Extending Precast Concrete Spans with the New WF100 "Super Girders"

by

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ABSTRACT

Delivered as part of the WSDOT I-405 Corridor Improvements Program, The I-405 Renton Stage 2 Design-Build project provided HOV improvements and new freeway connections to local City of Renton arterials. As part of this project, the existing 1970's vintage Benson Road Bridge spanning over I-405 was replaced with a new, wider, longer-spanning bridge that enabled widening of the freeway below.

The replacement bridge was initially conceptualized as a curved steel plate girder bridge. During design development, the design-build team revised the overcrossing alignment and bridge concept to enable use of emerging precast concrete technology, which provided for a much more cost-effective solution. Due to the requirements for the new bridge to span a widened interstate I-405 with minimal disruption to traffic, spans in excess of 200 feet were required, which is outside the range of typical precast concrete girder construction used for overcrossing structures in Washington State. The preferred solution identified was to utilize 100-inch deep precast concrete "super girders" erected in segments and post-tensioned to provide a fully integral composite structure, the first use of precast girders of this size in the State.

This presentation will focus on the unique design and construction considerations or the Benson Road Bridge, highlighting the applicability of spliced, post-tensioned super-girder technology to typical highway overcrossing structures using this cost-effective approach. Unique project aspects will be presented, including:

- Design considerations for fully composite spliced, post-tensioned precast girder design.
- Unique design and constructability considerations when using "super girder" technology.
- Transportation and erection considerations for large precast girders.
- Design and construction effects when utilizing large bridge pier skews.
- Seismic design considerations when utilizing this approach in high seismic areas.

Keywords: Spliced Girder, Precast Concrete Bridge, Bridge Construction, Design-Build

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Introduction

Delivered as part of the Washington State Department of Transportation (WSDOT) I-405 Corridor Improvements Program, the I-405 Renton Stage 2 Design-Build project provided HOV improvements and new freeway connections to local City of Renton arterials. As part of this project, the existing 1970’s vintage Benson Road Bridge spanning over I-405 was replaced with a new, wider, longer-spanning bridge that enabled widening of the freeway below (Figure 1).

Figure 1 - View of Existing and Completed Benson Road Bridge

The replacement bridge provides for two traffic lanes, bike lanes, and one sidewalk for curb-to-curb width of 40 feet. The bridge consists of a 3-span structure with spans of 132, 207, and 182 feet (Figure 2). The bridge was designed using spliced precast concrete girder technology, with Span 1 utilizing single segment precast girders and Spans 2 and 3 utilizing 2-segment precast girders. Four girder lines were used, with the multi-segment spans erected on temporary falsework bents with field-cast girder and pier closure pours constructed monolithically with the bridge deck placement. The bridge was then post-tensioned after deck placement, followed by placement of the abutment end diaphragms. The girders were then jacked at the abutments to re-set the elastomeric bearings to relieve short-term deformations caused by post-tensioning. The final result was a highly efficient, cost-effective, durable fully composite structure. The bridge construction was completed ahead of schedule and was opened to traffic in July, 2010.

