MDOT RC-1602

Improving Bridges with Prefabricated Precast Concrete Systems

APPENDICES

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Western Michigan University
Department of Civil & Construction Engineering
College of Engineering and Applied Sciences

Research

Improving Bridges with Prefabricated Precast Concrete Systems

Appendices

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APPENDIX A

PREFABRICATED BRIDGE ELEMENTS AND SYSTEMS

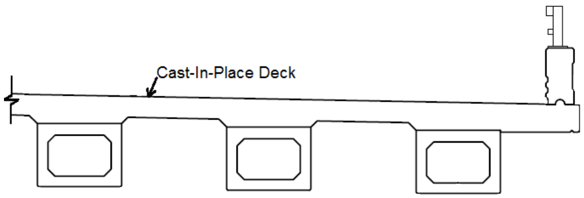
Girders

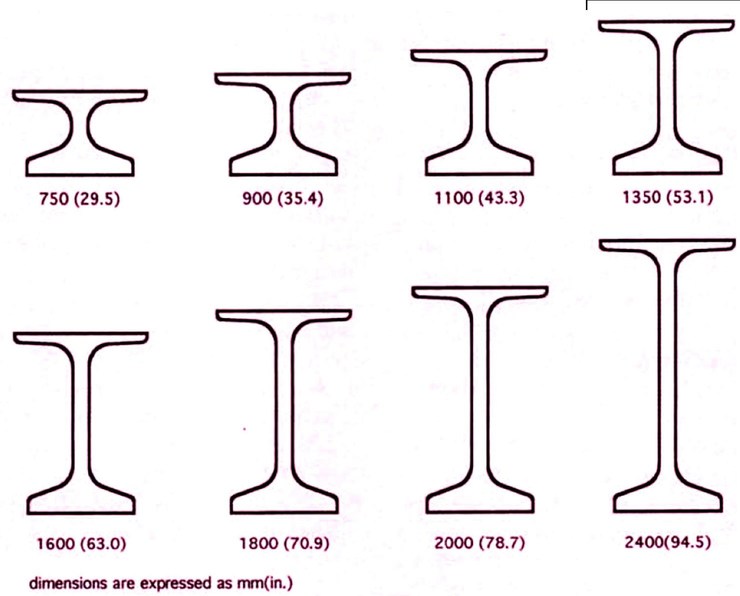
Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast concrete (PC) I-girders  (Source: PCSB 2011)	Standardized as AASHTO type sections. Used in several projects by the State DOT's since 1950's. Recent projects: I-5 Southbound Truck Route Undercrossing, CA. (Superstructure replacement) (2007) Parkview Avenue over U.S. 131, Kalamazoo, MI. (Bridge replacement) (2008)	Following attributes are presented based on the information provided in the listed references. Span range: refer the table beside Depth to span(D/S) ratio: 0.055 Typical girder depth ranges from 28 in. to 54 in. However, there are state specific girders that are much deeper than the standard sections. One such example is the70.9 in. deep MI-1800 girder. Concrete strength: 5000 psi to 7000 psi. MDOT–I beams (AASHTO types I to IV) span up to 114 ft MDOT–70 in. deep I beams span up to 120 ft MDOT–70.9 in. deep I beam (MI-1800girder) spans up to 145 ft	Standard sections. Designers, fabricators, and contractors are familiar with the sections. Forms are available at most of the prefabrication plants. Performance is well documented.	Implementation in ABC is only possible with partial-depth or full-depth deck panels. Girder sweep needs to be controlled when used with full-depth deck panels. Special details and cast-in-place construction is needed to develop continuity over piers. Identified as structurally inefficient compared to bulb-tee, Washington, and Colorado girders in terms of cost effectiveness (Bardow et al. 1997; TFHRC 2006) Cannot extend over long spans without using post-tensioning. Curved spans require use of straight girders. High probability of cracking at transfer with 0.7 in. diameter prestressing strands. (Vadivelu 2009)	Have been used in rapid bridge replacements by using heavy equipment such as SPMT (Ralls 2008) Sources of information: Chung et al. (2008); Abudayyeh (2010); MDOT-BDM (2011); Attanayake et al. (2012).

Girder	Depth (in.)	Span (ft)	28-day concrete strength (psi)
PC - I (Type I – IV)	28 – 54	~114	5,000 – 7,000
PC – I (Wisconsin type)	70	~120	5,000 – 7,000
PC – I (MI 1800)	70.9	~145	5,000 – 7,000

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Steel girders 	Used in several projects by the State DOT's since early 19th century. Recent projects: Oakland Eastbound I-580 Connector, CA (Superstructure replacement) (2007) Route 3 Mosquito bridge over Lake Winnisquam, Sanbornton & Belmont, NH (Deck replacement) (2004)	Following attributes are presented based on the information provided in the listed references. Span range up to 300 ft Depth to span (D/S) ratio: 0.04 to 0.045 which is smaller than D/S ratio of precast prestressed concrete girders.	Could be used on curved bridges. Continuous spans can be developed using the same section. Customized (built-up) sections can be developed to satisfy project requirements Weathering steel is a solution for controlling corrosion provided that there is no accumulation of water, chloride exposure, damages to the girder, etc. Material properties are well known and defined.	Implementation in ABC is only possible with partial-depth or full-depth deck panels. Welding of connections subject to fatigue Require more detailed inspection and maintenance for fatigue and corrosion Costly compared to precast concrete girders Field welding may be required Customized sections are very costly Maintenance requires painting, thus expensive and non-eco-friendly. Use of weathering steel in salt-laden environments is highly discouraged, since the protective layer may not stabilize but rather corrode more rapidly. Moreover, weathering steel is not rustproof in itself; therefore, if water is allowed to accumulate on it, corrosion rate sharply increases.	Has already been used in rapid bridge replacements using heavy equipment such as SPMT (Ralls et al. 2004; Ralls 2008) Sources of information: Chung et al. (2008); Richardson et al. (2009).

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast bulb-tee girders  (Source: PCSB 2011)	Used by States such as: New England, Washington, Colorado, Florida, New Mexico, Idaho, Oregon, etc. since several decades. Jetport Interchange, Maine (Bridge replacement) (1999) I 40 Bridge project, CA (Bridge replacement) (2006)	Following attributes are presented based on the information provided in the listed references. Spans range: up to 186 ft (UDOT 2010) Depth to span (D/S) ratio: 0.05 which is smaller than D/S ratio of precast concrete I-girder Depth range: 42 in. to 98 in. Concrete strength range: 6500 psi to 8000 psi Prestressing strands: 0.6 in. dia.	Provides greater capacity than standard precast concrete I-girders. Efficient than AASHTO type V and VI girders (Bardow et al. 1997; TFHRC 2006) Feasible for long spans.	Implementation in ABC is only possible with partial-depth or full-depth deck panels. Girder sweep needs to be controlled when used with full-depth deck panels. Controlling girder sweep is critical due to slenderness of the section compared to standard girders. Special details and cast-in-place construction are needed to develop continuity over piers. Curved spans require use of straight girders.	High Performance Concrete (HPC) with 10,000 psi 28-day strength, could be used to obtain longer spans and more durable structure. Sources of information: Lavallee and Cadman (2001); Fouad et al. (2006); Chung et al. (2008); UDOT (2010).

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast spread box girders   (Source: PCSB 2011)	Spread box-girders have not been used in any ABC projects.	Following attributes are presented based on the information provided in the listed references. Spans up to 140 ft. Depth ranges from 12 in. to 60 in. Width: 36 in. and 48 in. Concrete strength: 5,000 psi to 7,000 psi. There are records of using high performance concrete (HPC) with 28-day strength of 8,000 psi.	Shallow depth enables using at sites with tight underclearance. High torsional stiffness of the sections.	Implementation in ABC is only possible with partial-depth or full-depth deck panels Special details and cast-in-place construction are needed to develop continuity over piers. Box-beams are difficult to fabricate as they involve multi-step fabrication process (Culmo & Seraderian 2010) Access to confined space inside the box is not possible because of the Styrofoam blocks used during fabrication (Smith and Hendy 2002) Weep holes are required at the bottom flange. Not possible to detect deterioration inside the concrete box until rust stain is visible at the weep holes or girders crack. Spread box girders require formwork between the girders to form the deck.	Source of information: MDOT-BDM (2011).

<table>
<tr><th>Element</th><th>Project(s)</th><th>Attributes</th><th>Benefits</th><th>Limitations</th><th>Remarks</th></tr>
<tr>
<td>Precast NU I-girders
For NU I-girders with 60 - 0.6 in. diameter prestressing strands:
<table>
<tr><th>Depth (in.)</th><th>Span (ft)</th><th>28 day concrete strength (psi)</th></tr>
<tr><td>94.5</td><td>~200</td><td>12,000</td></tr>
<tr><td>78.7</td><td>~180</td><td>8,000 – 12,000</td></tr>
<tr><td>70.9</td><td>~172</td><td>8,000 – 12,000</td></tr>
<tr><td>63.0</td><td>~155</td><td>8,000 – 12,000</td></tr>
<tr><td>53.1</td><td>~135</td><td>8,000 – 12,000</td></tr>
<tr><td>43.3</td><td>~118</td><td>8,000 – 12,000</td></tr>
<tr><td>35.4</td><td>~110</td><td>8,000 – 12,000</td></tr>
</table>


</td>
<td>Bow river bridges in Calgary, Alberta, Canada

Pacific street bridge over I-680 in Omaha, Nebraska.

14th street bridge over I-80, Lincoln, Nebraska</td>
<td>Following attributes are presented based on the information provided in the listed references.

Span: refer the table beside
Depths: refer the table beside
Concrete strength: refer the table beside

Specified 28 day compressive strength of minimum 12000 psi is required if 0.7 in. diameter strands are used.

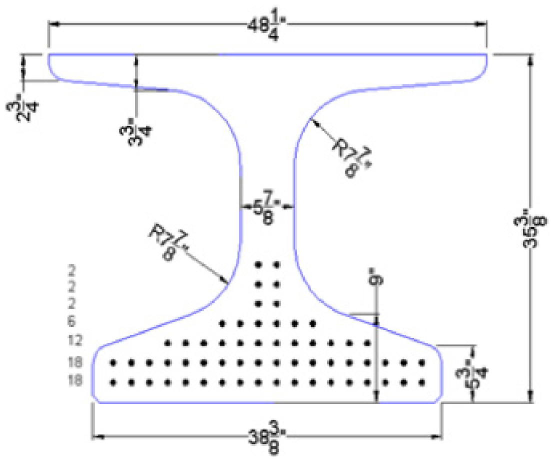
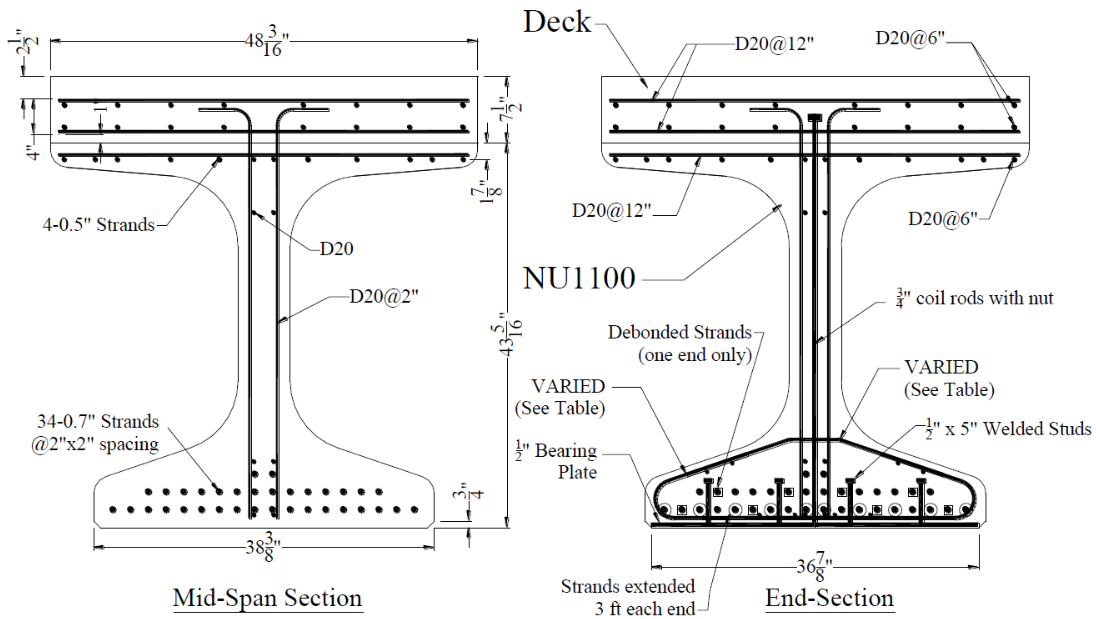
Prestressing strands: 0.5 in., 0.6 in., and 0.7 in. diameter 270 ksi low-relaxation steel.

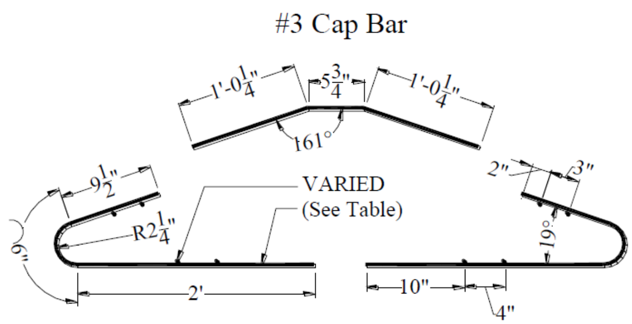
Typically, prestressing strands are spaced 2 in. horizontally and 2.5 in. vertically.</td>
<td>The NU I-girders have sections that can span up to 300 ft with longitudinal post-tensioning
Provides shorter deck spans in the transverse direction due to wide top flange.
Increased stability during shipping and handling due to virtue of its wide top flange and thick and wide bottom flange compared to AASHTO girders (see figure below for dimensions).
The reinforcement details are standardized such that the amount of post-tensioning, girder span, or girder spacing does not affect the reinforcement
The large span-to-depth ratio allows for using these sections in lieu of steel plate girders without increasing the superstructure depth</td>
<td>Implementation in ABC is only possible with partial-depth or full-depth deck panels
Special details and cast-in-place construction are needed to develop continuity over piers.

The lack of readily available hold down devices for depressing 0.7 in. diameter strands is an obstacle
These girder sections are not widely implemented; hence, local fabricators may not have the resources and/or expertise because the fabrication requires new forms. Also, devices with adequate capacity to accommodate 0.7 stands.</td>
<td>Flexural capacity of NU 900 I-girder with 28-day concrete strength of 15,000 psi ranges from 5800 kip-ft to 6000 kip-ft.
Shear capacity of NU 900 girder with 28-day concrete strength of 15,000 psi ranges from 780 kip to 800 kip

The NU 750 I-girder has not been used in any bridge projects.

