Prefabricated Bridge Elements and Systems

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33.1 Practical Applications

A prefabricated concrete bridge element is defined as part of a bridge that is precast away from its final position (Sprinkel, 1985). A system is a combination of elements. Prefabricated concrete bridge elements and systems are used to construct new bridges and to rehabilitate or replace old ones. Prefabricated elements can reduce design effort, enhance quality, simplify and expedite construction, lessen inconvenience to the traveling public, improve safety for workers and the traveling public, and minimize cost. Design effort can be reduced when the same design is used on multiple bridge projects. Historically, bridge-design engineers have customized bridge designs for each site, making the prefabrication of elements impractical except for use on major multiple-span bridge projects. Recent efforts have involved making more adjustments to the site to accommodate a standard design and have developed designs that are more versatile. Fabricating elements in the controlled environment of a precast or prestressed concrete plant enhances quality. Plants are typically certified and well established, although temporary on-site plants are constructed to produce elements for a major bridge project. Plants can use high-quality reusable forms; temperature, relative humidity, and wind can be controlled; the concrete can be batched at the plant; and labor is more efficient because tasks are repeated.

Prefabricated elements, set in place at the bridge site, simplify and expedite construction by minimizing forming, form removal, and placing and curing concrete in a difficult-to-control environment. In addition, prefabricating the bridge element away from its final location minimizes traffic safety issues for both the

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traveling public and the worker and minimizes delays and inconvenience for the motorist. Lanes can be open during peak travel periods and closed during off-peak periods for the rapid replacement of bridge sections. Once in place, the fully cured element is ready to receive traffic. Polymer concrete and high-early-strength patching materials now make the rapid connection of prefabricated elements easier. The most significant reasons to use prefabricated elements include the economy realized from the repeated use of forms, the reduction in on-site construction time, and improved safety because of the rapid construction. Initial construction costs can be lower, depending on the costs for cast-in-place concrete construction. Life-cycle costs will likely be lower because of the higher quality and longer life of the structure. When the costs of delays and inconvenience to the motorist are considered, prefabricated elements that can be assembled and put into use during off-peak traffic periods will almost always be economical. Prefabricated elements are increasingly popular as highway funds are used to rehabilitate and replace deteriorating bridges. Bridges with high volumes of traffic can usually only be replaced during off-peak traffic periods (at night or on weekends), and prefabricated elements provide an attractive solution. Mass-produced, easily assembled elements are just as practical for replacing bridges on low-volume roads.

Prefabricated elements, however, are not the best solution for every bridge construction and replacement project. The demand for a particular shape may be too low to justify an investment in forms. Shipping costs may be too high because the nearest plant is hundreds of miles away. Connection details may cause maintenance problems that result in a higher life-cycle cost. An advantage of concrete is that it can be formed into almost any shape; thus, the architectural and site requirements for a bridge may be so complicated that custom on-site forming is required and the prefabrication of elements is not practical. A decision-making tool can be used to decide whether or not a prefabricated bridge is effective for a specific location (Rawls, 2006).

A 1984 survey indicated that the use of prefabricated bridge elements was increasing and that the structures were economical in many situations (Hill and Shirole, 1984). Earlier applications included precast and prestressed slabs and I-beams for simple spans. Later, use expanded to include subdeck panels, deck slabs, parapets, and substructure elements. Currently, all elements in a bridge can be economically constructed or replaced with prefabricated ones. Entire spans and bridges can be moved into place with a brief road closure.

In the past, cranes were typically used to move large bridge elements into place. Recent developments with bridge-moving systems have facilitated the rapid replacement of entire bridges or bridge spans (FHWA, 2004). The new systems include self-propelled modular trailers that are multi-axle, computer-controlled vehicles that can move in any horizontal direction without damaging or deforming the element. Other systems include special load frames, modular jacking systems, horizontally skidding or sliding systems, incremental launching systems, floating barges, and vertically lifting systems.