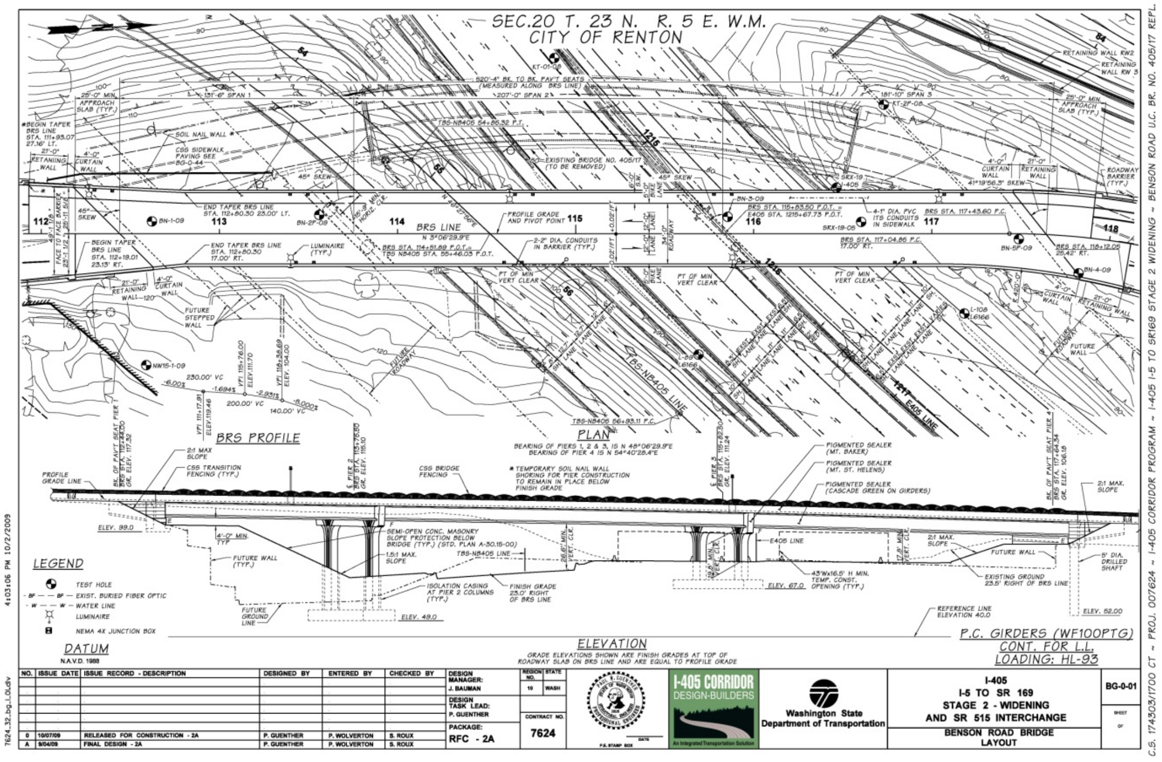

Figure 2 - Benson Road Bridge Plan and Elevation

This paper focuses on the unique design and construction considerations for the Benson Road Bridge, highlighting the applicability of spliced, post-tensioned super-girder technology to typical highway overcrossing structures using this cost-effective approach.

Design Considerations

The replacement for the existing Benson Road Bridge was conceptualized as a 5-span curved steel plate girder bridge in the original Request for Proposal (RFP) document. At 845 feet long, the RFP design represented a significant portion of the total project construction cost. The long lead time for the procurement of steel materials also posed a significant scheduling risk to the overall project.

During the proposal stage, the design-build team considered various alternatives including revising the overcrossing alignment and use of different structure types and materials. The final solution selected was a 3-span alternative that would significantly shorten the overall bridge length to approximately 520 ft. The revised alignment also allowed the bridge structure to be placed along a tangent alignment, thus making a precast concrete option feasible. Although an additional off-ramp overcrossing bridge (also a precast concrete structure) was needed to accommodate the revised roadway alignment, the reduction in total deck area and the change from steel to precast concrete reduced the total bridge cost by over $700,000. The use of concrete in lieu of steel also reduced future maintenance requirements and was perceived as an advantage by the owner (WSDOT).

Geometric Design Considerations and Constraints

Located in an urban environment, the project site is geometrically constrained. The owner's requirement to maintain all lanes of traffic on Benson Road and the I-405 freeway below during construction added additional site constraints. To avoid excessively long spans, one of the center piers (Pier 3) had to be located in the median of mainline I-405 and was thus constrained by the existing freeway on both sides (Figure 3). In order to limit the disruption to traffic, all construction work for Pier 3 had to be performed within a narrow work zone (approximately 20 feet wide) centered within the existing median. Carefully designed shoring was needed in this area with construction tolerances limited to a few inches. The orientation of the I-405 median relative to the new bridge alignment also dictated that the bridge would have to be placed on piers with heavy 45-degree skews.

Figure 3 - Pier 3 Construction in I-405 Median

The uneven terrain at the project site also played an important role in the design. In order to accommodate a future on-ramp near the south end of the bridge, one of the two intermediate piers had to be designed significantly taller than the other pier. This resulted in a significant challenge to the design in terms of meeting the distribution of lateral loads as well as the “balanced pier stiffness” requirements stipulated in the AASHTO Guide Specifications for Seismic Bridge Design.