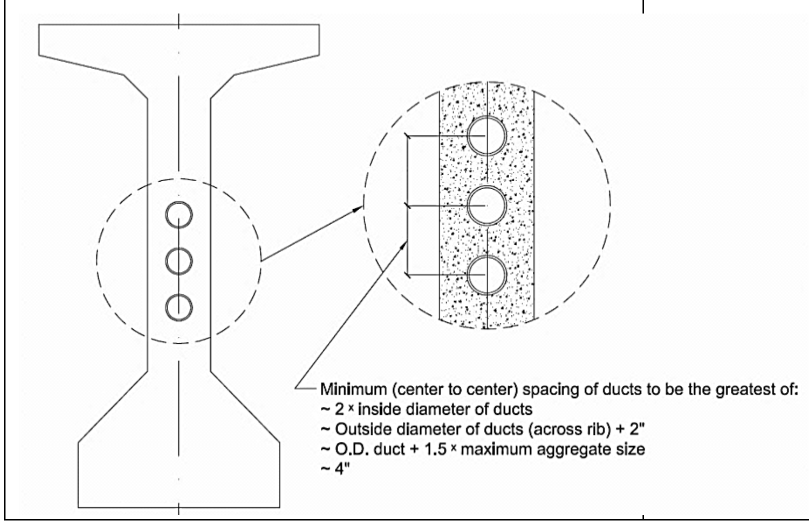
The NU 2400 I-girder has been generally used with post-tensioning.</td>
</tr>
</table>

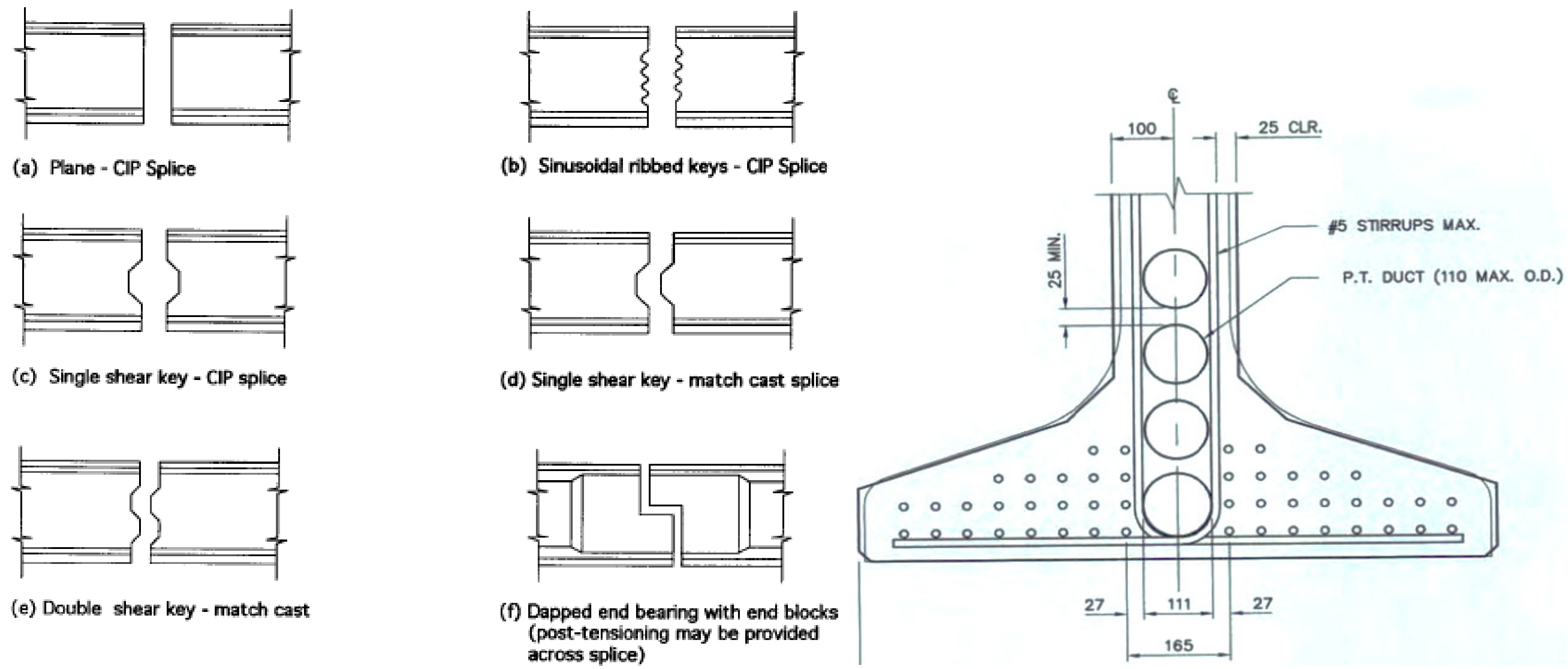
		Concrete deck 7.5 in. thick with 28 day compressive strength of 4000 psi.			Sources of information: Geren and Tadros (1994); Beacham and Derrick (1999); Hanna et al. (2010b); Morcous et al. (2011).
Standardized Welded Wire Reinforcement (WWR) for NU I-girders (Source: Hanna et al. 2010b): 					



WWM Confinment Reinforcement
(See Table for size and spacing)

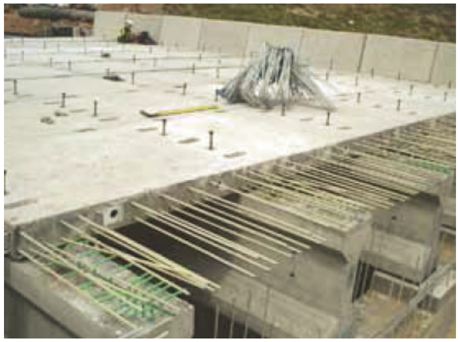
Girder Designation	Specified Confinement	Confinement Reinforcement	
		WWM	Cap Bar
1	2008 NDOR BOPP	D4 @ 4" entire length	#3 @ 12" entire length
2	2004 AASHTO LRFD	D11 @ 6" for 72" each end	#3 @ 6" for 72" each end
3	AASHTO + NDOR	D11 @ 6" for 72" each end D4 @ 4" middle	#3 @ 6" for 72" each end #3 @ 12" middle

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast girders with spliced details  Precast bulb-tee with post-tensioning in the web for splicing operation: 	Esker overhead bridge, British Columbia, Canada (Bridge replacement) (1990) I-15 Bridges, Salt Lake City, Utah (1999) Route 33 bridges at West Point, VA (2007)	Following attributes are presented based on the information provided in the listed references. Span ranges up to 220 ft Precast concrete I-girder, NU I-girder, or precast bulb-tee girder sections can be modified to accommodate post-tensioning for developing spliced details (see figure on the next page) Depth range: overall 6 ft to 9 ft. Over the piers, the depth varies up to 15ft 28-day concrete strength: 9000 psi. to 10,000 psi. Post-tensioning strands: 0.6 in. dia.	An option for developing precast concrete continuous spans Could be used for very high live load requirements Suitable for bridges with restricted pier placement	Implementation in ABC is only possible with partial-depth or full-depth deck panels Special details and analysis are required for spliced connections. Falsework or strongbacks required for splicing operation and could be time consuming Prolonged lane reduction required Large depth of girders and wide web required to accommodate post-tensioning ducts Cast-in-place diaphragm used at the splice locations Requires full-length post-tensioning	Sources of information: Mills et al. (1991); Geren and Tadros (1994); Seguirant (1998); Castrodale and White (2004); Browder (2007).

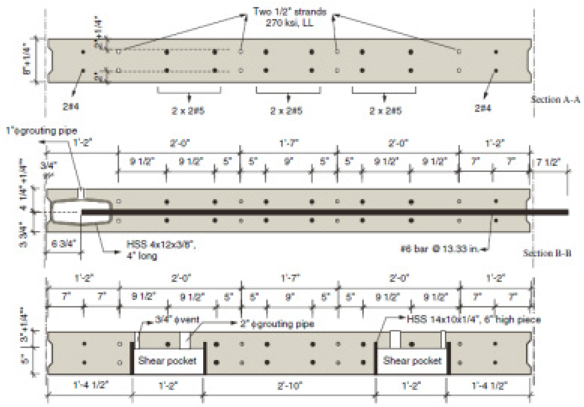
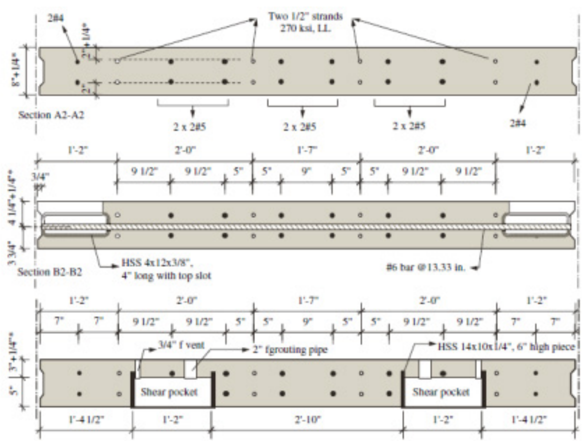


Note: All the dimensions are in mm (1 mm = 0.0394 in.)

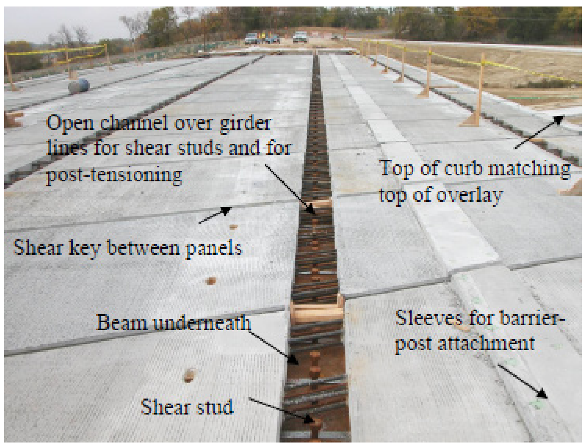
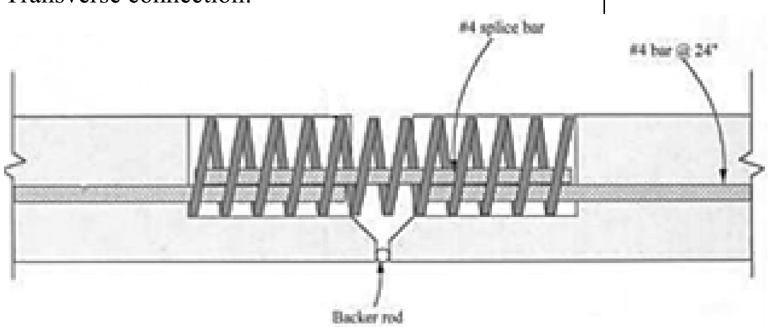
Decks

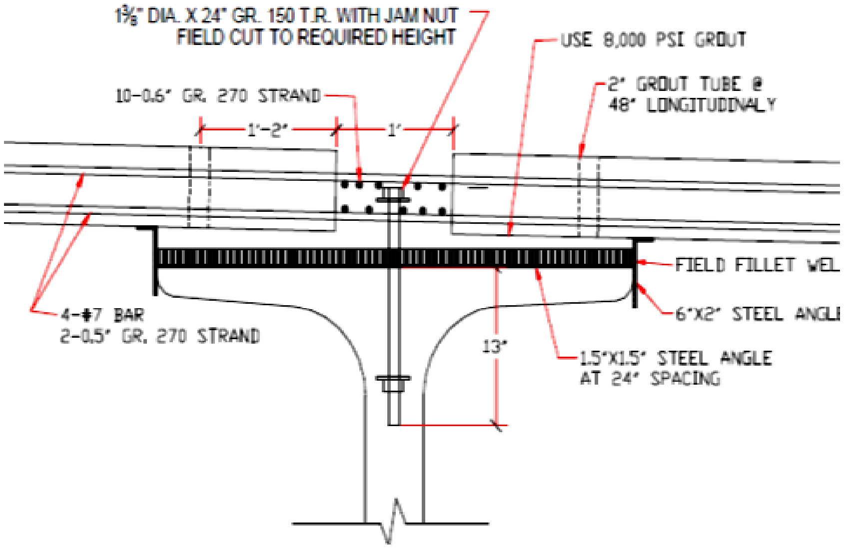
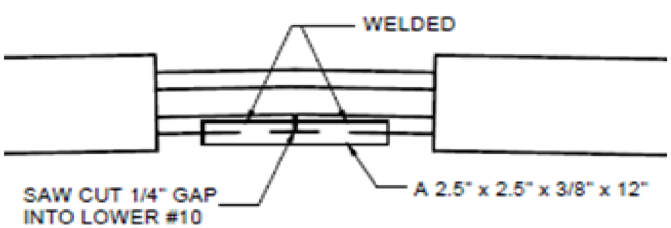
Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Full-depth deck panels Two types are commonly used: **Full-depth deck panels with transverse prestressing and longitudinal post-tensioning:**  **Full-depth deck panels with only longitudinal post-tensioning:** 	Lake Koocanusa Bridge, Lincoln County, Montana (Deck replacement) (2001) I-70 Bridge over Eagle Canyon, UT (Deck replacement) (2007) I-215 over 3900 South, UT (Deck replacement) (2007) I-80 Silver creek, UT (Deck replacement) (2010) Parkview Avenue over U.S. route 131, Kalamazoo, MI (Bridge replacement) (2008)	Following attributes are presented based on the information provided in the listed references. Length (in the direction of traffic) varies from 8 ft to 16 ft Width (in the transverse direction to traffic) varies from 24 ft to 40 ft. Nominal thickness: 8.5 in. Deck panel concrete used in the listed projects was required to have the strength of 4,000 psi at release and 5,000 psi in 28 days. Girder spacing for panels with transverse prestressing varies from 8 ft to 12 ft. Girder spacing for panels without transverse prestressing varies up to 10 ft.	Full-depth deck panels have been implemented in several ABC projects and the lessons learned reports are documented. Several states have experience with the system. Full-depth deck panel systems have been implemented long before the ABC concept was introduced and performance of the system is well documented. For skewed bridges, the end panels could be customized to accommodate the skew, while keeping the middle panels rectangular to alleviate fabrication Better workmanship and high quality could be achieved with plant fabrication Transverse	Post-tension is required to achieve durable transverse connections between panels. When repair, retrofit, and demolition are considered, use of post-tensioning is not desirable. Grouting prefabricated Element joints is challenging. The system consists of too many grouted connections thus make the construction challenging. Tighter tolerances and quality assurance are required during the fabrication process. Proper panel support is required until haunch grout achieves required strength. Reinforcing steel	At least 2 leveling devices per girder in each panel is required. Round PT ducts with 2 in. inside diameter are preferred over flat ducts to avoid difficulty in strand placement (Badie et al. 2006) Sources of information: Hieber et al. (2005); Badie et al. (2006); Higgins (2010); UDOT (2010); Attanayake et al. (2012).