High-performance concrete mixtures containing pozzolans and admixtures have led to the fabrication of elements with concrete compressive strengths in excess of 10,000 psi (68.9 MPa). The higher quality concretes allow smaller cross-sections, longer spans, greater girder spacings, and longer service. A variety of deck wearing and protection systems can be placed on the prefabricated elements to provide a smooth-riding, skid-resistant surface that retards the penetration of chlorides and water. Wearing and protection systems that have been used include a thin bonded hydraulic cement concrete overlay, waterproof membrane overlaid with asphalt, thin bonded epoxy concrete overlay, additional monolithically cast concrete on the precast element, and low-permeability concrete in the precast element (Sprinkel, 2004).

Already in the new millennium, many publications have supported the use of prefabricated bridge elements and systems. In response to public demand for minimized traffic disruption, the Texas Department of Transportation has been a leader in the use of prefabricated bridge elements in bridge design and construction (Pruski et al., 2002). Prefabricated bridges are meeting growing market demands for fast and efficient structures (Johnson, 2002). New girder designs, strand technologies, and concrete mixes are making precast prestressed concrete bridges more popular (Dick, 2002). New guidelines and load and resistance factor design (LRFD) specifications for full-depth, precast-concrete bridge deck panel systems with no overlays or post-tensioning are now available (Badie et al., 2006). According to the Federal Highway Administration (FHWA), the use of prefabricated elements can improve construction
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zone safety, minimize the traffic impacts, and improve constructability (FHWA, 2002). A brochure provides descriptions of 15 bridge projects that solved site-specific challenges using prefabricated bridge elements and systems (AASHTO, 2002). Implementation efforts by the Federal Highway Administration and the American Association of State Highway and Transportation Officials (AASHTO) have significantly increased the acceptance and use of prefabricated bridge elements and systems (AASHTO, 2004; FHWA, 2003; FHWA/AASHTO, 2004).

33.2 Types of Elements

The most frequently used prefabricated concrete elements and systems are the prestressed I-beam, prestressed box beam, prestressed channel, and slab span (Sprinkel, 1985). The prestressed subdeck panel was frequently used in the late 1970s and 1980s, but such use has declined in recent years because of reflective cracking in the site-cast overlay concrete. Precast parapets have been used on occasion, but problems with leakage under the parapet have curtailed acceptance. Recent years have seen increased interest in post-tensioned segmental construction for economy in medium and long spans, substructure elements to reduce the environmental impact of construction, and full-depth deck replacement slabs to facilitate the rapid replacement of decks during off-peak traffic periods. Longitudinal, partial-depth, or full-depth deck slabs that are precast on one or more concrete or steel beams have also been successfully used (FHWA, 2004).

33.2.1 Precast and Prestressed Slab Spans

Slab span elements (Figure 33.1) may be cast in various widths, depths, and lengths to accommodate spans up to 50 ft (15 m) (Table 33.1). Shorter slabs may be conventionally reinforced and fabricated at simple precast plants. Longer slabs are typically voided and prestressed or post-tensioned (PCI, 1975; VTRC, 1980). Slabs are easy to fabricate, transport, and erect. Department of Transportation (DOT) bridge crews have precast slabs (Sprinkel, 1976).
33.2.2 Multi-Stemmed Beam

Multi-stemmed beams (Figure 33.2) may be cast in various lengths and increments of width to accommodate short spans. Weld plates and grouted keyways provide shear transfer between beams.

33.2.3 Prestressed Double-Tee and Channel

Most prestressed concrete producers have forms for fabricating double-tees and channels for use in building construction. Additional prestressing, wider webs, and thicker flanges are typically required for bridge loadings (Figure 33.3) (Tokerud, 1975). Forms have been modified and new forms fabricated to produce members for highway applications when there has been sufficient support provided by a DOT to justify the investment in forms (Sprinkel and Alcoke, 1977). Channel beams and double-tees are typically used for medium-length spans, and shear transfer between beams is typically provided by grouted keyways or weld plates. Site-cast concrete is usually placed as an overlay, but channel and double-tee members have been overlaid with asphalt (PCI, 1975).

