PROJECT

Extradosed Prestressed Concrete Bridges

Proportioning guidelines and a design example

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The Odawara Port Bridge, Japan, is the world's first extradosed prestressed concrete bridge, completed in 1994. Photo: Steven Stroh.

Extradosed prestressed concrete bridges are a relatively new development in bridge engineering, with only about 60 of these completed worldwide. The extradosed prestressed concrete bridge has the appearance of a cable-stayed bridge with "short" towers, but behaves structurally closer to a prestressed concrete girder bridge with external prestressing.

Based on work by the author in developing the design for the first extradosed prestressed concrete bridge in the United States, the Pearl Harbor Memorial Bridge, and from reviewing existing extradosed prestressed concrete bridge designs worldwide,[1] this article discusses proportioning guidelines for this bridge type. These guidelines are then applied to the design for the Pearl Harbor Memorial Bridge.

Span Length Range

Extradosed prestressed bridges can be considered in the transition region of span lengths between traditional girder bridges and the longer-span bridge types such as truss, arch, and cable-stayed. Sources in Japan, where most of the extradosed bridges have been constructed, have set the applicable span range for extradosed prestressed bridges to be generally between 100 and 200 m (328 and 656 ft). A review of extradosed prestressed bridges worldwide shows span lengths ranging from 172 to 902 ft. Based on these data, a range from 300 to 600 ft is shown to be a common span range for typical bridges of this type, with span range applicability of 200 to 900 ft.

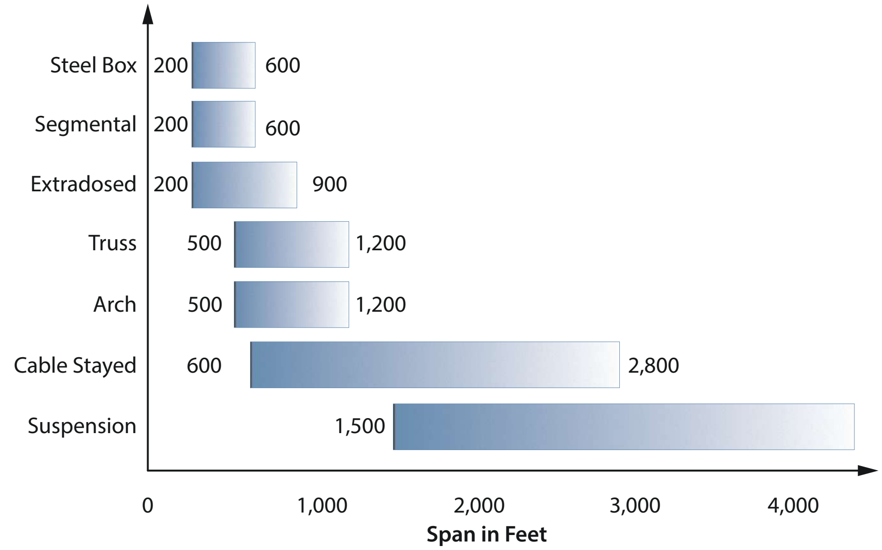
Side Span Ratios

The ratio between the main span length, *L*, and the side span length, *L1*, has an influence on the vertical reactions or anchoring forces at the anchor pier, the moment demands on the girder, and stress changes in the stay cables. For concrete cable-stayed bridges, an economical side-to-main span ratio (*L1/L*) is about 0.42. For concrete girder bridges, *L1/L* should range from about 0.8 for conventional cast-in-place-on-falsework construction to about 0.65 for balanced-cantilever construction.

A review of worldwide data on extradosed bridges shows that *L1/L* varied from 0.33 to 0.83 with a mean of 0.57.[1] The standard deviation is 0.12, so one standard deviation each side of the mean gives a range for *L1/L* of 0.45 to 0.69. This places extradosed bridges essentially between the envelopes of concrete cable-stayed bridges and balanced-cantilever-constructed concrete-girder bridges.