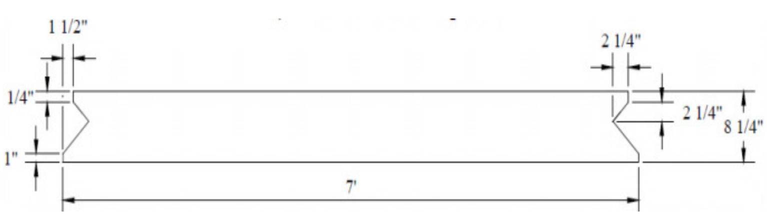
	Emma Park Bridge on U.S. route 6, UT (Bridge replacement) (2008) Trucker Bridge on U.S. route 6, UT (Bridge replacement) (2008) Mile post 200 Bridge on U.S. route 6, UT (Bridge replacement) (2009)	UDOT (2010) has skew allowances as shown below: Up to 15^{o} for skewed panels, and up to 45^{o} for rectangular panels with trapezoidal end panels. Top reinforcing clear cover of 2.5 in. is commonly used after leaving a 0.25 in. sacrificial layer for grinding. The minimum required bottom reinforcing clear cover is 1 in. Prestressing strands: 0.5 in. diameter, 270 ksi low-relaxation steel. AASHTO LRFD (2010) requirement is to have 250 psi after all the losses at the joint. Hence, it is necessary to analyze the continuous span structures to determine the level of prestress required over piers to achieve 250 psi after losses.	prestressing allows for thinner panels, wider girder spacing under the panels, and better crack control. Relatively fast construction, as CIP concrete topping is not required Panels could be used for either stage construction or full-width replacement of the facility.	in closure pour may have overlap issues. Significant tolerance enforcement is required at post-tensioning duct splicing locations and shear pockets in the panels Demolition of the bridge with post-tensioning is a challenge. Impact of vibration on grout bond needs to be considered when the bridge is used in staged construction.	

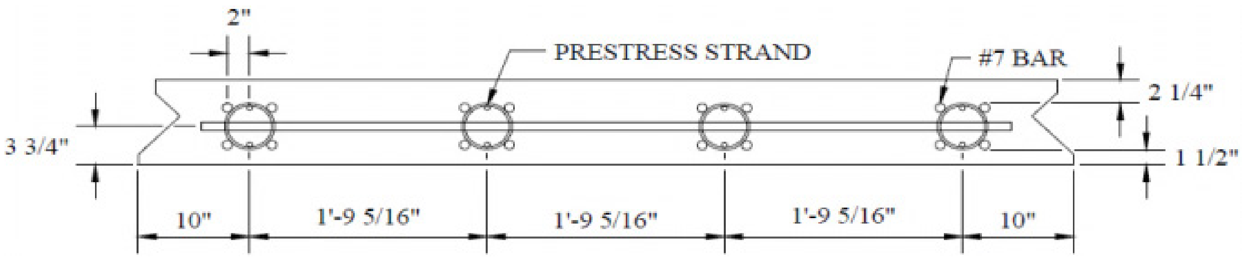
Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Full-depth deck panels with only transverse prestressing Galvanized bulged hollow structural steel (HSS) tube – configuration 1 Note: the figures given below shows the cross-section perpendicular to bridge transverse axis.  HSS tube is not bulged and is provided with a 1.5 in. wide top slot – configuration 2 	Three full scale bridge specimens with four steel girders, four NU 1800 girders, and four bulb-tee girders, respectively, were successfully tested at the laboratory of University of Nebraska-Lincoln under the subcontract with George Washington University, Washington, D.C.	Following attributes are presented based on the information provided in the listed references. Length: 8 ft (in the direction of traffic) Width: 44ft (perpendicular to traffic direction) Thickness: 8.25 in., wherein 8 in. is structural slab thickness and 0.25 in. is for a sacrificial layer. Supporting girders spacing: 12 ft Normal weight concrete with unit weight of 150 lb/ft^3 has been used until now. 28-day compressive strength of 6000 psi was used in the project.	Configuration 1 and 2 provides similar details except at the transverse panel connections. Panel with configuration 2 details is vertically placed and a 24.5 in. long splice bar is dropped through the top slot to complete the joint connection. Hence, constructability is enhanced through this detail. Eliminating the post-tension shortens the construction duration, lowers the cost of the deck, and simplifies the construction process. CIP joints between the panels could utilize rapid set concrete mix which will eliminate the limitations	New concept and details; hence, no past performance records. Connections without post-tensioning have proven to be ineffective in terms of durability. Hence, details need to be evaluated before implementing in multiple projects. The deck panels with **bulged HSS** (configuration 1 details) need to be tilted during placement to insert the extended reinforcement into the grouted pocket of the adjacent panel. HSS tubes incur additional cost of fabrication. The 48 in. shear stud cluster spacing is not yet included in LRFD specifications; hence, horizontal shear needs to be evaluated to determine	Following details are exclusively from the bridge specimens that are discussed in Badie and Tadros (2008). Transverse steel: Eight 0.5 in. diameter prestressed strands, 12 No. 5 bars, and 4 No. 4 bars are placed in two layers. A 2 in. top and bottom clear cover is provided. Longitudinal reinforcement: No. 6 bars at 13.3 in. spacing. Clusters of three 1.25 in. diameter double-headed steel studs are used as shear connectors. The clusters are spaced at 48 in. The clusters spaced at 48 in. were found sufficient for bridges with spans from 60 ft to 130

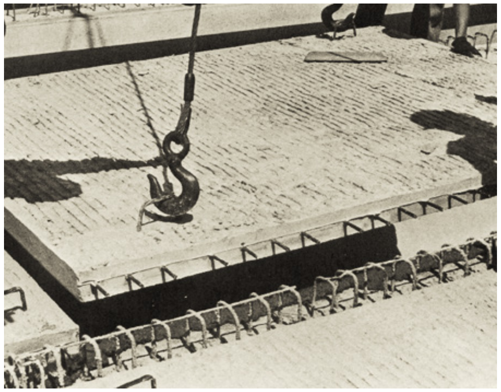
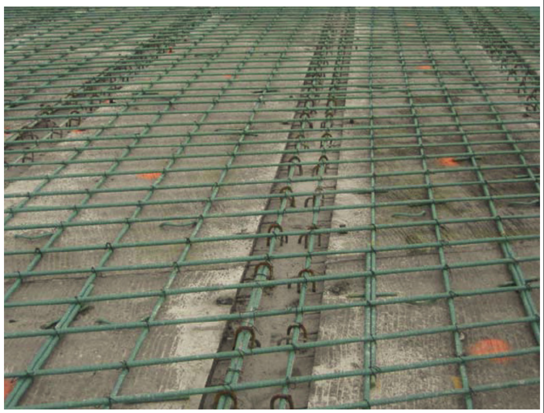
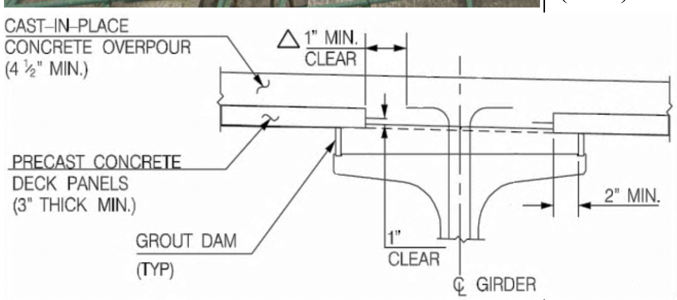
			imposed by grout properties (e.g., depth of fill). Ease of demolition or removal of panels by saw cutting the transverse joints	required number of studs.	ft and with girder spacing up to 11 ft (designed in accordance with the LRFD specifications) Source of information: Badie and Tadros (2008).

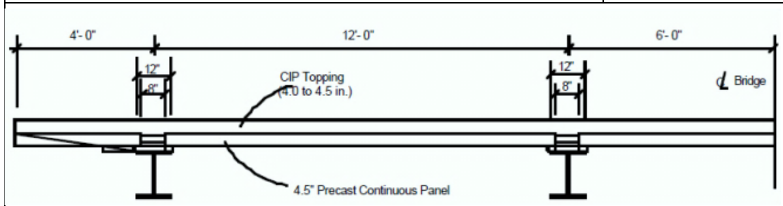
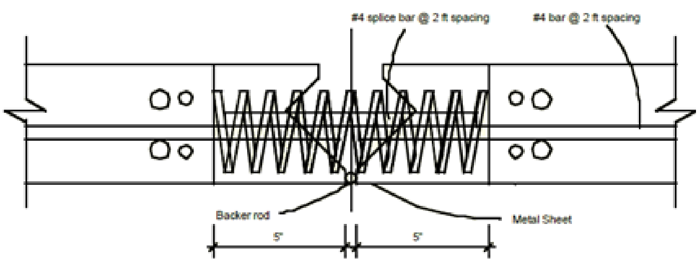
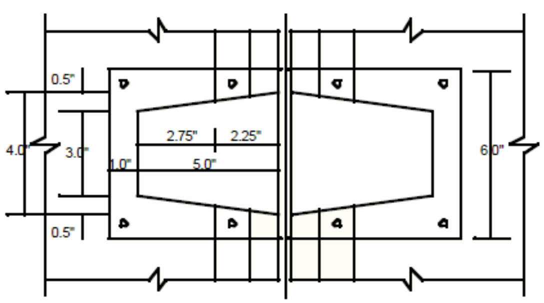
Element	Project(s)	Attributes	Benefits	Limitations	Remarks
NU-deck full-depth panels   Transverse connection:  **Panel-to-panel connection using spiral reinforcement.**	First generation NU-deck: Skyline Bridge, Omaha, NE. Superstructure was replaced in 2003. Second generation NU-deck: 176th Street bridge over I-80, east of Lincoln, NE. Full bridge was replaced in 2009.	Following attributes are presented based on the information provided in the listed references. Length: 12 ft in the direction of traffic. Width: full bridge width Thickness: 7 in. Concrete strength: Release strength of 4500 psi and 28-day strength of 8000 psi Overlay: 1.5 in. CIP topping with 8000 psi Supporting girder spacing: 12 ft Skew: up to 30° Full length channels: 1ft at each beam location Prestressing or post-tensioning strands: Uncoated, 0.6 in. diameter, 7-wire, 270 ksi low relaxation steel. Reinforcing steel: Grade 60	All materials required for fabrication are non-proprietary. The prestressing in panels helps in preventing cracks that may develop during fabrication and handling. Also, helps in reducing the panel thickness. Tolerance issues do not arise because the shear studs are arranged in single row. The 2nd Gen NU-deck has increased construction speed and ease of fabrication, as the crown is moved to a girder line location.	Durability is a major concern as the prestress and post-tensioning strands are placed in cast-in-place concrete joints. New concept and details; hence, past performance data is limited. Girder spacing (i.e., post-tensioning spacing) and post-tensioning sequence (i.e., releasing tendons after grouting the channels over the girders) may not compress the transverse connections which will yield to durability problems.. During fabrication of the 2nd Gen Nu-deck, crown forming in the channel is a challenge because the bars across open channel needs to be cut and welded.	Usually, the panels cover full-width of the bridge. 1st Gen: 1.5 in. CIP concrete overlay with 8000 psi. 2nd Gen: No concrete overlay but the panels are cast with 0.5 in. additional thickness. The deck is finally diamond ground and an asphalt overlay is used as the riding surface. All strands are post-tensioned with final force of 38.9 kips regardless of sequence. Structural steel angles are used to set the panel elevation.

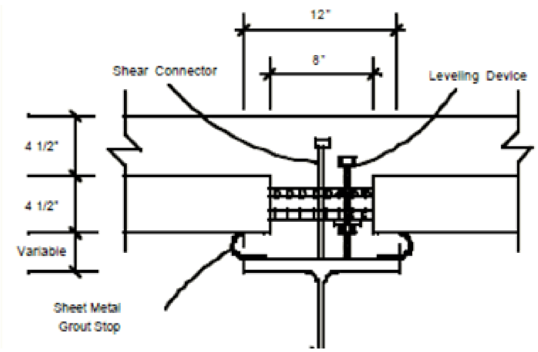
1st generation NU-deck panel: Longitudinal connection:  2nd generation NU-deck panel: Longitudinal connection:  **Crown detail in open channel at girder line.** 		Sources of information: Badie et al. (2006); Wipf et al. (2009b); Hanna et al. (2010a).

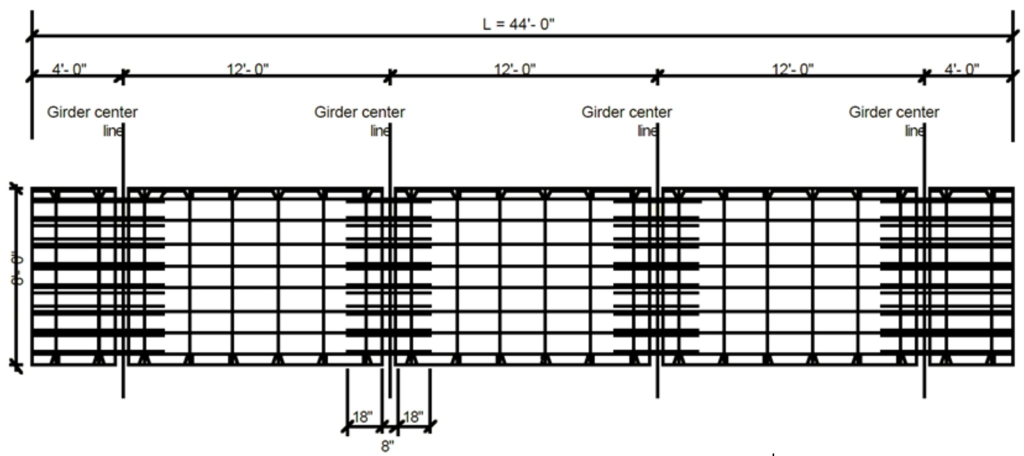
Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Modified NU-deck panel s Partial width, full-depth deck panels developed by the Iowa State University   	In 2006, the Mackey Bridge on 120th Street over Squaw Creek, Boone County, Iowa was replaced with a superstructure comprising of NU-deck panels (partial width, full-depth).	Following attributes are presented based on the information provided in the listed references. Width: Half-width of the bridge. Length: 10 ft Thickness: 8.25 in. Skew: Up to 60°. Concrete release strength of 4000 psi and 28-day strength of 6000 psi. Punching shear capacity of the panel is 135 kips. Flexural capacity of the panel is 263 kip-ft Reinforcement: Grade 60 mild reinforcing bars. Modulus of elasticity of 29,000 ksi is used in the design. Prestressing strands: Uncoated, 0.5 in. diameter, 7-wire, 270 ksi low relaxation steel	The panels are partial width. Hence, it is easy to develop the crown during deck placement. Longitudinal closure allows using this system for staged construction. The panels span from centerline to edge of the bridge, thus eliminate the overhang formwork The open channels provide adequate space for grouting the post-tensioning strands Panel supporting leveling devices are easily accessible from the channels  Partial width panels allow using smaller cranes.	Threading of post-tensioning strands through existing reinforcement is time consuming Durability is a major concern as the prestress and post-tensioning strands are placed in cast-in-place concrete joints. New concept and details; hence, past performance data is limited. Staggering of protruding reinforcement from deck panels at the longitudinal closure is a challenge Effectiveness of post-tensioning for compressing transverse joints needs to be evaluated because the post-tensioning is applied after grouting the	The channel consists of 2-layers of prestressing strands, 2-layers of mild steel reinforcement, 6-No. 2-layers of post-tensioning strands, and the leveling devices. According to the information provided in the literature related to the Mackey Bridge project, concrete mix for the channels contained the maximum aggregate size of 3/8 in. and 35% cement replaced with ground granulated blast furnace slag (GGBFS). The water-cementitious material ratio of the mix was 0.38. After adding a high-

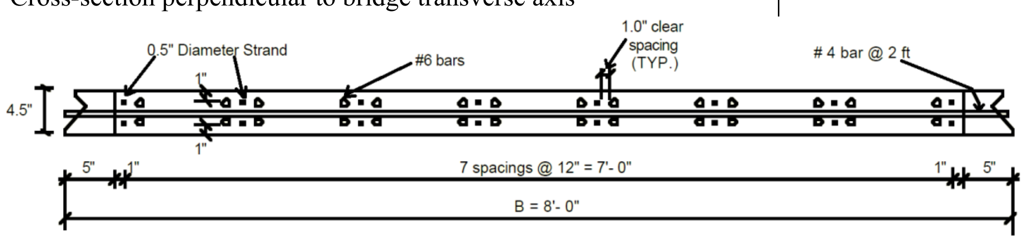
Middle panel reinforcing steel:  End panel reinforcing steel: 	joints which will transfer some of the forces to the deck panel supporting system (i.e., girders).	range water reducer, slump of the mix was 8 in. The minimum concrete temperature at time of placement was 70°F. Sources of information: Wipf et al. (2009b); Wipf et al. (2009c).