![Multi-stemmed beam](image)

**TABLE 33.1** Typical Span Lengths for Elements

<table>
<thead>
<tr>
<th>Element</th>
<th>Length (ft)</th>
<th>Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precast slab span</td>
<td>10–30</td>
<td>3–9</td>
</tr>
<tr>
<td>Prestressed slab span</td>
<td>20–50</td>
<td>6–15</td>
</tr>
<tr>
<td>Multi-stemmed beam</td>
<td>25–50</td>
<td>8–15</td>
</tr>
<tr>
<td>Prestressed double-tee and channel</td>
<td>20–60</td>
<td>6–18</td>
</tr>
<tr>
<td>Prestressed inverted channel</td>
<td>30–80</td>
<td>9–24</td>
</tr>
<tr>
<td>Prestressed single-tee</td>
<td>30–80</td>
<td>9–24</td>
</tr>
<tr>
<td>Prestressed I-beam</td>
<td>40–100</td>
<td>12–30</td>
</tr>
<tr>
<td>Prestressed box beam</td>
<td>50–100</td>
<td>15–30</td>
</tr>
<tr>
<td>Prestressed bulb-tee</td>
<td>60–80</td>
<td>18–24</td>
</tr>
<tr>
<td>Post-tensioned segmental</td>
<td>50–400</td>
<td>15–122</td>
</tr>
</tbody>
</table>

33.2.4 Prestressed Inverted Channel

The inverted channel (Figure 33.4) may be cast in the inverted position or cast in conventional channel forms and inverted before erection at the bridge site. Longer spans can be achieved in the inverted position because more prestressing can be placed in the bottom of the beam. The Missouri Department of Transportation used the inverted channel on many bridges (Salmons, 1971). Site-cast concrete must be
placed to connect the channels and provide a deck surface. An alternative to the channel is inverted T-beams placed adjacent to each other and then made composite with cast-in-place concrete placed between the webs of the tees and over the tops of the stems to form a solid member (see FHWA, 2004).

33.2.5 Prestressed Single-Tee

Prestressed single-tee beams are used in building construction. Prestressed concrete plants can sometimes fabricate the beams for shorter spans using the same forms as used in building construction with additional prestressing strands to accommodate the heavier loading. With adequate support from a DOT, a precast producer can invest in new forms to produce longer span beams (Figure 33.5) suitable for highway loadings (Sprinkel and Alcoke, 1977). The single-tee is unstable by design and must be supported at the bridge site to prevent overturning until the diaphragms can be cast and the keyways grouted. Site-cast concrete is usually placed to connect the tees and to provide a deck (Sprinkel, 1978). An asphalt wearing surface can be used when the flange of the tee is thick enough to accommodate shear loads.

33.2.6 Prestressed I-Beams

The prestressed I-beam (Figure 33.6) is the prefabricated element most used by DOTs (Sprinkel, 1985). Many prestressed concrete producers invested in forms during the construction of the interstate system. The standard AASHTO cross-sections simplify design and provide for mass production (Panak, 1982). The beams, cast in a variety of widths and depths, are economical for spans of 40 to 100 ft (12 to 30 m). Spans up to 140 ft (43 m) have been constructed (Anderson, 1972; PCI, 1975). Longer spans can be achieved by field-connecting the beams end to end and post-tensioning them (Fadl et al., 1977; Oesterle et al., 1989). The prestressed beams can be positioned more rapidly than a site-cast concrete beam can be constructed. For convenience, other elements are typically constructed with site-cast concrete, limiting the economy of mass production and rapid assembly to the beams. Prestressed concrete subdeck panels have been used, and a National Cooperative Highway Research Program (NCHRP) publication, *Rapid Replacement of Bridge Decks*, addresses the development of designs for prestressed full-depth deck panels.
to be used with the beams (Tadros and Baishya, 1998). A recently completed NCHRP project, Full-Depth, Precast-Concrete Bridge Deck Panel Systems, includes designs for full-depth, precast deck panels without post-tensioning and overlays (Badie et al., 2006).

