Synthesis on the Use of Accelerated Bridge Construction Approaches for Bridge Rehabilitation

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BRIDGE ENGINEERING CENTER
IOWA STATE UNIVERSITY
Institute for Transportation

About the ABC-UTC

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

About the BEC

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

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16. Abstract

Accelerated bridge construction (ABC) has received significant research attention in recent years. For the most part, these research endeavors have focused on means and methods for decreasing impact to the traveling public during new bridge construction. At the same time, great opportunities exist to further reduce traffic impacts by decreasing construction time associated with bridge repair and rehabilitation.

Most bridges undergo several small and one or two major rehabilitations during their useful lives and decreasing the traffic impacts during these events could have significant societal benefits. Fortunately, many of the new construction concepts may be able to be adapted for use in rehabilitation scenarios. In still other cases, new means and methods may be needed.

This research completes a synthesis of available rehabilitation alternatives and solutions that could be used by practitioners to complete rapid rehabilitation projects. In some cases, these alternatives are adaptations of new construction methods and, in others, they are strictly for rehabilitation activities.

This synthesis provides a comprehensive summary of available solutions.

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SYNTHESIS ON THE USE OF ACCELERATED BRIDGE CONSTRUCTION APPROACHES FOR BRIDGE REHABILITATION

Report
December 2015

Principal Investigator
Brent M. Phares, Director
Bridge Engineering Center, Iowa State University

Co-Principal Investigator
Terry J. Wipf, Bridge Engineer
Bridge Engineering Center, Iowa State University

Research Assistant
Meghan Cronin

Authors
Brent Phares and Meghan Cronin

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A report from
Institute for Transportation
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 / Fax: 515-294-0467
www.intrans.iastate.edu

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EXECUTIVE SUMMARY

Accelerated bridge construction (ABC) has received significant research attention in recent years. For the most part, these research endeavors have focused on means and methods for decreasing impact to the traveling public during new bridge construction. At the same time, great opportunities exist to further reduce traffic impacts by decreasing construction time associated with bridge repair and rehabilitation.

Most bridges undergo several small and one or two major rehabilitations during their useful lives and decreasing the traffic impacts during these events could have significant societal benefits. Fortunately, many of the new construction concepts may be able to be adapted for use in rehabilitation scenarios. In still other cases, new means and methods may be needed.

This research completes a synthesis of available rehabilitation alternatives and solutions that could be used by practitioners to complete rapid rehabilitation projects. In some cases, these alternatives are adaptations of new construction methods and, in others, they are strictly for rehabilitation activities.

This synthesis provides a comprehensive summary of available solutions.

Given that information related to bridge deck repair and replacement is considerably more prevalent than information related to the rapid repair of other components, the researchers suggest that future efforts be focused more so on the development of ABC methods that may be applied to rapid rehabilitation of girders, bridge piers and columns, and abutments.

CHAPTER 1. INTRODUCTION

Accelerated bridge construction (ABC) is bridge construction that uses innovative planning, design, materials, and construction methods in a safe and cost-effective manner to reduce the onsite construction time that occurs when building new bridges or replacing and rehabilitating existing bridges (Adams et al. 2012).

ABC has received significant research attention in recent years. For the most part, these research endeavors have focused on means and methods for decreasing impact to the traveling public during new bridge construction. At the same time, great opportunities exist to reduce traffic impacts by decreasing construction time associated with bridge rehabilitation as most bridges undergo several small and one or two major rehabilitations during their useful lives and decreasing the traffic impacts during these events could have significant benefits.

After conducting an extensive literature review, this report was developed and includes details for several rapid rehabilitation and repair methods currently available for bridges. Not all methods are applicable to all areas of a deteriorated bridge. As such, the report is grouped by bridge component.

The report includes the following sections: deck joints, decks, girders, piers and columns, and abutments. Within each chapter, appropriate means of rapid removal, repair, replacement, and case studies, where applicable, are provided.

Bridge decks experience the most deterioration over the service life of a bridge. For this reason, most of the information available—and presented in this synthesis—is related to the rapid removal, repair, and replacement of bridge decks. Detailed information is provided for remaining elements of bridges as well; however, more research on rapid repair and rehabilitation of these areas of bridges would be highly valuable.

With this synthesis, bridge designers will be more aware of the options available where rapid repair and rehabilitation is concerned. This synthesis will enable engineers to more easily decide which option is best for a given rehabilitation project and, where appropriate, provide engineers with design assistance.

CHAPTER 2. DECK JOINTS

A common location for deterioration to occur on a bridge is at the deck joints. Although a small component of the overall structure, deck joint performance is essential to the overall service life of a bridge.

This chapter discusses techniques used to rapidly remove concrete from joints for repair or replacement purposes as well as techniques used to rapidly repair these joints.

2.1 Rapid Removal

Similar to other areas of the bridge, before a repair can take place, the damaged contents must be removed. Miller and Jahren (2014) conducted a study focusing on current practices used to replace expansion joints. They held meetings with representatives of the Iowa Department of Transportation (DOT) to determine what their bridge crew leaders deem the best way to rapidly replace expansion joints as well as what they think is the best way to maintain them.

This study revealed that crew leaders believe hydrodemolition—a high pressure water jet—is an effective and quick way to remove concrete from the surrounding areas; however, it is costly and runoff containing small concrete particles is an issue that must be dealt with (Miller and Jahren 2014).

2.2 Rapid Repair

Rapid repair refers to accelerated methods that are applied to the repair of bridge deck joints. Included here are expansion joints and deck closure pours.

2.2.1 Expansion Joints

The same study by Miller and Jahren (2014) offered several different ways to replace damaged expansion joints in a relatively rapid manner. Iowa DOT staff stated that the easiest way to replace a deteriorated sliding plate expansion joint is to remove the joint in its entirety and simply fill the space with new concrete while leaving a flat gap between the abutment and deck for expansion and contraction of the bridge (Miller and Jahren 2014). Because sliding plate expansion joints are not designed to be watertight, this method of replacement is acceptable, and it avoids any unnecessary traffic delay.

Strip seal and compression seal joints may be repaired or replaced in a variety of ways. The easiest way to repair these types of expansion joints, if the repair in question needs the joint to be cleaned out, is simply to use compressed air or pressurized water to remove debris from the joint.

If a strip seal or compression seal is damaged, it may be removed and cleaned, and a new seal installed. A new section may be spliced in, or the entire length of the seal may be replaced (Miller and Jahren 2014).

If extrusion is damaged on these seals, a new section of extrusion may be installed; however, a new section should not be spliced between two existing sections, as buckling may occur (Miller and Jahren 2014).

Compression seal armoring can be replaced by removing existing concrete and replacing with new concrete for a flat riding surface; this operation can be done in several hours. An additional, more recently available method used to repair these joints is to use the Silicoflex joint sealing system from R.J. Watson, Inc.

This system is an inverted strip seal (an upside-down V-shaped seal) installed using adhesives instead of extrusions. It is installed to a clean, flat vertical face of the joint below the damaged extrusion. If no repair of the vertical face of the concrete is required, this replacement system can be installed in as little as 30 minutes per lane (Miller and Jahren 2014).

For larger expansion distances, finger and modular expansion joints are typically used (Miller and Jahren 2014). These types of joints are easily repaired by simply replacing the damaged joint component. For example, if a torn neoprene gland is present, instead of replacing the entire joint, the damaged gland need only be removed and the new neoprene gland installed (Miller and Jahren 2014).

Damage in integral abutment joints usually happens to the tire buffing and silicon sealant. To repair these deteriorated items, missing pieces from the tire buffing are replaced and new silicon is poured into the joint (Miller and Jahren 2014).

2.2.2 Deck Closure Pours

Deck closure pours are a frequently occurring phenomenon in the world of accelerated bridge repair and rehabilitation. For example, these closure joints must be utilized when precast concrete deck panels are used for a deck replacement project.

An effective material to fill these joints with is ultra-high performance concrete (UHPC). When using UHPC, the following recommendations pertaining to joint constructability apply (Hartwell 2011):

1. To attain adequate flow characteristics, the ambient temperatures at the time of batching must be carefully regulated.
    a. At temperatures of 65 degrees, UHPC can be found to be discharged from the mixer in the range of 82 to 85 degrees along with adequate flow, leading to good consolidation and flow around corners.
    b. At temperatures of 75.5 degrees, UHPC has been observed to reach 100 degrees.

        i. If this occurs, it is recommended to replace water with ice to lower the temperature of the UHPC to 60 degrees, allowing it to obtain acceptable flow characteristics.
    c. At acceptable output temperatures, UHPC has not been seen to create voids at the intersection of longitudinal and transverse steel reinforcing bars.
2. To provide hydrostatic head and aid material consolidation, UHPC should be poured from the lowest to highest elevation while applying top forms as the joints are filled, and a small chimney should be constructed at the highest elevation.
3. Full-depth stay-in-place acrylic bulkheads should be avoided as they create a possible infiltration plane for water.
4. To avoid infiltration gaps and maintain controlled placement of UHPC, a partial-height removable acrylic bulkhead should be utilized. Specifically, it should be used in those longitudinal joints where the UHPC will likely be in compression.

CHAPTER 3. DECKS

Compared to the rest of the bridge, decks are exposed to the most extreme conditions and, as a result, see the most deterioration over the structure's useful life.

This chapter contains information regarding rapid removal, rapid protection methods, rapid repair, and rapid replacement as it relates to bridge decks. Design and construction details are provided as available.

3.1 Rapid Removal

Rapid removal techniques that relate to the elimination of deteriorated or damaged sections of the deck prior to repair or replacement is a very commonly encountered situation because it is generally a requirement that the deteriorated concrete be removed before applying a repair treatment. Every project is different; when deciding which removal method will work best for a given project, several aspects need to be considered (Tadros and Baishya 1998):

- Quantity and quality of concrete to be removed
- Time available to complete the work
- Type of concrete component and its accessibility
- Cover to the reinforcement
- Restrictions with respect to vibration, noise, dust, and containment and disposal of debris

Many options are available for the removal of concrete decks and the ones deemed rapid are presented here: hydrodemolition, milling, sawing, crushing, and peeling.

3.1.1 Hydrodemolition

As mentioned previously, hydrodemolition is a process that makes use of a high-pressure water jet to remove damaged or deteriorated concrete. A hydrodemolition unit as well as a surface removed using hydrodemolition are shown in Figures 1 and 2, respectively.

Phares et al. 2014, Bridge Engineering Center at Iowa State University

Figure 1. Hydrodemolition machine

Phares et al. 2014, Bridge Engineering Center at Iowa State University

Figure 2. Removal area using hydrodemolition

Damaged concrete can be removed with relatively high precision, allowing the designer/contractor to be much more selective in their removal process. The interface created from the water jet provides for a very rough surface, which should result in a better bond between the remaining concrete and the repair materials compared to the surface generated by jackhammers and sandblasting. Furthermore, other methods may cause microcracking of the concrete or may damage the underlying steel reinforcement or superstructure; whereas, hydrodemolition leaves these areas unharmed, making it a good option for both partial- and full-depth removal (Phares et al. 2014).

In addition, hydrodemolition does not produce any dust or vibration like other removal methods often do (Phares et al. 2014). Drawbacks or disadvantages to this system include the production of wastewater, which must be contained and treated; noise; shadowing that may occur when steel elements lie below the concrete surface (Phares et al. 2014); and relative expense (Tadros and Baishya 1998).

Three types of hydrodemolition exist: hydraulic water jetting (1,450 to 5,800 psi), high pressure water jetting (5,800 to 17,400 psi), and hydro-jetting (17,400 to 35,000psi) (Radomski 2002). Hand-held hydrodemolition has proved to not be effective when large amounts of removal are needed; however, machine-mounted hydrodemolition can remove deteriorated concrete or reasonable depths of sound concrete by applying a combination of different water pressures, frequencies, lance angles, and nozzle types (Phares et al. 2014).

If hydrodemolition is chosen for a partial-depth deck removal, control of the water jet is critical to avoid penetrating the entirety of the deck depth (Tadros and Baishya 1998). The advantages and disadvantages of this system are outlined below (Wilson et al. 1999).

Advantages:

- Hydrodemolition requires a smaller workforce than other methods.
- Only weak concrete (i.e., concrete that needs to be removed) is eliminated.
- Rough edges provide for better bond quality.

Disadvantages:

- The surfaces are damp upon completion, potentially delaying repair time if the surface needs to be dry before placement of the patching material.
- The runoff requires attention.
- It is expensive to rent equipment.

3.1.2 Milling

Milling is a removal process that utilizes grinders to essentially crush the deteriorated concrete surface. A typical milling machine is comprised of a series of steel wheels with impact heads on each wheel line. Milling is frequently the most economical way to remove concrete down to the level of reinforcement, but often times a fractured surface is left in place (Sprinkel 2004). It is effective at removing concrete, but the bond strength between remaining concrete and replacement may be something that is sacrificed. To improve this bond strength, the remaining surface can be shot blasted or hydroblasted (Sprinkel 2004).

The advantages and disadvantages of milling are listed below (Wilson et al. 1999).

Advantages:

- When considering large areas, milling is efficient and economical.
- It leaves a rough, uneven surface that is beneficial to improving bond quality.

Disadvantages:

- If the size of the area to be removed is too small, the milling machine may remove more than

necessary due to the minimum milling head sizes available.
- It may cause damage to the areas outside the area to be repaired.

3.1.3 Sawing

This method of concrete removal usually involves using a diamond-segmented blade to cut the concrete deck into sections and then using a crane to lift the cut sections away from the bridge. These blades have fast cutting speeds and produce smooth cuts. Sawing methods can typically cut concrete at any angle with little to no vibration and without the worry of falling materials (Phares et al. 2014); however, sawing does present the risk of damaging the top flanges of steel girders and should be used with a coolant fluid for best results (Tadros and Baishya 1998).

Due to the costs associated with replacing blades and various safety concerns, it is recommended that personnel training be implemented if this method is chosen (Phares et al. 2014). The advantages and disadvantages to this system are listed below (Wilson et al. 1999).

Advantages:
- The saw leaves vertical edge faces.
- The forces experienced by the concrete are isolated within the sawed boundaries.
- Very little spalling of the remaining concrete occurs.
- Removing the deteriorated concrete within the sawed boundaries is usually easier and faster when the boundaries are sawed than when they are not.
- Familiarity of the process exists among most crews.

Disadvantages:
- A larger labor force is required when compared with some other removal procedures.
- Since water is used when sawing, the repair area is saturated for some time, possibly delaying the repair if it is necessary that the area be dry for patching material placement.
- Saw overcuts make the repair area weaker leading to it needing to be cleaned and sealed.
- The saw may intrude on the open lane of traffic.
- The vertical, fine edges may decrease the chance of having a good bond.

3.1.4 Crushing

Crushing applies opposing forces on both sides of the concrete element to cut the internal reinforcement and break the concrete simultaneously. This can be done with little noise and vibration. It is difficult to use over beams, and the concrete above girders still requires hand removal (Phares et al. 2014).

3.1.5 Peeling

Peeling is a simple, economical removal technique for concrete decks that applies vertical forces on the deck to break the concrete free from the girder. The concrete is then removed from the bridge with an excavator, slab crab, and machine-mounted bucket attachments (Phares et al. 2014).

3.2 Rapid Protection

Rapid protection relates to the techniques and methods that are used to coat and protect the deck from infiltration of water and chlorides and the associated deterioration that typically results. The systems outlined here are bituminous concrete overlays, polymer overlays, high early-strength hydraulic cement concrete overlays, and penetrating sealers.

A study conducted by Sprinkel and Sellars (1990) outlines several timelines for the different methods. The categories of analysis included time for traffic control measures to be implemented, surface preparation time, and placing and curing time. These time allowances are shown in Table 1. These are suggested timelines based on an extensive literature review. The times provided may need to be adapted based on project specifications.

Table 1. Rapid deck protection time requirements

System	Avg. Area (yd^2)	Traffic Control (hr.)	Surface Preparation (hr.)	Placing and Curing (hr.)	Total (hr.)
Bituminous Concrete Overlay on Membrane	587	2.5	3.7	6.5	12.7
Coating	519	2.0	1.8	5.7	9.5
PCC Overlay	1181	0.9	2.3	5.6	8.8
Penetrating Sealer	673	1.5	2.2	3.4	7.1
Polymer Overlay	481	1.2	4.0	4.7	9.9
Other Hydraulic Cement Overlay	452	0.9	4.0	3.1	8.0

Source: Sprinkel and Sellars 1990, Strategic Highway Research Program

From the same study, a compilation of service life and initial cost of the different methods was generated in Table 2.