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Partial-depth deck panels    	SH 249/ Louetta Road Overpass, Houston, TX (Bridge replacement) (1994) I-45/Pierce Elevated, Houston, TX (Bridge replacement) (1997) I-5/South 38th St Interchange, Tacoma, WA (Deck replacement) (2001) SH 66/Lake Ray Hubbard, Dallas, TX (Bridge replacement) (2002) SH 36/Lake Belton, Waco, TX (Bridge replacement) (2004)	Following attributes are presented based on the information provided in the listed references. Uncoated, 0.375 in. diameter transverse prestressing strands are provided at the mid-depth of the panels. Length: 8 ft Width: girder-to-girder span + 3in. to 3.5in. bearing on each girder Thickness: 3.5in. (typical) Thickness of CIP concrete deck on top: 4.5in. (typical) Concrete release strength of 4000 psi and 28-day strength of 6000 psi has been used. Skew: up to 15^{o} has been implemented, based on the information provided in listed references.	Requires no formwork for the CIP deck. Hence, disruption to feature intersected traffic can be minimized. Partial-depth panels can improve work-zone safety and construction speed. Fabrication and handling is simple compared to full-depth deck panels Construction is simple when compared to full-depth deck panels.	Reflective cracks in CIP deck over the transverse and longitudinal joints leads to durability problems and significantly reduce the bridge service life. CIP concrete deck requires extended bridge closure. Panels are typically fragile; therefore moving them frequently during precasting operations may result in a potential damage. The deck overhangs require formwork. The haunches need to be grouted and left intact to achieve required strength, before placing the CIP concrete; hence, there is a slight increase in the construction duration.	Mild steel reinforcement is provided in the cast-in-place concrete deck. The top surface of these panels is roughened to amplitude of 0.06 in. Grouting of haunches can be performed using high density low slump concrete, including high range water reducing admixture. Sources of information: Burkett et al. (2004); Hieber et al. (2005); PCI-NER (2001).

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
NU-deck stay-in-place panels **(NU-deck SIP panels)** (Developed and tested at University of Nebraska in 1998)   	This detail has not been used in any bridge projects.	Following attributes are presented based on the information provided in the listed references. Width: Full-width of the bridge. Length: 4 to 12 ft Thickness: 4.5 in. Thickness of cast-in-place concrete overlay ranges from 3.5 in. to 4.5 in. Self-consolidated concrete was used with the release strength of 4000 psi and 28-day strength of 10,000 psi. Minimum top and bottom clear cover of 1 inch was used. Width of the longitudinal channel over the girders is 8 in. Compressive strength of grout used to fill the channel was 4000	Due to continuity in longitudinal and transverse directions, these panels may eliminate the potential of reflective cracking. These panels eliminate the need of overhang formwork. Wide channels provided over the girders facilitate grouting operation. Since a cast-in-place concrete deck is placed over the partial depth deck panels, use of a high quality grout may not be needed. Deck crown can be formed during cast-in-place concrete placement. Increased load capacity due to continuity and prestressing compared to traditional partial depth deck panel systems.	New concept and details; hence, past performance data is limited. Durability of the system is a concern because the prestressing strands run through cast-in-place concrete. Using CIP concrete requires extended bridge closure.	Panels are prestressed in the transverse direction. Prestressing strand arrangement is similar to the NU deck full depth panels. Prestressing helps the entire panel acts as a transversely continuous member over the girders. Reinforced pockets and shear keys are used to maintain continuity in longitudinal direction. A spiral splice is used to provide full bar yield strength of 60,000 psi.

<table>
<tr>
<td>Longitudinal connection:


Typical plan of the NU-deck SIP panel showing the transverse prestressing strands:


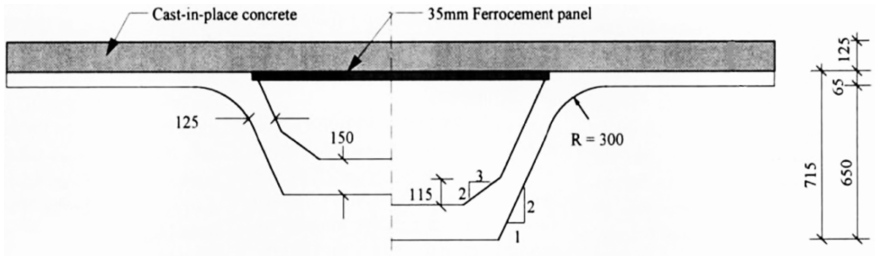
Cross-section perpendicular to bridge transverse axis

</td>
<td>psi.

Uncoated, 7-wire, 270 ksi low relaxation prestressing strands and grade 60 steel were used in the panels.
Skew: up to 30^{o}</td>
<td></td>
<td></td>
<td>Panels are supported over the girders using adjustable leveling devices that are placed within the channel over the girders.

Sources of information:
Badie et al. (1998); Versace and Ramirez (2004).</td>
</tr>
</table>

Modular Superstructure Elements and Systems

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast adjacent box-beam  (Source: PCSB 2011)  (Source: CPCI 2006)	Baldorioty de Castro Avenue Overpasses, San Juan, Puerto Rico (Bridge replacement) (1992) Mill street crossing in Epping, New Hampshire (Bridge replacement) (2004) Route 99/120 Separation Bridge (Bridge replacement) (2007)	Following attributes are presented based on the information provided in the listed references. Span ranges up to 127 ft. Depth ranges from 12 in. to 60 in. Width: 36 in. and 48 in. Concrete strength: 5000 psi to 7000 psi. There are records of using high performance concrete (HPC) with 28-day strength of 8,000 psi.	Great for sites with tight underclearance. Can accelerate construction by using a wearing surface over the girders. Does not require formwork for the cast-in-place concrete deck. High torsional stiffness. Can be used for constructing aesthetically pleasing structures. The entire bridge superstructure can be prefabricated with adjacent box-beams and kept ready for installation, before closing the traffic.	Reflective cracking is a major concern that leads to deterioration of the bridge superstructure. Not possible to inspect box-beam interior. Special details and cast-in-place construction are needed to develop continuity over piers. Not feasible for carrying utilities underneath Box-beams are difficult to fabricate as they involve multi-step fabrication process (Culmo & Seraderian 2010) Hard to replace a damaged girder when grouted post-tensioning is used in the transverse direction. Complete redesign of the transverse connectivity is essential as none of the existing designs are capable of mitigating reflective deck cracking (Aktan et al. 2009).	Sources of information: Stamnas and Whittemore (2005); Chung et al. (2008); MDOT-BDM (2011).

<table>
<tr><th>Element</th><th>Attributes</th><th>Benefits</th><th>Limitations</th><th>Remarks</th></tr>
<tr><td>Trapezoidal box girder


Note: All dimensions are in mm.</td>
<td rowspan="2">Following attributes are presented based on the information provided in the listed references.

Spans range: up to 95 ft

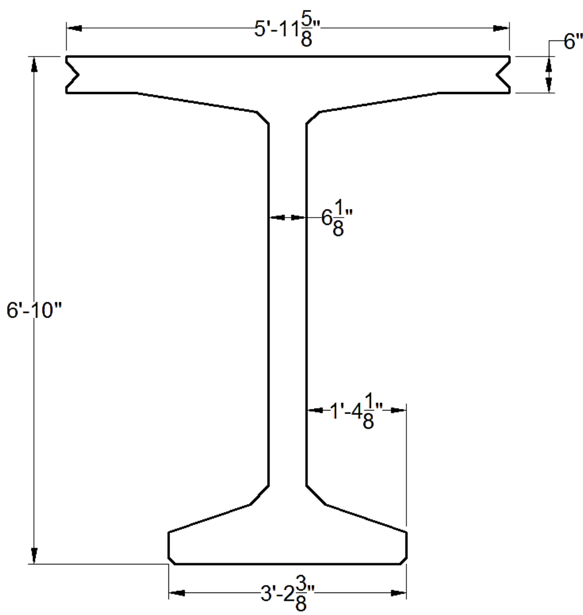
Depth range: 20 in. to 28 in.

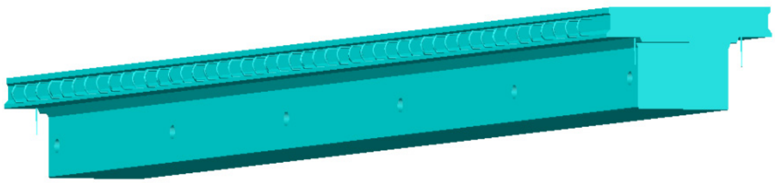
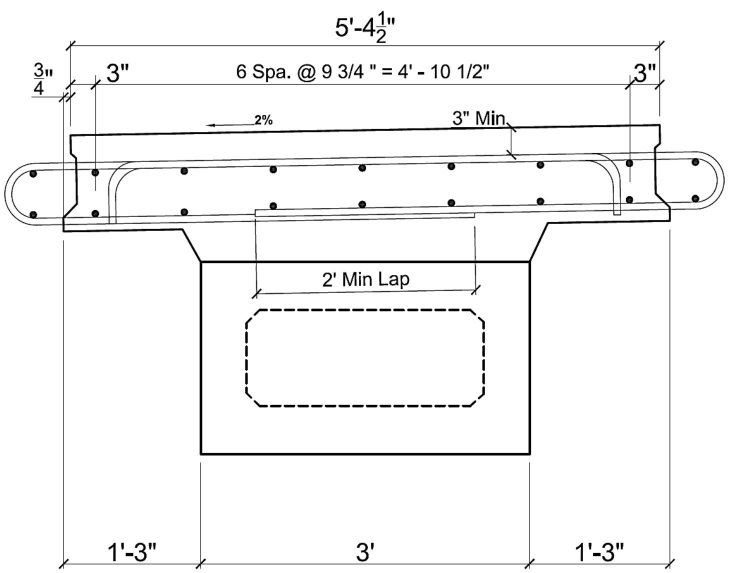
Width range: 6.5 ft to 12 ft

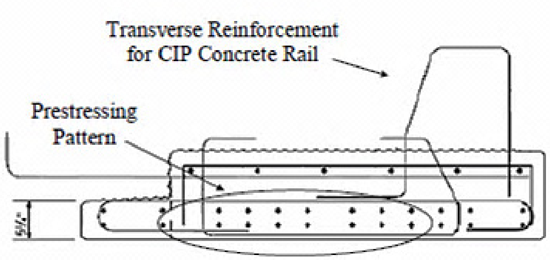
Concrete strength of the trapezoidal box section: 7400 psi. at release and 9000 psi at 28-day</td>
<td rowspan="2">Good for up to short-to-medium span bridges.
Trapezoidal box girders could cover the entire bridge with relatively few girders compared to AASHTO box girders.
Feature intersected is not disturbed during construction of the cast-in-place concrete deck.
Transverse post-tensioning is not required.
The relatively low weight of the girder (55 tons for a girder with 28 in. depth, 12 ft width, and 95 ft length) makes it feasible to be lifted with conventional lifting equipment.</td>
<td rowspan="2">New concept and details; hence, past performance data is limited.
Requires cast-in-place deck which extends the project duration.
Access to confined space of the box is limited. Hence, difficult to inspected deterioration that will initiate at the interior walls of the section.
Trapezoidal box girders are limited to 95 ft span.</td>
<td rowspan="2">Sources of information: Badie et al. (1999).</td></tr>
<tr><td>Project(s)
The open-top trapezoidal box girder has been used in several projects in Canada (CPCI 2006). But based on the data currently available, this system has not been implemented in any of the projects in the U.S.</td></tr>
</table>

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast segmental box girder 	Seven mile bridge in Monroe County, Florida (built 1982) Ramp I over I-75 in Florida (built 1984) I-75/SR 826 (5 bridges) in Florida (built 1986)	The sections are standardized as AASHTO-PCI-ASBI segmental box girders. Following attributes are presented based on the information provided in Freyermuth (1997). Span: up to 200 ft Depth: 6 ft to 8 ft Width: 27 ft to 44 ft Specified length is 10 ft for each segment to facilitate shipping. Concrete strength: 5000 psi. Post-tensioning: 7-wire, 0.5 in or 0.6 in. diameter, grade 270 low relaxation strands	A cost effective option for very large projects. Segmental construction techniques are feasible for crossing large waterways Feasible for longitudinal launching applications Optimum for design-build projects A large number of bridges in service. (e.g., by year 2010 there are 68 bridges in Florida. Segmental bridges are widely used in California also.) Hence, data is available to evaluate the performance and improve the design.	Qualified personnel or inspectors required for quality grouting and post-tensioning Durability problems associated with post-tensioning systems. Challenges in inspecting post-tensioning system.	The publication Freyermuth (1997) contains standard section details in metric system. The publication Freyermuth (1997) specifies a span range of 100 ft to 150 ft, for span-by-span construction, and a span range of 100 ft to 200 ft, for the balanced cantilever construction. Sources of information: Freyermuth (1997); Blanchard et al. (2010).