### 33.2.7 Prestressed Box Beams

The box beam (Figure 33.7) may be precast in a range of widths, depths, and lengths to accommodate spans of approximately 50 to 100 ft (15 to 30 m) (PCI, 1975). Boxes placed next to each other are typically tensioned in the transverse direction and covered with a wearing surface of asphalt. Boxes spaced apart
33.2.8 Prestressed Bulb-Tee

Some DOTs have developed modified versions of the AASHTO girder (Figure 33.8) that are more economical for spans greater than 80 ft (PCI, 1972; Rabbat et al., 1982). The beams have a high section modulus-to-weight ratio, and spans up to 160 ft have been constructed.
33.2.9 Segmental Construction

Elements (Figure 33.9) are typically full width, match cast, prestressed in the transverse direction, and post-tensioned in the longitudinal direction (VTRC, 1981). The elements are suitable for use on a wide range of span lengths. For shorter spans, the elements are usually erected on false work or assembled on a truss supported from pier to pier. For longer spans, the elements are erected by balanced cantilever, incremental launching, or progressive placing (Sprinkel, 1985). A patented segmental concrete overpass system economical for spans of 50 to 115 ft (15 to 35 m) provides at least 2 to 3 ft (0.6 to 0.9 m) of increased under-clearance and halves the on-site construction time for a two-span structure (Freyermuth, 1996). A procedure for the economical replacement of the top slab of a precast post-tensioned segmental bridge has recently been developed, so deck deterioration will not require the replacement of the superstructure (Stelmack and Trapani, 1991).

33.2.10 Prestressed Subdeck Panels

Prestressed subdeck panels are cast in a variety of lengths and widths, typically 4 to 8 ft (1.2 to 2.4 m). The length is a function of the spacing of the supporting beams. The panels are typically 3.5 in. (89 mm) thick and are set in a bed of grout about 0.5 in. (13 mm) thick. Site-cast concrete is placed over the panels to provide a reinforced deck (Figure 33.10). The panels are easily installed with a small crane and several laborers and do not require temporary forms or platforms to work from. Cracks usually occur in the site-cast concrete directly above the joints between the panels; consequently, many DOTs have discontinued or restricted the use of the panels. Cracking is less pronounced when the panels are placed on prestressed girders with short spans. Precast concrete subdeck panels can provide an economical and rapidly constructed deck (PCI, 1987).

33.2.11 Precast and Prestressed Deck Slabs

The deck is usually the first element in a bridge to deteriorate and to require funds for rehabilitation. In situations where traffic volumes are high, it is often necessary to rehabilitate or replace the deck in sections during off-peak periods. Because of the time required for site-cast concrete to cure, a number
of replacement strategies have been developed using prefabricated deck slabs (Issa et al., 1995a,b). Most of the systems involve a transverse segment (Figure 33.11) connected to the supporting beams with a rapid-curing polymer or hydraulic cement concrete. Shear transfer between adjacent slabs is achieved through the use of grouted keyways, site-cast concrete, and post-tensioning. Composite action is achieved through the use of studs on steel beams that extend into voided areas in the slabs that are then filled with polymer or hydraulic cement concrete.

Precast deck slabs can behave in a full-composite manner when connected to steel stringers with studs and epoxy mortar and when keyways are grouted with epoxy mortar (Osegueda et al., 1989). An earlier study identified some suitable connection details and concluded that the deck slabs are more economical than site-cast concrete because of the structural efficiency provided by post-tensioning and prestressing and because of the reduced construction time (Berger, 1983). Improved connection details for the use of panels on steel beams and prestressed concrete beams have been developed (Tadros and Baishya, 1998). More recently, a special loop bar reinforcement detail has been developed to provide live load distribution across transverse and longitudinal joints (see FHWA, 2004). A new full-depth precast prestressed concrete bridge deck slab system has been developed that includes stemmed slabs, transverse grouted joints, longitudinal post-tensioning, and welded threaded and headless studs (Tadros and Baishya, 1998). The deck slabs are thinner and lighter than a conventional deck and can be constructed faster.

Prestressed deck slabs typically have been used on major bridge deck replacement projects (Figure 33.12) such as the Woodrow Wilson Bridge (Lutz and Scalia, 1984). Also, most replacements have involved the use of transverse slabs. The decks on the George Washington Memorial Parkway were replaced using precast longitudinally post-tensioned transverse deck slabs (Jakovich and Alvarez, 2002). A latex-modified

FIGURE 33.12 Prestressed post-tensioned deck slabs were installed at night to replace the deck of the Woodrow Wilson Bridge.
Concrete overlay was placed over the slabs. The truss spans of the deck on I-95 in Richmond, Virginia, were recently replaced with night lane closures using the full-depth transverse deck slabs (Figure 33.13). The slabs were also used to replace the deck on Route 50 in Fairfax County, Virginia (Babaei et al., 2001). The Virginia Department of Transportation first used transverse precast deck slabs to replace a deck on Route 235 over Dogue Creek in Fairfax County in 1981 (Sprinkel, 1982). Longitudinal slabs were successfully used to rehabilitate the Freemont Street Bridge (Smyers, 1984), and a new bridge was built in Thailand (Zeyher, 2003).

