Cross-Section Efficiency: It's Not Just for Superstructures

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Precast, prestressed concrete beams and girders are common superstructure elements for tens of thousands of bridges in the United States. The cross sections of the most common beam and girder shapes (I, bulb tee, stemmed, and box) were developed with cross-sectional efficiency as a goal. Numerous engineers, going back to the prominent French bridge engineer Yves Guyon in the early 1950s, have proposed equations or methods to evaluate and compare the cross-sectional efficiency of various precast, prestressed concrete girders.[1] These methods all seek to provide structurally efficient cross sections that maximize flexural capacity while minimizing girder area and weight.

However, minimizing girder area is not the only consideration in developing structurally efficient precast, prestressed concrete sections. With precast, prestressed concrete girders, if engineers focus solely on optimizing flexural cross-sectional efficiency, the result may be a girder section lacking structural capability in other areas and that may be challenging in terms of fabrication and handling. For example, a highly efficient precast concrete girder section may have very thin webs and wide, thin top and bottom flanges (similar to a steel I-girder). Such cross sections could have bottom flanges that are not large enough to contain the prestressing strands required to make the section structurally capable relative to its depth. Or the flanges may be so wide and thin that achieving consistent concrete quality is challenging in the flange extremities, which also poses challenges for handling and transportation. The web may be so thin that proper consolidation of the concrete during placement is difficult and shear strength is compromised in favor of flexure.

Most transportation agencies have their own standardized precast, prestressed concrete girder cross sections that were developed taking multiple factors into consideration, and without sacrificing cross sectional efficiency. Standardization of cross sections greatly improves the cost-effectiveness of precast, prestressed concrete girder superstructures by enabling fabricators to invest in durable, reusable forms at a relatively low capital cost per use.

Substructure Cap Beams

Currently, more substructure cap beams are being constructed using precast or precast, prestressed concrete for many of the same reasons that make precast, prestressed concrete superstructure girders so effective: ease of fabrication, speed of construction, serviceability, and economy. Substructure cap beams can be used to reduce the proximity and duration of lane closures, traffic shifts, and equipment operation in construction work zones. Therefore, they can be an effective tool for accelerated bridge construction and optimizing worker and roadway-user safety.

However, because precast concrete substructure options are often a "one-off" solution for a particular project, many cap-beam cross sections are designed without adequate consideration of structural efficiency. Instead, they are often designed to use solid, uniform-width cross sections to conform with paradigms of typical cast-in-place construction practice, or the design vision is limited to precast concrete solutions used on previous projects with different constraints or purposes.

A Tale of Two Caps

An example comparing two bridge straddle cap beams, both 12 ft wide and 12 ft deep, highlights the differences between a solid, uniform-width cross section and a more efficient hollow cross section (**Fig. 1**). This simple comparison assumes that each post-tensioning tendon in the sections has an effective prestress of 1300 kip. The span length of each cap is 125 ft.

Table 1 lists the cap section properties and the effects of prestressing on the caps. The solid cap has a maximum unfactored self-weight moment of approximately 42,188 kip-ft, whereas the hollow, structurally efficient cap has a maximum self-weight moment of 15,820 kip-ft. To provide a Service I moment of approximately 47,000 kip-ft, which corresponds to acceptable stresses, 10

Figure 1. A schematic of the solid and hollow cap-beam cross sections used in the example calculation to demonstrate the design differences between the two sections. With the same design criteria, the solid section requires 10 post-tensioning tendons, whereas the hollow section requires 6 post-tensioning tendons. Figure: Modjeski and Masters.

