SHARING NEW TECHNOLOGY THROUGH PCI BRIDGE TECHNOQUESTS

Industry throws a curve to traditional ideas—the curved, trapezoidal box girder bridges

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The Perfect Time

The advancement of the precast, prestressed concrete industry over its 65-year history was largely incremental and methodical. Improvements in materials, manufacturing and construction efficiencies, product sizes and shapes, and quality assurance and reliability resulted in steady industry growth. In contrast, however, are recent developments in the deployment of bridge technology. In a remarkably short time span, not only has a new bridge solution been provided to the design community, but, as a result, a new segment of the market has opened up to manufacturers in the precast concrete industry. Now, for the first time, horizontally-curved trapezoidal box girder bridges are being built in several locations with spans approaching 300 ft.

As the industry grew, it was used to thinking in terms of long-line forming techniques; multiple products in a form and usually pretensioned all at one time from end to end. Horizontally-curved products generally haven't been considered due to deep-rooted plant processes, complex formwork, and other constraints that have recently been overcome.

This new solution materialized because a large number of critical techniques and capabilities became available. It takes the coalescence of many components to successfully achieve the desired results. Some of these industry accomplishments are quite recent while others have been adopted in the engineered precast concrete industry over the past 20 years or so. The developments that were required to come together and facilitate this important new technology include:

- The ability to form, cast, handle, and transport girders more than 8 ft deep with single-piece lengths of 200 ft and more.
- The methodical development, production, and general adoption by public agencies of large, trapezoidal, open-topped, precast, pretensioned concrete U-girders with spans over 150 ft.
- The development and widespread use of reliable high-performance concrete that provides high strength, low permeability, rapid strength gain, and exceptional flowability.
- Numerous techniques that allow field splicing of precast concrete girders in order to reduce the size of individual pieces that facilitates handling and transportation while achieving very long spans, in some cases more than 300 ft.
- The incorporation of post-tensioning materials and techniques in the precast concrete plant as a tool to accomplish prestressing in situations where pretensioning is not practical or even possible.
- Innovation in the manufacture of steel forms that provides the capability to adapt sophisticated forming systems to a variable set of conditions. This now includes the ability to form horizontally curved complex girder shapes with variable radii in the same reusable, adjustable form.
- The development of unique hauling equipment that can safely transport very large permitted loads up to about 340 kips on public roads.
- The availability of big mobile cranes that can lift these heavy, single-girder sections.
- Commercialization and availability of software that enables analysis of statical schemes that includes the many structural changes in section properties that occur during erection, including consideration of creep and shrinkage, and the determination of deflections and cambers throughout construction.
- The Precast/Prestressed Concrete Institute's (PCI's) deployment of its core competencies of knowledge collection, development, and dissemination.
- Continuous quality improvement embodied in the rigorous PCI Plant Certification program that allows control of more and more complex processes to assure compliance with demanding standards.

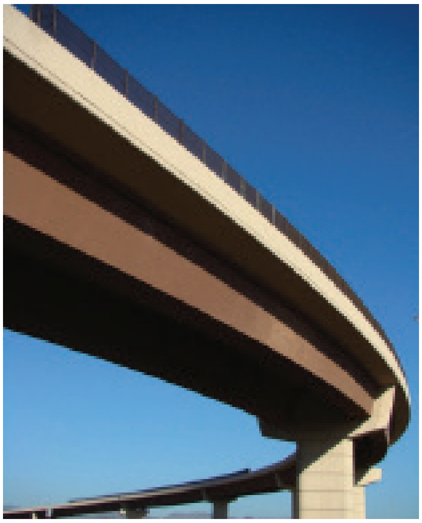


Figure 1. Two photographs of the Flyover Ramp A at I-70 and SH58 project that was built in 2008, which was the sixth plant-produced curved U-girder bridge built in Colorado at that time. Photos: Summit Engineering Group.

Figure 2. The I-25 Trinidad (Colorado) Viaduct features haunched girders that provide a 265-ft clear span over a rail yard. Photo: PCI.

This article will describe these new bridges, how they are constructed, and their advantages to the owner agencies and the public. It will reveal how the industry, through PCI, has taken the pioneering work of the Colorado Department of Transportation (CDOT) and a few designers, then developed a set of standards, and now conducts on-site programs to make the technology readily available to the design community.

Applications

A state-of-the-art report on curved bridges published by PCI[1] describes the application of these bridges:

Continuously-curved precast concrete U-girders [trapezoidal box girders] allow a unified appearance throughout the project at an economical cost. They provide an aesthetically appealing superstructure that uniformly follows the curvature of the roadway. This type of construction is most appropriate in highly visible locations because of its clean lines, non-varying bridge overhangs, and ability to span greater lengths. Span lengths can be extended by splicing girders at the site or by providing deeper or haunched sections at the piers to provide a slender span-to-depth ratio that enhances the visual appeal.

The need for complex interchanges and long-span grade separations has created the need for innovative solutions. Until now, these intermediate, relatively short structures, often with diverse requirements, were built with cast-in-place concrete or with structural steel. The remarkable success of recent projects demonstrates the advantages of using precast, prestressed concrete components to construct these structures in high-profile applications. The advantages are described in the following section.

While the girder sections can be used for simple spans, their spans are limited because they are heavy to transport. Span lengths can be greatly increased by splicing shorter sections together at the bridge site and then making multiple spans continuous over several piers. Span lengths can be further extended by providing deeper, haunched sections at the piers, like the project shown in Figure 2.

Benefits to the Owner

The benefits of U-girder construction are very similar to those of other precast, prestressed concrete bridges. Now, these benefits are extended to a new family of bridges available to owners.

Savings in long-term maintenance–The concretes used in these high-strength, precast bridges is remarkably dense, exhibiting very low permeability. When analyzed for long-term performance, the concretes are determined to provide performance in excess of 100-years. Surface treatments such as painting are unnecessary for long-term performance. The sections are especially robust. The construction sequence allows for the future removal and replacement of the deck.

Exceptional aesthetic appeal–Smooth bottom flanges and sloped webs result in clean lines and no ledges. The deck overhangs have a uniform width. Because they are generally cast with self-consolidating concrete, the surfaces are dense and especially smooth, showing uniform color. Often, surface stains are easily applied to match an agency's system color scheme. The girders are installed with slopes and elevations matching the superelevation of the deck.

Local, qualified manufacturers–The precast concrete girders are furnished by established producers with expertise in both casting and prestressing. The precast concrete girders are produced at a fairly rapid rate and result in reduced fabrication time compared to other methods. Plant production uses higher-strength concretes and thinner sections that allow less cover over reinforcement compared to site-cast concrete. Plant concrete mixture proportions utilize lower water-cementitious materials ratios than available in site-cast concrete. Girders are stored in the plant and delivered "just-in-time" as needed. This protects the girders and reduces space demands on the site. The producers have experience with quality control and assurance procedures as certified by PCI through the provisions of the industry's highly regarded Plant Certification Program. The production uses local labor and usually local material and is easily available to agency auditors.

