Using Embedded Corbels for the PHX Sky Train Project

by Colin Van Kampen, Modjeski and Masters Inc.

The PHX Sky Train Stage 2 Extension under construction at Phoenix Sky Harbor International Airport in Arizona will be a 2.2-mile extension of the automated train system from Terminal 3 west to the Rental Car Center (for additional details, see the Project article on p. 6). The construction schedule's critical path required continuous-span construction within the airport footprint while minimizing the project's impact on passengers and airport operations. Because minimal gate closures were permitted for precast concrete erection, the project needed a fast and effective construction method for the five-span post-tensioned (PT) unit. Further complicating construction of the PT unit was the existing terminal beneath span two of the unit, which had to remain open throughout bridge construction. The use of embedded corbels helped facilitate this challenging project and limited the impact of construction on airport operations.

Benefits of Embedded Corbels

In most instances, erection of spliced PT concrete structures involves constructing temporary supports to support the segments at splice locations. However, use of those typical means of support was complicated or prohibited within the apron of the active airport. The 676-ft-long, five-span spliced unit was composed of eight 78-in.-deep U-girder segments of varying lengths in three parallel girder lines, each with seven splices. Five of the splices were at locations that could accommodate traditional temporary supports and would not impact airport operations. The other two splice locations presented extraordinary obstacles to the construction of the unit's superstructure.

The critical stage of the PT unit's construction did not occur within its longest span, the 198 ft 2⅜ in. taxiway span. The taxiway span was easily accessible and far enough from existing airport infrastructure that it presented no unusual challenges and was supported using traditional temporary supports. Instead, the critical span was the 163 ft 6⅛ in. span over Terminal 2. Within this critical span, girder lines passed over the passenger security checkpoint and within close proximity to an aircraft jetway. An additional complication was a service road ramp; its presence meant the construction team had no access to level ground on which to build traditional temporary works.

Embedded corbels combined with staged PT construction proved the optimal solution and allowed clearance of the terminal without temporary works. The use of embedded corbels also eliminated any need for additional terminal closures to dismantle temporary works or remove strongbacks. Additionally, the embedded corbels, located on the drop-in segment and the previously erected cantilevered segments, were completely encapsulated within closure pours, which maintained the aesthetics of the superstructure.

Construction Sequence

Initially, the superstructure was designed using a single stage of PT construction. When the construction method was

Pier girder segment after arriving on site. The corbels projecting from the end diaphragm with bearing plates on top are lower in the section to support the corbels for the drop-in segment. Post-tensioning anchors are located near the top of the diaphragm for first-stage post-tensioning tendons. Smaller, plant-installed post-tensioning tendons are located at the top outer edges of the section. Photo: Modjeski and Masters Inc.

Drop-in girder segment (girder segment 3) arriving on site. The corbels projecting from the end diaphragm with bearing plates on bottom are higher in the section so they can rest on the corbels in the pier segments. Shear keys and embedded couplers for installing mild reinforcement for the splice are visible on the end of the girder. Photo: Modjeski and Masters Inc.

Overhead view of the construction site before drop-in segments were erected over Terminal 2. Splices and pier diaphragms are visible. Photo: Google.

changed to use embedded corbels to "float" the critical segment, several additional stages of construction and an additional stage of post-tensioning were required. Construction phasing for the complete five-span PT unit was as follows:

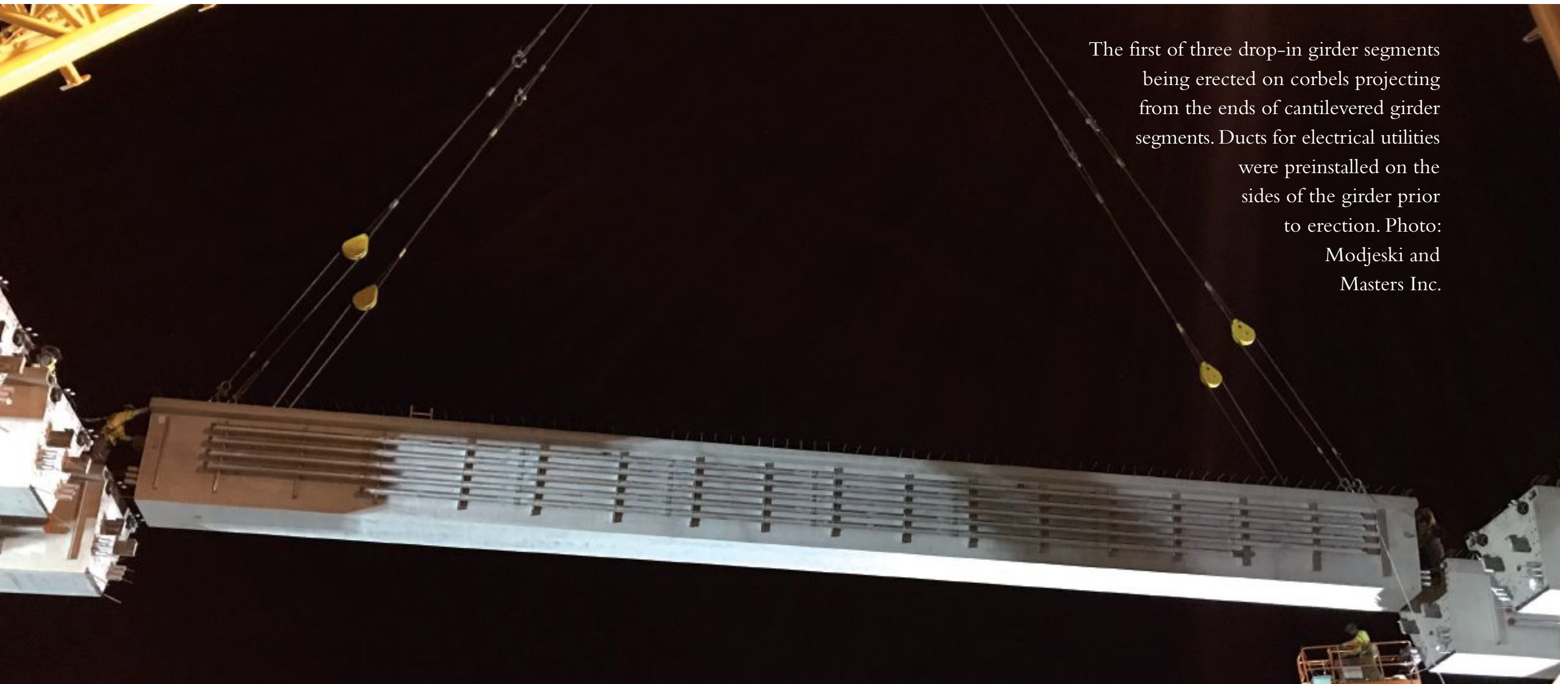
- Stage 1: Girder segments 1, 2, 4, 5, 6, 7, and 8 were erected on piers and falsework towers.
- Stage 2: PT ducts were spliced, and closure pours at splices and pier diaphragms were cast.
- Stage 3: Two PT tendons in each girder line were tensioned and grouted to form two subunits: girder segments 1 and 2 formed subunit 1, and girder segments 4 through 8 made up subunit 2.
- Stage 4: The drop-in segments (girder segment 3) were erected onto embedded corbels projecting from cantilevered ends of girder segments 2 and 4, and corbel connection bolts were installed.
- Stage 5: PT ducts were spliced, and closure pours at the remaining two splices were cast.
- Stage 6: Six PT tendons in each girder line that ran the full length of the unit were tensioned and grouted, completing the 676-ft-long continuous PT unit.