Longitudinal, partial-depth, or full-depth deck slabs that that are precast on one or more concrete or steel beams have also been used successfully (FHWA, 2004). The superstructure elements are set next to each other and are typically connected by transverse post-tensioning in the deck and diaphragms between the beams. Keyways in the deck are grouted. The deck on I-95 in Richmond, Virginia, was recently replaced with night lane closures using the full-depth deck slabs on steel beam superstructure elements. When partial depth deck superstructure elements are set next to each other, reinforced site-cast concrete facilitates the connection of the elements.

33.2.12 Precast Parapet

The precast parapet (Figure 33.14) lends itself to prefabrication because it has a standard shape and can be easily mass produced. Several connection details have been developed to anchor the parapet. The parapet has been used in a number of states, but acceptance has been slow because of problems with water and chloride solutions leaking between the base of the parapet and the top of the deck.

33.2.13 Substructure Elements

More time is usually required to construct the substructure than the superstructure, and major reductions in construction time can be achieved by prefabricating the elements of the substructure. Most substructure elements have been prefabricated. Examples include pilings, piers, pier caps, abutments, and wing walls. Figure 33.15 shows abutment and wing-wall panels placed on temporary pads and anchored with weld plates and a site-cast concrete footing (PCI, 1975). To simplify erection, abutment and wing-wall elements have been precast with the footing and set on a site-cast footing (Sprinkel, 1985). Prestressed piling has been used for years, but pile caps are usually site cast. Bridges with prefabricated piers, pier caps, abutments, and wing walls are limited in number but use is increasing, particularly by the Texas Department of Transportation (Billington et al., 1999; Matsumoto et al., 2001, 2002). A bridge with a

FIGURE 33.15 Precast abutment and wing wall. (From Sprinkel, M.M., Prefabricated Bridge Elements and Systems, NCHRP Synthesis 119, Transportation Research Board, Washington, D.C., 1985.)
A well-known example of the use of prefabricated piers is the Linn Cove Viaduct (Anon., 1984). The entire bridge was prefabricated to minimize environmental impact. Precast segmental superstructure segments were progressively placed and post-tensioned until a pier location was reached. Working from the cantilevered superstructure, holes were drilled into the ground. Prestressed piles were placed in the holes, and precast pier segments were placed and post-tensioned together. Site-cast concrete was placed around the bottom segment (Figure 33.16). The SPER system is a method of rapid construction of piers using precast concrete panels as both structural elements and formwork for cast-in-place concrete (see FHWA, 2004). The Texas Department of Transportation has developed and used a precast pier bent (Figure 33.17). The bent is placed on piers, and the voids in the bent around the reinforcement that extends from the piers are filled with grout.
33.2.14 Precast Culverts

Culverts can be used instead of bridges in situations where the cross-section will not restrict flow. Culverts are easy to install, do not have a deck to deteriorate, and seldom require extensive plans. Culverts cannot be used on navigable streams. Precast culvert designs (Figure 33.18) include the pipe, box, inverted U, and arch. Site-cast footings and end walls are typically used with the inverted U and the arch. Concrete pipe is used for spans of 1 to 10 ft (0.3 to 3 m), and concrete boxes are used for spans of 4 to 12 ft (1.2 to 3.7 m) (Concrete Pipe and Products Company, 1993). Precast U-shaped culverts have been used for spans up to 16 ft (4.9 m), and the arch shape has been used for 40-ft (12-m) spans (Conspan Bridge Systems, Inc., 1995; Lambert, 1982).