Construction time and cost savings–Where falsework is impractical for cast-in-place concrete box girders, the precast solution has been shown to be not only the least costly but results in far faster construction. Shoring is simplified. Experience has shown nominal setup costs.

Overall cost savings–These bridges provide an alternative to traditional designs, establishing competition. In every project to date but one, this construction method has resulted in significant savings in initial cost compared to the alternative steel solution. Considering the life-cycle savings through longevity and maintenance, savings in first costs, and the aesthetic appeal, the overall benefits of this solution promise to be dramatic. This now provides a solution in areas where the owner agency has a preference for concrete structures. The tools have been developed to enable the precast producer to work with the design-build contractor to deploy the solution to any procurement market condition.

Figure 3. The Park Avenue Ramp in downtown Denver, Colo., was designed by the Colorado Department of Transportation and was precast on site. It had a maximum 230-ft-long span. The project also used 200 precast concrete stay-in-place deck panels to span between the two girder lines. Photo: Colorado Department of Transportation.

4a) Girders being erected. Note the use of strongback hangers to suspend the drop-in girders from the cantilevers over I-25.

4b) Stay-in-place composite deck panels are used to span between girder flanges.

Figure 4. The Ramp K Flyover at I-25/SH 270 in Colorado is the first modern-day, plant-produced, precast concrete curved U-girder bridge in the United States. Photos: Summit Engineering Group.

A Brief History

The PCI state-of-the-art report on curved bridges published in 2012, includes a history of all of the known bridges built with similar construction described in this article, up to that time.[1] Several of the projects are included in the section of that report titled Project Studies. References were given so that information will not be repeated, but the reader is encouraged to refer to the history published there. This article reports on the general developments that occurred to bring the technology to the level of interest that it is receiving today. References are included here that were not cited in the 2012 report or have since appeared.

In May 1993, the annual meeting of the American Association of State Highway and Transportation Officials (AASHTO) Subcommittee on Bridges and Structures (SCOBS), was held in Denver, Colo. The attendees toured the site of the Park Avenue Ramp over I-25 project that was under construction at the time. A large number of state and industry engineers watched a large curved, precast concrete U-girder being lifted onto piers. Due to their size and weight, the 16 girders, which where straight and curved up to 121 ft long, were precast on site and post-tensioned prior to installation. The bridge was designed by CDOT and is shown in Figure 3. It was the first curved, precast concrete trapezoidal box girder bridge designed by the state. The PCI staff director of transportation systems was in the group watching the installation. He was fascinated and noted the potential these curved precast concrete girders could have on the precast products industry. Casting in the field required wooden formwork, larger tolerances, and practical limits on concrete strengths of about 5.5 ksi. Plant casting could improve on some of these practices, but the curved formwork, post-tensioning, and transportation of the heavy sections would be obvious impediments to the PCI producer at the time. Therefore, PCI kept this unique opportunity that was unfolding in Colorado in mind but continued to monitor developments.

More than a decade passed, when a member of the PCI Bridge Producers Committee from Denver reported during a meeting in 2004 that his firm was producing horizontally curved U-girders for a project in Denver. It was the Ramp K Flyover shown in Figure 4 linking I-25 and SH 270. It has a radius of 962 ft and total length of 1420 ft. The bridge also uses precast concrete "pie-shaped" pretensioned stay-in-place deck-panel forms to span between the webs of the U-girders.

From the completion of the Park Avenue Ramp in 1995 through about 2000, CDOT continued development of the concept. They refined it in ways that encouraged production in an established precast manufacturing plant. Moving production to a plant was deemed important because they knew these plants would invest in high-quality steel forms adjustable for radius that could be used over and over for many projects. The set-up time and costs would be lower; therefore the solution would be practical for projects as small as two or three spans. Plants with steel formwork produce superior surface finishes and can hold tighter tolerances. Formal quality control and assurance programs are in place in such plants. Also, the plants place and cure high-strength, low water-cementitious materials ratio concrete routinely without facing complex requirements for hot or cold weather procedures necessary in the field. Plant manufacturing optimizes the cross section by taking advantage of less required concrete cover over reinforcement. The move to plant production was a step that would compress schedules, reduce cost, and improve quality. CDOT reported on their work in *ASPIRE*™ magazine.[2]

Florida High Speed Rail

Early in 2010, the White House announced the award of $1.25 billion to the state of Florida to construct the first 84-mile section of a high speed rail corridor from Tampa to Orlando. That would be followed by another 240-mile leg to Miami. Work was slated to begin in 2011. The award was part of the American Recovery and Reinvestment Act (ARRA) of 2009. By June 2010, the Federal Railroad Administration issued its final decision that would allow design, land acquisition, and construction of the first phase. Subsequent grants had increased the initial award to approximately $2.02 billion. By July, early work had begun and informational meetings had been conducted for interested contractors and others.

The contacts made by PCI had stirred interest in the curved U-girders. The high speed rail route would require considerable elevated structures on curved alignments. Given the preference that the state has for low maintenance concrete structures, PCI attended agency meetings and at these locations, conducted "add-on" meetings to provide more information about the new curved girders. However, the need was obvious for more details that could be taken away, studied, and further developed by contractor-designer teams.

The precast concrete industry needed to be able to compete with other solutions. The necessity for rapid, prefabricated construction permeated nearly every conversation. Curved U-girders were just part of the solution being sought. There were three other key components. The first was a method to frame and construct the elevated stations. The others were for structure-mounted sound attenuation walls and crash barriers that would separate the trains from adjacent highway traffic.

Several PCI-certified producer-member companies (specifically Coreslab Structures, Dura-Stress, Gate Precast, and Standard Concrete Products), the Summit Engineering Group, and PCI all contributed to fund the further development of concepts for these elements. They also funded the completion of the U-girder drawing set that includes details specific to the codes and standards of the southeast U.S. region. The region comprises nine states that PCI designates "Zone 6." The drawings are now referred to as the PCI "Zone 6 Concept Plans."

In February 2011, the newly elected Florida governor abruptly rejected the federal funds. He cited the risk of cost overruns saying he believed the risks far outweigh the benefits.

While not germane to this article, it is interesting to note that a unique system was developed to build the stations and incorporate precast concrete sound walls and crash barriers, all using accelerated construction methods. Concept plans and details were distributed to designers and contractors along with the U-girder drawings.

Several developments were occurring during this time in the precast, prestressed concrete industry that facilitated the ability to produce these sections. Not the least of these was the design of transport vehicles able to handle payloads up to about 340 kips. One of these vehicles is shown in Figure 9.