Table 2. Rapid deck protection service life and initial cost

System	Average Service Life (yrs.)	Average Initial Cost ($/yd^2)
Bituminous Concrete Overlay on Membrane	9.7	50.84
Coating	--	--
PCC Overlay	17.9	83.21
Penetrating Sealer	5.0	5.45
Polymer Overlay	10.0	43.55
Other Hydraulic Cement Overlay	--	6.08

Source: Sprinkel and Sellars 1990, Strategic Highway Research Program

3.2.1 Bituminous Concrete Overlays

Bituminous concrete overlays are placed with a paving machine and compacted to a minimum thickness of 1.5 in. using a roller. These overlays are to be used in conjunction with a coating or sealer to prevent chloride ion penetration; however, they may not need to be used for low-permeability concretes. The sealers and coating offer the added benefit of improving skid resistance, so when these are not needed, skid resistance can instead be improved by applying a chip seal or surface treatment (Sprinkel and Sellars 1990).

The bituminous membranes include binders filled with aggregate and typically extend 1 in. up the face of curbs, across backwalls, onto approach slabs, and across all joints except expansion joints. Twenty-four hours prior to placement, the deck should be sandblasted to remove any unwanted materials, and it should be dry. The surface should be smooth for a good bond if a prefabricated sheet membrane is used and slightly textured if a liquid membrane is used (Sprinkel and Sellars 1990).

3.2.2 Polymer Overlays

Polymer overlays can reduce infiltration and increase skid resistance; however, they cannot be used to improve ride quality or drainage because of the relatively thin nature of their application. Because the polymer is very lightweight, it may have the added benefit of creating additional live load capacity on the deck by minimizing the additional dead load added (Sprinkel and Sellars 1990). Application of a polymer overlay is shown in Figure 3.

Bridge Engineering Center at Iowa State University

Figure 3. Polymer overlay application

The basic types of polymer overlay are multiple-layer, premixed, and slurry.

Multiple-layer overlays can be created by spraying one or more layers of resin (the most common being epoxy) or aggregate (Sprinkel and Sellars 1990). An hour later, the aggregate that was unbonded is swept away, and the second layer of resin and aggregate is applied. Most multiple-layer polymer overlays are constructed with two layers, yielding a total thickness of approximately 1/4 in. Multiple-layer polymer overlays have been seen to provide very good long-term adhesion especially in applications where bond strength is of concern (Sprinkel and Sellars 1990).

Premixed overlays are constructed in the following manner: the binder (most common being polyester styrene) is mixed at the job site, the surface should be coated with a polymer primer (the most often used is a special alkali-resistant polyester or high molecular weight methacrylate), and the polymer is placed, consolidated, and then struck off. The finishing thickness should be 1/2 to 1 in.

Slurry overlays are constructed by mixing and applying a flowable polymer mortar onto a primed deck surface. The mortar is then immediately struck off with a gauge to make sure the depth is approximately 1/4 in., after which an aggregate is placed on top. Once the aggregate has been placed, any excess is scraped off (Sprinkel and Sellars 1990).

The aggregate used in polymer overlays is usually silica sand or basalt. Different types of resins used in polymer overlays include acrylic, methacrylate, high molecular weight methacrylate, epoxy, epoxy-urethane, furfuryl alcohol, polyester styrene, and sulphur (Sprinkel and Sellars 1990). Studies have shown that when a deck is subjected to chloride ion content at the reinforcing bars less than 1.0 lb/yd^3, no corrosion should be expected if a multiple-layer epoxy overlay is used. For all other protection methods under the same chloride ion conditions, corrosion is expected in less than 15 years (Sprinkel and Sellars 1990).

One type of polymer overlay that has been specifically studied is methyl-methacrylate (MMA). This type of MMA overlay is used as a waterproofing layer that prevents moisture-related failure of bridge decks. Because it can be used as both a repair and waterproofing layer, it saves significant construction time and labor costs (Kim and Lee 2009).

3.2.3 High Early-Strength Hydraulic Cement Concrete Overlays

Several types of hydraulic cement concrete overlays are available. Portland cement concrete (PCC) overlays are the most prevalent. These PCC overlays require a minimum thickness of 1.25 in. for concrete with 15% latex by weight of cement and 2 in. for most other concretes. While these concretes can be placed at a thickness of 1 in., the lesser depth has a tendency to crack and does not provide much protection unless latex or silica fume is added to the mix (Sprinkel and Sellars 1990).

Adding Pyrament to PCC overlays allows for a suitable strength in less than 8 hours. Other admixtures that improve strength-gaining time include Type III Portland cement, corrosion inhibitors, high-range water reducers, latex, silica fume, and rapid hardening cementitious materials. If a project requires a lane closure of less than 56 hours, the designer should consider utilizing conventional high early-strength PCC overlays such as those with Type I and Type II Portland cement and silica fume or Type III Portland cement and latex (Sprinkel and Sellars 1990).

Other hydraulic cement concrete overlays include the use of alumina cement and magnesium phosphate cement. They can be placed in a similar fashion as PCC overlays and have the added benefit that they can be air cured rather than moist cured (Sprinkel and Sellars 1990).

3.2.3.1 Case Study: Repair of Southbound Lanes of I-395 Bridge Spanning George Washington (G.W.) Memorial Parkway in Washington, DC using Rapid-Set Latex-Modified Concrete (RSLMC) Overlay

In late 1998, crews were allotted 9 p.m. to 5 a.m. each day to repair the southbound lanes of the I-395 Bridge over the G.W. Memorial Parkway in Washington, DC. The original plan was to complete 150 ft by 20 ft sections each night. The entire repair was completed in only 4 days (Concrete Products 1999). The project utilized two truck-mounted mobile batcher mixers. These mixers were equipped with latex additive systems. They placed the RSLMC at a thickness of 2 in. (Concrete Products 1999).

This specific project showed cylinder strength test results for the RSLMC of 2,156 psi in 2 hours, 2,632 psi in 3 hours, and 4,785 psi in 7 days. This project was able to be opened to traffic in approximately 3 hours. It is estimated that "by using this type of system, departments of transportation spending at least $5 million annually on deck rehabilitation can save up to $1.25 million a year" – Michael Sprinkel (Concrete Products 1999).

3.2.4 Penetrating Sealers

Options available for sealers include acrylic, epoxy, gum resin, rubber, urethane, silicone resin, silane, and siloxane. To achieve adequate skid resistance, sealers must be placed on heavily textured surfaces. These textured surfaces can be created by tining fresh concrete, shotblasting a hardened concrete surface, or sawcutting grooves in the hardened concrete. The surface must be clean and dry for proper bond of the sealer to the concrete (Sprinkel and Sellars 1990). Sealers can be applied by way of spray, roller, brush, or squeegee (Sprinkel and Sellars 1990). Sealers can protect against significant chloride ion penetration for 7 to 10 years, but performance of these sealers varies (Sprinkel and Sellars 1990).

Methyl methacrylate concrete has very high compressive strengths and good adhesion, but caution should be taken when using it, as prolonged exposure to fumes may cause health hazards (Wilson et al. 1999).

3.3 Rapid Repair

Rapid repair information summarized here includes information gathered on the different processes available for small "spot" repairs on bridge decks; these are cases for which removal of the entire deck and replacement is not economical. The materials and processes available for repair of bridge decks are very similar to those that exist for rapid protection. These systems include asphalt concrete patches, polymer concrete patches, and high early-strength hydraulic cement concrete patches. Where a patch repair is not warranted, it is more than likely that a crack repair and seal need to be performed.

A study conducted by Sprinkel and Sellars (1990) provided the data in Tables 3 and 4 on time requirements, service life, and initial costs of each patching system.

Table 3. Rapid deck patching time requirements

System	Average Area (yd^2)	Traffic control (hr.)	Surface prep. (hr.)	Placing and curing (hr.)	Total (hr.)
Bituminous Concrete Patch	5	0.9	0.4	0.7	2.0
Portland Cement Concrete Patch	9	1.7	3.3	2.6	7.6
Polymer Concrete Patch	202	2.1	1.9	5.2	9.2
Other HCC Concrete Patch	43	1.5	2.2	3.1	6.8

Source: Sprinkel and Sellars 1990, Strategic Highway Research Program

Table 4. Rapid deck patching average service life and average initial cost

System	Average Service Life (yrs.)	Average Initial Cost ($/$yd^2$)
Bituminous Concrete Patch	0.6	40.57
Portland Cement Concrete Patch	14.8	202.17
Polymer Concrete Patch	5.5	247.07
Other HCC Concrete Patch	3.8	235.16

Source: Sprinkel and Sellars 1990, Strategic Highway Research Program

These are suggested timelines based on an extensive literature review. The times provided may need to be adapted based on project specifications.

3.3.1 Asphalt Concrete Patching

Bituminous materials are fairly inexpensive, easy to place with small crews, and need little to no time to cure (Wilson et al. 1999), making them an effective choice for a rapid repair; however, based on a study conducted by Sprinkel et al. (1993), projected minimum service lives for this treatment option based on field evaluations is only 1 year, meaning that this should only be used as a temporary repair option and should be replaced with a material that provides a longer service life.

To apply an asphalt patch, the contractor must remove any dust from the area to be patched, apply a tack coat, place the patching material, and compact it. An advantage of using asphalt concrete to repair deteriorated concrete is that there are hot and cold mixes available, allowing the contractor to repair the area no matter the climate or weather conditions (Sprinkel and Sellars 1990).

3.3.2 Polymer Concrete Patching

The polymer concrete patching method of repair is effective when the area to be patched is less than 0.8 in. thick. If this is the case, the polymer can be troweled into place and finished (Sprinkel and Sellars 1990).

Polymer cement concrete is quick setting (15 to 20 minutes) and has a short time to full material strength, which is relatively high. The polymer cement concrete forms a good bond to old concrete and has a high resistance to environmental conditions. It is prepared in a similar fashion to regular concrete: the polymer is added during the mix (latex-modified being one of the most common) with a 0.1 to 0.2 latex cement ratio by weight, and a corresponding water to cement ratio of 0.3 to 0.4 (Radomski 2002).

Epoxy concrete in particular is impermeable. It has excellent adhesive qualities. However, it must be thermally compatible with the underlying material; otherwise, the patch may fail. It should not be used to patch spalls caused by reinforcing steel corrosion (Wilson et al. 1999).

3.3.3 High Early-Strength Hydraulic Cement Concrete (HCC) Patching

Using high early-strength HCC for patching is the most common method of patching. A typical patching job is as follows (Sprinkel and Sellars 1990):

1. Square up the area to be patched.
2. Sawcut the perimeter to a depth of 1 in.
3. Remove the concrete to the required depth with pneumatic hammers weighing less than 30 lb with a sharpened chisel point at least 3 in. wide.
4. Blast the concrete and rebar with sand or slag.
5. Apply bonding grout if necessary.
6. Fill the cavity with the patching material.
7. Consolidate and strike off the material.
8. Apply liquid or other curing material.

Full-depth patches to be repaired with high early-strength HCC require formwork, which can either be suspended from reinforcing bars or supported by beam flanges (Sprinkel and Sellars 1990). The most commonly used admixture is rapid-hardening cementitious material meeting ASTM C 928 standards. These admixtures give a compressive strength of 2,500 to 3,000 psi in 3 hours or less. This time can be extended by adding 50 to 100% coarse aggregate by weight of cement and sand. The contractor could also choose to use a premixed material, which has the added benefit of having optimum mixture conditions already prescribed, potentially adding to construction time savings; however, the difference in shrinkage between these prepackaged materials and bridge deck concrete should be taken into account. Shrinkage can be reduced by altering the mix proportions to minimize cement and water content, while maximizing aggregate content (Sprinkel and Sellars 1990). Projected minimum service lives for concretes using

Portland cement or magnesium phosphate is equal to 25 years in both cases (when subjected to average daily traffic/ADT of 5,000) (Sprinkel and Sellars 1990).

3.3.4 Crack Repair and Sealing

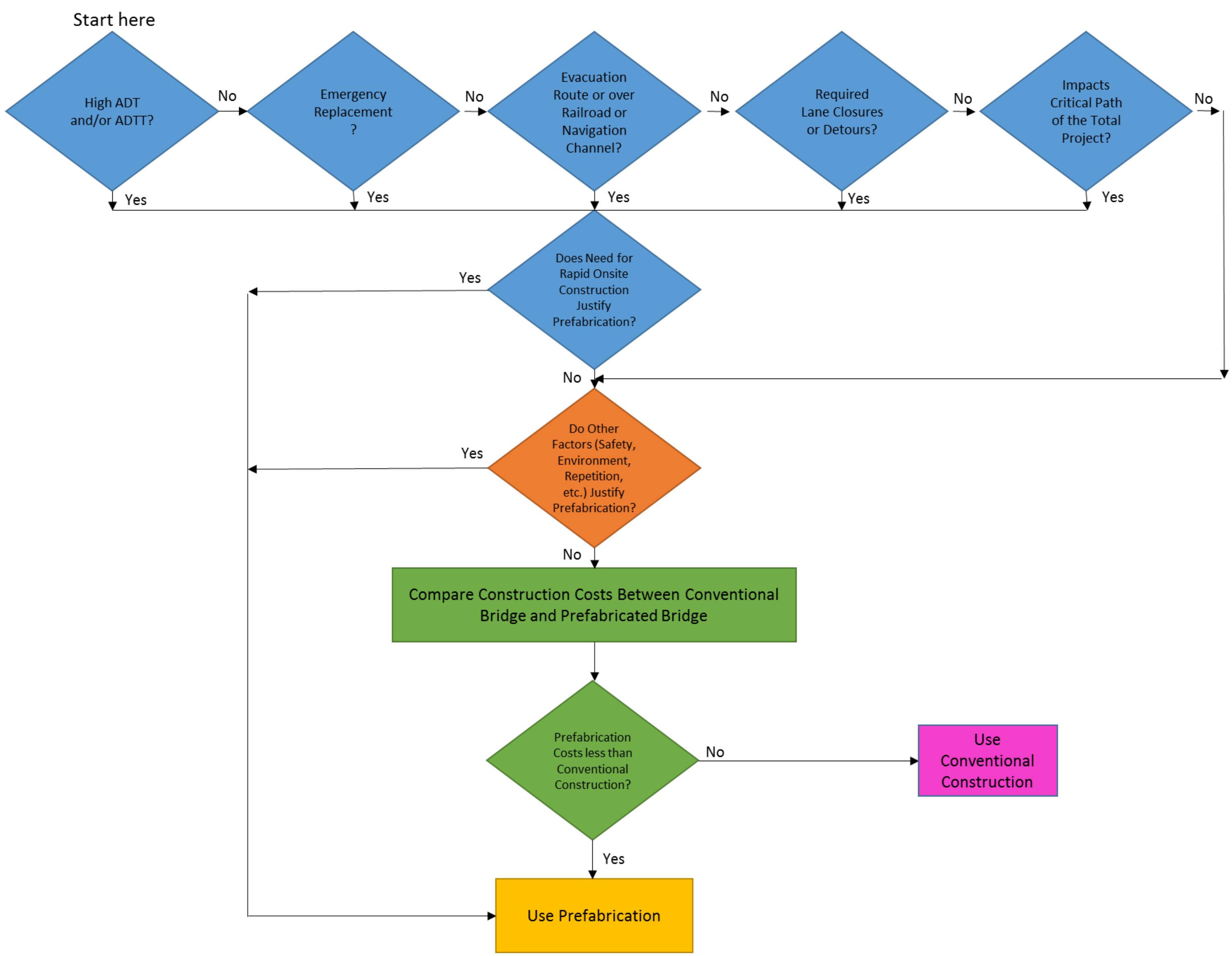
Several methods of crack repair and sealing exist. These techniques include repair by way of gravity fill, grout and seal, V-groove and seal, and vacuum injection (Sprinkel and Sellars 1990).

High molecular weight methacrylates with viscosity of less than 25 centipoise (cp) are effective at repairing cracks with widths 0.008 to 0.079 in. A minimum crack width of 0.02 in. is recommended to warrant the use of gravity fill with epoxy resins with viscosity of 100 cp or more. Plastic shrinkage cracks should be filled with a monomer that is brushed into cracks (Sprinkel and Sellars 1990).

3.4 Rapid Replacement

In certain situations, too much of the deck may be damaged to warrant the use of rapid repair methods for each deteriorated section of the deck. In such cases, it may be more economical to replace the deck in its entirety. Rapid replacement methods available are described within this section.