Alternative Designs Concepts Considered

Precast Concrete Spliced Girder Alternative

Although the project scope only involved widening existing I-405 to 4 lanes in each direction (1 HOV lane and 3 general purpose lanes), the replacement bridge needed to be able to accommodate a much wider future I-405 (6 lanes in each direction, including HOV direct access ramps) as envisioned in the I-405 Corridor Master Plan. To meet this requirement, the longest span of the replacement bridge needed to be in excess of 200 feet.

During the preliminary design phase, conventional prestressed precast girders were first considered for the replacement spans due to their lower unit cost and the contractor’s familiarity with this type of construction. Prior to 2008, the longest span lengths typically achieved with conventional prestressed precast girder sections available in Washington State was approximately 180 feet[1], well short of the required span length. Among the possible alternatives, post-tensioned precast spliced-girders quickly emerged as a strong contender for several reasons. First, span lengths in excess of 200 feet were readily achievable with this type of construction[2]. Secondly, spliced-girder construction gives the designer greater latitude in selecting the number and location of piers, segment lengths and splice locations (hence temporary falsework tower locations) – an important requirement for this project due to the extremely constrained site. Lastly, although the span lengths for spliced girder bridges may be comparable to those of typical box girder bridges, construction methods are more conventional. This allows more bridge contractors to pursue the work rather than requiring specialty contractors. As the result, a post-tensioned spliced girder alternative using a WF83PTG girder section with 6 girder lines was initially selected as the preferred alternative during the proposal-phase design.

Shortly after the preliminary design had begun in late 2008, WSDOT approved a new series of precast girder sections, including one of the deepest precast sections available in the State: WF100G/PTG (PTG indicates a post-tensioned girder section). Together with the older WF83G and WF95G sections, these precast sections are commonly dubbed as “super girders” in the State, both due to their large size and their greater span capability. In the case of prestressed WF100G girders, the span capability exceeds 200 feet. The top flanges of these wide flange "super girder” sections are generally 4’-1” to 4’-2¾” wide. The web is 6 $^{1}/_{8}$” wide for conventionally prestressed girder and 7 $^{7}/_{8}$” wide for post-tensioned sections. The depth of the sections varies from 6’-11” for WF83G girders to 8’-4” for WF100G (Figure 4).

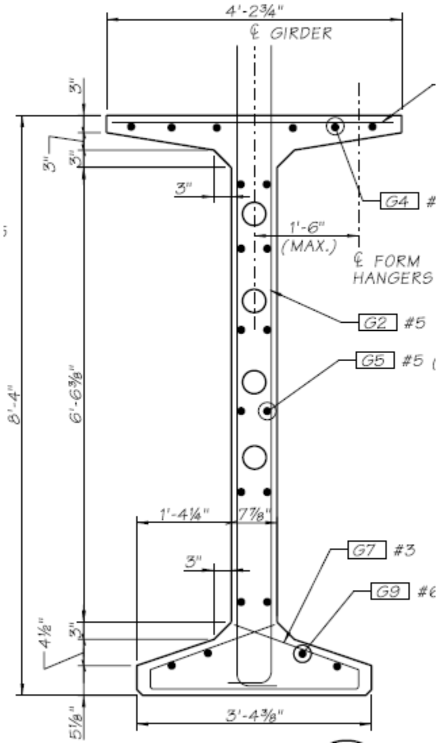

Figure 4 - WF100PTG Girder Cross Section

Although conventional pretensioned WF100G girders could achieve the span length required for the Benson Road Bridge, the design-build team eventually decided to choose the post-tensioned spliced girder alternative in order to minimize transportation risks. Based on detailed comparative cost comparison analysis, a second alternative with 4 lines of WF100PTG girder emerged to as the more cost effective solution. With a 10’-6” girder spacing, using the deeper WF100PTG section allowed the designers to employ two fewer girder lines compared with the WF83PTG alternative, resulting in significant cost savings.

Segment Arrangement and Post-Tension Design and Spliced Girder Design Details

As noted above, span lengths in excess of 200 feet are readily achievable using spliced girder construction. However, span lengths in this range are often achieved with haunched pier sections with a drop-in middle section. This type of segment arrangement is commonly used for river crossings but not always considered for typical highway overcrossing structures. For the new Benson Road Bridge, the design team decided to use a constant depth girder section and divided each of the two longer spans into two girder segments.