The information reported in that PCI committee meeting in 2004 created a buzz of enthusiasm. PCI felt it had sufficient evidence of the viability of the concept and began an effort to transplant the technology. A four-page article about curved girders and the Denver project appeared in the Summer 2005 issue of PCI's *Ascent* magazine,[3] a national publication. That same year, staff encouraged the PCI Board of Directors and the Committee on Bridges to authorize the formation of a subcommittee on curved concrete bridges. The subcommittee met for the first time in April 2006. The subcommittee's chair and vice-chair were Mary Lou Ralls, former Texas Department of Transportation bridge engineer, and Gregg Reese of Summit Engineers in Denver, Colo. Ralls had much experience with the development and use of the popular Texas U-Beam. Summit Engineers is located near Denver and Reese had already had a substantial amount of experience with the precast trapezoidal U-girder projects in Colorado, having worked for contractors as a specialty engineer or the engineer of record for design build projects. The committee decided to publish a detailed state-of-the-art report that discussed the design of all curved precast concrete bridges; beginning with those built with a curved deck on straight, chorded girders and concluding with an extensive section on horizontally curved girders. Following all of the requisite reviews and incorporation of the newest details, the report was published in 2012[1].

In about 2009, the PCI managing director of transportation systems, William Nickas, began making presentations on this new system for curved bridges and ramps in many different venues. Through 2012, Nickas and Reese made presentations to several departments of transportation (DOTs), contractors, and precast producers. Agencies in Florida and Texas expressed particular interest. From the questions that arose from a variety of audiences, Nickas concluded that a more aggressive effort was needed at the national level. There was clearly a need to furnish details that would answer the questions he heard from the consultants, owners, and industry. There was clearly a need to establish confidence that this solution was viable and adaptable to local, state, and regional practices and codes.

It was during 2010 that Nickas and Reese began to develop the first set of concept plans and details (see the sidebar that describes the Florida High Speed Rail initiative and the necessity for development of concept plans). These concept plans would answer typical questions and provide the technology and confidence needed for implementation by the owner agencies and their consultants.

Looking back, the technology progressed in Colorado over some 20 years. It evolved with collaboration between owner, contractor, specialty designer, and precaster, and was delivered under design-build or contractor alternate contracts. When PCI took on the challenge to develop the concept plans, the technology was in its 3rd generation, having been shown to be both constructable and economically advantageous.

The PCI Zone 6 Concept Plans

These drawings comprise 20 sheets that begin with a page of general notes that

6a) The girder with tongue extension following removal from the casting form.

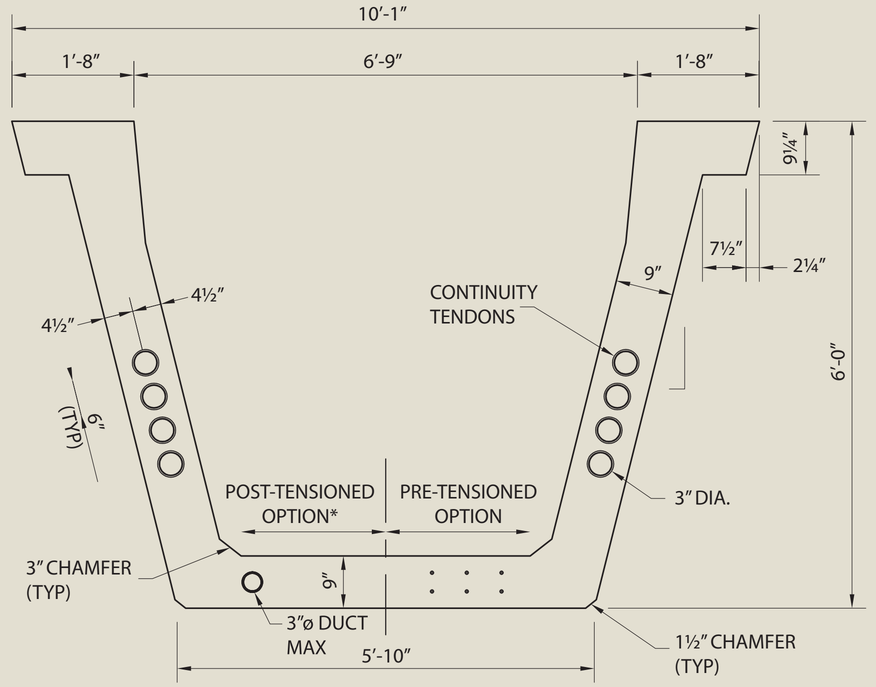
6b) Girder tongues support the girders on abutment of Ramp H, SR 416–Boggy Creek Interchange seen during TechnoQuest 2 tour.

Figure 6. An innovative solution to provide space for post-tensioning is the girder "tongue"— an extension of the bottom flange that supports one end of the girder. Photos: J. Dick Precast Concrete Consultant.

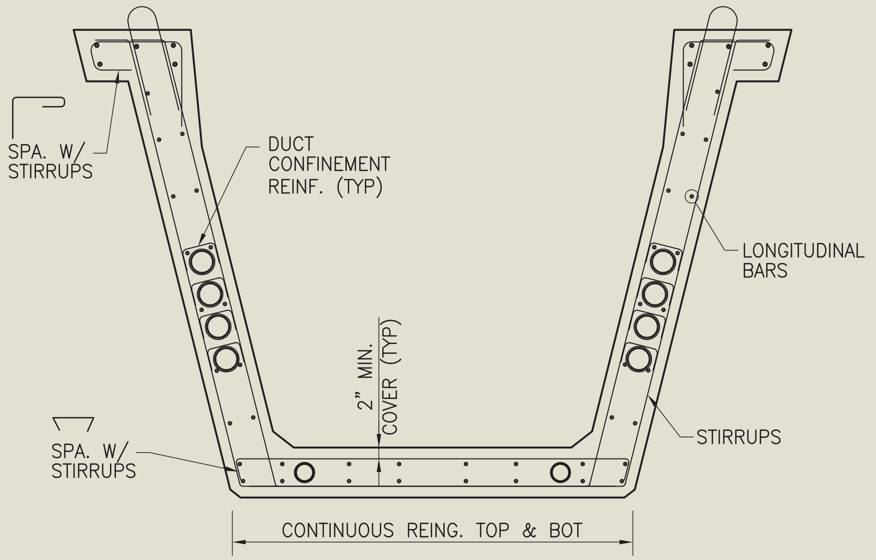
define the intent of the drawings and the assumptions upon which they were based.

Typical bridge cross sections are shown for a 40-ft-wide roadway with two girders. One drawing shows a cast-in-place concrete deck and the other shows a deck with composite, nonprestressed, stay-in-place precast concrete deck forms. The precast panels support the full, 8½-in.-thick cast-in-place concrete structural deck.

Three drawings show maximum spans that can be achieved with these three framing configurations: 1) three continuous spans of spliced, constant depth girder sections, 2) a single simple span using three spliced girder sections, and 3) three continuous spans of spliced girder sections with haunched pier girders. Maximum spans are shown using various configurations of precast and cast-in-place desks and normal weight and lightweight concrete.



5a) Typical dimensions of the 72-in.-deep girder.



5b) Typical reinforcement for the 72-, 84-, and 96-in.-deep girders.

Figure 5. These are details shown in the PCI Zone 6 concept plans. Webs are inclined with a 12 in. rise and a 3 in. run. The web thickness of 9 or 10 in. is determined by the required diameter of the post-tensioning ducts. Drawings: PCI.

