VERTICALLY CURVED PRECAST PRESTRESSED CONCRETE GIRDERS

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ABSTRACT

The Portland, Oregon's Streetcar system is expanding its line and in addition to adding the Streetcar to several existing vehicular bridges, the expansion project includes a new first-ever Streetcar-only bridge. The new bridge is a 425-foot-long, 4-span precast prestressed concrete girder bridge. Site constraints due to vertical clearance for the Union Pacific Railroad tracks and overhead power lines required a steep crest vertical curve. Constructing typical girders and detailing up to 16 inches of concrete buildup on top of the girders to accommodate the track profile was not structurally feasible.

The structural design team worked with the local precast fabricator to develop a section that would match the profile of the crest vertical curve. The solution was a 60-inch Bulb Tee (BT60) girder, approximately 115 feet long with 13 inches of built-in camber. The precast fabricator was able to modify a BT60 form with a series of straight segments connected by wedge segments to match the profile. The strand pattern required special design considerations including strand "hold-ups" along the length. The varying girder center of gravity resulted in special design considerations regarding deflection calculations. This innovative bridge provides a smooth bridge profile that matches the Streetcar track profile.

Keywords: Creative/Innovative Solutions and Structures, Aesthetics and Finishes

INTRODUCTION

The phrase "curved girders" typically implies steel girders or cast-in-place concrete girders. However, this paper describes an innovative design solution for vertically curved precast prestressed (PC PS) concrete girders. Perhaps horizontally curved PC PS concrete will be next.

The project on which these unique girders were constructed is the Portland Streetcar Loop Project in Portland, Oregon. The streetcar system is well developed on the west side of the Willamette River in downtown Portland. This project, also called the East Side Extension, expands the line over the Willamette River. On the east side of the river, the Streetcar follows Martin Luther King Boulevard (MLK Blvd.) and Grand Avenue. Figure 1[1] shows the project work in the solid blue lines.

Schiels Obletz Johnsen (SOJ) is the firm that was hired to administer the Portland Streetcar Loop Project. The project team consisted of URS as design lead, with David Evans and Associates, Inc. (DEA) as structures lead. The project is set up as a Contract Manager General Contractor (CMGC) project, with Stacy and Witbeck Inc. (SWI) as the CMGC. SWI selected several bridge contractors for the project, and Mowat Construction Company served as the lead on the OMSI Viaduct Bridge, the bridge with vertically curved PC PS girders. The PC PS fabricator was Knife River Corporation.