A haunched pier section was decided to be undesirable primarily due to the limited vertical clearance over mainline I-405 near Pier 3 and also to simplify girder fabrication. The girder segment lengths are typically determined by the available locations for temporary shoring towers. Although not optimal for prestress girder design, the locations of the girder splices (between adjacent precast segments) were selected so that shoring towers could be constructed without impacting traffic on I-405. The first span consisted of a single segment approximately 125 feet in length. The center span consisted of two segments of essentially equal length (100 feet). In the third span, the girders were splayed to accommodate the deck flare at the northern end of the bridge, resulting in varying segment lengths. The longer segments were approximately 100 feet in length, with the shorter segments approximately 75 feet long. Fabricating each of the two longer spans using two girder segments provided for segment sizes that were more easily transported and erected.

After segment lengths and girder spacings were determined, detailed prestressed girder design was performed. The design was performed using the commercial software PGSuper[3] and CONSPLICE[4], supplemented with proprietary spreadsheets. During each stage of construction, the prestressed girders had to meet both Strength and Service limit states for stress, moment and shear capacity. Each girder line was analyzed separately taking into consideration creep, shrinkage, prestress loss, and other time-dependent effects.

In the first stage of the design, the pretensioning strands in the precast concrete girders were designed according to the stress states the girders were expected to experience during casting, transportation, and erection. This stage is similar to conventional pretension prestressed girder design. The girder segments were then erected at their final location at the end of this stage, supported on temporary shoring towers (Figure 5).

After the concrete at the closure pours, diaphragms and deck had been poured and the desired design strength attained, post-tensioning running full length of the bridge was applied to connect all segments into a continuous fully composite section. Applying post-tensioning after the deck was cast allowed the full composite section to be utilized to resist post-tensioning forces, thus increasing structure's efficiency similar to cast-in-place post-tensioned concrete box girder construction. One disadvantage to this solution is that it precludes the possibility of full future deck replacement.