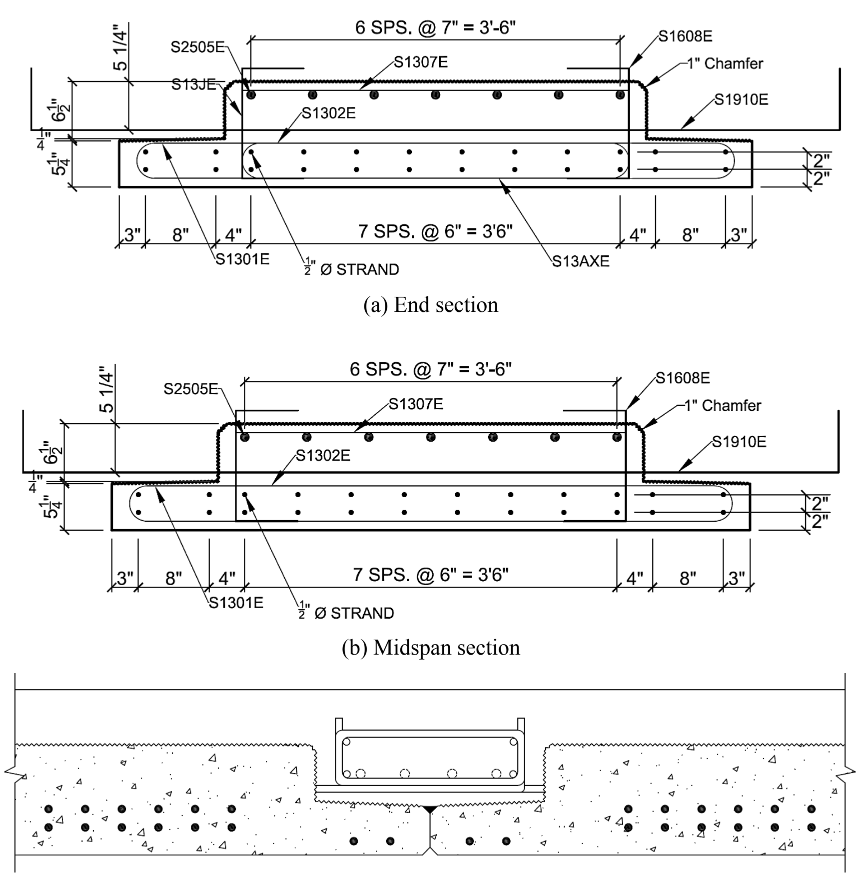
Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Double-tee girder  	This section was the earliest development in the precast prestressed concrete sections. Used in several projects since 1950's, but low-volume roads only. Recent project: Russian River Bridge (Superstructure replacement) (2006)	Following attributes are presented based on the information provided in the listed references. Standard span range: 32 ft to 65 ft Depth range: 27 in. to 36 in. Width range: 5 ft to 8ft Concrete strength: 4000 psi. at release and 7000 psi at 28-day Prestressing strands: 0.5 in. or 0.6 in. dia.	Most of the prefabricators are familiar with the section as it is widely used in parking structures. Top flange servers as formwork for CIP concrete deck and working surface for the construction crew Single pour production; hence, it is easy to fabricate compared to box-beams Can accommodate utilities underneath	Requires a CIP concrete deck which extend duration of bridge closure Producers / manufacturers reported vertical and diagonal cracks in the stems of double-tee girder, developed during handling process due to lateral force on the stem. Extreme care should be taken during handling, so that lateral forces are not applied (PCI Committee 1983) The deck slab without transverse post-tension may be a source of durability concern due to potential cracking. Limited for short span bridges with low traffic-volume.	Generally used with CIP concrete deck Sources of information: PCI committee (1983); Bergeron et al. (2005); Chung et al. (2008); Li (2010).

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Decked bulb-tee girder  	This section emerged from the bulb-tee girder section. States like Utah and New England utilized this section in several projects. Recent projects: Graves avenue over I-4, Florida (Superstructure replacement) (2006) Route 31 bridge in Lyons, New York State (Bridge replacement) (2009)	The section is standardized. Following attributes are presented based on the information provided in PCI-BDM (2001) and UDOT (2010). Span range: up to 180 ft (UDOT 2010) Depth range: 35 in. to 98 in. Top flange width range: 4 ft to 8ft Concrete strength range: 6500 psi to 8500 psi Prestressing strands: 0.5 in. or 0.6 in. dia.	Can accelerate construction because only a wearing surface is needed over the girders. Section has been used in several projects; hence, structural durability performance data is available. Single pour production; hence, it is easy to fabricate compared to box-beams Can accommodate utilities underneath. More capacity and efficiency than AASHTO type V and VI girders (Bardow et al. 1997) Due to modular nature of the units, the entire bridge superstructure can be prefabricated and kept ready for installation, before closing the traffic	Depth of about 8 ft, not feasible for bridges with underclearance limitations Limited to roadways with ADT up to 30,000 (UDOT 2010) Possibility of flange-to-flange connection failure unless moment transfer connections are used.	Developed in 1969 by Arthur Anderson based on the standard tee girder section details. Standardized as AASHTO/ PCI deck bulb-tee in 1988. Commonly used flange-to-flange connection: Female-to-female grouted shear key or flange-to-flange welded plate connection Sources of information: PCI-BDM (2001); Shah et al. (2006); Graybeal (2010); UDOT (2010); CPMP (2011); Culmo (2011).

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Decked box-beam  (Source: Michigan M-25 Bridge over White River CAD)  (Source: Michigan M-25 Bridge over White River Bridge plans 2010)	M-25 Bridge over White river, Michigan (Bridge replacement) (2011).	Following attributes are presented based on the information provided in MDOT M-25 Bridge plans. Design is similar to that of a spread-box girder bridge, but with additional connection detailing. Span: 47 ft Depth of the module including the deck is 3 ft Top flange width of the module is 5 ft - 5 in. Specified compressive strength of decked box-beam modules at 28-day is 7000 psi. Post-tensioning: 7-wire, 0.6 in. diameter, grade 270 low relaxation strands	Shallow depth enables using at sites with tight underclearance. Does not require a cast-in-place concrete deck. High torsional stiffness. Can be used for constructing aesthetically pleasing structures. Feasible for carrying utilities underneath.	New concept and connection details; hence, past performance data is limited. Not possible to inspect box-beam interior. Special details and cast-in-place construction are needed to develop continuity over piers. Hard to replace a damaged module when grouted post-tensioning is used through the cast-in-place diaphragms. Box-beams are difficult to fabricate as they involve multi-step fabrication process (Culmo & Seraderian 2010) Not possible to detect deterioration inside the concrete box. Deck reinforcing and casting process should be performed promptly, before the box-beam concrete starts setting.	During the manufacturing process, primarily the box-beam is casted, then the deck reinforcement is placed on top of box-beam, and finally the deck is casted. Source of information: MDOT M-25 Bridge plans (2010); MDOT-BDM (2011).

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Inverted-T precast slab Design is based on French Poutre Dalle system   	Projects listed here are Bridge replacements. Truck Highway (T.H.) 8 bridge over Center lake channel, Center City, MN (2005). T.H. 72 bridge over Tamarac river, Waskish, MN (2005). T.H. 65 bridge over Groundhouse river, Kanabec county, MN (2007). T.H. 65 bridge over Ann river, Kanabec county, MN (2007). T.H. 76 bridge over South fork of Root river, Houston county, MN (2007). T.H. 238 bridge over Swan river, Morrison county, MN (2009). T.H. 238 bridge over Pike creek, Morrison county, MN (2009). T.H. 60 bridge over Cannon river, Rice county, MN (2009)	Following attributes are presented based on the information provided in the listed references. Span range: 20 ft to 65 ft Width: 6 ft Structure depth: 30 in. for 65 ft span. Structural depth includes a 24 in. deep precast section and 6 in. thick cast-in-place concrete deck Concrete strength of the precast inverted-T precast slab element is 6,500psi. Cast-in-place concrete deck strength is 4,000psi. Prestressing strands: 0.5 in. dia.	High span-to-depth ratio; hence ideal for projects with underclearance limitations. Does not require formwork for the cast-in-place concrete deck.	New concept and details; hence, past performance data is limited. Requires cast-in-place deck which extends the project duration. Degree of moment continuity provided by the longitudinal connection detail needs to be evaluated. Limited to short span bridges due to individual Element weight.	Composite action between precast section and CIP deck is established through shear reinforcement (#6 bars). The longitudinal reinforcement detail used at the longitudinal joint is expected to alleviate reflective deck cracking. Transverse hooks with 90^{o} angle protruding from webs enables connectivity between reinforcement cage and the girder. Source of information: Bell II et al. (2006); French et al. (2011).

Old detail of the inverted-T precast slab:

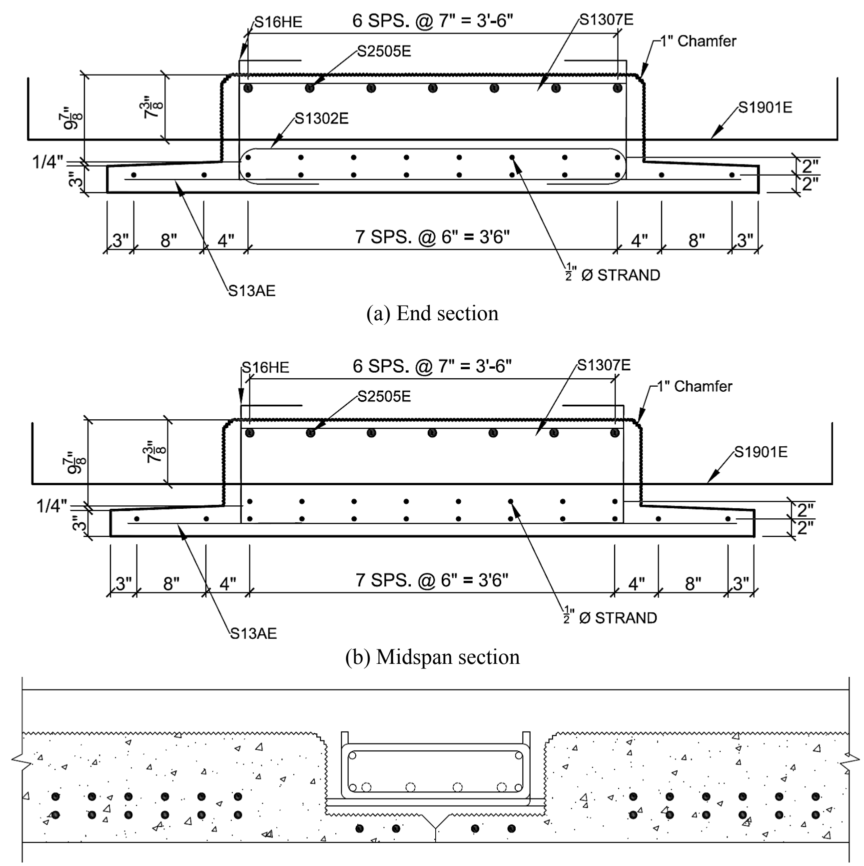


(a) End section

(b) Midspan section

(c) Longitudinal reinforcement cage

New detail proposed by the NCHRP for the inverted-T precast slab:

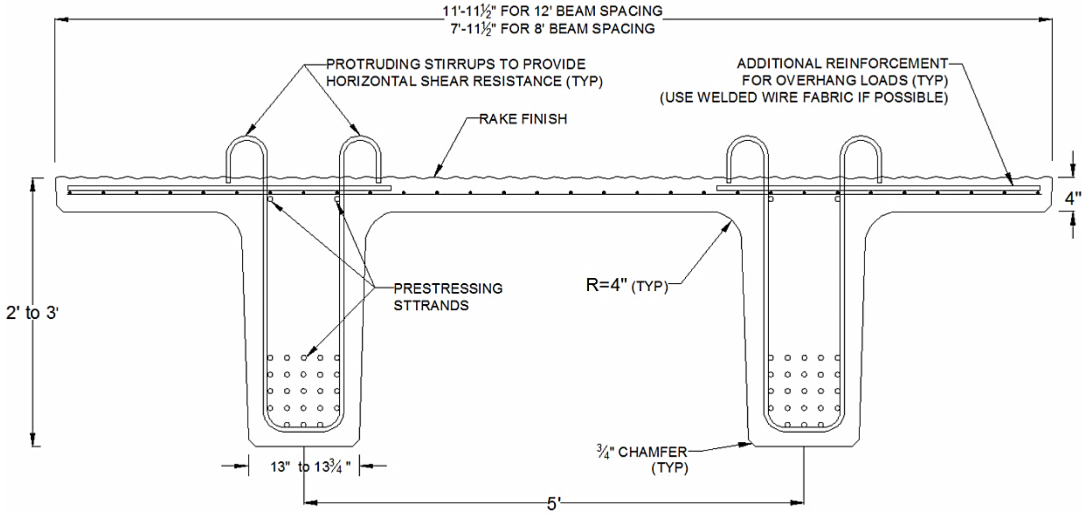
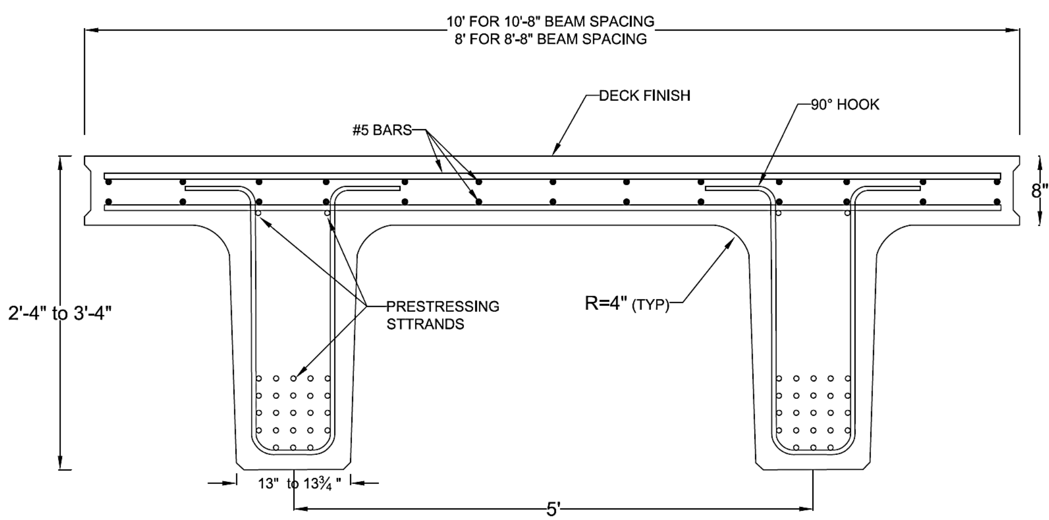