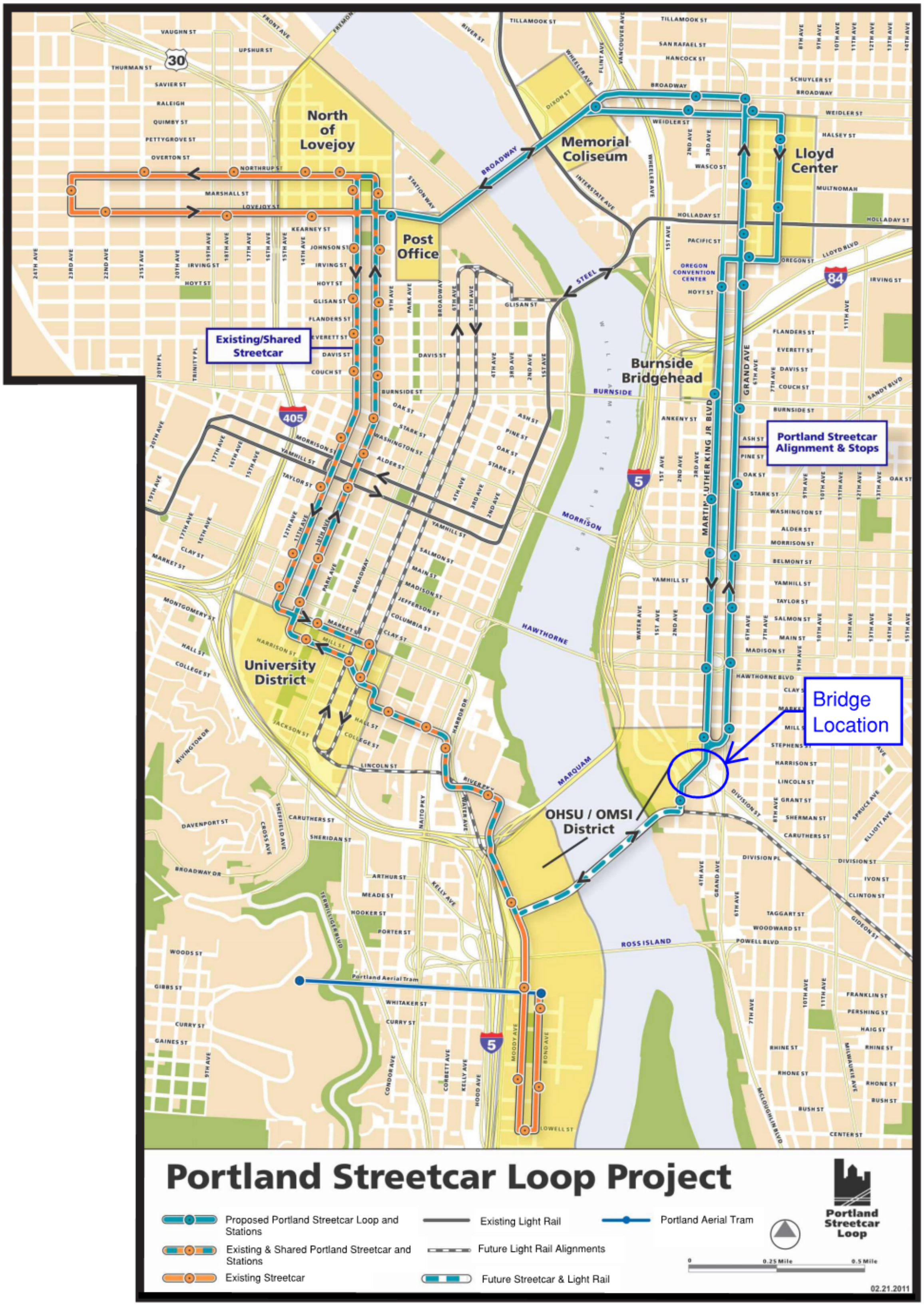

Fig. 1 Map of Portland Streetcar Loop Project[1]

In addition to adding the Streetcar to several existing vehicular bridges, the project includes a new first-ever Streetcar-only bridge. This bridge, which extends from MLK Blvd. over several railroad lines to the Oregon Museum of Science and Industry (OMSI), is titled the "OMSI Viaduct Bridge." Photo 1 shows an aerial view of the site. The photo looks northwest towards the Willamette River and downtown Portland. The OMSI Viaduct Bridge is in the center of the photo and has orange construction fencing on it.

Photo 1 OMSI Viaduct Bridge Site Aerial

The OMSI Viaduct Bridge is a 425-foot-long, 4-span precast prestressed concrete girder bridge.

DESIGN CRITERIA

Initial phases of this project sought to define the loading design criteria for the streetcar. The Portland Streetcar agency did not have defined design criteria, so DEA worked with the client to develop criteria. The light rail agency in Portland, TriMet, has well-defined design criteria[2], and these were used as the bases for the Portland Streetcar. The TriMet design criteria consider two trains trailing each other on a single track, or two trains passing each other on adjacent tracks. Consideration is also given for derailment, in which two axles have a 100% increase in load.

DEA worked to verify the Streetcar vehicle weight and axle configuration. There is no consideration for "lane" loading. The OMSI Viaduct Bridge is designed for Streetcar vehicles only. No cars or trucks, other than high-rail maintenance trucks, are allowed on the bridge. Pedestrians are also not allowed on the bridge. Live load impact was evaluated to be 26%. The resulting live load design criteria had similar effects to AASHTO HL-93 loading. Figure 2 shows the streetcar vehicle load diagram used in the design.