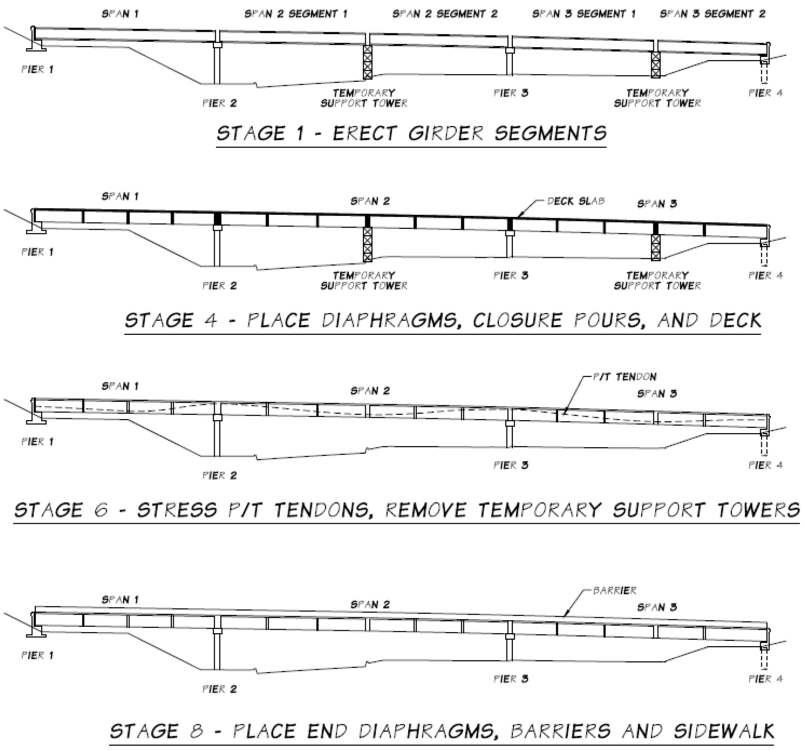

Figure 5 - Bridge Construction Sequence

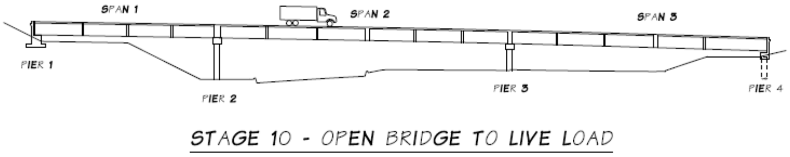

Figure 5 - Bridge Construction Sequence

A total of 4 post-tensioning tendons were designed for each girder, each containing 19-0.6 inch diameter low relaxation strands that were stressed to a maximum of 3400 kips at the time of jacking. During post-tensioning, the girders lifted up from their temporary supports at the shoring towers, which were then removed. The sidewalk and traffic barriers were then installed. In addition to the enhanced structural efficiency of the resulting system, a fully composite post-tensioned structure has the added benefit of being entirely in compression under service loads, thus eliminating flexural cracking and increasing the durability of the structure.

The 28-day strength for the precast girders was selected to be 9.0 ksi, within the normal range typically used for prestressed bridge construction in Washington State. The 28-day strength for the field-cast splices was set at 6.0 ksi. The cast-in-place section at the splices was designed as 2’-0” long in accordance with WSDOT standard practice. At each end of the bridge, the girders feature a thickened web end block in order to accommodate the post-tension anchorage hardware and necessary anchor zone steel reinforcing (Figure 6).

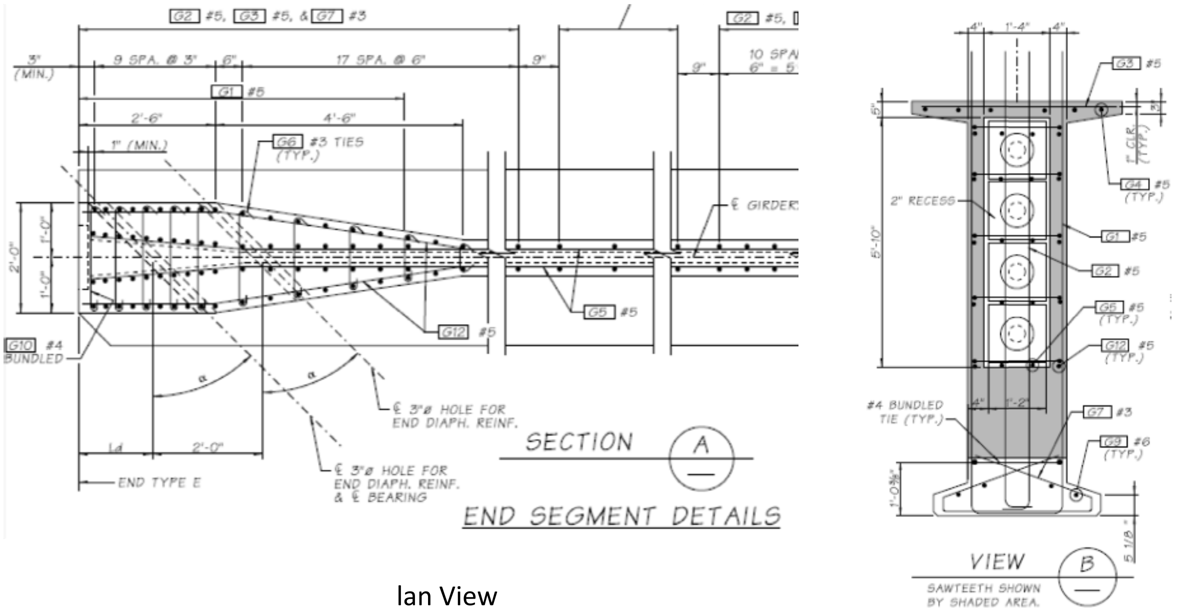

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Figure 6 - Girder End Block Details

Related Design Considerations

Live-load Distribution Factors and Effects of High Skew

Live load distribution factors for girder design were calculated in accordance to AASHTO LRFD Specifications Section 4.6.2.2. It is noted that the K_g value calculated for the WF100PTG girder exceeds the range of applicability stated in the AASHTO LRFD Specifications. This is presumably due to the fact that the WF100PTG section is a new girder section and is larger than the sections evaluated as part of the design code development. A detailed 3-dimensional finite element model was built using SAP2000[5] to determine the actual live load distribution factors for each girder. Comparison between the code equation values and the finite element results showed that the AASHTO LRFD equations are conservative and can be reasonably extrapolated for use with the WF100PTG girders for this span range.