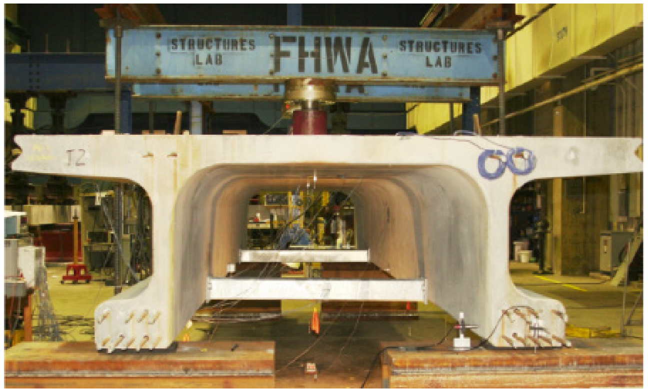
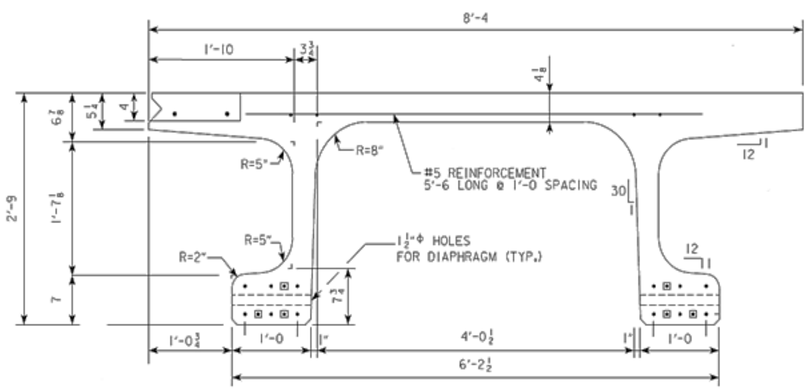
(a) End section

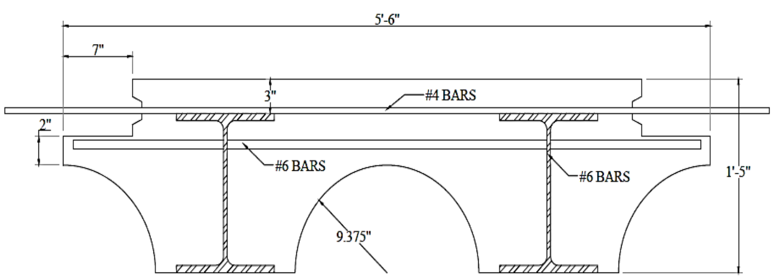
(b) Midspan section

(c) Longitudinal reinforcement cage

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Northeast Extreme Tee (NEXT) beam 	NEXT F –Route 103 bridge over York river in York, Maine (Bridge replacement) (2011) NEXT F – Queen's Blvd over Van Wyck Expressway in New York City (Bridge replacement) (2012) NEXT D – White Boulevard Bridge, Florida (Bridge replacement) (2011)	The cross-section dimensions and span length of both F and D sections shown below are based on the information provided in the listed references. Span ranges from 40 ft to 90 ft Depth of the section ranges from 24 in. to 36 in. with 4 in. increment. Width of the section ranges from 8 ft to 12 ft Stem spacing is 3 ft for 8 ft wide section and 6 ft for 9 ft –12 ft wide sections Stem thickness ranges from 11 in. to 13 in. Prestressing strands: 0.6 in. dia. According to PCI NE (2011) span charts, concrete strength is as follows: 8000 psi at release and 10,000 psi at 28-day. 6000 psi. at release and 8000 psi. at 28-day. 4000 psi. at release and 6000 psi. at 28-day.	Ideal for projects with underclearance limitations. Greater load carrying capacity than standard double tee and box girders. The stem could incorporate more prestressing strands compared to standard double tee girders. Single pour production A range of beam sizes could be produced with one set of formwork. Since the depth, spacing, and size of stems are standardized. No intermediate diaphragms Due to modular nature of the units, the entire bridge superstructure can be prefabricated before closing the traffic. Good for short and up to short-to-	New concept and details; hence, past performance data is limited. NEXT F beam requires 8 in. CIP concrete deck which extends project duration Durability of the longitudinal connections between NEXT F and D beams is a concern. Shipping and handling limitations due to heavy weight.	Approved in CT, MA, ME, NH, RI, VT, DE, MD, NJ NEXT F beam weighs 120 kips for 90 ft length with 4 in. thick flange NEXT D beam weighs 160 kips for 90 ft length Sources of information: Calvert (2010); Culmo and Seraderian (2010); PCI NE (2011); Culmo (2011).

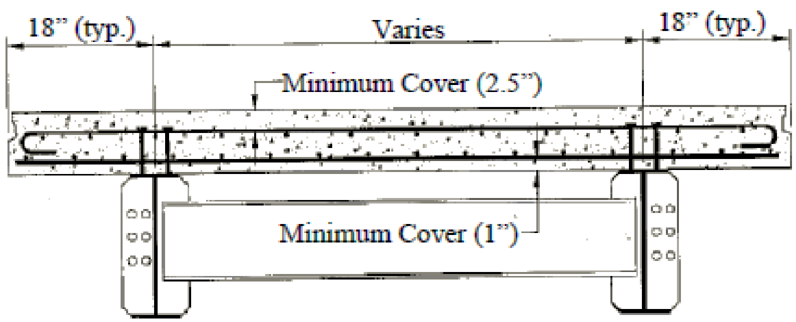
NEXT F beam: flange serves as stay-in-place form for cast-in-place concrete deck  **NEXT D beam:** flange serves as complete deck  	medium span bridges.		

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Pi-girder **2nd generation UHPC pi-girder**  	Jakway Park Bridge, Buchanan County, Iowa (Bridge replacement) (2008)	Following attributes are presented based on the information provided in the listed references. Span: **up to 65 ft** (computed based on limiting tensile stresses to the cracking threshold) Graybeal (2009) estimated **maximum span of 87 ft** with increased prestressing force. Depth: 33 in. Weight: 932 lb/ft Compressive strength of Pi-girder UHPC at release is 12,500 psi and at 28-day is 21,500 psi. Steel tube diaphragms at 1/4rth span and midspan.	Can accelerate construction because only a wearing surface is needed over the girders. The system is good for sites with underclearance limitations. Good for short and up to short-to-medium span bridges. The unhydrated cement content of UHPC would provide crack-sealing capabilities through secondary hydration. Cost savings could be achieved by using partial prestressing in UHPC pi-girder design (i.e., allowing cracking on the bottom of the bulbs under maximum service loads). Transverse mild steel reinforcement could be used in the pi-girder deck, if needed	New concept and details; hence, past performance data is limited. Expensive due to proprietary UHPC. Investigation of torsional properties of 2nd generation pi-girder and its ability to resist eccentric loading, for longer spans is required. Lighter and slender section may amplify dynamic loads on the bridge and need be investigated.	1st generation UHPC pi-girder was developed at Massachusetts Institute of Technology in 2002. For fabricating the UHPC pi-girder, batching of UHPC is performed in the ready-mix concrete trucks In the pilot project, the pi-girder ends were seated on neoprene bearing pads and were encased in CIP concrete diaphragms The girders are steam cured using thermal blankets for 48 hrs at 195°F Sources of information: Graybeal (2009); Matt et al. (2011).

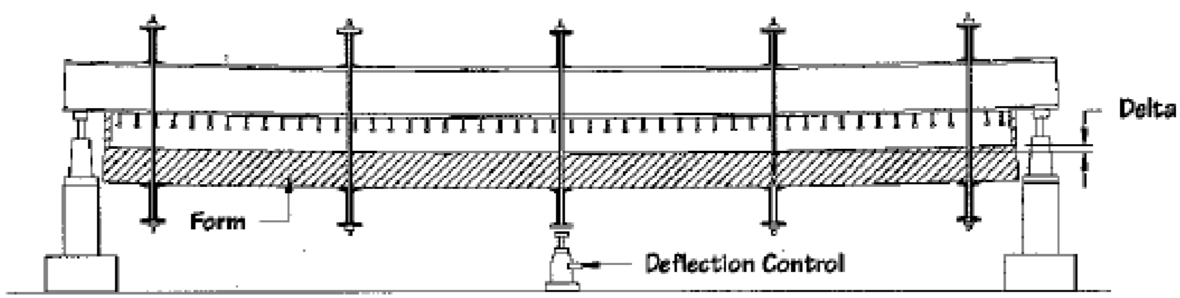
Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast modified beam in slab Longitudinal joint:  Complete bridge:  Typical section of the module:  	Mt. Vernon road bridge, Black Hawk County, Iowa (Bridge replacement) (2006) Marquis road bridge, Black Hawk County, Iowa (Bridge replacement) (2007)	Following attributes are presented based on the information provided in the listed references. Span: 40ft to 50ft Width: 4.5ft to 5.5ft Consists of embedded W14 sections spaced at 2 ft-9 in. Depth of the module: 17.25 in. at girders and 7 in. in between Skew: up to 45° Compressive strength at 28-day is 5000 psi Structural steel strength: 50,000 psi Concrete mix was developed with water-cement ratio of 0.43, cement content of 624 lb/cy, and an air entraining admixture.	Can accelerate construction because only a wearing surface is needed over the modules. The system is good for sites with underclearance limitations. The steel girders are embedded in concrete, therefore protected against corrosion and maintenance.	New concept and details; hence, past performance data is limited. Good for short span bridges only.	Original module was developed in 1997 and finally modified in 2004 to formally known as **precast modified beam in slab bridge** module. The module was developed by the Iowa State University Bridge Engineering Center in cooperation with Blackhawk county. Before placing concrete in the longitudinal joints, 14 in. long #4 bars are placed at the center of #4 reinforcing bars protruding from each module. The #4 protruding reinforcing bars are spaced at 15 in. center-to-center for each module. Source of information: Klaiber et al. (2009).

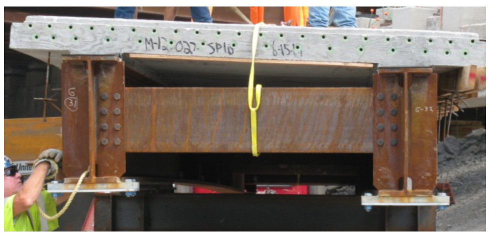
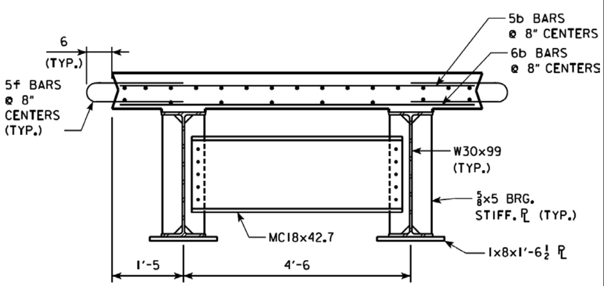
System	Project(s)	Attributes	Benefits	Limitations	Remarks
INVERSET^{TM} system **(Proprietary)** Developed in Oklahoma in early 1980's and tested in 1997 (PennDOT 1997)  	Used in several projects in New York and Pennsylvania, since 2000. Creek Road over I-295, Burlington county, NJ (Superstructure replacement) (2010) Eastern Ave Bridge over Kenilworth Ave, NE (Bridge replacement) (2010)	It is a standard proprietary module. Following attributes are presented based on the information provided in the listed references. Span: up to 100 ft Steel girder: W 30x99 Depth of the module: girder depth + deck thickness. Deck thickness: 7.5 in. Width: up to 12 ft Skew: up to 60^{o} Deck compressive strength at 28-day is 8500 psi	Had been used in several projects, thus performance data is available. Can accelerate construction because only a wearing surface is needed over the module. The system is good for sites with underclearance limitations Good for short and up to short-to-medium span bridges in non-corrosive environments. The deck of the system will be in compression under its own weight, therefore, prevents transverse deck cracking; hence, and improves the deck durability. Due to modular nature, the entire bridge superstructure can be prefabricated and kept ready for installation, before closing the traffic	Increased cost due to proprietary nature. The pre-compressed deck of the module could not be replaced in the field, thus requires removal of the entire module Steel girders are used in this system; hence, it is expensive to maintain than concrete girders. Weathering steel is useful for corrosion prevention; however, not good for states where deicing salts are used, as it is sensitive to salt-laden environments. Further, there are several durability concerns with regard to fabrication and maintenance, such as: special welding requirements, and maintenance of the nearby structures that develop rust stains due to normal surface weathering of the weathering steel.	The INVERSET system is casted upside-down; hence, the deck is precompressed due to self-weight of the module Sources of information: Versace and Ramirez (2004); Pate (2008); Fort Miller Co. (1998; 2010); NJDOT (2010); Chamberland and Patel (2011).

INVERSET™ module

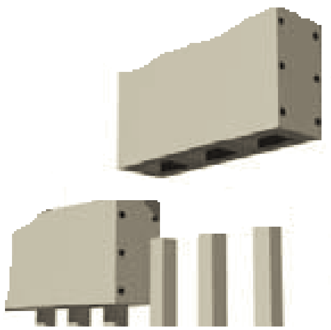
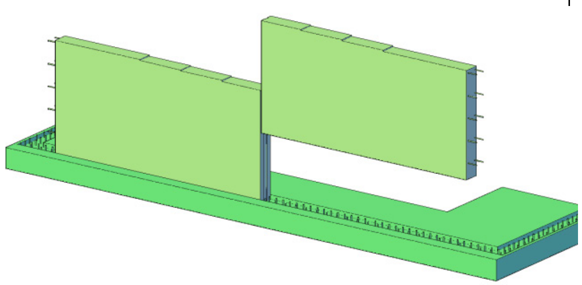