Embedded Corbel Design

The embedded corbels were designed to resist the dead load, construction live load, and wind load to which the girders would be subjected during stages 4 and 5. For each connection, casting the closure pour around the corbel connection provided additional stability and capacity to support temporary and permanent loads, although no allowance for design live load was included in the corbel design.

The *PCI Design Handbook*[1] has comprehensive information on the design of embedded steel corbels for concrete structures. This design methodology was adopted on this project to check the capacity of the steel corbels as well as the concrete capacity of the cross section. For these design checks, the lower resistance factors were adopted from the *PCI Design Handbook* while the higher load factors of American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[2] were used for load combinations and load factors. This resulted in a conservative design. The shear block check and design of the additional reinforcement were also based on AASHTO LRFD specifications, as well as the allowable concrete compression stresses.

The resulting corbel consisted of a 3-ft 9-in.-long hollow structural section (HSS) tube 12 by 4 by ⅝ in. with ⅜ by 8 by 6 in. bearing plates containing either slots or holes for the ⅞-in.-diameter A325 bolted connection. The HSS tube was pierced with no. 5 U-shaped reinforcing bars and filled solid with concrete having a compressive strength of 7000 psi. Fully assembled and filled with concrete, each corbel weighed approximately 365 lb. Additional



The first of three drop-in girder segments being erected on corbels projecting from the ends of cantilevered girder segments. Ducts for electrical utilities were preinstalled on the sides of the girder prior to erection. Photo: Modjeski and Masters Inc.

Embedded corbels projecting from drop-in girder segments, here shown at right, resting on corbels projecting from cantilevered ends of girder segments on left. Photo: Hensel Phelps.

reinforcement consisted of no. 4 closed-loop stirrups that surrounded the embedded portion of the HSS tube.

Incorporation of Embedded Corbels and Precast Concrete

Using a U-girder section for this project provided great benefits, including ample space for incorporating corbels into the ends of the precast concrete girders. While embedded corbels have been used in precast, prestressed concrete bulb-tee girders in many previous instances with great success, their incorporation can require additional forming at girder ends. The availability of space within the U-girder cross section allowed corbels to be incorporated without additional forming and also allowed a wider spacing of the corbels, resulting in better elevation control and lateral load resistance.

To create the end block that the corbels required, the interior form was simply held back from the girder end, creating a solid section capable of housing the corbel and associated reinforcement. This was a twofold solution because the staged PT sequence also required PT anchorages to be placed in these end blocks.

Projection of the corbel from the end face of the girder did require modification of the end form. Strict quality control and placement tolerances were adopted during casting to control corbel projection length and location, as well as both lateral and horizontal projection angles.

The addition of the solid end section posed a challenge to girder stability during erection. The additional weight of the solid ends at the end of the cantilevered portion of the pier girder segments caused additional overturning that had to be properly addressed to ensure adequate safety factors for stability during construction. The solution incorporated temporary ballast weight and hold-downs at the pier girder segments' temporary end supports.

Conclusion

For the PHX Sky Train Extension, the combination of staged PT spliced concrete girder technology and embedded corbels provided a streamlined solution to challenges associated with the restrictive site conditions. With the use of these technologies, the critical construction path activities could continue uninterrupted without substantially disrupting the operations of a major airport. Using embedded corbels in the ends of the girder segments allowed three 187,000-lb drop-in concrete girder segments to "float" over existing airport infrastructure, supported at the splice locations by the previouly erected girder segments. This eliminated the need for both external support hardware and secondary crane mobilizations to dismantle temporary works near active gate facilities, thus simplifying construction while also minimizing terminal closures during construction. This complex embedded corbel construction strategy was vital to the successful completion of the PHX Sky Train Extension superstructure.

References

1. Precast/Prestressed Concrete Institute (PCI). 2010. *PCI Design Handbook*, 7th ed. Chicago, IL: PCI.
2. American Association of State Highway and Transportation Officials (AASHTO). 2017. *AASHTO LRFD Bridge Design Specifications*, 8th ed. Washington, DC: AASHTO.

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