Due to the heavy skew, the 3-dimensional finite element model was also used to investigate the torsional effects that would not be otherwise captured through a 2-dimensional analysis. The finite element results showed that the torsional effects were more pronounced at the ends of the bridge as expected, with the girders closer to acute corners displacing more than girders near the obtuse corners of the bridge. However, due to the relative slenderness of the bridge supestructure, the differences in displacements between adjacent girders were small and torsional effects had negligible impacts on the design.

Seismic Design Implications

As a result of the post-tensioning, a spliced girder bridge behaves as a continuous, fully integral unit under lateral loads. This characteristic is considered especially beneficial in high seismic regions such as Puget Sound. The new Benson Road Bridge was designed using a displacement-based approach in accordance with the newly adopted AASHTO Guide Specifications for LRFD Seismic Bridge Design, 1st edition (Guide Spec). A major difference between the new Guide Spec and the older AASHTO LRFD approach is that the column design based on the new Guide Spec is controlled by the Strength limit state, rather than by the Extreme limit state as was typically the case using the previous code requirements. For an integral structure, forces resulting from temperature, shrinkage and creep deformation usually control column strength case design. An byproduct of the selected structural solution was that any refinements in superstructure design, such as adjusting post-tensioning forces, had impacts on the column design forces as well as the foundations, which, according to the Guide Spec, are sized based on the “capacity-protected member” principle and must be capable to resist column plastic hinging forces.

Figure 7 - Pier 2 with Isolation Casings

Another requirement of the new Guide Spec is for the substructure columns to have similar lateral stiffness, often referred to as the “Balanced Stiffness” requirement[6]. This criterion requires the stiffness of the adjacent bents to be within 75% of each other. For the Benson Road Bridge, geometric constraints required that the columns at Pier 2 were almost 20 feet longer than those at Pier 3. In order to compensate for the resulting stiffness imbalance, the design team evaluated several different approaches, including increasing the diameter of the Pier 2 columns to 6.5 feet from the 4.5 feet used for Pier 3, use of isolation casings, using higher concrete strength, and adding more column reinforcing (Figure 7). Even with these measures, strict compliance with the balanced stiffness criteria was not attained. However, the designers were able to demonstrate to WSDOT's satisfaction that adequate displacement ductility of the bridge was achieved, resulting in seismic behavior consistent with the intent of the design guidelines. Consequently, strict adherence to the balance stiffness parameters recommended by the design code was waived by WSDOT.

Construction Considerations

Girder Fabrication

Construction of deep precast girders poses some unique fabrication challenges for the precast supplier, primarily due to the increased depth of the girders. Typical precast girder fabrication involves fabricating the reinforcing steel cages and formwork in assembly-line strings, wth multiple girders being fabricated at one time. Access exclusively from the ground is no longer possible since the girders are much taller than the workers assembling them. In the case of "super girders", access for workers to tie rebar, place post-tensioning ducts, and place concrete becomes much more difficult since the girder depth (over 8 feet deep in this case) requires that additional access means (scaffolding) and fall protection be provided to workers in order to reach the full limits of the work (Figure 8). Hence, special fabrication beds and formwork need to be developed to access and assemble these larger girders. In addition, fabricators need larger yard cranes to handle them. Super girders also typically require higher girders strengths, requiring more robust concrete mixes using high early strength cement and heated curing beds to achieve the higher release strengths needed to enable daily rotation of the forming beds.


Figure 8 - Girders Being Fabricated at Precast Plant

Construction Considerations Unique to Deep Precast Girders

Transportation and Erection

Although conventional pretensioned prestressed WF100G sections can span up to 220 feet[7], the significant size and weight of the girder units poses unique difficulties for girder shipping and handling. At 205 feet long, the shipping weight of a single WF100G girder is approximately 250 kips. Special equipment is required to ship these larger girders within legal load limits, increasing total delivery time to the site. There is currently only one trucking company operating in the Puget Sound area that can handle these larger girders, which is a minor limitation to their use (Figure 9).