Multi-span Bridge Application

Cable-stayed bridges are typically either two-span or three-span arrangements. These span arrangements are ideal for cable-stayed bridges because back stay cables can be provided from the anchor piers to the top of the towers to provide stiffening of the towers. A recent review of more than 1200 examples of cable-stayed bridges worldwide revealed that only seven cable-stayed bridges are multi-span bridges (meaning more than three spans).[1] Design of a multi-span cable-stayed bridge presents a special challenge, in that there is no opportunity



Span ranges for common bridge types. Drawing: Federal Highway Administration.

Ibi River Bridge, Japan, is a multi-span, extradosed prestressed concrete bridge. Photo: Steven Stroh.

for backstay cables in the central spans, and special design considerations must be made to address the resulting flexibility of the structural system. Solutions for multi-span cable-stayed bridges include the provision of very stiff towers or providing crossing backstay cables that are anchored from the central tower to the base of adjacent towers.

Extradosed prestressed bridges do not rely on back stay cables. So, unlike cable-stayed bridges, multi-span extradosed bridge arrangements do not require special measures. A recent review of more than 60 extradosed bridges built around the world to date showed 19 of these bridges had four or more spans (representing nearly 30% of the bridges built).[1] The extradosed bridge type is well suited to long multi-span bridge arrangements.

Tower Height

An important parameter for extradosed bridges, and one that differentiates them from cable-stayed bridges, is the tower height. The tower height directly influences the stay stress variation under live load (the fatigue stress range) and the proportion of loads shared between the girder and the cables.

For cable-stayed bridges, the optimal ratio of the tower height, *H*, to main span, *L*, is typically between $\frac{1}{4}$ and $\frac{1}{5}$.

For extradosed bridges, the role of the cables is to act as external post-tensioning tendons and provide prestress to the girder. For an extradosed bridge, the post-tensioning is elevated above the cross section of the girder using a short tower, providing a much larger eccentricity, and therefore a more efficient use of the prestressing steel. However, if we continue raising the tower, at some point the vertical component of the cable reaches a force level that starts to carry a significant portion of the vertical live load of the structure.

A review of extradosed bridges constructed worldwide shows a typical range of the *H*/*L* to be between $\frac{1}{7}$ and $\frac{1}{13}$, with an average value of $\frac{1}{10}$.[1]

Girder Depth

Extradosed prestressed bridges are typically constructed in balanced cantilever and their behavior is similar to that of a girder bridge constructed in balanced cantilever, but with more efficient external prestressing. Therefore, a reduction in the structural depth at the support is expected when compared to a girder bridge. For extradosed bridges in the 300- to 600-ft span range, the span-to-depth ratio at the tower varies from 25 to 35 based on a review of existing bridges.[1] Within this range, a typical span-to-depth ratio is about 30.

The girder depth at midspan for an extradosed bridge should be similar to a girder bridge constructed in balanced cantilever. Therefore, a recommended midspan depth-to-span ratio for variable-depth extradosed bridges is 50.

Case Study—The Pearl Harbor Memorial Bridge

The Pearl Harbor Memorial Bridge in New Haven, Conn., is the first extradosed prestressed concrete bridge built in the United States. The Pearl Harbor Memorial Bridge is a three-span, continuous, cast-in-place, segmental concrete box-girder structure with a 515-ft-long main span and 249-ft-long side spans.

The northbound and southbound roadways are carried on separate parallel structures, each having five lanes, a tapering auxiliary lane, and 10-ft-wide shoulders, on a deck that varies in width from 95.4 to 107.6 ft. The superstructure consist of a five-cell concrete box-girder section. The girder depth varies through a parabolic haunch from 11.5 ft at midspan to 16.4 ft at the towers. The cast-in-place segmental concrete box-girder superstructure is post-tensioned longitudinally and transversely.

At the two interior supports, the twin decks are supported by three towers that extend above the deck and an additional intermediate column below each deck. The hollow towers have a constant cross section and are elliptical in shape. Foundations are 8-ft-diameter drilled shafts founded on rock.

Pearl Harbor Memorial Bridge is the first extradosed prestressed concrete bridge designed in the United States. Photo: AECOM.