A page is devoted to girder geometry for the typical and haunched girders. Dimensions are defined for the typical 72-, 84-, and 96-in.-deep sections. Post-tensioning duct and reinforcement details are provided. An example of the girder details is shown in Figure 5.

Several sheets are devoted to girder section splices and splice reinforcement, post-tensioning details, types of diaphragms, bearings, integral piers, precast concrete deck panel details, and access hatch details. A unique detail shown is the girder "tongue," the bottom flange extension more than 4 ft long, which supports the girder on the abutment and on expansion piers. It allows space to insert the jack for post-tensioning. An example is shown in Figure 6.

Three sheets detail construction sequences for the three bridge configurations described previously.

The final two sheets show erection bracing, details for rigging, crane placements, erection sequences, and erection notes.

The details in the southeast region are somewhat different from those used in Colorado. For example, more robust post-tensioning systems are needed due to the corrosive environment. Lightweight concrete is included in the span tables.

PCI makes these drawings available as CAD files. They are particularly valuable for estimating quantities of concrete, mild reinforcing steel, and post-tensioning materials. Download the PDF version at http://www.pci.org/uploadedFiles/Siteroot/Design_Resources/Transportation_Engineering_Resources/PCI%20Zone6%20Curved%20Spliced%20Girders.pdf.

Another Milestone

The Florida DOT, Office of Design, maintains the website "Invitation to Innovation." In September 2012, the subject "Curved Precast Spliced U-Girder Bridges" was added to the short list of suggested innovative topics. See the sidebar, Invitation to Innovation and visit the website at http://www.dot.state.fl.us/officeofdesign/innovation/.

The following year, more information was shared in an article in *ASPIRE* magazine about a major project on the I-25 Trinidad Viaduct located in Colorado.[4]

PCI Bridge TechnoQuest 1

With the development of the standards and growing interest, PCI planned and conducted two "TechnoQuests." These seminars were designed for those with special interests: the owner agencies, their consultants, precasters, equipment suppliers, and contractors. The attendees spent time with designers and other participants in previous projects and visited completed bridges and bridges under construction (Fig. 7).

Invitation to Innovation

The Florida Department of Transportation's website, Invitation to Innovation, states the department has embarked into a bold new era for innovative ideas. "Success… depends on the ability to innovate the products and services Florida's transportation system provides its users." It continues with this endorsement:

> "After researching and evaluating many innovative ideas, the Central Office has developed a list of concepts, products and services that may be the best solution to the project's needs or design challenges…We encourage you to propose one or more of these innovations for project specific solutions with confidence of approval by the Districts…Many of these innovations have been successfully implemented in other states and countries. Not all projects benefit from these innovations and the Department is not advocating the general use of new products or designs where an economical well proven solution exists and is the most appropriate solution for the situation. Please consider these innovations as possible solutions to your project-specific needs…"

On their site, a link is provided to "Curved Precast Spliced U-Girder Bridges": http://www.dot.state.fl.us/structures/innovation/UBEAM.shtm. This site contains much more information and links to yet more information. One link provides the set of "PCI Concept Drawings." This set contains 17 sheets. Three sheets showing details about the use of precast U-girder lids and precast concrete stay-in-place deck forms was omitted because Florida does not permit the use of these slabs at this time. There are three PDF copies of slide presentations containing more background information.

Florida Department of Transportation concluded that the girders offer lower fabrication times, faster construction, longer spans, and increased aesthetic appeal.[9]

The notice of innovation was followed by a Structures Design Bulletin 13-07 dated June 6, 2013 with the subject, "Spliced Pretensioned/Post-tensioned U-Girders." This new document contains very specific requirements for the design and construction of these girders. The bulletin was reviewed and approved by FHWA. It can be viewed at: http://www.dot.state.fl.us/structures/Bulletins/2013/StructuresDesignBulletin13-07.pdf.

Figure 7. TechnoQuest 1 was held in Denver, Colo. Attendees are shown at one of several completed bridges that were visited. Photo: PCI.

The first TechnoQuest was held in September 2012 in Denver, Colo. Those attending were two engineers from the Texas DOT and eight precast producers from Texas. From Florida, two engineers from the Orlando Orange County Expressway Authority (OOCEA) attended along with six of their design and construction engineering and inspection consultants. (Note: OOCEA was transformed in mid-2014 into a more regional organization by the Florida legislature and now operates as the Central Florida Expressway Authority (CFX). Others included an engineer from the CDOT, the executive director of the Precast Concrete Manufacturers' Association of Texas, three consultants who were instrumental in the Colorado curved bridges, and PCI staff engineers including the PCI president and managing director of transportation systems.

Over 2½ days, the attendees heard nine speakers in several classroom sessions. They traveled to two manufacturing plants that had produced curved U-girders, and they visited six curved bridges, two of which were under construction.

There were important outcomes of the PCI 2012 Colorado TechnoQuest. Read about one of these in the SR 417–Boggy Creek Interchange sidebar.

Another result of the Denver TechnoQuest was assurance from the Texas DOT that they planned to work with the state producer group to develop their own plans for curved precast U-girder bridges. However, following attendance at TechnoQuest 2, the state announced they would adopt the PCI Concept Plans and hoped to undertake a bridge in 2015.

Production Technology Transfer

While not a U-girder TechnoQuest, another event occurred that was important to PCI-member bridge producers. In November 2013, PCI conducted a Production Workshop in Denver, Colo. These regular workshops are designed to provide exposure to regional production practices for precast producers from other areas. Because there was interest in U-girder production techniques, PCI arranged for a tour of two curved U-girder producer plants and a visit to the I-25 Trinidad Viaduct project then under construction. The workshop attracted more than 150 plant personnel and was another unique educational opportunity for the industry members. A unique and popular part of many PCI schools and workshops is the contest—"Ideas That Pay Off," where participants share clever production ideas and techniques. They left this workshop full of information about the production of curved U-girders!

SR 417–Boggy Creek Interchange

This project is at the south entry to the Orlando International Airport. The project is important to this article because it became the site for the second bridge TechnoQuest, 2 years after the first. It had three flyover ramps designed using curved steel box girders. The CFX project received construction bids in early July 2012. There were six bidders. Contractors could submit bids on several options. The lowest 3 bidders submitted bids on "Option 4," which was a contractor redesign using the PCI Zone 6 drawings for curved precast concrete U-girders. The other bidders selected "Option 1" that was the original steel beam design. The difference between the low bidder on Option 4 and the low bidder on Option 1 was just over $13M.

Contractors had taken notice of the "Colorado bridges" and the PCI Zone 6 Concept Plans. Several meetings were held with contractor-designer teams.

While this savings in the bidding was welcome, it turned out the project needed to be revised for other reasons. In mid-August 2012, the Authority rejected all bids, decided to split the project into two parts (roadway realignment and ramps), and called for new bids. They were, of course, keenly aware that the original bidders considered concrete girders more cost effective than steel. However, this method of construction had never been used in Florida.

Then the opportunity came to attend TechnoQuest 1 in Colorado and learn more from engineers there. As mentioned in the article, two engineers from the Authority and six engineers from their consulting teams attended.