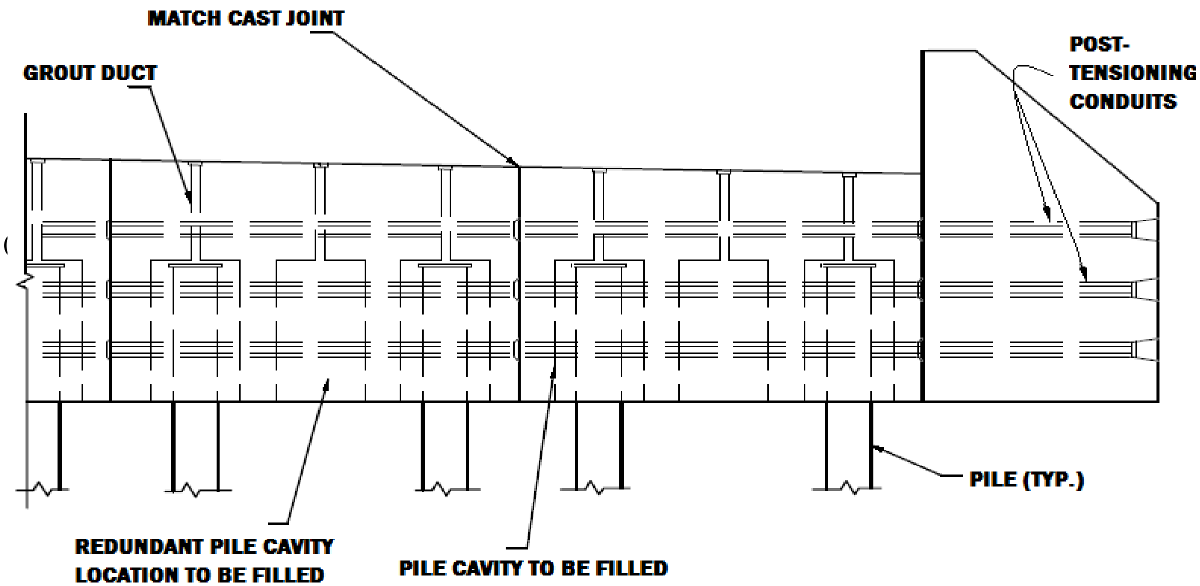
INVERSET™ module casting process

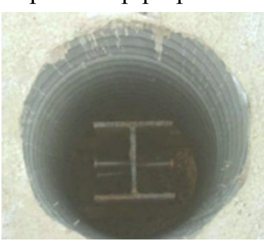


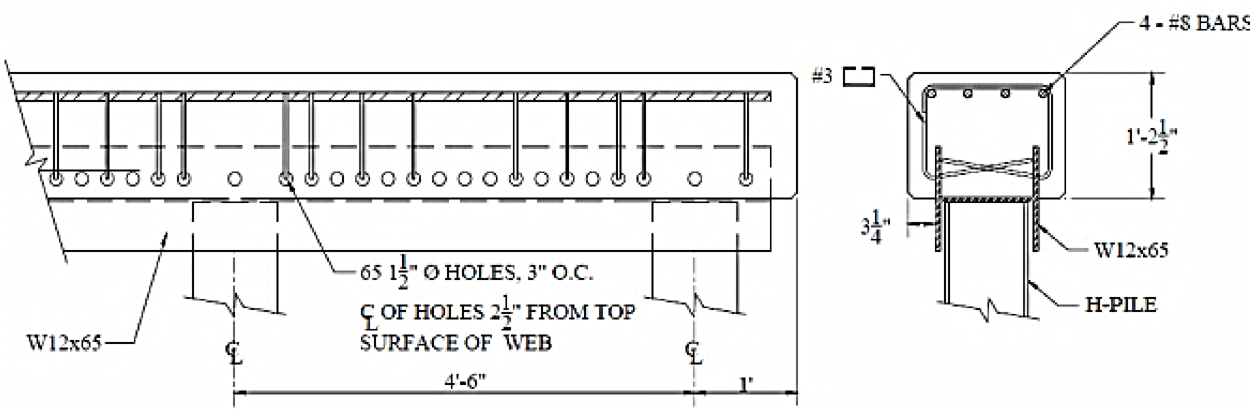
System	Project(s)	Attributes	Benefits	Limitations	Remarks
Decked steel girder system (also referred as decked steel girder module)   Above pictures are from the MassDOT Fast14 project The following detail is used in the Iowa project. 	I-93 Fast 14 Project, Medford, MA. Superstructures were replaced using this system in 2011. Keg Creek Bridge Replacement in Pottawattamie County, IA. Used for the superstructure of a full structure replacement project in 2011.	Following attributes are presented based on the information provided in the listed references. Longest span used until now is 73.2 ft (MassDOT 2011) Steel girder: W 30x99 (depth: 29.7 in.), ASTM A709 grade 50W Width: 8 ft to 9 ft Precast deck: 7.5 in. to 8 in. thick Deck compressive strength at 28-day is 4000 psi to 5000 psi	Can accelerate construction because only a wearing surface is needed over the module. The system is good for sites with underclearance limitations Good for short and up to short-to-medium span bridges in non-corrosive environments. The decked steel girder modules are more biddable by contractors, as they can be prefabricated with conventional designs and processes (non-proprietary). Due to modular nature of the units, the entire bridge superstructure can be prefabricated and kept ready for installation, before closing the traffic	New concept and details; hence, past performance data is limited. Steel girders are used in this system; hence, it is expensive to maintain than concrete girders. Weathering steel is useful for corrosion prevention; however, not good for states where deicing salts are used, as it is sensitive to salt-laden environments. Further, there are several durability concerns with regard to fabrication and maintenance, such as: special welding requirements, and maintenance of the nearby structures that develop rust stains due to normal surface weathering of the weathering steel.	The module was developed under SHPR II project and is non-proprietary. In MassDOT project, the modules were placed adjacently and connected through a reinforced high-early strength concrete closure pour: 2000 psi was achieved within 4 hrs of final set and 4000 psi at 28-day. Iowa project used full, moment-resisting ultra-high performance concrete (UHPC) joints at piers and between deck panels. The bridge deck was diamond grind for profile improvement after UHPC closure pour reached minimum of 14,000 psi. Sources of information: Shutt (2009); LaViolette (2010); MassDOT (2011); IowaDOT (2011); Moyer (2011).

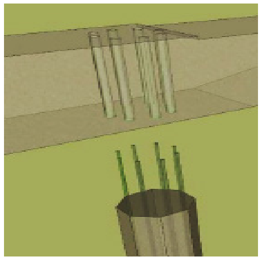
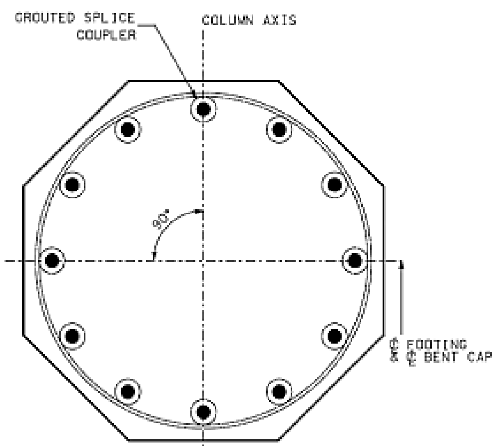
Substructure Elements

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast abutment stem/wall (a) Precast abutment stem segments on piles (Source: Culmo 2009)  (b) Precast abutment wall segments on footing (also known as cantilever abutment) (Source: Michigan M-25 Bridge CAD drawing) 	Precast abutment stem segments on piles – Upton Maine Bridge, Maine (2004) Precast abutment wall segments on footing – Epping, New Hampshire (2005) Precast abutment wall segments on footing – M-25 Bridge over White river, Michigan (2011)	The sections are not standardized. Following attributes are presented based on the information provided in the listed references. Height of abutment stem: 4ft Height of abutment wall: 7ft to 10ft Length of each segment: up to 14 ft Thickness: 2 ft for abutment wall, and 3 ft to 4 ft for abutment stem 28-day compressive strength of precast abutment segments is 5,000 psi.	Abutments precast in segments will alleviate the shipping and handling limitations. Abutment weight can be reduced by creating redundant cavities. **This concept helps to achieve light-weight components for alleviated shipping and handling.** Large prefabricated elements are advantageous for remote locations where access to the ready-mix concrete is difficult.	Abutment segments usually weigh 60 kips or greater; therefore, transportation and mobility of large cranes should be investigated. Grouting large cavities will be challenging because the grout manufacturers may limit the fill depth. A level subbase is required for the abutments on piles. The pile cavity forms makes the fabrication process challenging. Tighter tolerances are required for the pile driving operation. Tighter tolerances are required for proper fit-up between the precast elements while using grouted splice sleeve connections. Proper grouting of the channel in spread footing, at the abutment stem connection is	The abutments could be integral, or semi-integral, based on the design. However, it is encouraged to use semi-integral abutments because it is easy to replace bridge superstructure as needed and also minimize the stresses developed in the system due to thermal loads. The abutment wall segments on spread footing use grouted splice sleeve connections. The redundant pile cavities in an abutment stem can be filled with grout only.

(c) Precast abutment stem segments with redundant pile cavities (Source: Culmo 2009)  	critical. Proper grouting of the splice sleeve connection is critical. Grouting of the vertical shear keys between the abutment segments (figure-b) should be investigated. Projects have reported joint forming and sealing issues under significant pressure head due to height of the abutment.	Sources of information: Stamnas and Whittemore (2005); Culmo (2009); UDOT (2010); PCI-BDM (2001).

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast pile cap **with Corrugated Metal Pipe (CMP) cavities** Using as a precast pile cap:  Using as a precast bent cap :  H-pile and pipe-pile in the CMP cavity:  	Mackey Bridge on 120th Street, over Squaw Creek, Boone County, Iowa (2006)	The sections are not standardized. Following attributes are presented based on the information provided in the listed references. Height: 3ft to 3ft-6 in. Length: varies (usually full-width of superstructure) Width: 3ft to 4ft 28-day compressive strength unusually specified is 5000 psi or greater. Yield strength of reinforcing steel is 60,000 psi.	Potential for using as a bent cap as well as a pile cap. Good for bridges with shallow embankments and abutments. Could accommodate large tolerances. Potential of precasting the pile caps at a staging area near the bridge site. The CMP cavities allow easy and effective grouting/ concreting of the connection. **The use of full-depth CMP cavities in a component also provides the benefit of achieving light-weight component, for alleviated shipping and handling.**	Large amount of grout/concrete is required, leading to additional curing and setting time. May face challenges if grout is to be used because manufacturers limit fill depth for neat grouts. Shipping and handling limitations due to wide and heavy section. If used as a bent, formwork is necessary for supporting the section until the grout/concrete achieves required strength. The CMP cavities in the section were observed to create localized tensile stresses on sides; this aspect requires further investigation (Wipf et al. 2009a)	Projects where an integral abutment is desired, a CIP portion is constructed on top of the precast pile cap to form the integral abutment. Mechanical splices are embedded in the pile cap for connecting the reinforcement of the CIP portion. The CMP cavities in a pile cap or bent cap can be filled with either grout or high early strength self-consolidating concrete. Sources of information: Wipf et al. (2009a); Wipf et al. (2009b); IowaDOT (2011).

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast pile cap with embedded wide flange sections   	Mt. Vernon Road bridge, Black Hawk County, Iowa (2006) Marquis road bridge, Black Hawk County, Iowa (2007)	The sections are not standardized. Following attributes are presented based on the information provided in the listed references. Height: 1 ft-2.5 in. + ½ flange-width of W 12 section Length: varies (usually full-width of superstructure) Width: 1ft-6in. 28-day compressive strength usually specified is 5000 psi	The pile cap section could be used at abutments and bent caps at the bridge site with shorter substructure (e.g., trestles over streams or bays). The concrete section in composite action with W-section allows for **increased load carrying capacity with reduced section depth (reduced weight),** compared to conventional concrete section.	Suitable for connecting steel sections. Difficult to establish connection with circular sections or concrete sections. Shipping and handling limitations due to wide and heavy section. As the W section is exposed to the environment, corrosion limitations are likely. Field cutting and welding operation of the piles require certified workers. Precision is required in field cutting and grinding of the piles, to obtain required elevation of the pile cap. Overhead field welding is a challenging process.	The pile caps are fabricated by casting concrete around the upper half of W 12 section oriented for weak axis bending. During fabrication, holes are torched in the flange portion which is to be embedded into the concrete. Stirrups are inserted, and concrete is allowed to flow through these holes. After pile driving is completed, the piles are cut off to the desired elevation and then field welded with W section of the pile cap. Sources of information: Klaiber et al. (2009); Wipf et al. (2009a)

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast columns (a) Octagonal section (Source: UDOT 2010)   (b) I-section (Source: Shahawy 2003) 	I-section (Figure-b): U.S.-41/ Edison Bridge over Caloosahatchee River, Fort Myers, FL (1991) Octagonal section (Figure-a): I-287 in Westchester County, NY (1999) Circular section (Figure-c): Parkview Avenue over U.S. route 131, Kalamazoo, MI. (2008) Circular section (Figure-c): I-5, Grand Mount Interchange Bridge, WA (2011) Rectangular/square section (Figure-d): Keg Creek Bridge Replacement in Pottawattamie County, IA (2011) Octagonal section (Figure-a): used by FDOT, TXDOT, UDOT, and PCI-NE in several projects.	The sections are not standardized. Dimensions: vary based on the bridge configuration. Conventional material strengths and design procedures are used. 28-day compressive strength usually specified is 4000 psi.	Octagonal and rectangular columns are easy to fabricate as they can be casted in a horizontal position. Octagonal and rectangular columns are easy to transport. Fabricators could build long forms and cast multiple columns at one time. Octagonal column's seismic performance is identical to a round column. I-section columns are good for tall structures where increased moment of inertia is required, complying the weight limitations. Prestressing could be used for more durable and taller columns. Great durability in corrosive environments. **The I-section precast columns are optimal for supporting inverted-U section**	Shipping and handling may be a limitation depending on the height and weight of column. Fabrication of round column is challenging due to the vertical casting requirement. Rectangular section is not an optimal cross-section due to redundant material. Tighter tolerances are required to avoid tilting of columns and for aligning splice bars with the sleeves. If prefabricated bent cap is used, feasibility of slight tilting of columns during assembly should be considered. This may be considered when specifying bent cap tolerances.	Round columns show better seismic performance compared to other sections. Octagonal shaped columns are preferred instead of round columns due to complex fabrication and vertical casting process of the latter. The columns are connected to the foundation and pier-cap using grouted splice sleeves. Sources of information: LoBuono (1996); Shahawy (2003); UDOT (2010); Khaleghi (2011); Attanayake et al. (2012).

(c) Circular section (Source: Courtesy of MDOT)   (d) Rectangular/square section (Source: IowaDOT 2011)  	**bent cap that is designed to achieve light-weight component.**		

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<tr><th>Element</th><th>Project(s)</th><th>Attributes</th><th>Benefits</th><th>Limitations</th><th>Remarks</th></tr>
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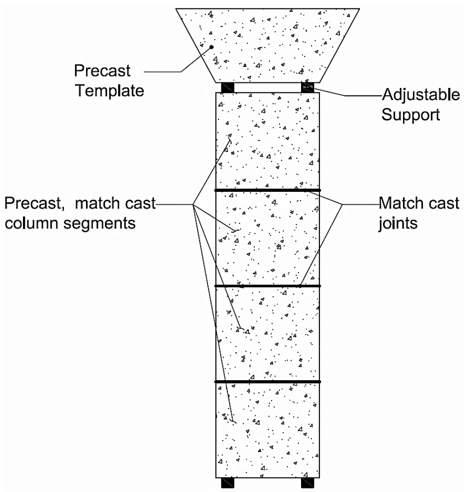
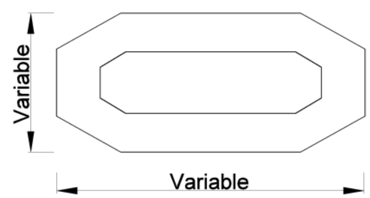
Precast segmental columns

Elevation:



Section details:



Short span bridge with precast segmental columns: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Seven mile bridge, FL (1982)

Linn Cove viaduct, NC (1983)

SH-249/ Louetta Road overpass, Houston, TX (1994)

U.S. route 183 elevated Austin, TX (1997)

Victory Bridge, NJ (2005)
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The sections are not standardized. Following attributes are presented based on the information provided in the listed references.

Height of each segment: varies from 3 ft to 6 ft

Length of cross-section: varies from 4 ft to 10 ft

Width of cross-section: 4 ft

28-day compressive strength usually specified is 5000 psi
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Weight of the segments can be limited to match the available resources.

Good for short and short-to-medium span bridges.

Desired column height could be achieved easily by increasing/ decreasing the number of segments and their individual heights.

Potential of eliminating the bent cap beam.

Provides ease in shipping and handling compared to full height precast columns.

The match-cast joints between the segments allow accelerated construction.

