Design Considerations for Horizontally Curved Precast Concrete U-Girders

by Thomas W. Stelmack, Parsons

Plant produced horizontally curved, precast concrete U-girders began in Colorado about 10 years ago with the Ramp K flyover ramp linking Interstate 25 (I-25) and State Highway 270 (SH 270) in Denver. This generated interest in the precast industry and led to the development of the PCI Zone 6 concept plans in 2012. A full discussion of the history of the curved U-girder development may be found in the Summer 2015 issue of *ASPIRE.*™ Several more similar structures were constructed in Colorado, all being contractor-developed alternate designs or value-engineering change proposals. The SR 417/Boggy Creek Road interchange in Orlando was the first standard design-bid-build project in the United States to use the curved precast concrete U-girder concept (see article beginning on page 14). This milestone project illustrates that the concept is viable for typical project delivery, in addition to contractor alternate designs and design-build.

Figure 1. Detail for the expansion end of girder with tongue extension for bearing support. All Photos and Figures: Parsons.

Applications

While most curved bridge structures can be designed and constructed with the precast concrete curved U-girders, the most common application has been interchange flyover ramps where aesthetics are important, the curve makes chorded girders impractical, and highways and ramps below make precast concrete construction advantageous. The girders are also well suited to rail structures with a girder line below each track.

Special Design Considerations

One of the most critical and limiting aspects of this girder type is the girder weight. When possible, additional dead loads such as diaphragms, lid slabs, and bottom slab thickening, should be designed such that they can be cast after the girders are erected at the site. This requires analyzing the casting sequence, checking stresses, and providing the necessary details in the plans.

Figure 2. Detail for an interior end of girder adjacent to closure joint.

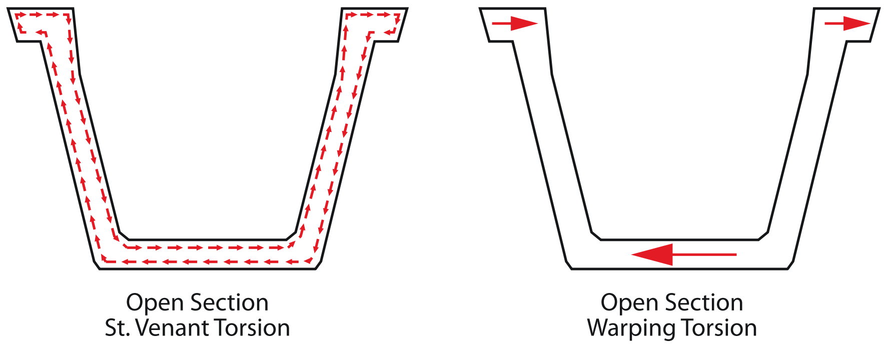

Figure 3. St. Venant and warping torsion shear flow.

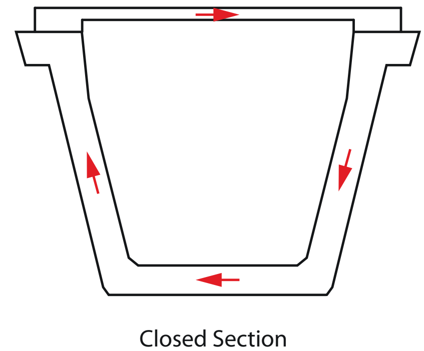

Figure 4. Torsional shear flow with lid slab cast on U-girder to form a closed section.

One detail that has been developed to reduce girder weight is the use of a lower "tongue" at the expansion joint ends of girders (Fig. 1). This detail provides sufficient concrete to support the girder on the permanent bearing, while allowing the contractor to cast in place the remainder of the diaphragm, both within and between the girders. Not only does this save weight, but it also allows the reinforcing steel and post-tensioning hardware for the continuity tendons to be placed efficiently by crews that are typically more experienced with this type of construction detail.

Geometric limitations for U-girders are typically driven by the transportation and lifting restrictions. Assuming that the girders are transported over state-owned highways, the girder weight and dimensions will control the girder length and radius. Girders weighing up to about 300 kips with a length of about 100 ft have been successfully used, but the designer should always verify whether loads like these are acceptable for a project. The minimum radius depends on the girder length and the total allowable width for transportation, but radii as low as 800 ft have not been a problem. By using the spliced and post-tensioned method of construction, span lengths up to about 230 ft are currently obtainable for 84-in.-deep, constant-depth standard sections.

Another important design consideration is the girder to pier cap connection. Options include using bearings, or making the girders integral with the caps. Integral caps can be more economical, as they allow the cap and diaphragm to be one rather than separate and it saves the cost of bearings. It also eliminates the need for bearing inspection and maintenance by the owner. However, the columns need to be of sufficient height and flexibility in order to not penalize the design of the substructure from superstructure longitudinal rotation and translation.

The most unique and probably least-understood aspect of designing a curved precast concrete U-girder structure is the fact that the girders are curved. This requires special care and understanding of the behavior during each phase of the construction process, as the behavior and critical aspects change as the elements and structural system change. For the individual girder segments, generally the contractor is responsible for lifting, support locations, and stability. The designer should ensure that the girder ends are stiffened or braced so that no distortion occurs at the ends. This has been done with both steel bracing and integral concrete stiffening ribs at webs and bottom slab and a strut between the top of webs. The ribs also allow for a thicker closure joint and additional shear key area (Fig. 2).