In the end, the CFX decided to redesign the SR 417/Boggy Creek Rd Interchange using curved, precast concrete U-girders—without an option. This was the first owner-led design in the U.S. of curved U-girders based on the PCI Zone 6 Concept Plans. Previous projects resulted from design-build or contractor redesigns.

Bids were opened in early October 2013. The low bid was approximately $71M, estimated to be a savings of $7-$9M over a steel solution. The notice to proceed was issued in early January 2014. Much more information about CFX and its projects can be seen at: https://www.cfxway.com/TravelersExpressways.aspx and by clicking on "Doing Business With Us" at the top of the page.

PCI Bridge TechnoQuest 2

With the SR 417–Boggy Creek Interchange project under construction, the second PCI Bridge TechnoQuest was held in Orlando, Fla., September 18 and 19, 2014. The event was cosponsored by the Federal Highway Administration (FHWA). Interest had continued to grow and 86 people attended. Among them were: 10 from state DOTs (Florida, Texas, Oregon, Colorado, and Georgia); 2 from FHWA; 3 from CFX; 38 consultants; 18 people from 11 precast concrete manufacturers; 7 from concrete associations (PTI, PCI, Florida Precast Concrete Association, Georgia/Carolinas PCI, Precast Concrete Manufacturers' Association of Texas); 7 form and equipment manufacturers; and a contractor.

The first day was spent traveling on buses to the precast manufacturing plant shown in Figure 8 where the fabrication process was seen almost in its entirety: bending welded-wire reinforcement and tying cages, viewing the assembled and disassembled radiused interior and exterior forms, placing the self-consolidating concrete, and girders in storage and on the specialized delivery trucks (Fig. 9). Several representatives of the plant were on hand to describe each step.

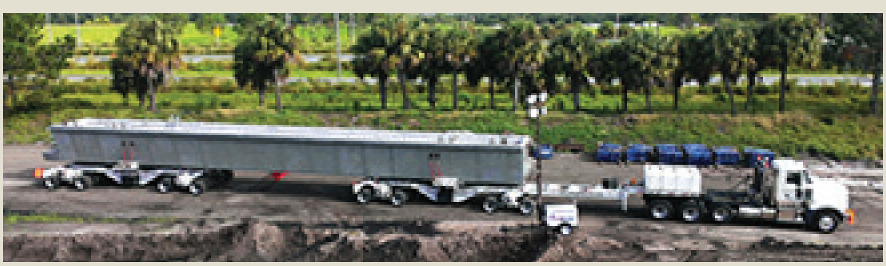
8a) Section of interior bucket form for casting trapezoidal U-girder.

8b) Workers use a custom bending machine to fabricate special welded-wire reinforcement of No. 5 bars.

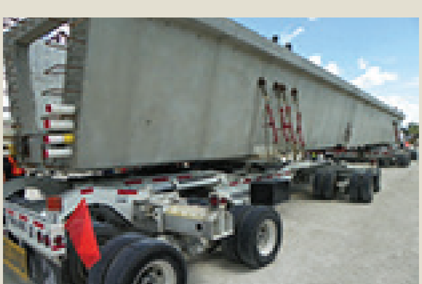
8c) Work in progress to preassemble a reinforcement cage containing post-tensioning ducts.

8d) No. 9 Reinforcing bars are headed at top and bottom to provide development in a short length. These bars will terminate in the cast-in-place deck.

Figure 8. TechnoQuest 2 Tour of Dura-Stress Inc. plant in Leesburg, Fla. Photos: J Dick Precast Concrete Consultant.



9a) As it arrives at the jobsite, the length of the truck and trailer is 150 ft. Photo: Dura-Stress Inc.



9b) The steerable dollies of the trailer visible at right center. Photo: J Dick Precast Concrete Consultant.

9c) The trailer's axles extend laterally on command to 19 ft out-to-out. This enables the load to travel in two lanes when crossing structures. Photo: J Dick Precast Concrete Consultant.

Figure 9. Custom steerable trailers capable of transporting up to 340-kip girder sections.

From the plant, buses traveled to the manufacturing facility that designed and fabricated the specialized variable curved steel formwork for this project.

The final stop was the construction site shown in Figure 10 where attendees were able to access the superstructure under construction from one of the abutments, walk around the piers and temporary towers from below, and view the foundations, permanent bearings and temporary supports.

On the second day, some 15 classroom presentations were delivered by prominent participants in this featured project and from previous projects. These included the pioneers of the concept from the CDOT. Others were the FHWA, PCI, the precaster and contractor for the featured project, manufacturers of the various specialized equipment, and the CFX. The classroom setting is shown in Figure 11.

The PCI Bridge TechnoQuests have been appreciated enthusiastically by those in attendance. The opportunities to see the jobsite details firsthand, experience the step-by-step fabrication process, and walk beside and inspect the 150-ft-long delivery vehicle were invaluable experiences. The technology transfer doesn't end with time spent with the experienced professionals. Each attendee left with a flash drive containing some 650 files (6.5 GB) including all presentations, hundreds of photos, and complete plans and specifications from previous projects.

It is understood that the states of Alabama, Illinois, Georgia, North Carolina, and Oregon may be evaluating the Zone 6 Plans for implementation.

Already, preliminary plans are underway for PCI Bridge TechnoQuest 3 (date and location to be announced). If interested in attending, see the contact information for this project in the Conclusions section.

The Construction

Horizontally-curved U-girders are cast in sections in steel formwork, which can be set-up to accommodate various radii as short as 500 ft. Two such forms are shown in Figure 12. The precast concrete sections contain post-tensioning ducts in the bottom flange and webs. The

Figure 10. Engineers at TechnoQuest 2 arrive to inspect SR 417–Boggy Creek Ramp H in Orlando, Fla. Single temporary towers are located at girder splices. Towers rest on spread footing foundations. Photo: J Dick Precast Concrete Consultant.

13a) Single tower used at splice location on Ramp H, CFX Project, cross-braced to withstand hurricane-force winds when only one girder is in place.

13b) The I-25 Trinidad Viaduct used temporary, cast-in-place concrete columns to support the girders at splices. Sand jacks on the columns support the steel positioning beams. The columns were later easily removed and discarded.

Figure 13. Temporary towers are designed for each project to accommodate the contractor's unique requirements and skills. Photos: PCI.

11a) Don Bernhoft, SEMA Construction, described the considerations necessary for efficient construction processes.

11b) Michael L. McMullen, retired from Colorado DOT, presents the historical perspective of the first generations of curved U-girder bridges.

Figure 11. During TechnoQuest 2, speakers presented a variety of topics from history to design methodologies in a comfortable classroom setting. Photos: J Dick Precast Concrete Consultant.

12a) A steel casting form viewed during TechnoQuest 1.

12b) A girder section being removed from its form during TechnoQuest 2. Two straddle carriers are necessary to lift the section.

Figure 12. Specialized formwork capable of being configured to cast curved sections with variable radii. Photos: PCI.

sections may be removed from the forms as mildly reinforced members or may be partially post-tensioned if needed to control handling stresses. In some cases, the bottom flange contains special monostrand tendons that are tensioned prior to stripping the girder from the bed. However it is done, all sections are prestressed by post-tensioning before leaving the plant.