The column segments consist of hollow core that leads to reduced weight and thus can be erected using standard construction equipments and alleviates assembling process.

The precast template helps in aligning the pier with bent cap or the girder elevation.

Hollow portion of the segment could accommodate drainage ducts.
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Vertical post-tensioning is required to connect all the segments including the foundation.

The footing should be specifically designed to accommodate PT ducts.

Requires match-casting of the segments during fabrication.

If the segments are not match-cast, then they should be connected through a grout layer which requires forms and curing at the site.

Appropriately labeling and delivering the segments is necessary, which may otherwise lead to fit-up limitations and extended project duration.

A challenging construction process.
</td>
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This is an outcome of FHWA and TxDOT research.

The first column segment is placed and aligned on the adjustable supports on the footing. Post-tensioning (PT) ducts are spliced and the PT bars are tied. The connection is completed by a CIP concrete joint.

The precast segments are coupled together using PT bars and epoxy. The complete column is post-tensioned with PT strands that run through the ducts.

The precast template is aligned with the bent cap or girder elevation using the adjustable supports on the top precast segment. The joint between the top precast segment and precast template is filled with high-strength epoxy grout.

Sources of information:

Billington et al. (2001); Shahawy (2003).
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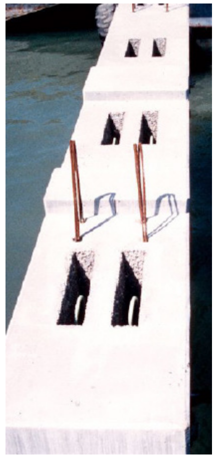
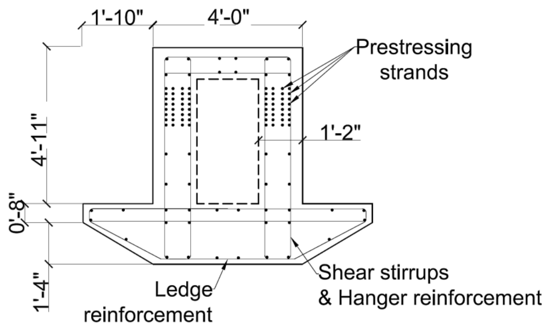
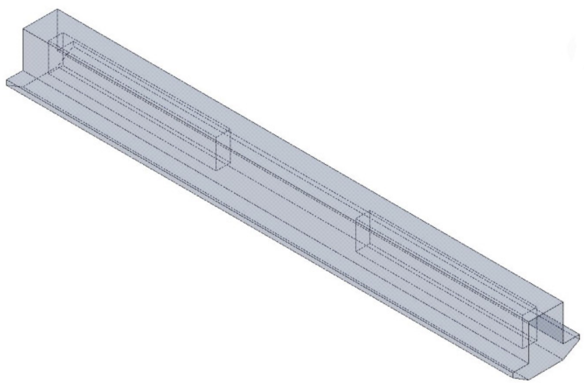
Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast pier/bent cap (a) Bent cap with grouted pockets (Source: Ralls et al. 2004)   (b) Bent cap with grouted ducts (Source: Ralls et al. 2004)  	Bent cap with grouted pockets (Figure-a): Red Fish Bay project, TX (1994) Bent cap with grouted ducts (Figure-b): Lake Belton Bridge over SH 66, Bell County, TX (2004) Bent cap with grouted ducts (Figure-b): Mountain Valley Road Bridge over I-40, New Mexico (2004)	Most of the sections are not standardized. Following attributes are presented based on the information provided in the listed references. Height: 3ft to 4ft-6in. Length: varies (usually full-width of superstructure) Width: 3ft to 4ft 28-day compressive strength usually specified is 5000 psi or greater	Bent caps with grouted pockets are easy to align with the column slices. Pier caps are beneficial for bridge sites with features such as power lines, waterways, and a parallel roadway underneath. Use of pier caps reduces number of prefabricated columns and footings. **To retain the bent cap weight within limits for a wide bridge superstructure, multiple bent caps can be utilized** as shown in Figure-d (next page). Further, **tapered cantilever shaped bent caps can be utilized to achieve reduced weight** compared to a rectangular bent cap; thus alleviating shipping and handling process.	The pockets/ ducts in the bent cap should be filled completely with pumped grout. Temporary supports should be used to set the elevation, and must remain in position until the grout achieves required strength. Shipping and handling limitations may arise due to heavy weight. Tighter tolerances are required for the bent caps with grouted ducts.	Most commonly prefabricated substructure element in a bridge. Standardized as single column hammer head bent, two column bent or three column bent (UDOT 2010). Prestressing is used to reduce the height of the segment, thus, reducing the weight. Connection details are available from research projects: Matsumoto et al. (2001); Restrepo et al. (2011). Sources of information: LoBuono (1996); Matsumoto et al. (2001); Ralls et al. (2004); Unlu (2010); UDOT (2010); Restrepo et al. (2011).

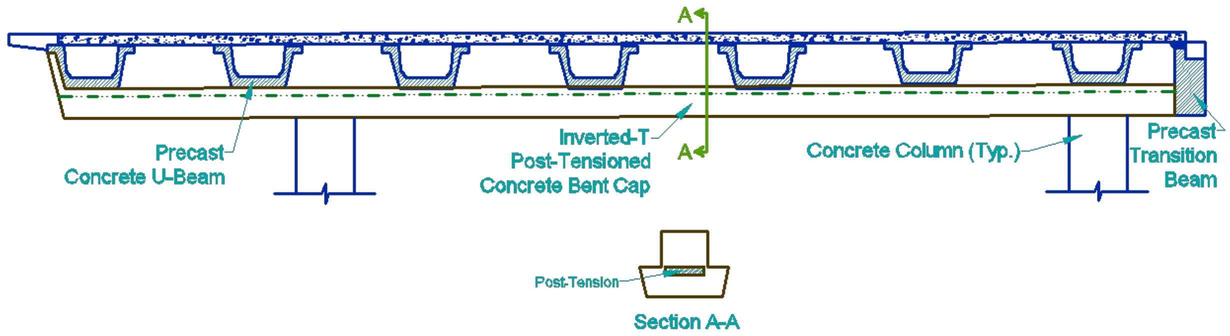
(c) Rectangular bent cap (Source: http://facilities.georgetown.org/2009):

(d) Trapezoidal bent cap (Source: Restrepo et al. 2011):

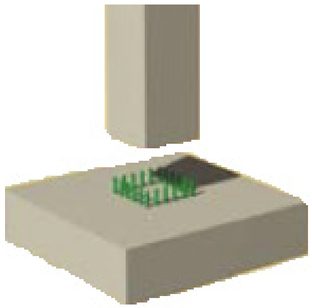
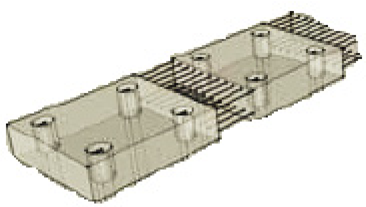
(e) Inverted-U section bent cap (Source: Culmo 2009)

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast pier/bent cap (a) Inverted-T bent cap (Source: Shahawy 2003)  	Inverted-T bent cap (Figure-a): Dallas/Fort Worth International Airport–elevated people mover, TX (2004) Inverted-T bent cap with canted ledges (Figure-b – next page): Austin-Bergstrom International Airport, Austin, TX (2000) Precast bent cap with cavities (Figure-c – next page): Conway Bypass Highway Bridge, Horry County, SC (2001)	Following attributes are presented based on the information provided in Shahawy (2003). Height: 4 ft to 5 ft (height of Inverted-T bent cap is 6ft-10in. including the flange) Length: varies (usually full-width of superstructure) Width: 4ft (width of Inverted-T bent cap is 4 ft at the web and 7ft-6in. at the flange) 28-day compressive strength usually specified is 5000 psi or greater	For the inverted-T bent cap, based on the flow of forces the unnecessary material can be removed to create box void and canted edges at bottom corners (Figure-a), or canted ledges (Figure-b – section A-A). **Thus the bent cap weight and the amount of reinforcement is reduced** compared to conventional bent cap design. **The cavities in the precast bent cap** (Figure-c) are casted to reduce the concrete material in the tension zone and **achieve reduced weight** of the component. Reduced weight of the components alleviates shipping and handling limitations.	New concept and details; hence, past performance data is limited. Temporary supports should be used to set the elevation, and must remain in position until the grout achieves required strength. Fabrication and reinforcement detailing may be challenging because of the hollow core.	Inverted-T bent cap could extend up to a length of 42.7 ft for a single bent. Sources of information: Billington et al. (1999); Powell and Powell (2000); Billington et al. (2001); Shahawy (2003); Culmo (2009).

(b) Inverted-T bent cap with canted ledges (Source: Powell and Powell 2000; Shahawy 2003)



(c) Precast bent cap with cavities (Source: Culmo 2009)

Element	Project(s)	Attributes	Benefits	Limitations	Remarks
Precast footings Footing on subbase:  Spread footing on piles:  Spread footing on subbase: 	Spread footing on subbase: South Maple Street Bridge over Scantic River, Enfield, CT (2011)	Most of the sections are not standardized. Following attributes are presented based on the information provided in the listed references. Conventional material strengths and design procedures are used. Thickness: 3ft Width: 8ft to 10 ft Length: varies	Good for small footings. Large footings could be developed by combining small segments. Good for bridges with shallow footings. Shallow footings have a potential to be supported on piles, in regions where piles are necessary.	A level concrete subbase preparation is necessary, which is an additional operation. Shipping and handling limitations may arise due to heavy weight. The connection between spread footing segments is a CIP closure which extends project duration. Special leveling screws are necessary for aligning the segments of a spread footing. Each individual leveling screw should be capable to withstand entire weight of the segment, without bending. A grout layer is required to ensure full bearing contact with the subbase. Significant amount of grout is required for this operation.	The precast footings serve as shallow foundations for a bridge. Very few projects utilized this element. This is due to requirement of preparing, roughening, and curing the subbase, which is an additional operation while using precast footings. UDOT (2010) developed standard footing designs, but till date, have not implemented on significant projects. Sources of information: UDOT (2010); Unlu (2010); Swanson (2011).

Miscellaneous

Construction technology	Project(s)	Attributes	Benefits	Limitations	Remarks
SPMT move: steel girders with CIP deck  **Slide-in**: CIP adjacent box girders 	SPMT move – Utah I-215 at 4500 South, UT (Bridge replacement) (2007) SPMT move – I-80 State street to 1300 E. multiple structure, Salt Lake city, UT (Bridge replacement) (2008) Slide-in – San Francisco Yerba Buena Island Viaduct (Bridge replacement) (2007)	Design attributes are similar to designing a prestressed concrete girder with a deck, a steel girder with a deck, or a modular superstructure system. But design considerations should also concentrate on the lifting and moving aspects of the structure.	Least disruption to traffic and improved work-zone safety. Bridge can be replaced overnight. Feasibility of maintaining high quality.	A large staging area adjacent to the site is required. Extremely tight tolerances are required. Support points should maintain their relative elevations. SPMT and Roll-in operations' cost are extremely higher than the cost of typical CIP and other ABC construction methods. While the SPMT and roll-in operations can be completed in days or hours, the preparation and construction of new structure still requires extended amount of time. Slide-in is not feasible for, skew or horizontally curved or superelevated structures. Not feasible if utilities are present in the moving path. Require continuous monitoring of carrier beams and deflections.	Light weight concrete is used to reduce the required number of modular transporters. Roll-in operation max. span: 177ft (till date) Sources of information: Baker (2007); Peterson and Ralls (2008); Chung et al. (2008).

Material	Remarks
High Performance Concrete (HPC)	

Proportioning of High Performance Concrete, Class AA low cement requirements as per Vermont AOT (2011) are shown below:

HPC Class	Req.** Cem. Mat. (lbs./cy)	Maximum Water-Cem. Mat. Ratio	Max. Slump (in.)	Air Content (%)	Coarse Aggregate Gradation Table	28-Day* Comp. Strength (psi)	28-Day* Modulus of Rupture (psi)
AA Low Cement	611	0.44	6	7.0 ± 1.5	704.02A	4000	650

* The listed 28-day compressive strength or modulus of rupture will serve as the basis of designing or approving the concrete mix.
** See tables located below for required cementitious materials.

Cement (lbs/cy)		Fly Ash (lbs/cy)		Silica Fume Admixture (lbs/cy)		Cementitious Materials (lbs/cy)
449	+	122	+	40	=	611

OR

Cement (lbs/cy)		GGBFS (lbs/cy)		Silica Fume Admixture (lbs/cy)		Cementitious Materials (lbs/cy)
418	+	153	+	40	=	611

OR

Blended Silica Fume Cement (8.0%) (lbs/cy)		Fly Ash (lbs/cy)		Cementitious Materials (lbs/cy)
489	+	122	=	611

OR

Blended Silica Fume Cement (8.0%) (lbs/cy)		GGBFS (lbs/cy)		Cementitious Materials (lbs/cy)
458	+	153	=	611

Remarks:

Central Pre-Mix Prestress (CPMP 2011) utilizes the concrete mixes as shown below to achieve 10,000 psi strength:

Materials	Quantity
Cement, type III	685 lbs/cy
Slag cement	65 lbs/cy
Fine aggregate 1	449 lbs/cy
Fine aggregate 2	800 lbs/cy
Coarse aggregate (AASHTO # 67)	548 lbs/cy
Coarse aggregate (AASHTO # 8)	1210 lbs/cy
Water	260 lbs/cy
Air entrainer	As required
High-range water-reducing admixture	As required
Water-cementitious materials ratio	0.35 per cy

Material	Remarks

Ultra High Performance Concrete (UHPC)

Typical field-cast UHPC mix composition (Graybeal 2010):

Material	Amount	Percent by weight
Portland cement	1200 lbs/cy	28.5
Fine sand	1720 lbs/cy	40.8
Silica fume	390 lbs/cy	9.3
Ground quartz	355 lbs/cy	8.4
Super plasticizer	51 lbs/cy	1.2
Steel fibers	263 lbs/cy	6.2
Water	218 lbs/cy	5.2

Average material properties of UHPC are shown below (Graybeal 2009; Graybeal 2010):

UHPC material properties (average)	
Property	**Value**
Unit weight	156 lbs/ft^3
Modulus of elasticity	6200 ksi – 8000 ksi
Compressive strength	18 ksi – 35 ksi
Post-cracking tensile strength	1.0 ksi –1.5 ksi
Chloride ion penetrability (ASTM C1202)	Negligible

Design values for material properties of UHPC are shown below (Graybeal 2009; Graybeal 2010):

UHPC material properties (design)	
Property	**Value**
Modulus of elasticity at release	5800 ksi
Modulus of elasticity final	7800 ksi
Nominal compressive strength at release	12.5 ksi
Nominal compressive strength final	21.5 ksi
Nominal tensile strength final	1.2 ksi
Allowable compressive release stress 60% of 12.5 ksi	7.5 ksi
Allowable compressive stress at service 60% of 21.5 ksi	12.9 ksi
Allowable tensile stress at service 70% of 1.2 ksi	0.84 ksi