Table 1—Recommended Proportioning Guidelines for Extradosed Prestressed Concrete Bridges

Parameter	Guideline
Common span range	300 to 600 ft
Side span-to-main span ratio	0.6
Girder depth at tower*	25 to 35
Girder depth at midspan†	50
Tower height above deck‡	$\frac{1}{10}$

* Guideline on ratio of main span length-to-girder depth at tower.
† Guideline on ratio of main span length-to-girder depth at midspan.
‡ Guideline on ratio of tower height above deck-to-main span length.

Application of Recommendations

The side span-to-main span length ratio for the Pearl Harbor Memorial Bridge is 0.48, which is at the low end of the recommended range. The span length was selected for the Pearl Harbor Memorial Bridge based on geometric constraints. In final design, the result of this relatively short side span was an uplift condition at the anchor piers under certain live-load conditions.

A concrete counterweight was cast inside the box girder at each anchor pier to balance this uplift condition and result in a net positive reaction under all load conditions. It is noted that if the side spans were shortened even more, this uplift condition would become a significant design issue. Therefore the lower range limit to the side span ratio is an important design parameter.

The tower height selected for the Pearl Harbor Memorial Bridge (measured from deck level to the uppermost cable) is 60 ft. This gives an *H/L* of $\frac{1}{8.6}$. The tower height for the Pearl Harbor Memorial Bridge was selected with a slightly taller tower height than the suggested value, but well within the suggested range. This decision was made based on the wide deck of the bridge, and the desire to reduce demand on the girder system.

A girder depth of 16.4 ft at the towers was selected in order to provide adequate negative moment capacity for the cantilever construction of the girder prior to installation of the first stay. This gives a span-to-depth ratio of 31.4, in the middle of the recommended range. At midspan, a depth of 11.5 ft was selected. This depth was chosen in part to provide a 6.5 ft internal clear height within the box girder for inspection access purposes. This depth gives a span-to-depth ratio of 45, close to the recommended range. For more information about this bridge, see *ASPIRE*™ Fall 2012.

Closing Remarks

Extradosed prestressed concrete bridges are an emerging bridge technology, applicable to bridges in the 300- to 600-ft span range. Basic proportioning parameters for this bridge type are well understood and are summarized in Table 1.

Reference

1. Stroh, Steven L., 2012. *On the Development of the Extradosed Bridge Concept*, a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Department of Civil and Environmental Engineering, College of Engineering, University of South Florida, Tampa, February 8, 2012.

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AESTHETICS COMMENTARY

by Frederick Gottemoeller

In the Fall 2012 issue of *ASPIRE*, I commented on the aesthetics of the Pearl Harbor Memorial Bridge in New Haven, Conn., identifying three aesthetic challenges for extradosed bridges:

- the appropriate shape for the towers
- the appropriate size and shape of the girder
- striking a good visual balance between the girder and the towers

This article provides specific proportioning guidelines for tower heights and girder depths based on structural considerations. Aesthetic considerations suggest that girder depths should be near the shallow end of the depth range to have the best appearance. However, aesthetic considerations don't provide such clear guidance with regard to tower height. Considering the tower only, one might think that taller would be better. But the eye judges the combination of tower, cable array, and girder together, not the three elements separately. The eye most strongly reacts to the ratio of the tower height and the girder depth (at the tower) to the span length. The higher that ratio (thus the shorter the tower) the more graceful will the bridge appear. Inevitably the short tower will appear stubby. So, what is the solution for that?

The two Japanese bridges deal with a short, stubby tower by tapering it vertically. The Odawara Port bridge minimizes the apparent thickness of the tower at the top by accommodating the cable anchorages in a separate element that protrudes from the body of the tower. The contrast in thickness between the base and the top makes the top seem smaller than it really is.

The Ibi River bridge takes a different approach. It uses a compound taper to minimize the width of the tower as soon as it emerges from the deck. Having a single row of towers and planes of stays along the median simplifies the appearance of this bridge and makes the structural achievement seem even more dramatic.

In tower design, as in any aesthetic endeavor, it is wise to remember that there are many options available.