The sections are transported on high-load capacity tractor-trailers like the one shown in Figure 9. They are spliced together on the project site on temporary support towers. Two different tower solutions are shown in Figure 13.

At this stage, the tops of the U-girders are closed with "lid slabs" cast in the field. In some circumstances, the lid slabs could be cast in the plant before shipment, although the additional weight could be prohibitive. Precast concrete lid slabs placed in the field have also been used and are recommended. The lid slabs and several other steps in the construction process are shown in Figures 14, 15, and 16. With the tops closed, the girders are significantly more torsionally rigid. Then, diaphragms containing post-tensioning anchorages are cast at the ends of a continuous unit. This is followed by closure placements between spliced sections. If girders rest on bearings, the continuous units are post-tensioned at this time. If, however, the substructure is made integral with the superstructure, which is recommended whenever possible, the post-tensioning is generally applied before casting the integral diaphragm to avoid transferring elastic shortening forces into the substructure.

14a) Here, the CFX Project girders at the abutments are formed and ready for the cast-in-place concrete lid slabs. Photo:J Dick Precast Concrete Consultant.

14b) Observed during TechnoQuest 1, precast lid slabs are stored in the precast plant awaiting delivery. Photo: PCI.

14c) Precast concrete lid slabs with deck overhang cantilevers are used with precast concrete stay-in-place deck panels between girders on the I-25 Trinidad Viaduct. Photo: PCI.

14d) Removable grout bedding form used under precast concrete deck panels like those shown in the PCI Zone 6 concept plans Photo: PCI.

14e) Closer view of stepped-thickness precast concrete stay-in-place deck panels on a project with cast-in-place lid slabs. Photo: Summit Engineering Group.

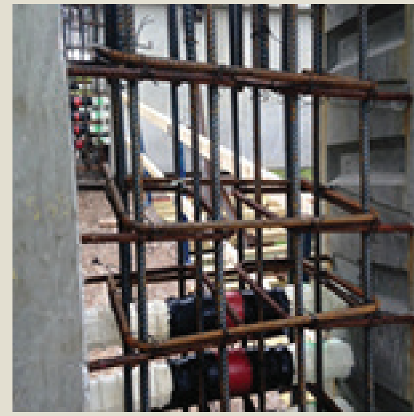
Figure 14. Girder lid slabs are critical to the performance of girders by increasing the torsional stiffness 100 times. They can easily be made a composite part of the deck slab, if desired.

Design and Construction Considerations

This section describes many of the typical design considerations and construction practices that are now being used to build curved, U-girder bridges. These include:

- Preparation of plans and specifications—The development of precise design-bid-build contract documents is encouraged. However, the owner and engineer of record (EOR) should provide flexibility for the contractor and its specialty engineer and precast concrete manufacturer. Examples of the need for flexibility can be found in Forars et al.[5] and the CFX project.
- Determination of splice locations
  - Determine length and weight of girders. Section lengths are selected to reduce shipping weight and facilitate placement of temporary towers to avoid traffic or other obstacles below. Generally, the EOR makes the original determination often by assuming a maximum length and shipping weight of about 100 ft and 250 kips, respectively.
  - Splices are usually located near inflection points, if possible, to minimize bending stresses at the splice.
  - The EOR should clearly state on the plans all assumptions made. Such things include:
    - Construction load factors
    - Post-tensioning losses
    - Minimum length and location of short continuity tendons
    - Construction loading criteria
    - Girder lifting and storage locations
    - Girder erection and stressing sequences
    - Expected deflections, cambers, and build-ups on girders
- Contractor specialty engineer—These projects require that the contractor retain an experienced construction engineer. The engineer should be registered in the project's state and have a minimum of 5 years of experience in the design and construction of complex post-tensioned concrete structures or segmental concrete structures. This engineer often works with the contractor to identify possible savings that can be realized through adjustment of section lengths or other procedures that take advantage of the contractor's specific expertise and equipment. All such revisions must be coordinated and approved by the EOR. The specialty engineer must develop an erection manual that should include:
  - Step-by-step erection sequence, ages of girders at erection and closure placements

15a) Post-tensioning anchorages are installed in abutment diaphragms.



15b) Duct splices and reinforcement ready for closure placement at section splice.

Figure 15. Many construction details are like those used in spliced, post-tensioned I-girder work. Photos: PCI.

16a) Cantilevered girders are made integral with the pier. Note the drop-in girder hung from strong backs over traffic.

16b) The girder is supported above the pier cap where bearing grout will be inserted. Some reinforcement has been placed. Often, transverse post-tensioning extends through diaphragm and girder.

Figure 16. Whenever possible, integral piers are recommended to eliminate bearings. Photos: Summit Engineering Group.

  - Temporary works and falsework, including defining construction loads and providing falsework locations and loads
  - Construction controls—Define maximum deflections, cambers, and haunch thicknesses
  - Equipment, post-tensioning, and grouting procedures; quality assurance
  - Field survey and geometry control
  - Time dependent analysis with stress and force summary
  - Truck and crane placement with radius of operation diagrams
  - If a thickened bottom slab is required, determine whether it should be field cast or plant cast.
  - Determine refined location and forming (integral or secondary pour) for interior post-tensioning blisters.
- Temporary supports or strong backs
  - A primary consideration is maintenance of traffic; this may require straddle bents. Towers require foundations, vertical support members, and girder support frames. The frame supports a sand jack and shims used to accurately support the girder section at the correct cross slope and elevation at the closure placements and diaphragms. Experience suggests using a separate tower under each girder line for flexibility of adjustments particularly in locations with poor soils. Foundations in poor soils may need pile supports to reduce the footprint, minimize settlement, or to resist uplift. Towers are generally designed by the contractor and plans usually provide horizontal and vertical girder section reactions. Wind loadings on girders on towers should not be overlooked. The condition of a single girder on a single tower meant to support two girders should be investigated for stability.
- Construct foundations, piers, and abutments; post-tension pier caps, if necessary, and grout ducts.
- Fabricate girders; tension and grout bottom flange ducts.
- Erect shoring towers. Some girders may be spliced together on the ground but this is unusual and requires large cranes for the heavier lifts.
- Erect girders and girder sections; brace sections as directed by the approved erection drawings.
- Cast all closures and diaphragms over interior piers including expansion piers.
- Close the open topped girders by forming and casting relatively thin (approximately 4¼-in.-thick) lid slabs, or place and grout precast concrete lid slabs to make the curved sections torsionally rigid. When closed, the trapezoidal box greatly facilitates geometry control and minimizes cracking.
- Tension full-length tendons.
- Connect substructure to superstructure if made integral.
- Tension short bottom or top continuity tendons if required.
- Grout all ducts.
- Tension and grout transverse post-tensioning at integral bents if used.
- Remove shoring towers.
- Form and cast the full-thickness deck slab or install precast concrete stay-in-place

Bracing, Hold downs and strong backs at Boggy Creek Interchange. Photo: A^2 Group Inc.

deck panels between girders and cast the remaining structural deck.
- Cast approach slabs and bridge rails.
- Install expansion joints and bearing assemblies, as required.
- Install membrane or latex-modified concrete topping, if required.