33.3 Construction Considerations

On-site construction time is typically reduced when prefabricated elements are used because the concrete forming, casting, and curing occur at a precast plant. Quality elements are typically produced under controlled conditions. Elements are typically inspected at the plant and approved for shipment. Elements should fit together at the site when they are fabricated to the tolerances prescribed by the Prestressed Concrete Institute (PCI, 1977, 1978). Precasting operations should be organized to minimize the number of times an element must be moved. Excessive handling is costly and time consuming and increases the chances for damage (Waddell, 1974). The contractor should have an approved erection plan. Proper communication between the fabricator and contractor is essential. Elements should be delivered in the order in which they are to be assembled. Each element should be checked for damage that might have occurred during delivery and the plant stamp of approval should be verified. The hardware, rigging, and equipment required for handling the elements and the lifting locations should be preapproved before lifting an element. Handling and erection stresses can be greater than in-service stresses. Care should be taken to keep the stresses to a minimum. When feasible, elements should be supported during erection.
as they are during delivery and storage. When lifting equipment is to be placed on the structure, the design should be checked and approved to ensure that the structure is not overstressed. Lifting equipment should be large enough to handle the elements. It is better to have equipment that is too large than too small.

Before placing elements, bearing areas should be properly prepared. Elements that fit properly can be assembled in a few minutes. Additional time is required to make corrections for improperly fitting elements. The advantage of match casting elements is a good fit. Several mortars and grouts for hydraulic cement and polymer concrete have been developed to facilitate the erection and connection of prefabricated elements (Gulyas et al., 1995). Temporary shims may be used. High-early-strength mortars and grouts can anchor the elements in a short time. When the elements have been assembled, a wearing and protection surface is usually installed. Asphalt is popular because of its low cost, but it should be used in connection with a properly installed membrane to prevent the infiltration of water and chloride ions into the prefabricated elements. Hydraulic cement concrete overlays can be installed to provide the final wearing surface. Bonded hydraulic cement concrete overlays can have a life of 30 years or more; however, these overlays are not easy to install, and construction should be done according to recommended practice. The recent failures of a number of bonded concrete overlays on major bridges before opening them to traffic or shortly thereafter illustrate the difficulties associated with constructing a successful overlay. Thin epoxy overlays have been used successfully as a wearing and protection system. Finally, deck elements can be precast with the final wearing surface, and irregularities can be removed by shot blasting or grinding the surface to provide good ride quality (Sprinkel, 2004).

### 33.4 Looking Ahead

The use of prefabricated bridge elements and systems will continue to increase for many reasons. With prefabrication, the work force can be more productive and can produce a better product in the controlled environment of a precast plant, compared to forming and placing reinforcement and concrete outdoors. The enhanced productivity and quality promote economy. The need to replace bridges and bridge elements is growing as our transportation system ages. The number of structures subjected to high volumes of traffic also continues to increase. Element replacement during off-peak traffic periods is becoming a necessity, and replacement with prefabricated elements is one of the few feasible options. Reducing delays for the traveling public is an additional economic incentive to use prefabricated elements. In recent years, the connection details that have caused maintenance problems and reduced the service life of elements have been improved. Better designs, enhanced materials, and more post-tensioning are allowing the construction of bridges with prefabricated elements that are more economical on a life-cycle basis than bridges constructed with site-cast concrete. There will always be a place for site-cast concrete, because concrete can take the shape of any form in which it is placed. This flexibility and versatility are necessary to satisfy many construction needs. It would be foolish to try to prefabricate concrete for every situation. Even so, the outlook for prefabricated bridge elements and systems has never been better. The use of prefabricated bridge elements and systems has increased significantly since the first edition of this Handbook was published. Universities, state DOTs, the FHWA, and the bridge industry have taken leadership roles in the new developments. The FHWA Summary of Prefabricated Bridge Elements and Systems website provides abstracts and contact information for recent publications on the subject (FHWA, 2004). Use will continue to increase as our roadways become more congested.

### References


Conspan Bridge Systems, Inc. 1995. Dayton, OH.


PCI. 1975. *Short Span Bridges*. Prestressed Concrete Institute, Chicago, IL.

PCI. 1977. *Manual for Quality Control for Plants and Production of Precast Prestressed Concrete Products*. Prestressed Concrete Institute, Chicago, IL.


Waddell, J.J. 1974. *Precast Concrete: Handling and Erection*. American Concrete Institute, Farmington Hills, MI.

(a) Test specimen, University of California, San Diego; (b) precast seismic bracing elements, Paramount Building in San Francisco, California.