Several of the options presented require the use of prefabricated elements. The Federal Highway Administration (FHWA) offers the following flowchart (Figure 4) and related table of questions (Table 5) to assist the designer in deciding if prefabrication is necessary for a given project.



Recreated from FHWA 2005

Figure 4. Decision-making flowchart for prefabricated elements

Table 5. Decision-making tool for prefabricated elements

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

Source: FHWA 2005

3.4.1 Cast-in-Place (CIP) High Early-Strength Concrete

This option for deck replacement makes use of cast-in-place (CIP) high early-strength concrete. It is the most popular option where rapid deck replacement is concerned. Because this option requires the use of formwork, to hasten the process, the use of stay-in-place (SIP) forms could be considered. The advantages and disadvantages of this system are as follows (Ramey and Oliver 1998).

Advantages:

- The materials required are readily available.
- The construction methods are well-known.
- The contractor familiarity and ease of access to materials make for a low-cost product.
- Because the deck is CIP, field adjustments to the riding surface profile can be made easily.
- The finished product has good durability.
- The finished product has an excellent riding, wear, and skid-resistant surface.

Disadvantages:

- The deck is comprised of materials with a relatively high unit weight.
- Compared to other rapid replacement methods, CIP decks are relatively slow to construct.
- Although the overall cost is low, there is a high cost of field forming and placing reinforcing bar.
- Traffic may be delayed further due to the significant curing time.
- There is a higher likelihood of cracking in the newly constructed deck due to differential shrinkage between the deck and the underlying girder (Tadros and Baishya 1998).
- If welded wire fabric is used, splicing can be a challenge, and it should be noted that epoxy coating can have an effect on the development and anchorage (Tadros and Baishya 1998).

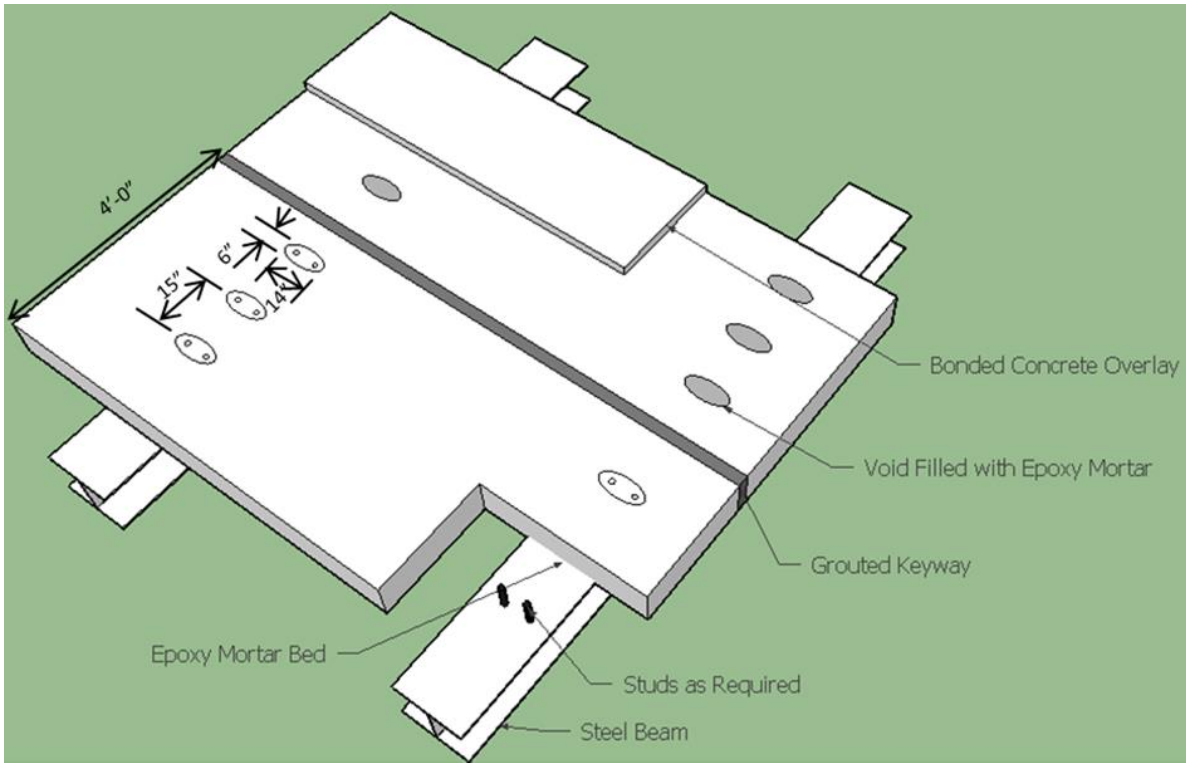
3.4.1.1 Case Study: Pickaway County State Route 22 Bridge over the Scioto River: A Design-Build Contract that Helped Complete a Typically 18-Month Bridge Rehabilitation in Only 47 Days

In the summer of 2003, the Pickaway County State Route 22 Bridge over the Scioto River (30 miles south of Columbus, Ohio) was in need of a deck and girder replacement. The structure to be replaced, “was a 45-year-old concrete slab-on-steel stringer bridge. The 700 ft long, six-span bridge had 90 ft approach spans and 112 ft 6 in. main spans, consisting of four concrete girders supported by concrete hammer-head piers. The three western spans bridged the main channel of the river while the remaining spans bridged the flood plain. The deck was 29 ft 4 in. wide, accommodating a two-lane roadway and two, 3 ft wide sidewalks. The existing structure was is need of retrofit/replacement because of severe deterioration of girders, and a wider roadway was desired” (Swanson and Windau 2004). The roadway was widened by 10 ft.

The deck replacement utilized CIP concrete with SIP forms. Traffic was completely shut down during the construction period. To assist the use of SIP forms, “ladders” were used. “The supports, known as ‘ladders,’ consisted of pairs of parallel angles connected by bar stock so that they could straddle the top flanges of the girders and support the ends of the stay-in-place forms” (Swanson and Windau 2004). These supports were prefabricated and were reported to save a significant amount of on-site time. The concrete was placed with two pumpers, one at either end of the bridge. The design-build team was awarded $500,000 for opening the bridge to traffic 10 days in advance of what was required.

3.4.2 Precast Concrete Deck Panels

A common form of deck replacement is to use precast concrete deck panels that are joined together by transverse and longitudinal deck joints and connected to the girders via shear keys and blockouts, which are filled with a grout or mortar to ensure that the bridge deck is composite with the girders. Figure 5 shows a typical precast deck panel.



Recreated from Ramey and Oliver 1998, Highway Research Center, Harbert Engineering Center, Auburn University

Figure 5. Typical precast concrete deck panel

The advantages and disadvantages of using a precast concrete panel system are as follows (Ramey and Oliver 1998).

Advantages:

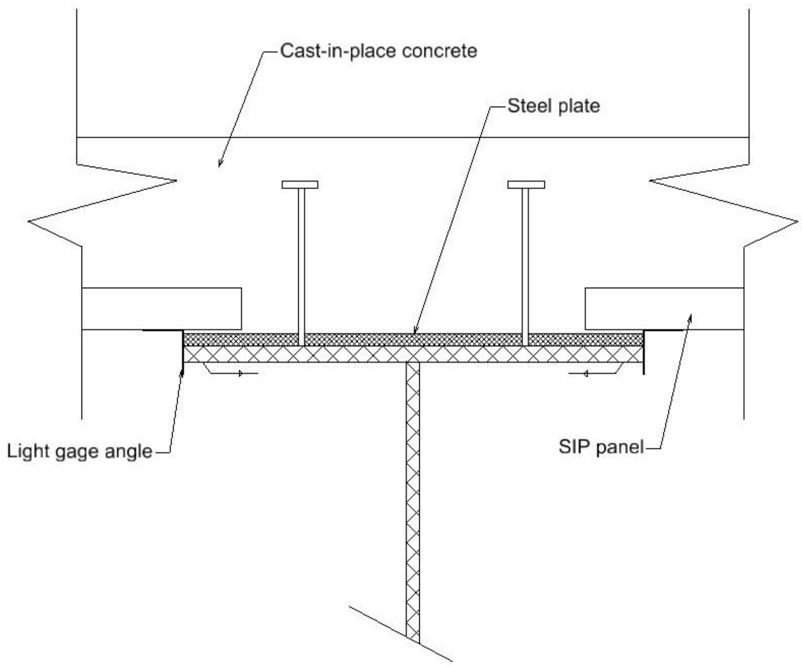
- The quality control of each panel is exceptional.
- Because each panel is precast, deck replacement time can be reduced significantly.
- The panels allow for a nearly immediate riding surface.
- The panels come at a relatively low cost, but are more expensive than using a traditional CIP concrete deck.
- The panels allow for longitudinal post-tensioning and a nearly crack free and stiffer deck.

Disadvantages:

- There is added complexity where design and construction details for shear transfer to supporting girders are concerned.
- Leakage into one (or several) of the many cold joints in the deck surface could cause issues. To avoid this problem, the addition of a wearing surface may need to be considered.

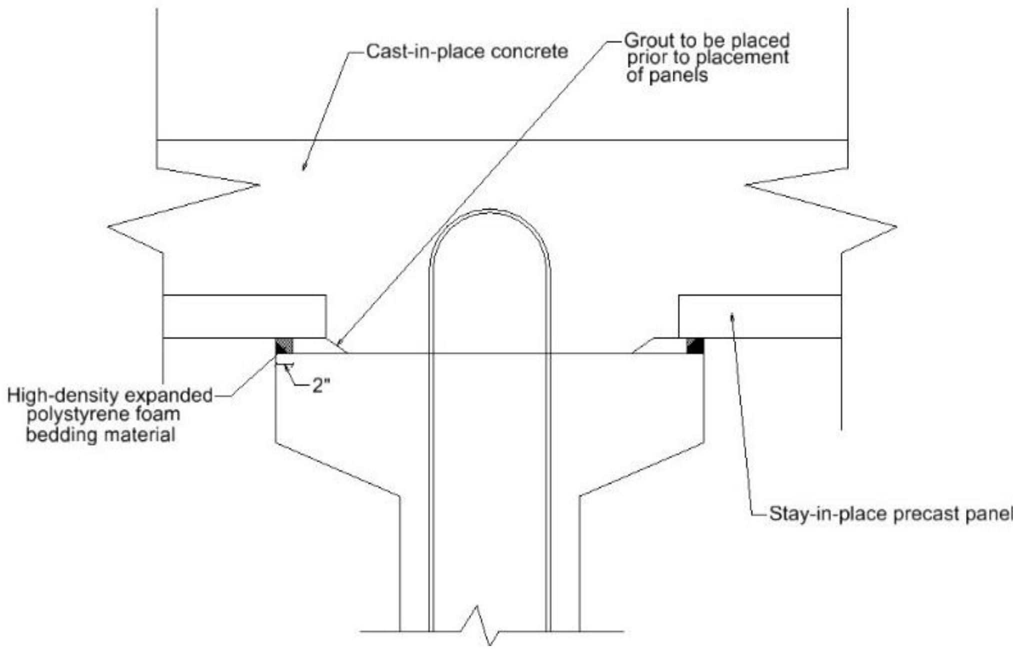
3.4.2.1 Partial-Depth Precast Prestressed Concrete Deck Panels

Partial-depth precast concrete deck panel systems usually consist of 2.5 to 3.5 in. thick precast modular panels that are prestressed with 3/8, 7/16, or 1/2 in. strands. These panels range in width from 4 to 8 ft. The deck is completed with the addition of a CIP portion ranging from 3.5 to 6 in., depending on the needs of the project (Tadros and Baishya 1998). A typical detail of a connection of one of these panels to a steel or concrete girder is shown in Figures 6 and 7, respectively.



Recreated from Tadros and Baishya 1998, NCHRP

Figure 6. Detail of a partial-depth precast panel connection to steel girder



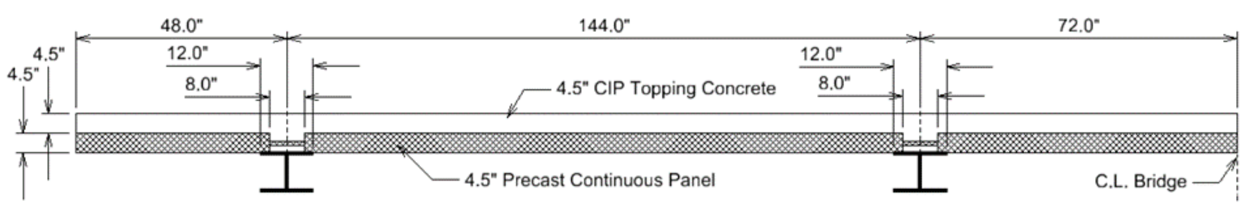
Recreated from Tadros and Baishya 1998, NCHRP

Figure 7. Detail of a partial-depth precast panel connection to concrete girder

Cracks forming at the edges over the prestressing strands is a realistic occurrence that can be minimized by the following (Tadros and Baishya 1998):

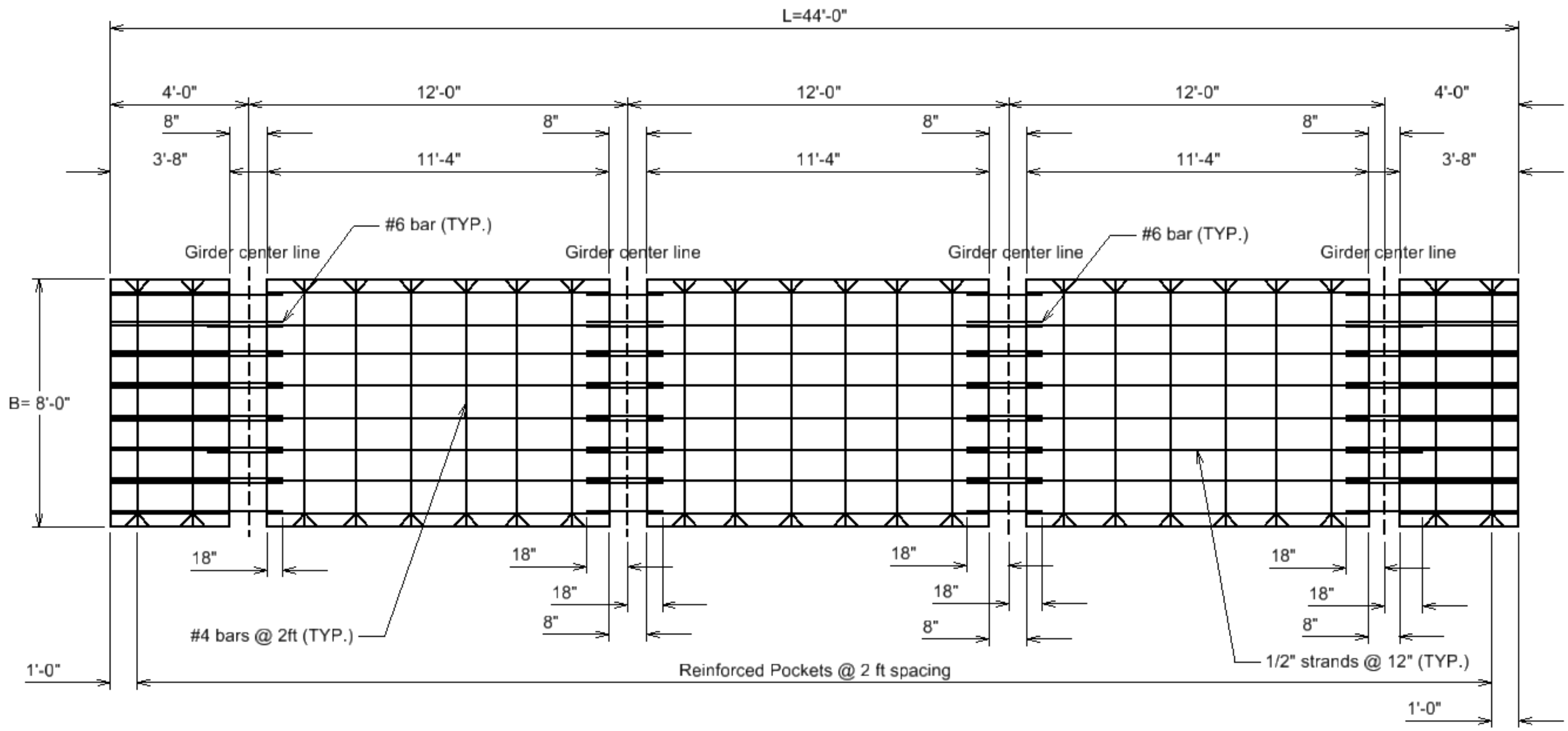
- Utilizing additional rebar placed perpendicular to the strands near the transverse edges
- Gently releasing the prestressing strands
- Uniform spacing of the prestressing strands
- Ensuring that the strands are placed at mid-height in the panel

Ramey and Oliver (1998) reviewed a specific type of this partial-depth system—one called the NU Continuous Precast Prestressed Stay-In-Place System—from the University of Nebraska. It consists of a 4.5 in. thick precast continuous prestressed concrete panel that is topped with a 4.5 in. CIP concrete layer. The CIP portion of the deck is reinforced with epoxy-coated welded wire fabric. Figures 8 through 13 show the details of the system studied.