A construction sequence should be included in the plans. The sequence described above applies to most projects. It can and should be modified by the specialty engineer to recognize unique project requirements with approval of the EOR.

At this writing, there have been two noteworthy presentations recently that may be helpful to readers. These deal with design and construction issues gained from experience with two projects. The first was a paper presented at the 2014 PCI National Bridge Conference cosponsored with the FHWA and the National Concrete Bridge Council. It reports on the CFX project described earlier in this article.[5] It concludes with an important section of lessons learned. The paper was excerpted from the Conference Proceedings and is available by selecting the resources button on www.aspirebridge.org.

The second presentation was made in December 2014, as part of the Accelerated Bridge Construction Center's webinar series. It describes the design and construction of the longest bridge of this type of curved U-girder ramps in Colorado.[6] The recorded video presentation is available at the Center's website. See http://abc-utc.fiu.edu/index.php/technology/monthly_webinar_archive/view/ and scroll down to the 1 hour Colorado video.

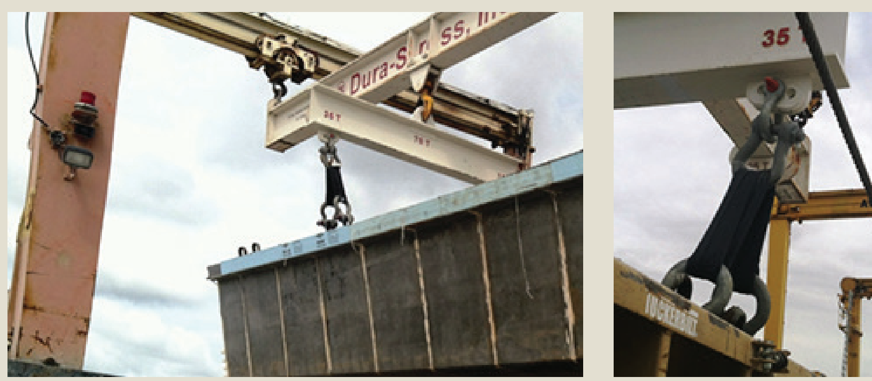
Important Discussions at the TechnoQuests

Experienced bridge engineers frequently raise questions and concerns as experience with U-girder design and construction unfolds. The following are some of these issues raised at the TechnoQuests:

- **Girder weight**—Equipment has been developed to handle the sections. Regarding design, the weight aids in this analysis because wind load often controls. It has been shown that the Florida project needed only one additional pile per girder per pier more than the steel girder design.
- **Torsional analysis**—The single biggest difference between spliced, post-tensioned straight girders and curved girders is the torsion resulting from the curvature. It is critical that the girders be analyzed correctly and designed for properly for torsion at all stages of construction. This includes: 1) bracing of the open sections, 2) properly closing the section prior to applying the loads that an open section would not resist, 3) adequate shear and torsion analysis and design during in-service loading, and 4) proper design and detailing for skewed supports. Particular attention must be paid to live load design when reviewing the *AASHTO LRFD Bridge Design Specifications* Section 4.6.1.2.4c. This section states that effects due to curvature may be ignored for live load when designing for longitudinal flexure and shear if the arc span divided by girder radius is less than 0.3. It has been found that this is not the case for multiple box girder sections and that the recommendation appears to be only for single box sections. Also, *AASHTO LRFD Bridge Design Specifications* Section 5.8.2.1 requires that torsion be considered in the shear design when the factored torsion exceeds ¼ the nominal cracking torsional moment.

  The *AASHTO LRFD Bridge Design Specifications* do not address bracing requirements or allowable torsional stresses when the girder is in the open condition. The practice has been adopted to allow ½ the cracking torque for open U-girders. The EOR will need to state this requirement and the specialty engineer must carefully review the contractor's means and methods to control cracking.
- **Specialty engineer and post-tensioning contractor**—Both of these specialists will likely be employed by the precast manufacturer as well as the construction contractor. Both should have separate contract agreements with both employers to clearly differentiate roles and responsibilities.
- **Construction engineering and temporary works**—There is no one correct method for temporary works design. This includes the question about single versus dual towers. A schematic tower concept is typically shown in the set of contract plans for information only. The contractor and his engineer are required to provide a design based on their preferences, the material available, site constraints, the chosen erection scheme, and the like.

Figure 17. Threaded bars are shown inserted in form savers in the Colorado precast plant. Contact surfaces have been chemically retarded and sandblasted to improve bond with the secondary concrete cast. Photo: PCI.



18a) A steel lifting spreader is employed to align the lift load in the same plane as the web.

18b) Short attachments transfer the horizontal component of the weight into the spreader.

Figure 18. The method for lifting the girder must be carefully considered. Photos: PCI.

- **Skewed piers and abutments**—Due to both the design and construction complexities resulting from skewed supports; they should be avoided except where it is not possible. Often, a slightly longer span may be more economical than using a skewed support and should be evaluated during design.
- **Handling and erection stability**—The EOR should evaluate girder handling and erection stability from a sectional stand point and all assumptions for the review should be stated in the contract plans. Ultimately, it is the contractor's responsibility to ensure that the girders are stable and within allowable stresses at all times based on the chosen erection scheme, sequence, and details. This must be ensured by the construction engineer.
- **Post-tensioning**—A post-tensioning system, including tendon sizes, anchorage dimensions, and tendon path, is determined by the EOR during final design. Should the contractor deviate from those assumptions, the modifications need to be checked and the effects evaluated by the contractor's engineer and verified by the EOR. These responsibilities are dependent on the contract requirements.
- **Build-up and lid slab options**—The EOR should show the lid slab design and time of assembly in the contract plans, based on the assumed erection sequence. The camber and amount of build-up required over the webs should also be given in the plans. Should modifications be made by the contractor that deviate from the assumptions made by the EOR, changes may also need to be made in the lid slab details and build-up values. The responsibility for the determination of these changes and/or verification of these values should be identified in the contract.
- **Thickened flange options**—When cantilevered over a pier, the girder will require a thicker bottom flange to resist the negative moment compressive stresses. Two methods have been used. In order to minimize the shipping weight, the precast manufacturer can install threaded reinforcing bar receivers, sometimes called form savers, on the interior face of the girder as shown in Figure 17. A secondary cast is made to thicken the bottom flange after erection. It is recommended the precast manufacturer supply and install the threaded bars into the form savers before shipping. The contractor finishes the cage assembly on site. For the CFX project, the precast manufacturer formed and cast the thickened bottom slab integrally by using special interior forms, thereby eliminating the need for a secondary cast in the plant since the additional weight was not prohibitive in that case.
- **Precast fabrication**—Several issues were identified and recommendations made for future projects. These include:
  - A full-scale test section should be cast to replicate as closely as possible actual production procedures. This will reveal the performance (flow) of the self-consolidating concrete, manipulation and stabilization of the form, procedures for tying and handling the reinforcement cage, quality control procedures, etc.
  - Welded wire reinforcement is recommended in lieu of individual bars to maintain dimensional control, provide rigidity for handling pretied cages,

Overall area of Boggy Creek Interchange showing pouring sequence. Photo: A² Group Inc.

and allow fast assembly.