Figure 9 - Girders Being Trucked to Site

The girders are also almost 9 feet tall when including the exposed height of the shear stirrups. Adding the height of the truck carriage, the top of the girders are over 15 feet above the roadway surface, approaching the vertical clearance limit of many bridges currently in service. A carefully planned haul route is needed to ensure access to the site, which may pose a limitation for application of these deeper girders to more remote sites, but is often not a constraint in urban settings where freeway access is available.

Figure 10 - Sicklesteel 650 Ton Crane

While the use of super girders enables larger girder segments to be used, the cranes needed to handle these larger girders need to be carefully considered during design. Crane access, reach, and maneuverability must be carefully evaluated on a case-by-case basis for each site. The girder segment weight and length are both significant factors in this evaluation. Use of these girders places a premium on a well-planned erection scheme, which is more easily solved in a design-build setting where the construction contractor has proactive input during design. In the case of the Benson Road Bridge, a Sicklesteel 650 ton wheeled crane was mobilized for girder erection (Figure 10). This crane is one of the largest wheeled cranes available in the United States.

The segment size selected for this project enabled this crane to successfully handle the girder segments at the site. Depending on crane access constraints at a given site, large tracked cranes may be required which often have limited availability and significant mobilization costs.

Safety Deck

Precast girder construction requires that a "safety deck" be installed between girders to provide worker access for deck formwork stripping and also debris containment when construction occurs over traffic or over sensitive river environments. For more typical precast girder construction, the safety deck is installed by supporting the deck between the bottom flanges of the girders. In the case of taller super girders, this deck must be raised to limit the fall distance from the tops of the girders to the deck to less than 6 feet in order to meet fall protection requirements for worker safety, as well as to provide reasonable worker access for construction of intermediate diaphragms and deck formwork construction and stripping. Construction of an elevated safety deck requires that inserts be provided in the girder webs to allow the safety deck to be installed at the proper elevation. This adds cost to the girder fabrication and requires close coordination with the girder fabricator to ensure the inserts are installed at the proper locations.

Girder Closure Pours

Spliced precast girder construction requires use of field-cast girder closure pours which are placed between girder segments to create a continuous girder (Figure 11). The construction of these closure pours becomes more difficult as girder depths increase. The presence of post-tensioning tendons also increases congestion at these field connections, putting a premium on concrete placing methods to achieve adequate concrete flow and consolidation. Typical WSDOT practice has been to utilize 2-foot wide closure pours at in-span splice locations. For deeper super girders, increasing the closure pour widths should be considered to improve constructability of these critical joints.

Figure 11 - Girder Splice Region Prior to Concrete Placement

Intermediate Diaphragms

Figure 12 - Typical Intermediate Diaphragms

Typical precast girder construction in Washington State involves construction of field-cast intermediate diaphragms between girders to provide increased distribution of loads between adjacent girders (Figure 12). These elements are often thought of as minor construction details. However, in the case of “super girders”, the intermediate diaphragms can be significant construction elements in their own right. In the case of the Benson Road Bridge, the intermediate diaphragms totaled the equivalent of 180 linear feet of 8 inch wide by 8-foot deep diaphragm walls. Achieving adequate flow of concrete below the girder top flanges can be an issue with these deeper girders, which can be improved through use of pour holes in the girder top flanges at diaphragm locations.

Deck Overhangs

The use of larger precast girders can often lead to designer decisions to use larger deck overhangs than would typically be considered. Deck overhangs for precast girder construction are typically limited to around 3 feet. Use of larger deck overhangs requires that more expensive "non-standard" overhang brackets be used for deck forming, so larger overhangs should be used with due consideration to this added cost.

Conclusions

The precast bridge design and construction industry is continuing to make advancements resulting in more cost-efficient solutions that reduce material quantities and speed construction, making better use of today's limited capitol project dollars. The application of precast "super girders", combined with spliced precast construction techniques, are a prime example of these advancements. Once used primarily for larger more significant long span bridge crossings, this technology is quickly becoming more mainstream with fabricators, construction contractors, and design engineers all becoming more comfortable with their more routine application.

Effective use of precast spliced super girders requires special design and construction considerations that may limit their use at some sites, with particular emphasis on girder weight, transportation, and erection. However, with proper foresight and planning, these obstacles can be overcome at many sites, making this an effective solution for a wide range of bridge projects, from smaller grade separations and stream crossings to major bridges.

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Precast Supplier: Concrete Technology Corp., Tacoma, WA

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