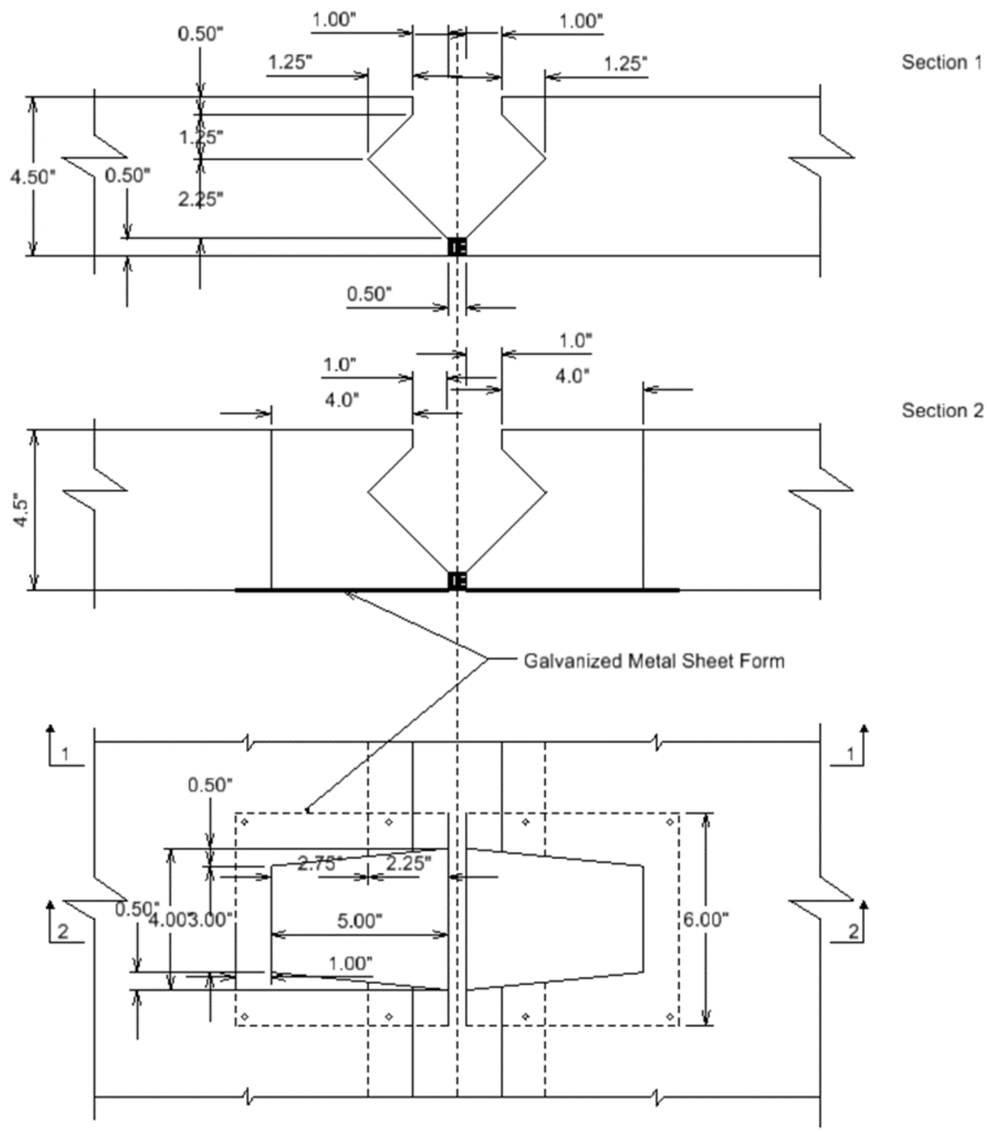
Recreated from Ramey and Oliver 1998, Highway Research Center, Harbert Engineering Center, Auburn University

Figure 8. Cross-section of NU continuous precast prestressed panel



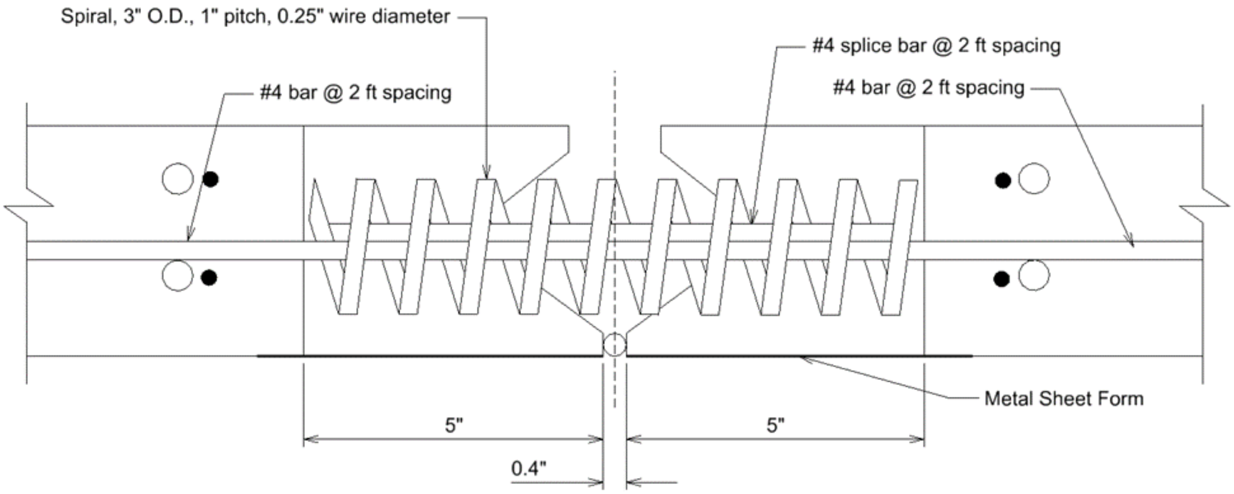
Recreated from Ramey and Oliver 1998, Highway Research Center, Harbert Engineering Center, Auburn University

Figure 9. Plan view of NU continuous precast prestressed system



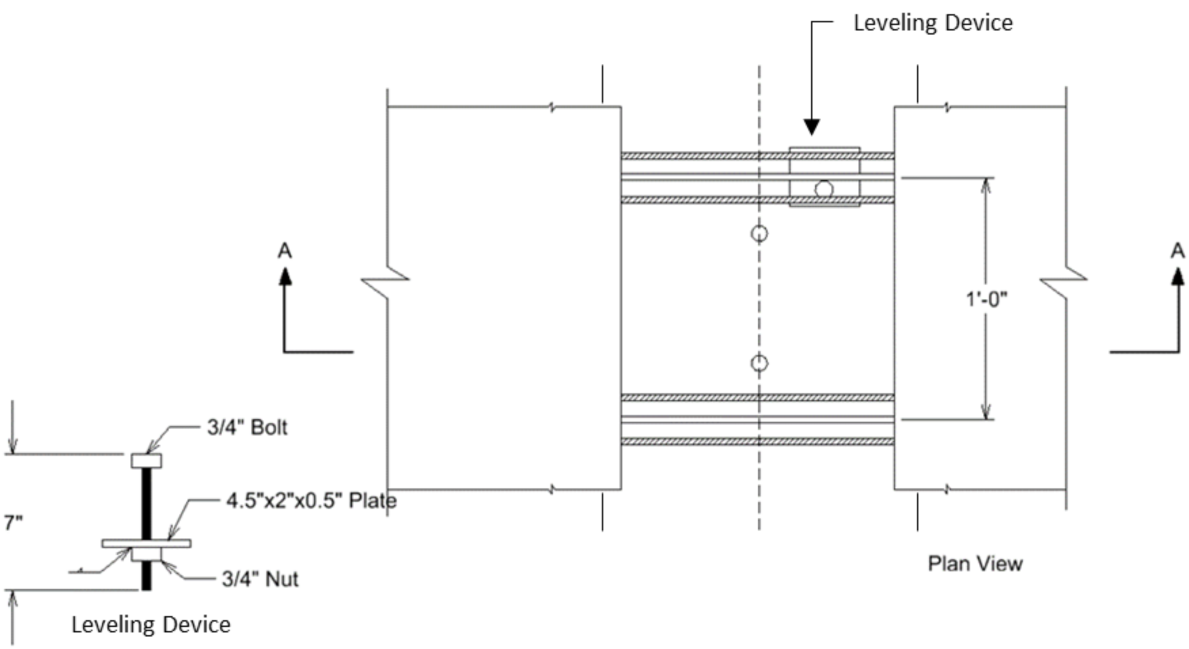
Recreated from Ramey and Oliver 1998, Highway Research Center, Harbert Engineering Center, Auburn University

Figure 10. NU continuous precast prestressed panel transverse joint details



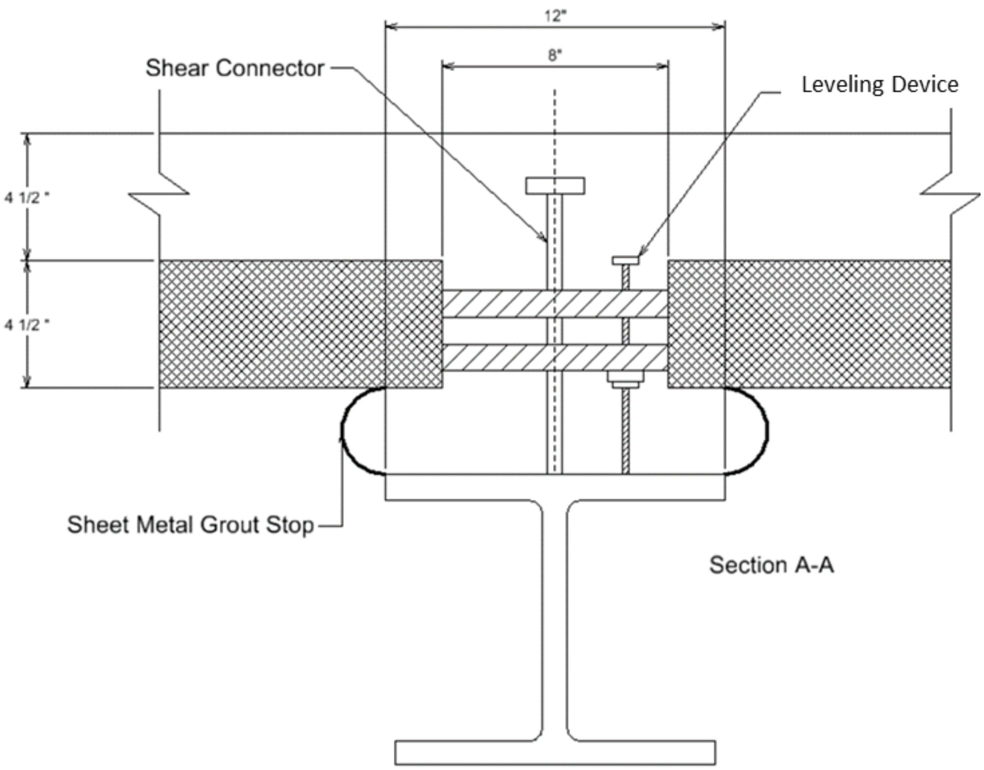
Recreated from Ramey and Oliver 1998, Highway Research Center, Harbert Engineering Center, Auburn University

Figure 11. NU continuous precast prestressed panel reinforced pocket detail



Recreated from Ramey and Oliver 1998, Highway Research Center, Harbert Engineering Center, Auburn University

Figure 12. NU continuous precast prestressed panel leveling device



Recreated from Ramey and Oliver 1998, Highway Research Center, Harbert Engineering Center, Auburn University

Figure 13. NU continuous precast prestressed panel leveling device

For this NU system, construction time may be decreased by 60% compared to construction time using a completely CIP system, and it is reduced by 20% compared to typical SIP precast systems (Ramey and Oliver 1998).

When compared to regular partial-depth precast prestressed systems, this NU panel system offers several advantages as follows (Ramey and Oliver 1998):

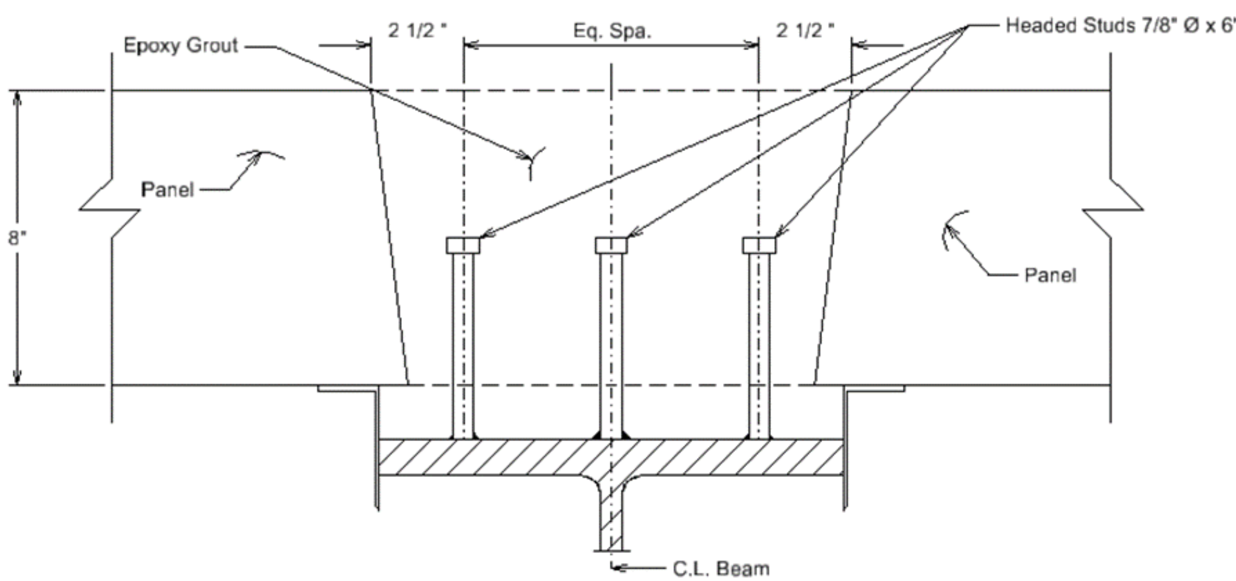
- The materials that comprise the panels come at a relatively low cost.
- The use of welded wire fabric reduced construction time by 55% compared to the construction time of the full-depth panels with conventional reinforcing.
- No field forming is necessary for deck overhangs.
- This system allows for the panel to be crowned.
- Better distribution of loads and elimination of reflective cracks can be observed due to the continuity of the panels in both directions.
- The only cracks that are seen are minor top cracks over the girder lines from cyclic loading.
- The creep of the prestressed concrete and continuity of the SIP panels contribute to compressive stress gains in the CIP concrete, which can help reduce service tension stresses in the negative moment regions.
- The prestressing strands are fully developed in maximum positive moment sections, which prevents the system from experiencing sudden one-way shear failure.
- It has almost twice the capacity of the original SIP system.