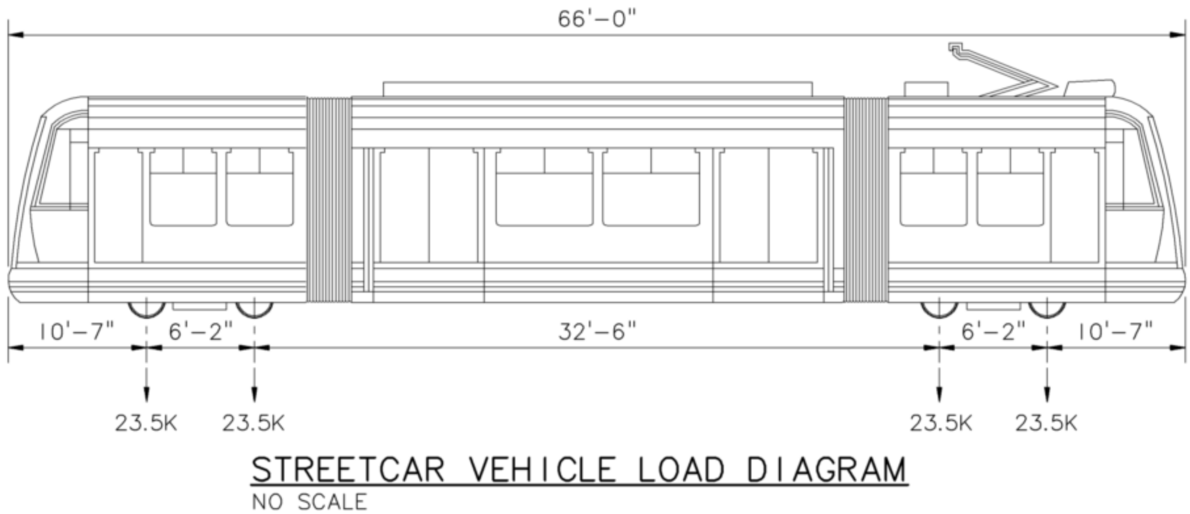

Fig. 2 Streetcar Vehicle Load Diagram

The bridge is designed to the AASHTO Standard Specifications for Highway Bridges 17th Edition, 2002[3].

THE CHALLENGE

The OMSI Viaduct Bridge site has several constraints that control the configuration of the bridge. The alignment crosses two streets and several railroad lines with below-bridge vertical clearance constraints. On the west end of the bridge, an overhead high-voltage power line that could not be relocated constrained the maximum height of the bridge. Checks were performed to maintain electrical isolation between the overhead high-voltage power lines and the overhead Streetcar catenary power system. These two constraints—below the bridge and above the bridge—dictated the detailing of a crest vertical curve with a 2.7% incoming slope and a 7.0% outgoing slope. In addition, pier locations were constrained by horizontal clearance requirements to the streets and railroad lines below. As a result, the 120-foot-long crest vertical curve was centered on Span 2 of the OMSI Viaduct Bridge. Crest vertical curves on multi-span bridges are best accommodated by locating the center of the crest near supports, but this could not be achieved on this bridge. Figure 3 shows an elevation view of the bridge.

