in the field. According to Bruce and Hebert (1974) the piles splices can be categorized as; Welded splices, Bolted Splices, Mechanical Locking Splices, Connector Ring Splices, Wedge Splices, Sleeve Splices, Dowel Splices, and Post-Tensioned Splices. Many state DOTs have developed standard details for connecting precast driven piles that need to be spliced. Precast concrete pile industry has also developed their standard pile splicing details [80]. Figure 3.86 shows a detail for splicing hollow square prestressed concrete piles usedby the Florida DOT as a form of dowel splice connection. These details consist of a reinforced concrete closure pour between pile elements.

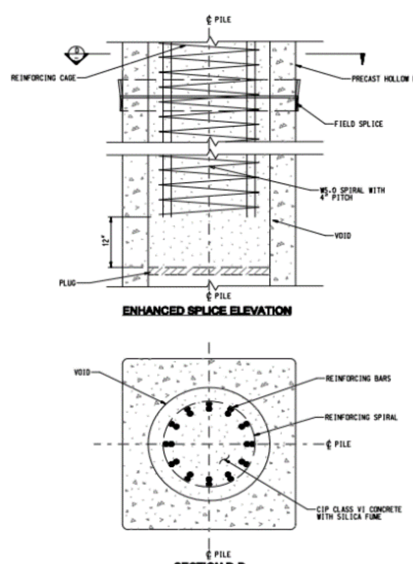


Figure 3. 86 Connection between concrete square piles using splice [8].

Florida Department of Transportation has also used alternative dowel material for epoxy dowel pile splices including Carbon Fiber Reinforced Plastic (CFRP) and Stainless Steel (SS) to prevent corrosion damage especially in the marine environment and splash zones. They are currently investigating the feasibility of using Glass Fiber Reinforced Plastic (GFRP) dowels for pile splices.

FORTHCOMING CHAPTERS

An initial literature review has been completed for Chapter 1, 2 and 3. The necessary information is being collected to develop future chapters. Following chapters are envisioned to offer the information described above in Chapter 1. Forthcoming chapters will be classified as follows:

Chapter 4 - Construction methods

In this chapter construction methods applicable to short span bridges will be discussed.

Chapter 5 - Inspection and performance

In this module, a review of performance of ABC short-span bridges with an emphasis on joints will be carried out. Moreover, information on performance of general ABC construction and summary of deterioration patterns will be discussed. Additionally, inspection methods and means applicable to ABC short-span bridges will be explored.

Chapter 6 - Decision making process

This module will introduce available decision-making methods applicable to ABC short-span bridges. This will include decisions on the use of ABC as an alternative to conventional method, selection of construction method most applicable, and determination of type of elements and subsystems, as well as selection of the type of inspection required.

Chapter 7 - New developments

For this module new and ongoing developments that can affect the future of Accelerated Bridge Construction will be discussed with a focus on short-span bridges.

Schedule

Progress of tasks in this project is shown in the table below.

Item	% Completed
Percentage of Completion of this project to Date	50

Research Task	2019										2020	
	M	A	M	J	J	A	S	O	N	D	J	F
Task 1 - Literature Review												
Task 2 - Develop the outline of the course												
Task 3 - Develop course modules												
Task 4 - Conducting a trial course for FDOT												

Work Performed
Work To be Performed

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