A second type of partial-depth SIP system that was specifically researched by Khayat and Meng (2014) is a UHPC partial-depth panel reinforced with polymer fibers. These fibers include micro-steel fibers, glass fiber-reinforced polymer grids, or carbon fiber-reinforced polymer grids. Design details for the panels themselves are not yet available, but it has been concluded that UHPC is a good option for the material to use in these panels. UHPC reinforced with polymer fibers has several advantages (Khayat and Meng 2014):

- Creates a more durable and lighter product
- Simplicity of use leading to faster construction time
- Volume needing to be transported is decreased
- Units fit together easily
- A smooth finish to the surface, meaning no need for extra surface work
- Reduced carbon emissions
- Could possibly be applied to other elements of bridge replacement not relating to the deck

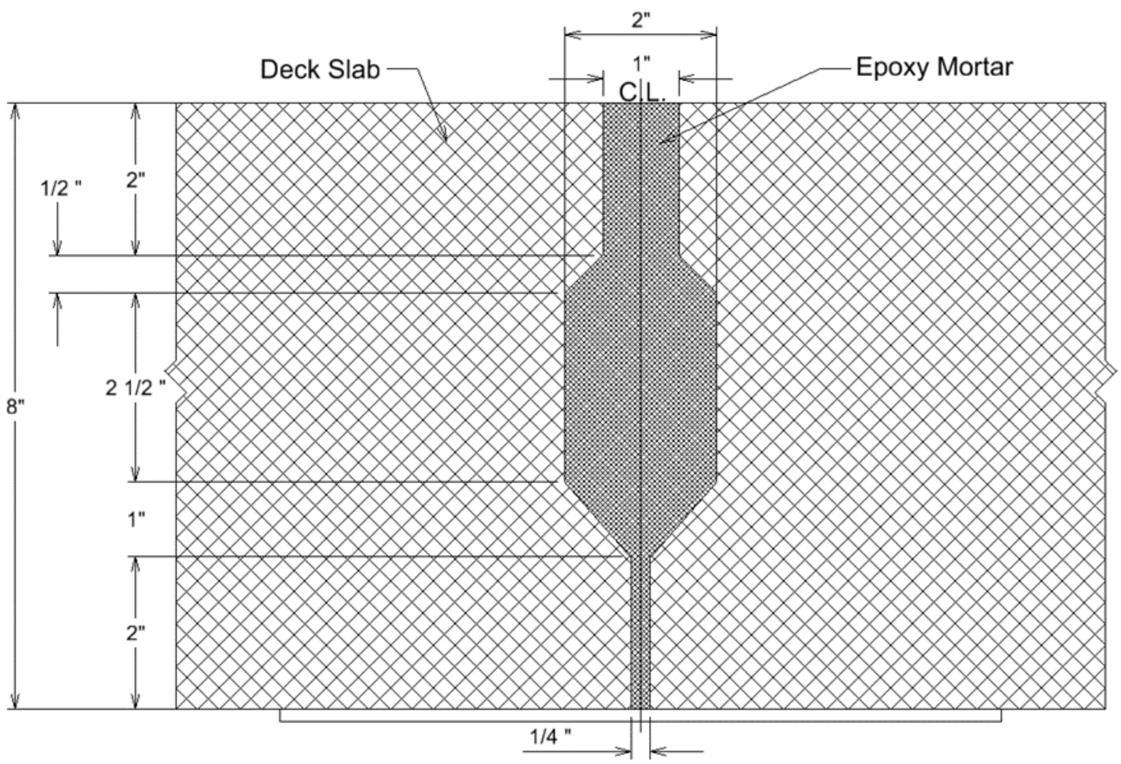
3.4.2.2 Full-Depth Precast Prestressed Concrete Deck Panels

Full-depth precast panels are entirely precast and require no additional layer of CIP concrete. Like the partial-depth option, these panels also require closure pours between panels and a filling of shear connectors for composite action of the entire structure. Closure pours occurring at deck ends and crowns should be filled with high early-strength concrete (Culmo 2000). Typical details of these shear keys are shown in Figures 14 and 15.



Recreated from Osegueda and Noel 1988, Texas Transportation Institute

Figure 14. Typical shear connector detail



Recreated from Osegueda and Noel 1988, Texas Transportation Institute

Figure 15. Typical keyway

Utilizing full-depth panels allows for the entire replacement procedure to be completed safely and adequately under normal supervision. When a panel has been fabricated but is not yet ready to be installed, it can easily be stockpiled offsite, meaning that panels can be fabricated whenever convenient and stored until installation (Tyson 1976).

As seen in Figure 14, it is typical to use 7/8 in. diameter shear studs; however, it has been suggested that 1.25 in. shear studs may be used instead to decrease the number of shear studs to install and significantly reduce overall installation time and congestion (Tadros and Baishya 1998). The shear connector pockets in which the shear studs are placed should be roughly rectangular at the top and trapezoidal from top to bottom. Corners should be rounded to eliminate the possibility of cracking due to release of prestress. To ensure composite action is present, 2 to 4 shear studs should be placed in each pocket (Culmo 2000).

In Figure 15, a 1/4 in. bottom opening in the keyway is displayed; however, it could be as wide as 3/4 in. or as small as 0 in. (Culmo 2000). It is recommended that the top opening be at least 1 in. wide for ease of grout placement (Osegueda and Noel 1988). These keyways should be filled with a non-shrink grout (Culmo 2000).

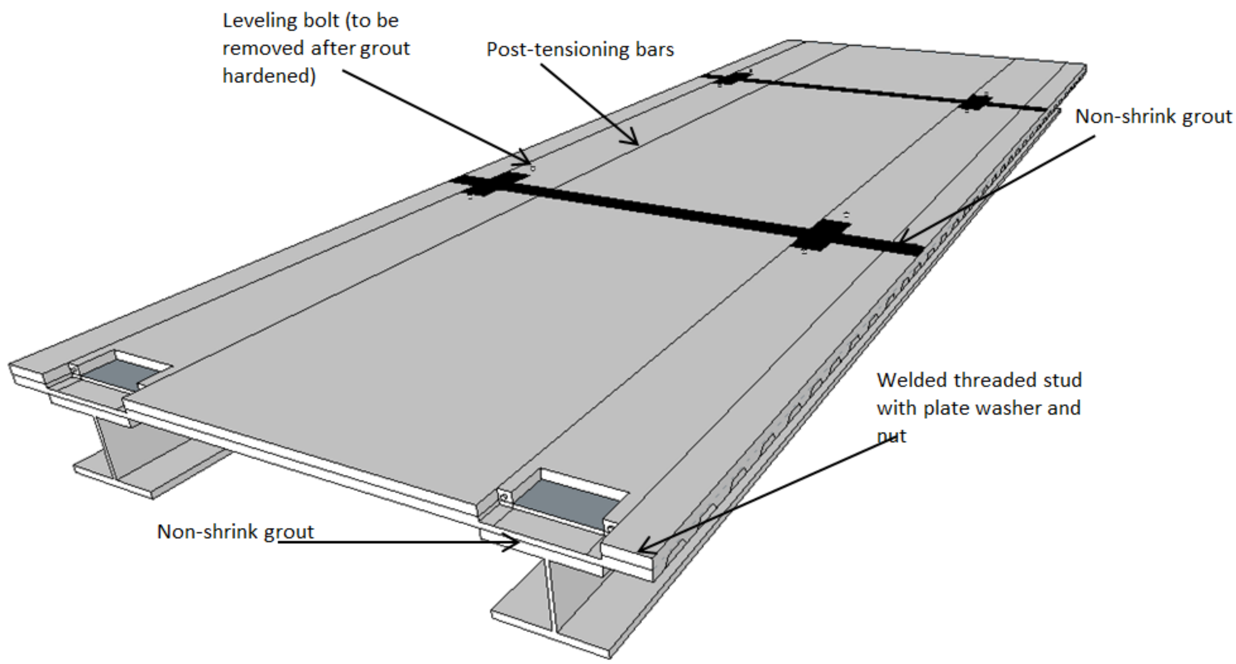
Generally, 8 in. deep panels are sufficient for most beam spacings, and they can be continuous across the width of the bridge unless there is a crown. If there is a crown, there should be a reinforced closure pour at the crown. To protect the panel, a wearing surface should be used (Culmo 2000).

The precast panels should be reinforced with epoxy-coated mild reinforcing, transverse to the girders, for main flexure reinforcement. Prestressing should be utilized in the interior bays. For ease of leveling of the panels in the field, a leveling bolt system should be installed (Culmo 2000). Where leveling bolt systems are not chosen to be used, it is recommended that each panel be placed on its own bearing pad to avoid tedious elevation adjustment during installation of each panel (Osegueda and Noel 1988).

The grout used to fill the joints between panels is a key ingredient in constructing a durable deck. A study conducted by Virginia Polytechnic Institute and State University looked at the connection between full-depth precast deck panels and precast I beams. The report included the following recommendations (Scholz et. al. 2007):

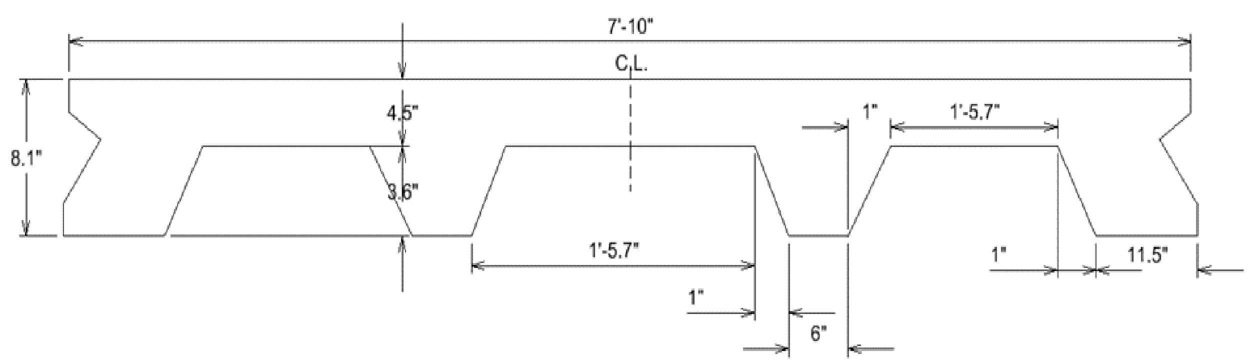
- A grout with a high compressive strength in 2 hours is recommended, as anything shorter will inhibit flow and workability of the mortar.
- A minimum compressive strength of 4,000 psi in 1 day and 5,000 psi in 7 is suggested.
- The recommended tensile strength at one day is 200 psi and 400 psi at 10 days.
- A very low shrink grout should be used with a maximum of 0.04% in 28 days.
- A work time of less than 15 minutes and a set time less than 30 minutes is ideal.
- The bond strength of the grout should provide an adhesion of at least 100 psi.
- If aggregate extension is necessary, the aggregate should be 3/8 in. pea gravel, and the extension should not exceed 50% by weight.
- Water content should not be greater than that specified for each grout, and water should not be added once pouring has begun.

Similar to the partial-depth panels, the University of Nebraska developed their own full-depth panel system. The advantages of this system include two-way prestressing that allows for crack control in both directions, longitudinal and transverse. It is 10% thinner and 20% lighter than CIP decks or conventional precast panels and it has a relatively rapid construction time. The disadvantages include contractor unfamiliarity and that it may require a bonded overlay or grinding to obtain an acceptable riding surface. The details of these full-depth panels are provided in Figures 16 through 19 (Tadros and Baishya 1998).



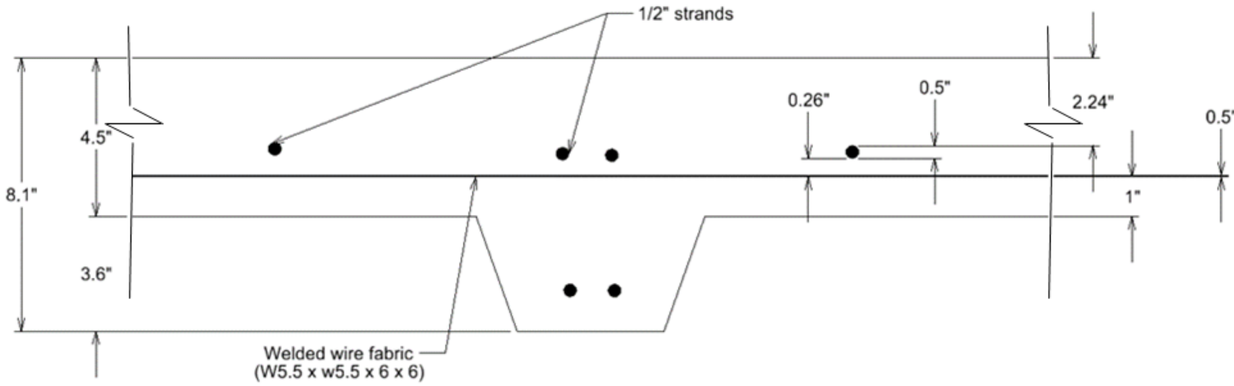
Recreated from Tadros and Baishya 1998, NCHRP

Figure 16. Precast prestressed full-depth concrete panel system



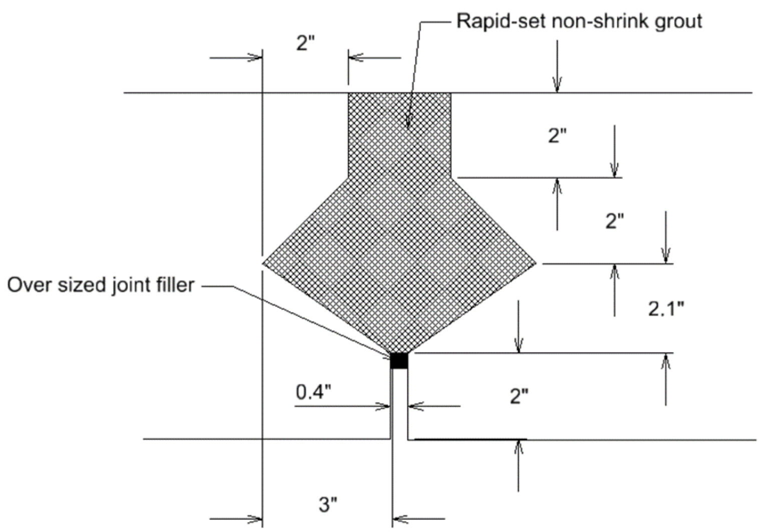
Recreated from Tadros and Baishya 1998, NCHRP

Figure 17. Typical transverse cross-section of full-depth panel



Recreated from Tadros and Baishya 1998, NCHRP

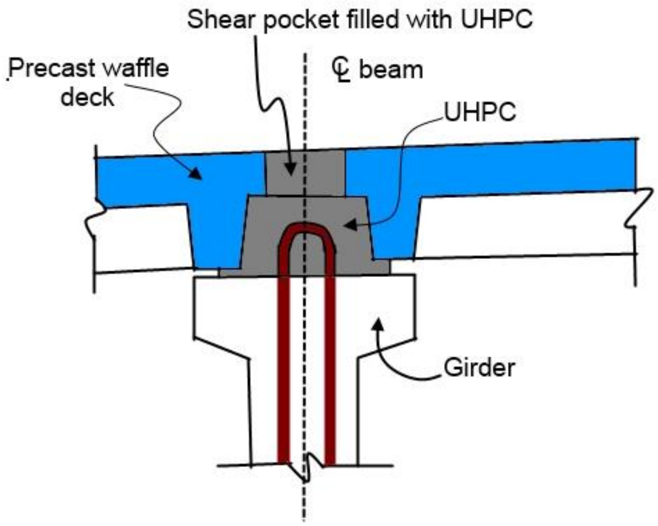
Figure 18. Typical steel arrangement in full-depth panel



Recreated from Tadros and Baishya 1998, NCHRP

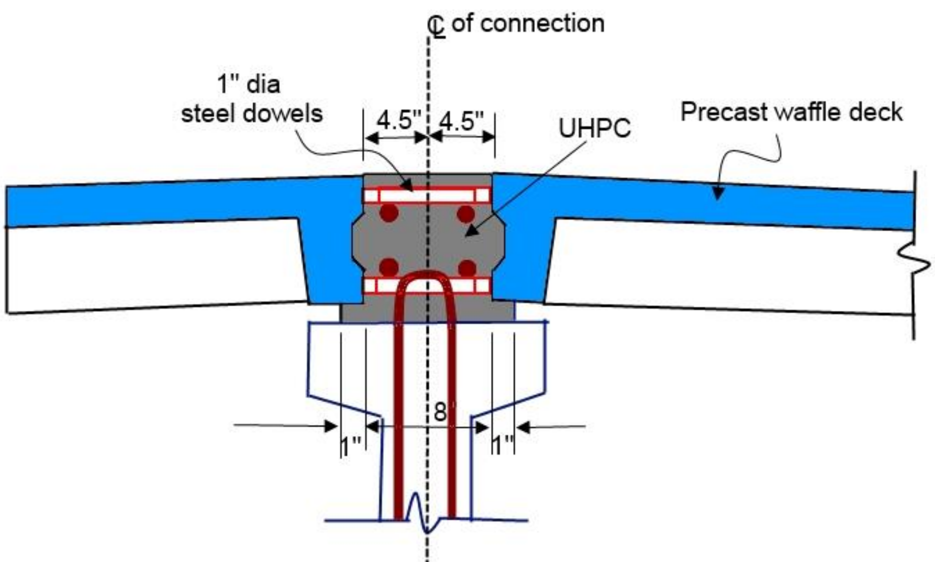
Figure 19. Transverse shear key detail for full-depth concrete panel

A second specific type of precast prestressed panel that has been developed is the UHPC waffle deck panel, depicted in Figures 20 through 22.