American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications* Article 4.6.1.2.4c addresses horizontal curvature for closed box and U-girders. It states that curvature may be neglected in the analysis for main axis bending and shear if girders are concentric, bearings are not skewed, the arc span divided by the girder radius is less than 0.3 radians, and the girder depth is less than the box width at mid-depth. The author has found that the difference between the outer and inner girder live load shear can be 45% and flexural moments 25% for an arc span to radius ratio of even 0.17 radians. Therefore, for multiple box-girder sections, it is recommended that curvature be considered when the arc span to radius ratio is greater than about 0.10 radians.

The other design aspect of horizontal curvature to be considered is torsion. A full discussion of torsional analysis and design is beyond the scope of this article. However, it is important to understand that there are two fundamentally different cases to be considered for torsion: for the open U-girder section and for the closed box-girder section once the decks slab has developed sufficient strength.

Open sections, which are flexible and weak in torsion, resist applied torsion by both St. Venant and warping torsion (Fig. 3). Warping torsion resistance becomes insignificant on longer spans and cracking also significantly reduces the torsional stiffness. It has been found that typically the individual girder segments can resist their own weight without additional bracing of the webs along their length, although it should always be checked. However, they are not capable of resisting the torsion due to their self-weight and that of the wet deck slab concrete once they are connected and span from pier to pier. By using a thin lid slab to close the open sections (Fig. 4), the torsional stiffness of the section is increased by about 100 times. Thus, the sequence requires the lid slabs to be cast after the closure placements have been made and the first level of continuity post-tensioning has been stressed. Next, the remaining continuity tendons are stressed, the shoring tower supports removed, followed by the casting of the full deck slab.

Besides the reinforcing steel design for the added web shear due to torsion and live-load distribution between girders, the design for the

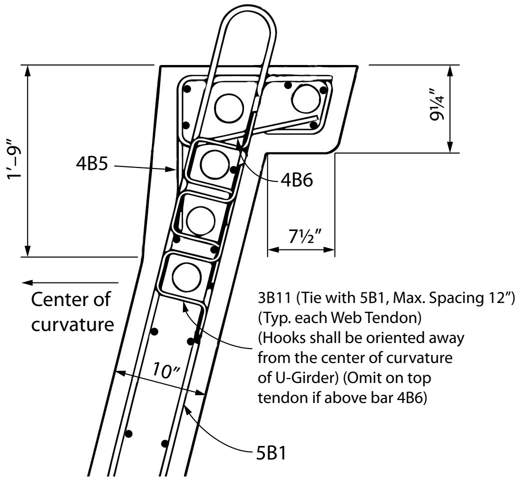

Figure 5. A typical reinforcing detail for restraining curved tendon ducts in the web.

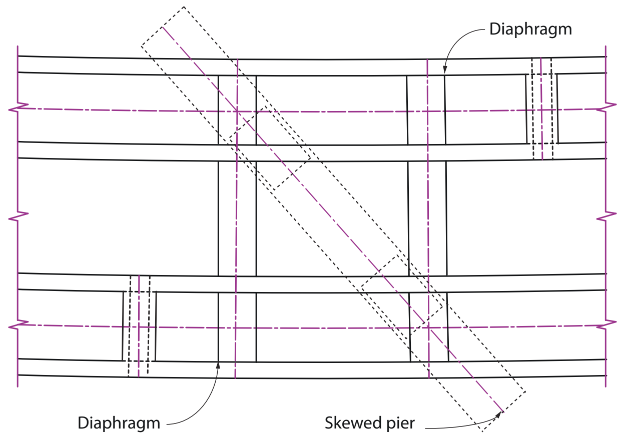

Figure 6. Diaphragm layout in plan for a skewed pier.

radial forces due to internal web post-tensioning along the curved alignment is also critical. This is addressed in AASHTO LRFD Specifications Article 5.10.4.3. The design radial force is calculated by dividing the ultimate tendon force by the curvature radius. The reinforcing steel should be sized and proportioned to limit the steel stress to $0.6f_y$. The reinforcement is typically made up of hairpin-shaped bars that wrap around the duct and adequately developed with hooks on the open end of the bar. Figure 5 shows a typical detail for the bars.

In addition to the horizontal curvature effects, additional torsion can be created when a pier support is skewed. In addition to designing for the added web shear, it is important to minimize the differential deflections that can occur in the box girders due to the non-radial orientation of the bearings from one girder to the next. It is recommended that two sets of radial diaphragms be used to connect the two box girders, one at each bearing location (Fig. 6). This also simplifies the constructibilty of the diaphragms by eliminating the skewed orientation of a single diaphragm, with respect to the precast concrete girders.

Tremendous progress has been made in the past 10 years regarding the development of plant produced horizontally curved precast concrete U-girders. By using standard sections that fabricators can purchase forms for, they are becoming a viable alternative to cast-in-place concrete and steel box girders for standard delivery design-bid-build projects. For this development to continue, it will be important for engineers in the industry to become familiar and proficient with the design and construction details of the girders.

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EDITOR'S NOTE

For more information on the history of the curved U-girders, see "Sharing New Technology through PCI Bridge Technoquests" in the Summer 2015 issue of ASPIRE *or the* ASPIRE *website for a longer version of the article.*