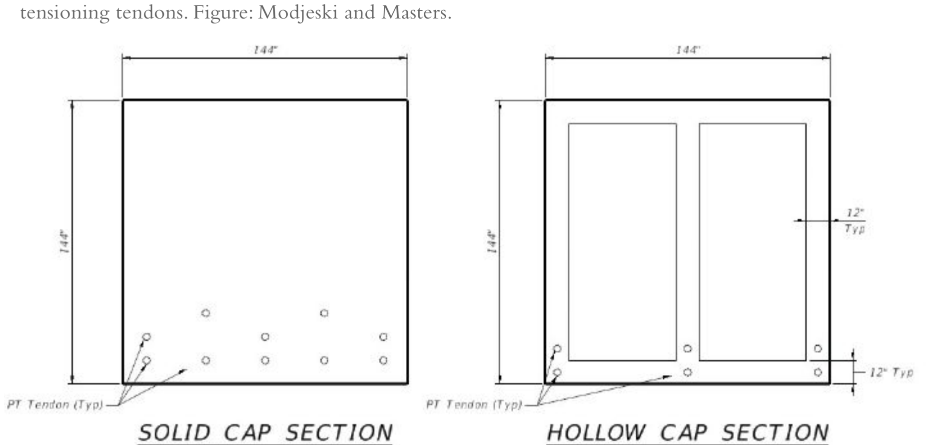

Table 1. Comparison of straddle cap sections

	Solid section	Two-cell section
Cap span length, ft	125	125
Cap area, in.²	20,736	7,776
Cap self-weight, kip/ft	21.6	8.1
Cap moment of inertia *I*, in.⁴	35,831,808	5,225,472
Cap section modulus *S*, in.³	497,664	281,664
Cap self-weight moment, kip-ft	42,188	15,820
Number of tendons, row 1	5	3
Row 1 eccentricity, in.	64	64
Number of tendons, row 2	3	3
Row 2 eccentricity, in.	56	56
Number of tendons, row 3	2	0
Row 3 eccentricity, in.	48	—
Effective prestress, kips per tendon	1300	1300
Service I moment required to provide acceptable stresses, kip-ft	47,079	46,724

Table: Modjeski and Masters.

tendons consisting of thirty-seven 0.6-in.-diameter strands each are needed for the solid cap, whereas only 6 tendons are needed for the hollow cap. A large percentage of the prestressing is needed just to overcome the additional weight of the solid cap.

While the solid cap may be slightly easier to construct than the hollow cap, it may require special measures to mitigate mass concrete placement issues. If precasting is an option, the lower weight for lifting and transportation of the hollow cap is clearly advantageous.

Strategies for Efficient Cap Beams

Hollow sections are one of the first considerations for developing a structurally efficient substructure cap beam. A closed, hollow section is an excellent selection, especially when torsion is present. Not all interior voids need to be rectangular in shape. They could be circular or other shapes, depending on the method of forming, whether using removable plywood forms or foam that is cut to shape and left in place. Another attractive aspect of hollow caps is the ability to vary the cap beam's web thickness internally to assist with shear demands without altering the outward appearance of the cap.

If torsional resistance isn't a primary issue, open shapes such as a T-section or an inverted U-section may be attractive choices to achieve structural efficiency. If the cap is to be precast concrete, a T-section may be a better choice than an inverted U-section because no internal formwork is needed. **Figure 2** shows an example of a variable-depth T-section used for a precast, prestressed concrete hammerhead pier cap.

Conclusion

To take full advantage of the benefits of prestressing and/or precasting substructure cap beams, designers need to adopt the principle of cross-sectional efficiency in their designs, rather than proportioning cap cross sections using the past practices and constraints of traditional cast-in-place concrete construction. Such efficiency principles have been successfully applied on several projects in Texas, such as three bridges on Loop 1604 in San Antonio, U.S. Route 183 in Austin, the Interstate 2/Interstate 69 design-build project in Hidalgo County, and the Gulf Intercoastal Waterway Bridge at Sargent Beach in Matagorda County (see the Project article in the Winter 2022 issue of *ASPIRE*® for more information).

Reference

1. Rabbat, B. G., and H. G. Russell. 1982. "Optimized Sections for Precast Prestressed Bridge Girders." *PCI Journal* 27 (4): 88–108. https://doi.org/10.15554/pcij.07011982.88.106.

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Figure 2. Variable-depth T-shaped precast, prestressed concrete hammerhead pier cap. Photo: Bexar Concrete Works.