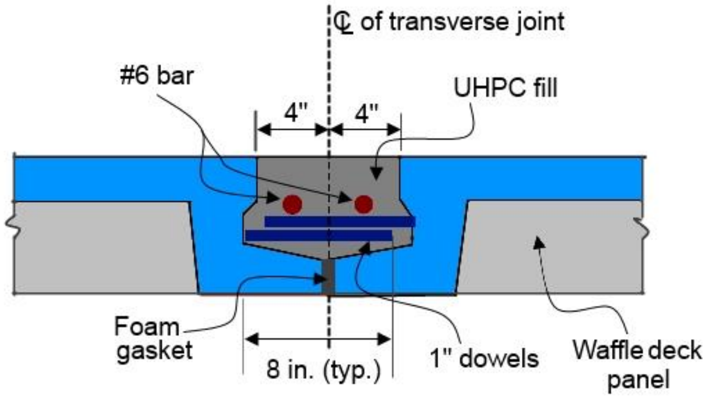
Aaleti et al. 2014, Bridge Engineering Center at Iowa State University

Figure 20. Connection detail between girder and waffle deck



Aaleti et al. 2014, Bridge Engineering Center at Iowa State University

Figure 21. Connection detail between center girder and waffle deck



Aaleti et al. 2014, Bridge Engineering Center at Iowa State University

Figure 22. Connection detail between deck panels

Instead of a constant 8 in. thickness like typical precast concrete panels, these precast panels have a 2.5 in. thick uniform slab cast integrally with concrete ribs, 5.5 in. deep, spanning in the transverse and longitudinal directions (forming the appearance of a waffle on the underside), for a total depth of 8 in. Similar to normal precast panels, this system utilizes shear blockouts and keyways to ensure that the deck is composite with the superstructure (Aaleti et al. 2014). The connection details for this system are shown in the figures.

Because this system does not have a constant 8 in. depth, it is relatively light compared to a conventional precast deck panel system. It has been tested, and it has been concluded that this a practical solution for a rapid deck replacement. Specific information related to the design of these waffle decks can be found in the FHWA *Design Guide for Precast UHPC Waffle Deck Panel System, including Connections* (Aaleti et al. 2013).

3.4.2.3 Case Study: Accelerated Bridge Deck Replacement with Prefabricated Modules on Route 7 Interchange at Route 50 in Fairfax County, Virginia

Two structures carry Route 7 heavy traffic (ADT of 35,000 vehicles per day/vpd) over Route 50 in Fairfax County, Virginia. These two single-span bridges (built in the 1950s) are 138 ft long and 48 ft wide on a 56-degree skew with steel-plate girders and a composite concrete deck (Fouladgar 1999).

The bridges were due to undergo deck replacement using accelerated methods. This meant doing all construction during the nighttime hours from 9 p.m. to 5 a.m. Using precast full-depth concrete panels, the project was completed in 6 weeks, with a final price tag of approximately $700,000 (Fouladgar 1999).

The panels were fabricated and stored offsite until they were installed. Construction consisted of removal of the existing deck, fabrication of new panels, placement of new panels, post-tensioning the panels, and placing a watertight overlay. The contractor also had to ensure that the bridge could be safely traveled during the daytime hours, which meant work had to be carried out in stages (Fouladgar 1999).

The design challenges encountered included how to adjust panel elevations ensuring shear transfer along transverse joints, moment along longitudinal joints, and composite action of the new deck, as well as how to temporarily hold the panels in place (Fouladgar 1999).

To solve the issue of adjusting panel elevations, leveling bolts were installed for easy and rapid vertical movement. Keyways and shear studs were used to ensure shear transfer and composite action and were filled with rapid-setting cement grout. To hold the panels in place, special bolts were installed in conjunction with a steel plate, which spanned the width of the blockouts. When the blockout was ready to be filled with grout, the steel plate and hold-down bolts were removed, and the rapid-setting grout was placed (Fouladgar 1999).

3.4.2.4 Case Study: Bridge Deck Replacement on US 189 over I-80 in Summit County, Utah

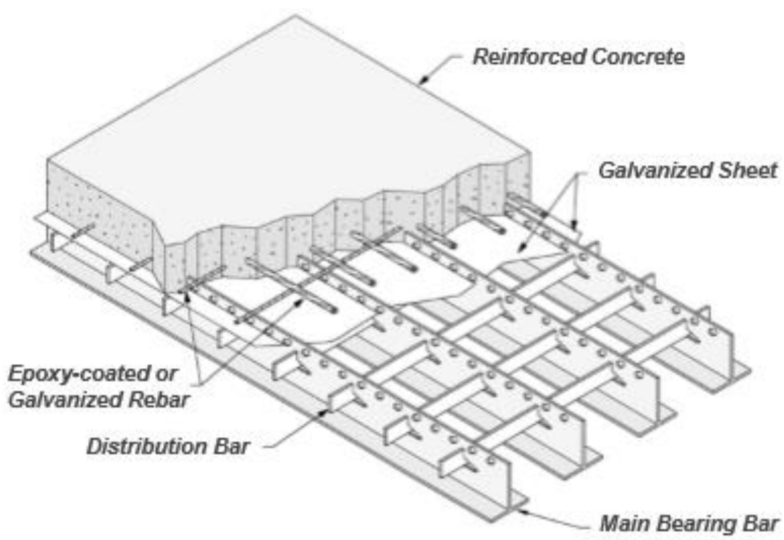
The US 189 bridge over I-80 in Summit County, Utah, 1.9 miles east of Wanship, was rehabilitated by the Utah Department of Transportation (UDOT). It is a four-span, 248 ft long, continuous-steel-plate girder bridge on an approximately 45-degree skew, built in 1967. The bridge deck consists of two 12 ft lanes, 3 ft shoulders, and 3 ft barriers, for a total width of 36 ft (URS 2003).

Because of the low traffic volume, UDOT decided to completely shut down the road during construction; however, they had to maintain one lane in each direction on I-80. To reduce traveler inconvenience, UDOT implemented a $100,000 graduated incentive reward, with the maximum closure time being 14 days (URS 2003).

UDOT explored two options for the deck replacement: 40 ft long by 17 ft wide mildly reinforced precast deck panels with transverse and longitudinal deck connection pours or full bridge width precast deck panels with longitudinal post-tensioning. Because of the extremely tight timeline, the skew of the bridge, and the complexities that come with post-tensioning, it was decided that the first option was the most practical for this specific project (URS 2003).

3.4.3 Exodermic Deck Panels

Exodermic deck panels are modular sections comprised of a steel grid on bottom—a system of inverted WT sections interlocking with steel distribution bars—with a thinner (approximately 4.5 in.) precast reinforced concrete slab on top, which sits atop a thin galvanized steel plate (Figure 23).



D.S. Brown Company 2007

Figure 23. Three-dimensional rendering of exodermic deck panel

These panels are designed such that, in the positive moment regions (i.e., compression on top), the concrete in the top of the panel takes the compressive forces, while the steel grid on the bottom takes the tensile forces. This eliminates the issue of the "unused" concrete in traditional concrete decks where the concrete near the deck bottom is assumed to be cracked and not contributing to the strength of the deck.

In the negative moment regions (i.e., compression on bottom) the steel grid on the bottom now takes the compressive forces, and the reinforcing bar in the reinforced concrete slab is in place to handle the tensile forces (Bettigole 1997).

These panels utilize shear keys and blockouts to connect panel to panel similar to full-depth precast concrete panels. The advantages and disadvantages to using this Exodermic deck panel system are as follows (Ramey and Oliver 1998).

Advantages:

- It is much lighter weight than a traditional reinforced concrete slab.
- The shear keys between panels permit rapid field placement.
- The reinforced concrete deck provides for an excellent (and almost immediate) riding surface.
- The construction staging is simplified.

Disadvantages:

- Contractor unfamiliarity is likely.
- It comes at a much higher cost than most alternatives (save orthotropic decks).

3.4.3.1 Case Study: William A. Stickel Bridge over the Passaic River

The William A. Stickel Bridge carries I-280 over the Passaic River and connects Hudson County, New Jersey to Essex County, New Jersey. The bridge was constructed in 1948 and is a 626 ft long, six-span, six-lane vertical-lift bridge with a through main truss span that sees more than 90,000 vpd.

A lightweight cast-in-place Exodermic deck system was used for this project. It was challenging to install along the gutter lines, at the scupper cutouts, where the roadway flared out, and at stage construction lines. Also, it was assumed by the contractor that the shear studs used for the lift span's steel grid deck would require less time than a welded grid and be more constructible; however, the shear studs proved difficult to use (Anella et al. 2009).

It is estimated that the accelerated methods employed in rehabilitating this bridge saved 15 months of time: 12 in the design phase and 3 in the construction phase (Anella et al. 2009).

3.4.3.2 Case Study: Route 27 Bridge over Pitman Creek in Kentucky

The Route 27 Bridge in Pitman Creek, Kentucky is a heavily traveled 700 ft long by 33 ft 2 in. wide, three-span, continuous, Warren deck truss and the reinforced concrete deck was in need of major repair.

The new deck was to be wider and have increased live load capacity. Because the replacement deck was to have an increased load rating over the existing, the new deck had to contribute to the strength considerably while still being lightweight to account for the fact that part of the deck would be cantilevered because of the widening. For this reason, an Exodermic deck option was chosen.

The steel grid was accompanied by a 4 in. precast reinforced concrete topping, yielding a total depth of 8.25 in. for the deck. The estimated installed weight of these panels was 73 lb/ft^2. Rapid-setting concrete was used to fill the blockouts and make the deck composite with the existing structure (Bettigole 1997).

Closing the route completely would mean a 90-minute detour for travelers. For this reason, the Kentucky Transportation Cabinet (KYTC) decided to complete the work at night, keeping one lane of traffic open at all times. Construction lasted from July 1993 to November 1993. "Both the state and the contractor consider the project a major success" (Bettigole 1997).

3.4.3.3 Case Study: Milton Madison Bridge over the Ohio River

The US 421 bridge over the Ohio River between Milton, Kentucky and Madison, Indiana was in need of rehabilitation. The bridge is 3,200 ft long, consisting of 19 spans and two lanes.

Because of the length of the detour, it was decided that one lane of traffic needed to stay open for the duration of the project. The narrow bridge width and the need to get the project completed quickly led to the decision to use Exodermic panels (Bettigole 1997).

3.4.3.4 Case Study: Troy-Menands Bridge

This structure carries the four lanes of Route 378 (approximately 36,000 ADT) over the Hudson River between Troy, New York and Menands, New York, running a distance of 1,070 ft.

The New York State DOT (NYSDOT) wanted the new deck to have a higher live load rating, which meant that the new deck had to be lightweight. The contractor wanted a lightweight deck for other reasons: it allowed for a lower boom angle on the crane used to lift the panels. The Exodermic panels used weighed roughly 40 to 50% of the old deck (Bettigole 1997).

Construction took place only at night and one lane of traffic was maintained at all times. Placement of the panels was very rapid, taking only minutes per panel. The quick placement time can be partially attributed to the built-in leveling system. Rapid-setting concrete was used to fill all joints and shear keys. This concrete reached 2,500 psi in roughly 2 hours, and the bridge was fully opened to traffic once this occurred.

Using Exodermic panels and this construction sequence allowed for 47,500 ft^2 of deck to be replaced in only 3 months (Bettigole 1997).

3.4.4 Open Steel Grids

This option for rapid deck replacement consists of a grid of interlocking steel bars that form a surface similar to that of a metal grate. The advantages and disadvantages to this system are as follows (Ramey and Oliver 1998).

Advantages:
- It is lightweight, meaning a decrease in dead load.
- Because of the open grid, the wind pressure acting on the grid is relatively low.
- The open grid allows for a self-draining surface.
- As soon as the panels are placed, a riding surface is provided.
- Connection to existing steel girders for composite action is simple.

Disadvantages:
- The panels have poor skid resistance.
- It makes for poor riding quality.
- Because of the open grid concept, there is no protection for the supporting elements below from weather-related damage.
- The intersections of the grids are highly susceptible to corrosion and failures.

3.4.5 Orthotropic Deck Panels

An orthotropic deck is one that consists of a series of folded steel plates, as shown in Figure 24, that form closed ribs, which support a steel plate surface.

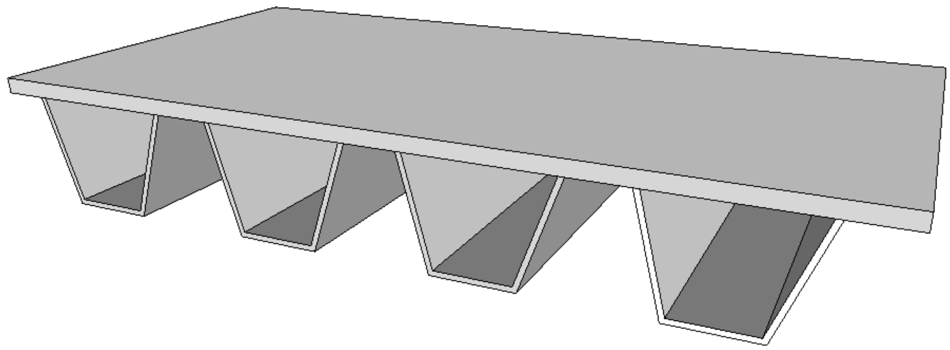


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Figure 24. Orthotropic steel deck panel

These deck panels are typically overlaid with, first, an epoxy polymer, followed by layers of asphalt and asphalt coatings (Jia et al. 2014). The advantages and disadvantages to this rapid replacement option are as follows (Ramey and Oliver 1998).

Advantages:

- System provides very low self-weight.
- Panels can be prefabricated, which speeds up replacement.

Disadvantages:

- Cost is higher than most other rapid replacement alternatives.
- Because of the steel surface, a wearing surface needs to be added.
- A poor bond between the wearing surface and the steel surface can lead to shoving and rutting.
- Connections between panels are sometimes a problem.
- They come with added design and construction complexities.

Using orthotropic steel deck panels is an innovative idea for widening existing bridge decks, because of their light weight. The low dead weight could potentially lead to cost savings where piers and foundations are concerned; however, these are not practical for shorter-span steel bridges. Orthotropic deck panels should be considered for use on widening projects when there is a longer-span bridge with a concrete deck (Huang and Mangus 2008).

3.4.5.1 Case Study: Angus L. Macdonald Bridge in Halifax, Canada

This bridge's concrete deck was replaced using orthotropic steel deck panels. Construction began in May 1997 and it reopened October 31, 1999.

Each panel was covered with a wearing surface at the fabrication facility, and then again with a second wearing surface upon installation in the field. The use of the lightweight system allowed for the addition of a third traffic lane (Huang and Mangus 2008).

CHAPTER 4. GIRDERS

Similar to decks, girders also experience deterioration throughout a bridge's useful life.

This chapter covers means of repairing and replacing girders.

4.1 Rapid Repair

Where prestressed concrete girders are concerned, fiber-reinforced polymer (FRP) strips are a practical option for repair. To ensure a good bond, concrete surfaces should be cleaned and sandblasted prior to placement of the FRP strip. It is recommended that any cracks and voids in the girder be repaired and filled first before application of the polymer strip (Green et. al. 2004).

A very common method of rapidly repairing and rehabilitating prestressed girders is by using externally bonded carbon fiber-reinforced polymer (CFRP) strips. Advantages and disadvantages to using this method are as follows (Radomski 2002).

Advantages:

- CFRP strips are extremely lightweight.
- These strips have a very high strength.
- There are very few, if any, corrosion problems.
- They can be easily handled and installed, which means low labor costs.
- They need not be installed with any special tools.

Disdvantages:

- Material cost is relatively high.
- Some unfamiliarity in use can be expected.
- Load bearing is in the longitudinal direction only.