- When oval post-tensioning ducts are used, they should have tendons inserted prior to placing concrete in the event duct deformation occurs.
- In some projects, transverse steel struts have been welded across the tops of webs to stiffen the section during removal from the form. For the CFX U-girders, specially designed clevis and lifting slings were used to keep the lifting forces in line with the slope of the webs to eliminate transverse bending stresses. Figure 18 shows this innovation. All such special devices do wear out and good rigging practices are necessary.

The information given here is a summary and generalization of the issues. More details are provided in the PCI curved bridges report.[1] Even more will be presented at future PCI Bridge TechnoQuests and provided at the completion of the extensive work now ongoing and described in the Conclusion section that follows.

Role of the Institute

A vital responsibility of a technical institute is to monitor the activities and developments occurring within its sphere of influence. When an innovative technology is being successfully used in a local region, and that technology is recognized as applicable to a much larger area–even nationally, the institute's obligation is to act. The new technology explained in this article is advantageous to the owner agency and therefore the public. Also, it is beneficial to the industry by creating additional markets by providing a superior solution to steel.

An institute is recognized as the repository of the body of knowledge for its industry. It devotes considerable effort to establish itself as credible through the balanced participation of its diverse membership. The marketplace responds through confidence in its work. The institute has the recognition and resources necessary to marshal the efforts capable of refining processes and systems that can be implemented nation-wide.

Looking back the precast, prestressed concrete industry has fabricated horizontally-curved girders since 1966. Following a unique project in Philadelphia in 1983, PCI published a detailed report on the subject.[7] In 2011, it published more information on the topic in its popular and comprehensive *Bridge Design Manual*.[8] Then, with the dramatic work accomplished in Colorado, PCI's Bridges Committee, Subcommittee on Curved Bridges published its report.[1]

Since 2004, PCI's plan has been to first monitor and learn, then refine and develop resources, and finally to educate the bridge design and construction industry about this remarkable new technology.

Conclusion

Innovative and bold engineers with the CDOT created original technology that took advantage of a strong and willing precast concrete industry in their state. Partnering with the precast and construction industries and a few equally innovative consultants, solutions soon evolved that competed successfully with curved steel bridges and ramps.

Through the venues available at PCI and the exposure they provided, engineers in other areas began to take note. PCI understood it would next require a campaign to nationalize the Colorado details and to prepare to respond to a myriad of questions that would ultimately arise.

Working with its member base, the Institute has taken a local concept, tested and tried in that environment, and adapted it to national codes and standards. With work now ongoing in more states, the technology is maturing—garnering confidence among practitioners.

In board stability bracing used for both girders supported on single towers designed as reusable modules. Photo: A² Group Inc.

Proven competitive and constructable, a new solution is now available in the owner agency's repertoire. It provides a rapid, economical solution that will withstand the test of time.

And the development continues. A 2014 contract between PCI, the American Association of State Highway and Transportation Officials, and the FHWA will provide additional significant resources. PCI will prepare a comprehensive guidance manual to fully explain the design principles and decisions required to produce plans and specifications. It will be the basis for instructor-led training workshops. These deliverables are scheduled to be available in early 2016.

As stated earlier, additional PCI Bridge TechnoQuests are being planned. To be contacted with more information as it becomes available, email BridgeEngineer@PCI.org.

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References

1. PCI Committee on Bridges. 2012. *Curved Precast Concrete Bridges State-of-the-Art Report*, (CB-01-12). Precast/Prestressed Concrete Institute, Chicago, IL. 80 pp. https://netforum.pci.org/eweb/DynamicPage.aspx?webcode=storeItemDetail&parentKey=66a06cc7-abdc-488c-9a94-210876dbc973&catKey=5d967c30-b4c7-4993-bab8-f3cd6142e004 (Fee)

2. McMullen, Michael L., Jamal I. Elkaissi, and Mark A. Leonard. 2008. "Long-Span Precast U-Girders in Colorado." *ASPIRE*, Precast/Prestressed Concrete Institute, Chicago, IL. (Fall), pp. 64-67. http://www.aspiremagazinebyengineers.com/i/306888/65

3. Endicott, Wayne A. 2005. "A Fast Learning Curve." ASCENT, Precast/Prestressed Concrete Institute, Chicago, IL. (Summer), pp. 36-39.

4. Gilbert and Holderness. 2013. "I-25 Trinidad Viaduct." *ASPIRE*, Precast/Prestressed Concrete Institute, Chicago, IL. (Winter), pp. 16-19. http://www.aspiremagazinebyengineers.com/i/296997/17

5. Forars, Kristian P., Arthur Wolek, Jessica Alkhub, David N. Pretorius, and Thomas E. Davidson. 2014. *Design and Construction of Florida's First Spliced Curved Concrete U-Girder Bridges: The SR 417 and Boggy Creek Road Interchange*. Proceedings, 60th Anniversary Convention and National Bridge Conference (CD Format), Washington, DC. https://www.pci.org/bookstore/storefront.aspx (Fee)

6. Mohseni, Mansour Mike, Ken Saindon, and Clint Krajnik. 2014. *Colorado Flyover Ramp Showcases Precast Pier Caps and Curved Spliced Precast U-Girders*. A webinar presentation of the Accelerated Bridge Construction Center, Florida International University, Miami, FL. December 18. http://abc-utc.fiu.edu/index.php/technology/monthly_webinar_archive/view/ and scroll down to the 1 hour Colorado video.

7. ABAM. 1988. Precast Prestressed Concrete Horizontally Curved Bridge Beams, Special Report, *PCI Journal*, Precast/Prestressed Concrete Institute, Chicago, IL. Vol. 33, No. 5, (September–October), pp. 50–95 and as a separate publication, JR 350-88, Precast/Prestressed Concrete Institute, Chicago, IL.42 pp. http://www.pci.org/view_file.cfm?file=W1560_JR350.PDF

8. PCI. 2014. *Bridge Design Manual*, Third Edition, Second Release, (MNL-133-14). Precast/Prestressed Concrete Institute, Chicago, IL. 1620 pp. https://netforum.pci.org/eweb/DynamicPage.aspx?webcode=storeItemDetail&parentKey=345d2a31-53c2-43f9-8578-a7514e34b0a3&catKey=5d967c30-b4c7-4993-bab8-f3cd6142e004 (Fee)

9. Shutt, C. A. 2012. "Curved, Spliced, U-Girders Gain Momentum." *ASPIRE*, Precast/Prestressed Concrete Institute, Chicago, IL. (Fall), p. 13. http://www.aspirebridge.com/magazine/2012Fall/CCC.pdf

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EDITOR'S NOTE

A shorter version of this article appeared on page 27 of the Summer 2015 issue of ASPIRE.