Prestressed CFRP strips are also an option for the rapid repair of damaged girders (Radomski 2002). The main failure state of externally bonded CFRP strips is debonding from the substrate concrete. This debonding can be identified by the failure of the thin layer of cover concrete immediately adjacent to the polymer strip. Debonding is a major issue, as once the debonding occurs, the girder is no longer strengthened (Kasan et. al. 2012). There are several advantages to stressing the polymer strips before they are installed (Kasan et. al. 2012):

- Base materials can resist higher loads before yielding.
- It is a possibility that service-level displacements and performance of the structure can be restored.
- Cracks are distributed in a more favorable manner and they are smaller.
- The strengthening material is better utilized.
- Steel reinforcement is able to be slightly unloaded.

There are three approaches to prestressing or post-tensioning CFRP strips (Kasan et. al. 2012):

- Prestressed CFRP is the first method. This entails putting the strip under tension using an external device and then adhesively bonding it to the concrete substrate while it is still under tensile stress. This continues until the bond material has cured. Once the bond has been formed, the tension is released, and the stress is transferred into the concrete. This method is capable of seeing large losses at the time of stress transfer and long-term losses due to the creep of the bonding material.

- The use of unbonded post-tensioning is the second method. Here, the CFRP strips are put under tension using the member being repaired. "Stress is transferred to the member only through mechanical anchorage. Typically, a hydraulic or mechanical stressing system is used to apply the tension to the CFRP, after which it is locked off of the stressing anchorage." Losses may occur during the lock off process.

- The third method is bonded post-tensioning of the CFRP strips. The strips are stressed in the same manner as with the unbonded post-tensioned strips, but following anchorage, the CFRP is bonded to the concrete, yielding a composite system. The creep experienced with the first method is not as prevalent here, as the adhesive material is not stressed by the post-tensioning process.

Near-surface-mounted (as opposed to externally bonded) CFRP (NSM-CFRP) strips are another option for rapid repair of damaged concrete girders. This option requires that fiber-reinforced polymers be placed into grooves cut into the surface of a concrete member for strengthening purposes (Kalupahana et al. 2013). These strips offer several advantages (Bank et. al. 2003):

- Simple hand tools can be used.
- The materials are lightweight.
- There's no need to have skilled laborers.
- The surface need not be prepared.
- The strengthened structure can be used immediately following installation.

NSM-CFRP strips were tested at the University of Wisconsin-Madison, and it was concluded that they are a viable, rapid option for concrete bridge strengthening. It is especially recommended where externally bonding FRP strips would be a difficult and time-consuming process—in areas where the adhesive would not bond well to the concrete—and when short-term strengthening is required (Bank et. al. 2003).

Recently, Oregon has introduced the use of titanium bars in place of CFRP for near-surface-mounted operations to combat the concern of bond failure with CFRP. Titanium has high strength and a ductile response. In addition, it is impervious to chlorides, making corrosion less of an issue. Oregon State University conducted tests using these titanium bars epoxied into the grooves. Test results showed that titanium bars were effective for near-surface mounted strengthening (Higgins et al. 2015).

Strand splices with couplers (available for strand diameters up to 1/2 in.) are an effective means of repairing damaged strands in prestressed girders. The coupler is turned, while the two threaded anchors within the coupler are pulled toward each other, introducing a prestress force in the damaged strand (Harries and Miller 2012).

4.2 Rapid Replacement

If a girder is too damaged to be repaired, it may be more economical to replace it. Because the girders support the deck, it may be difficult to replace the girder without also replacing the deck. The following subsections cover methods that offer the option for a combined girder/deck replacement. A method of replacing girders that has been shown to save time is to design the girders to be replaced as simply supported, and then make them continuous by pouring an integral diaphragm (Swanson and Windau 2004).

4.2.1 Inverset Panels

Inverset girders are beams that are cast inverted in forms so that, when they are turned upright, the tension areas are already precompressed, leading to a potential increase in durability. This system is shown in Figure 25.

Image: Missouri Department of Transportation 2001

Figure 25. Inverset panel being lifted into place

With the Inverset panel system, the top flanges of the girders can serve as the bridge deck (Capers and Cheng 2007). It is estimated that this system saved a project in Trenton, New Jersey, more than 22 months of construction time and user costs of more than $2 million.

4.2.2 Precast Modified Beam-in-Slab Bridge (PMBISB) System

Developed by Black Hawk County, Iowa, the precast modified beam-in-slab bridge is an integral girder and deck system. The PMBISB is to be used on short-span bridges (less than 50 ft). A section view of the system is shown in Figure 26, and Figures 27 and 28 illustrate the preferred connection between panels.

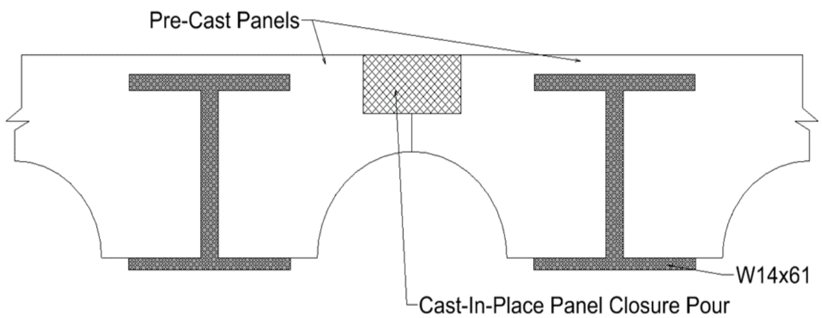

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Figure 26. Section view of precast modified beam-in-slab bridge system

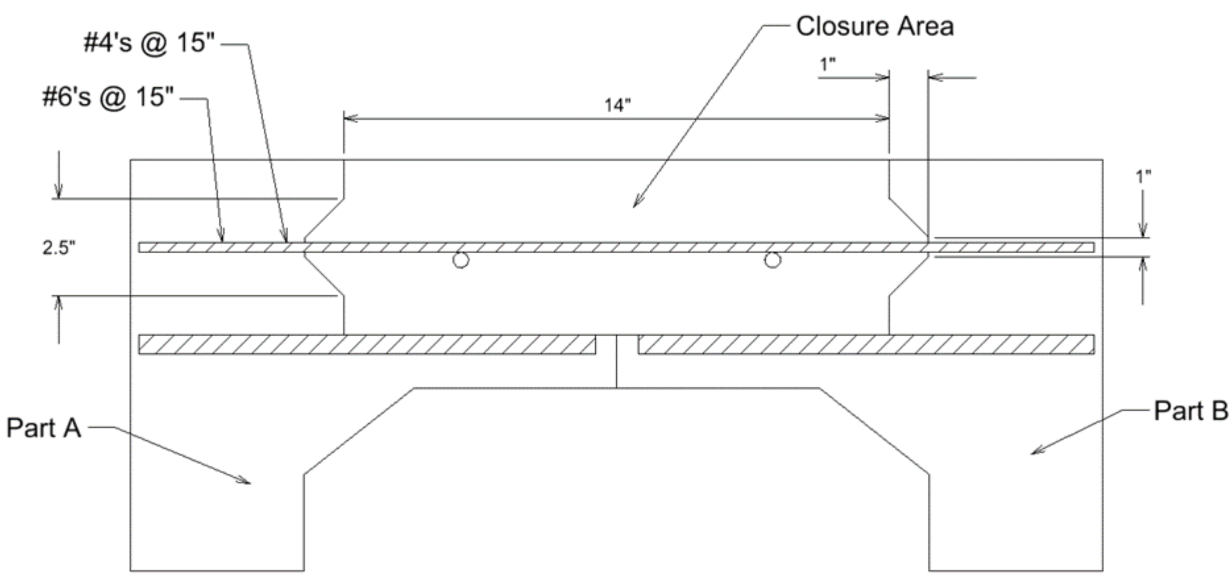

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Figure 27. Side view of panel-to-panel connection for precast modified beam-in-slab bridge system

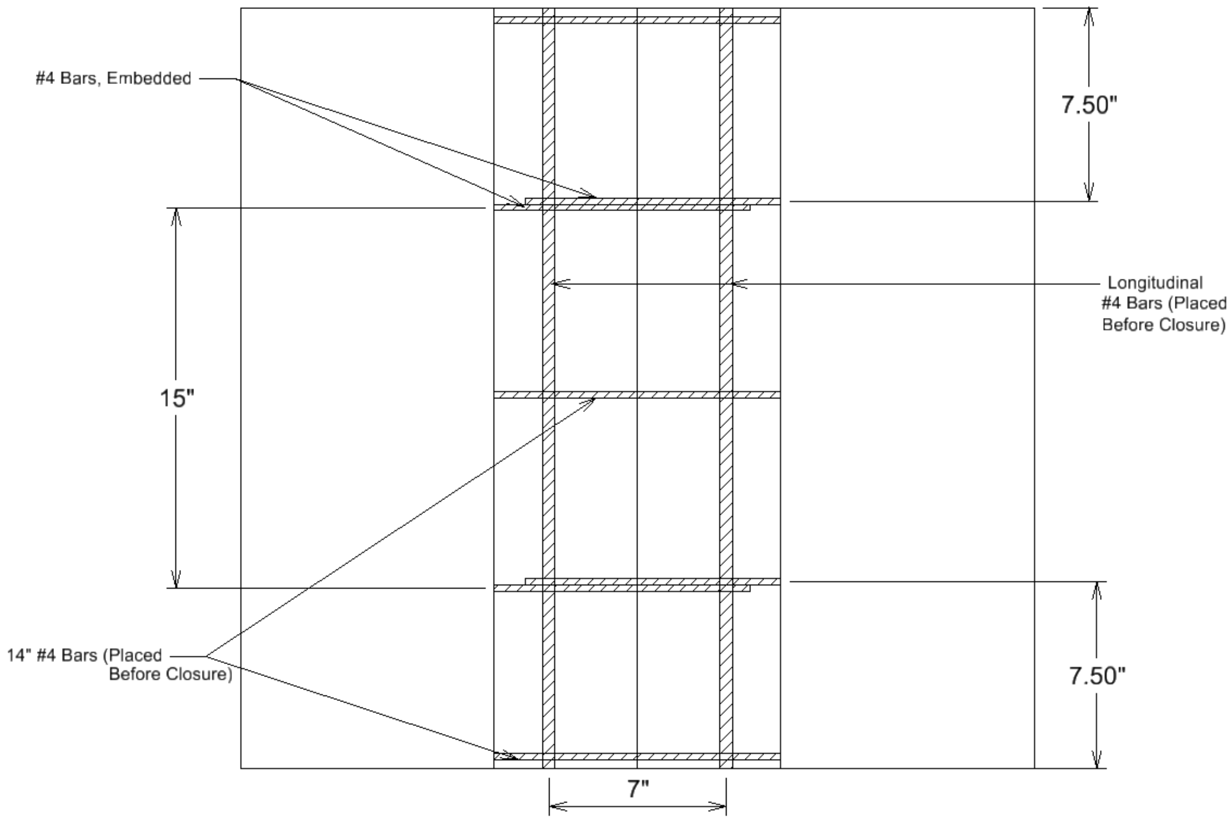

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Figure 28. Top view of panel-to-panel connection for precast modified beam-in-slab bridge system

Similar to precast deck panels, shear keys should be filled with non-shrink grout and closure pours between panels should be filled with CIP concrete (Wineland 2009).

4.2.3 Adjacent Box and Tee Beams

Adjacent box and tee beams are convenient where rapid replacement is concerned, and are shown in Figures 29 and 30, respectively.

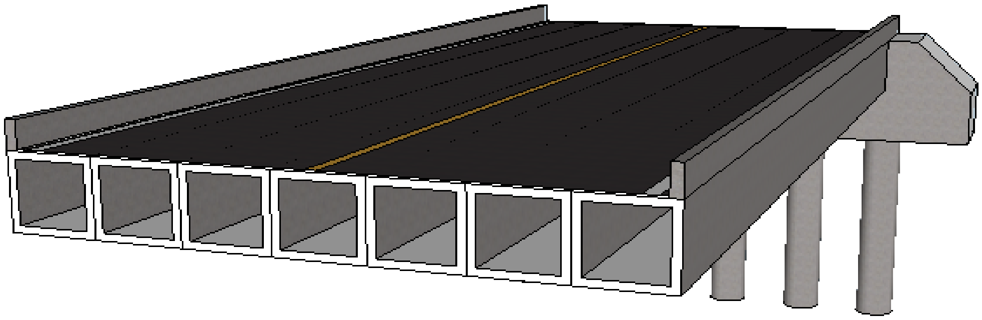

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Figure 29. Adjacent box beams

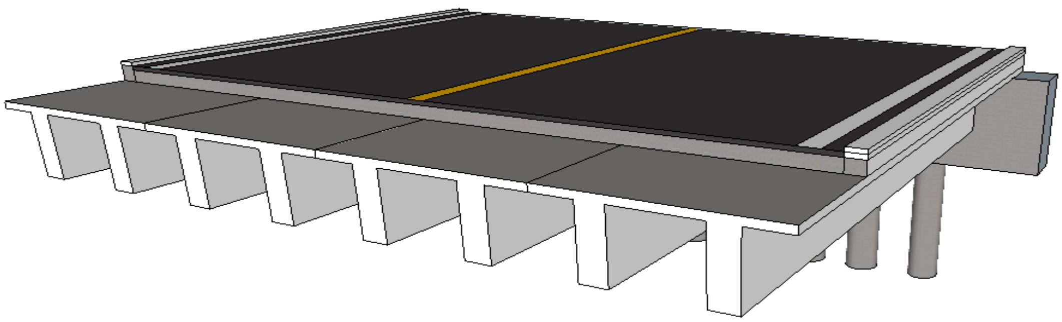

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Figure 30. Adjacent tee beams

Shear keys should be filled with a non-shrink material to help avoid the development of cracks. For best results, the area to be grouted should be sandblasted and cleaned, and grout should be allowed to properly cure (Lopez de Murphy et. al. 2010).

Similar to the adjacent tee beam is the adjacent deck bulb tee beam. Similar to the tee beam, the deck bulb tee's top flange may be overlaid and used as a riding surface (FHWA 2015). This system is shown in Figure 31.

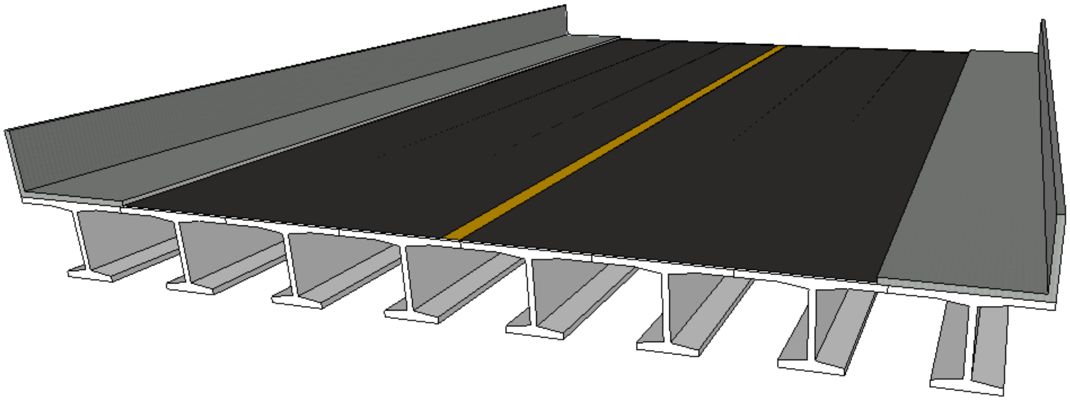

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Figure 31. Adjacent deck bulb tee beams

4.2.4 Fenrich Concrete Girder

Similar to the adjacent box beam, the Fenrich Concrete (FC) girder is one in which the top of the girder can also function as the traveled roadway. It is an inverted U-shaped precast prestresed girder. The shear keys are to be filled with a non-shrink grout (Khattak and Cheng 2004). A single cross-section of a single girder and a cross-section of a width of a bridge are provided below. Figure 32 shows a single Fenrich Concrete girder cross section, while Figure 33 illustrates a series of these girders to create a continuous superstructure.

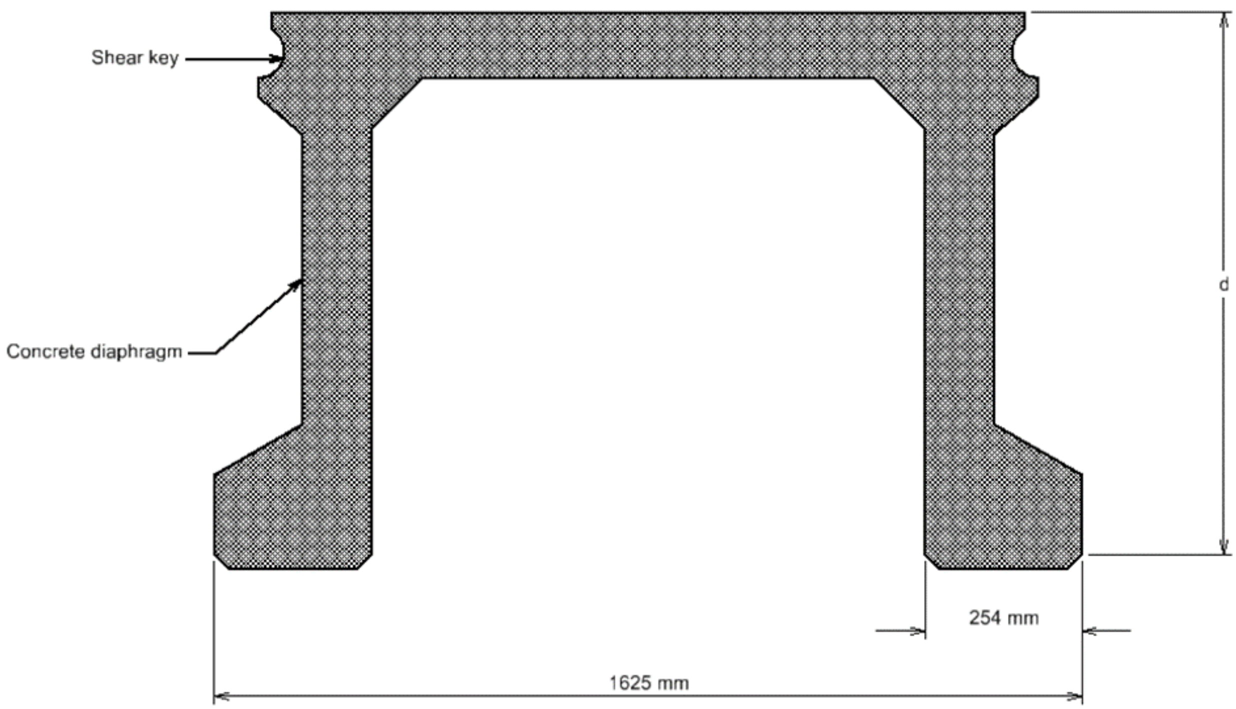

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Figure 32. Cross-section of a single Fenrich Concrete girder

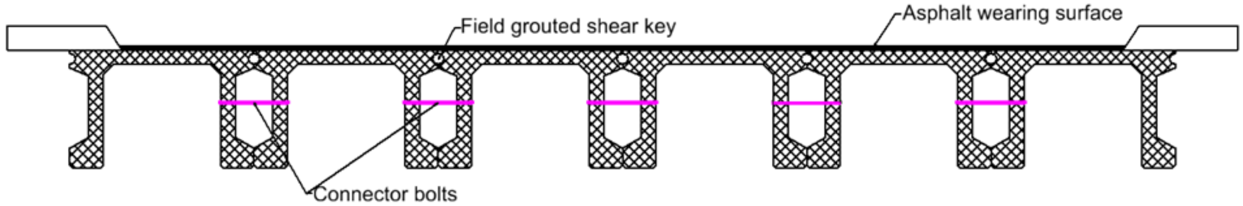

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Figure 33. Cross-section of series of Fenrich Concrete girders

CHAPTER 5. PIERS AND COLUMNS

Piers and columns deteriorate similar to other bridge elements; however, because they are not usually directly impacted by traffic, their deterioration rate is often much slower than that of decks or girders. As such, less information is available on the repair of these components.

This chapter presents the information that is available on piers and columns.

5.1 Rapid Repair

Rapid pier rehabilitation can be completed by saw-cutting the area to be repaired and patching with non-shrink concrete or other material. If a pier is in need of strengthening, the following methods exist: reinforced concrete strengthening band, reinforced concrete jacket, cement injections, drilled piles, fiberglass jackets, and sheet pile wall addition (Radomski 2002).

For damage such as flexural cracks, spalling, shear cracks, or visible reinforcing bars, CFRP jackets can be used as a rapid repair method (Vosooghi and Saiidi 2012). More information related to FRP strips can be found in the section on rapid repair of girders.

In addition, methods described in Section 4.1 may also be applied to piers, pier caps, and columns.

5.2 Rapid Replacement

When a column or pier is damaged past the point of repair, it may be more economical to replace it. Replacing solely a pier or column, and not the rest of the bridge is not a common occurrence. The scope of this project focuses on repair of bridges, and not entire replacements; therefore, information pertinent to a single pier being replaced is limited. The available information is presented here.

5.2.1 Case Study: Long Key Bridge in Florida

The structure that connects US 1 from Miami to Key West, Florida has 101 spans of 118 ft and two end spans of 113 ft. The superstructure is supported by precast concrete V-piers resting on two 3.5 ft-diameter drilled shafts. Because these piers are sitting on drilled shafts surrounded by seawater, corrosion was an imminent threat and led to the V-piers needing to be replaced (Moreton 1998).

Precast piers were used to replace the damaged substructure. To do this, a temporary support system had to be put in place. This support system consisted of two floating pontoons on either side of the pier with adjustable legs and shoes. While the columns sat on the pontoons, the precast piers were slid into place under the superstructure. It is estimated that each pier can be replaced in 10 to 12 days using this system (Moreton 1998).

CHAPTER 6. ABUTMENTS

Abutments deteriorate similar to other bridge elements; however, because they are not usually directly impacted by traffic, their deterioration rate is often much slower than that of decks or girders. As such, less information is available on the repair of these components.

This chapter presents the information that is available on abutments.

6.1 Rapid Repair

If an abutment needs to be stabilized, this can be done with a reinforced concrete strut, anchors, stabilization of backfill, a diaphragm wall, an unloading plate on pile foundations, or a counterfort with pile foundations (Radomski 2002). To repair cracks in concrete, a method that has been observed to be rapid and effective is using shotcrete or a rapid-setting mortar (Gulyas and Navarro 1994).

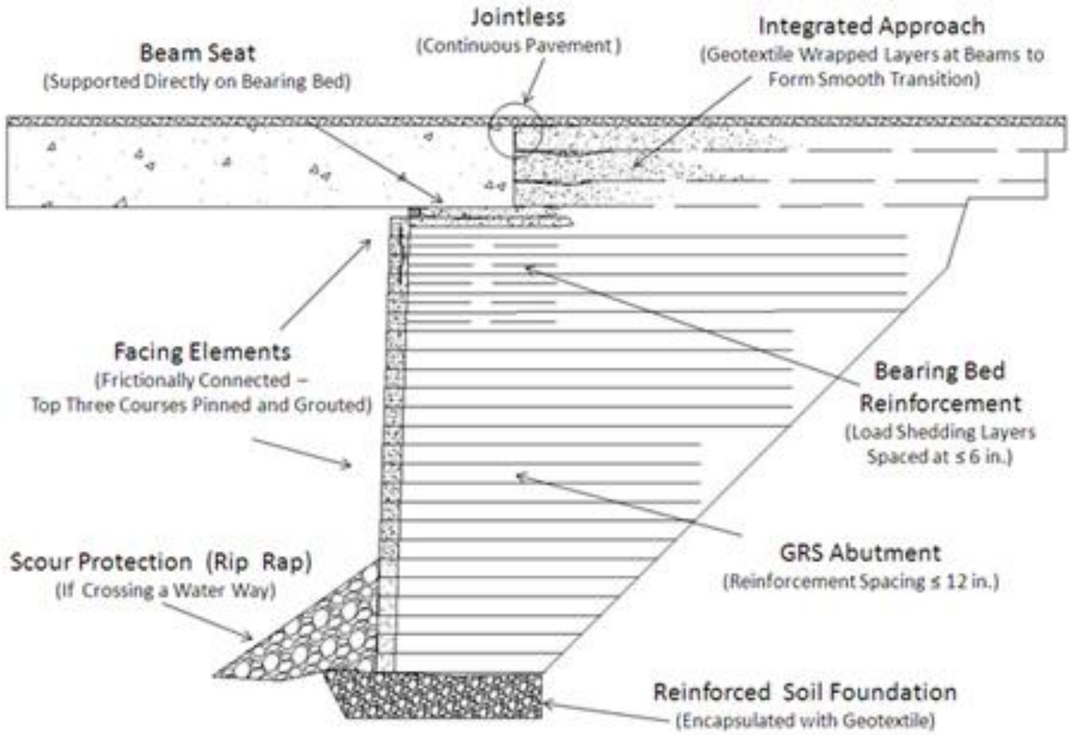
In addition, methods described in Section 4.1 may also be applied to abutments.

6.2 Rapid Replacement

When an abutment or embankment is damaged past the point of repair, it may be more economical to replace it. Replacing only an abutment and not the rest of the bridge is not a common occurrence. The scope of this project focuses on repair of bridges, and not entire replacements; therefore, information pertinent to only an abutment being replaced is limited. The available information is presented here.

6.2.1 Geosynthetic-Reinforced Soil

If it has been determined that the abutment or surrounding embankment can no longer perform as desired, an efficient method of replacement is the installation of geosynthetic-reinforced soil (GRS). The GRS system is a series of soil layers that are reinforced with geosynthetic fabric. It eliminates the need for deep foundations and is very fast to construct. An elevation view of a typical GRS abutment is shown in Figure 34.



Adams et al. 2011, FHWA

Figure 34. Elevation view of geosynthetic-reinforced soil abutment

Although these GRS abutments are easy and quick to assemble, they have been known to perform poorly when scour is an issue; therefore, these are best suited for bridges with shallow scour depths or no scour at all (Adams et al. 2011). Scour countermeasures may be added to prevent scour failure; they include riprap aprons, gabion mattresses, and articulating concrete blocks (Adams et al. 2011). However, the effectiveness of these countermeasures is questionable.

The basic process consists of laying a row of facing blocks, adding a layer of compacted fill, which reaches the height of the previously laid blocks, and, finally, placing a layer of geosynthetic fabric. This process is repeated until the desired height of the wall is achieved (Campbell et al. n.d.).

Two documents, entitled *Geosynthetic Reinforced Soil Integrated Bridge System Synthesis Report* and *Geosynthetic Reinforced Soil Integrated Bridge System Interim Implementation Guide*, released by the FHWA, offer more detailed design and construction guidance for GRS-integrated bridge systems (Adams et al. 2011 and 2012).

6.2.1.1 Case Study: Geosynthetic-Reinforced Soil (GRS) Abutment Project on Route B over Bus. Loop 70 in Columbia, Missouri

A bridge located in Columbia, Missouri, on Route B over Bus. Loop 70 was deteriorating, and needed repair. This structure is a 50 ft single-span bridge on a skew with a roadway width of 29 ft. The existing footing was to be removed and replaced (along with the superstructure) (Arounpradith 2014). Three different design alternatives were considered for the new structure: single span with piling and MSE walls, three-span on piling or drilled shafts, and single-span GRS (Heckman 2014).

After considering project needs and a subsurface exploration, the designers determined that a GRS foundation would be best for the project despite having freeze-thaw conditions and an estimated soil settlement of 1.75 in. The engineers developed a final design that included an approximately 17 ft-high wall with solid facing blocks spaced at 16 in. and a backfill slope of 1:1 (Arounpradith 2014). The GRS abutment portion of the project was bid for approximately $240,000 (Heckman 2014).

The construction of the foundation went fairly quickly. For the first four rows being placed, the labor was completed at a rate of 5 hours for each 8 in. layer. The fifth and sixth row took 2.5 hours to complete an 8 in. layer, while the seventh row and above took only 1.5 hours to complete per 8 in. layer.

The Missouri Department of Transportation (MoDOT) learned several important lessons over the course of this project. One of those lessons was that a dry-cast concrete masonry unit (CMU) block does not meet freeze-thaw requirements. Wet-cast block was used instead, and they determined it was more durable. A drawback to this type of foundation is that it is not easy to re-level to the desired elevation; removal is also difficult (Arounpradith 2014).

Although the project was a success, MoDOT officials said that GRS abutments will have limited use in Missouri due to the fact that there are few situations to which they can be applied (e.g., single-span bridges over other roads) (Heckman 2014).

6.2.1.2 Case Study: Dennehotso Bridge Replacement in Arizona

The Dennehtso Bridge is located near the northeast corner of Arizona. The existing structure consisted of steel girders with an open steel grid deck and a steel barrier rail, all of which were in need of replacement. The subsurface consisted of alluvium deposits of unconsolidated surficial deposits of valley fill alluvium deposits, which are scourable and erodible. The subsurface Navajo sandstone was found to be very weak and erodible. The hydraulic conditions at the site (i.e., floodwaters) were causing erosion of the road fill and alluvial soil. In addition, the stream had migrated, leaving a sharp stream bend upstream of the structure and a skewed flow through the bridge (Kraig n.d.).

The goal of the project was to replace the bridge and to obtain a better alignment. The engineers wanted to avoid CIP concrete, as well as use soils in the area for roadway fill. All of this was to be done in a cost- and time-effective manner, while satisfying hydraulic concerns.

To achieve these goals, the project team decided to implement GRS abutments. The new abutments would support a 107 ft long by 28 ft wide structure consisting of seven prestressed box girders with an asphalt wearing surface (Kraig n.d.).

Choosing the GRS abutments eliminated the need for CIP construction as well as the need for piles. The abutments are simple to construct and cost effective, while still being reliable. In addition, because of the simplicity, a specialty contractor didn't need be hired, and local labor could be used. The engineers expect that floodwater erosion may remove fill soil behind the abutment; however, these abutments are designed to resist erosion of road embankment material (Kraig n.d.).

6.2.2. Precast Concrete Abutments and Foundation Elements

Another alternative to complete abutment replacement is replacement with precast elements. The New Hampshire Department of Transportation (NHDOT) developed a completely precast abutment system. This development includes full-height cantilevered abutments on spread footings comprised of a flowable grout bed, precast footings, leveling screws, grouted shear keys, precast stems, and full-moment connection provided by way of grouted splicers (Stamnas and Whittemore 2005).

NHDOT implemented this precast substructure system in the replacement of an existing bridge. The contractor was able to assemble the entire bridge in only eight days and the substructure in only two days. When the cost of the precast option was compared to that of the cast-in-place option, the precast substructure alternative was almost twice the cast-in-place alternative; however, when paired with precast girders and no need for a temporary crossing, the entire bridge cost was only 8% higher than the total cost for the cast-in-place bridge (Stamnas and Whittemore 2005). Some of cost difference was determined to be a matter of contractor unfamiliarity due to the concepts not being commonplace at the time of construction (Stamnas and Whittemore 2005).

CHAPTER 7. LONG-TERM PERFORMANCE OF RAPID REHABILITATION AND REPAIR

In addition to being completed quickly and efficiently, rapid repair and rehabilitation methods are also durable—if designed and detailed correctly (Culmo 2011). This is especially true of the precast elements used in deck and girder replacement. Because of the lack of constraint during curing, shrinkage cracking is considerably lessened—although not altogether eliminated due to friction between the precast member and the forms—when compared to cast-in-place elements (Culmo 2011). Less cracking at the beginning of these members' useful lives can reduce the possibility of corrosion and, in turn, avoid a premature end to the element's service life (Culmo 2011).

The bridge elements needing the most attention after an accelerated repair—similarly to those repairs that are not considered rapid—are typically the joints, and specifically grouted joints exposed to salt and other chemical treatments. These joints still offer long-term performance if they are designed and constructed correctly; however, they should be monitored and inspected regularly. If damage is noted, old grout should be removed and new grout put in its place (Culmo 2011).

CHAPTER 8. SUMMARY AND CONCLUDING REMARKS

ABC has received significant research attention in recent years. For the most part, these research endeavors have focused on means and methods for decreasing impact to the traveling public during new bridge construction. At the same time, great opportunities exist to reduce traffic impacts by decreasing construction time associated with bridge rehabilitation.

This report presents different means and methods of rehabilitating deteriorated bridges. In some cases, the information pertains to accelerated (new) bridge construction techniques that may be adapted for use as rehabilitation. These techniques can be used for removal, protection, repair, or replacement of damaged components and result in a durable, long lasting product. Repair/rehabilitation information was identified for the following bridge components: deck joints, decks, girders, piers and columns, and abutments.

Many methods can be applied only to certain areas of the bridge; however, techniques are included that may be applied to several bridge elements (i.e., reinforced polymer strips).

Given that information related to bridge deck repair and replacement is considerably more prevalent than information related to the rapid repair of other components, the researchers suggest that future efforts be focused more so on the development of ABC methods that may be applied to rapid rehabilitation of girders, bridge piers and columns, and abutments.

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