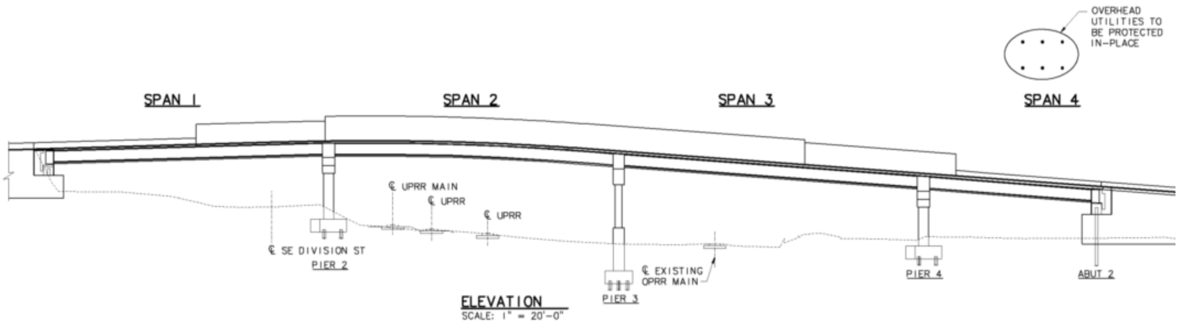

Fig. 3 OMSI Viaduct Bridge Elevation

Photo 2 shows an elevation view of the bridge with Span 1 on the right side of the photo and Spans 2, 3, and 4 on the left side of the photo. Note that Span 1 is on a vertical tangent, and Span 2 contains the crest vertical curve over the railroad. The overhead, high-voltage electrical power pole is also visible on the left side of the photo. The rail lines below Span 2 are very active and required close coordination with the railroad during construction.

Photo 2 Bridge Elevation

BRIDGE CONFIGUATION

The bridge typical section consists of four bulb-T girders, each 60 inches deep. The cast-in-place bridge deck accommodates two tracks. The Streetcar tracks are supported by cast-in-place concrete plinths. The plinths provide the vertical and horizontal control for the rail. See Figure 4 for the bridge typical section.

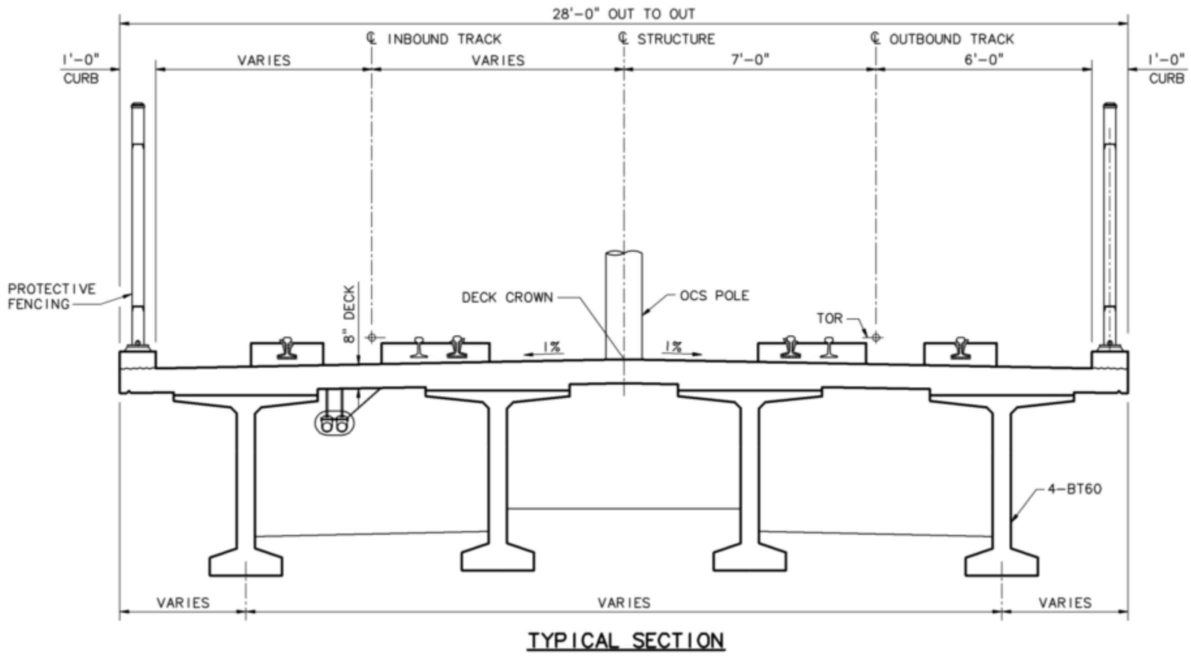

Fig. 4 Bridge Typical Section

The construction photo, Photo 3, was taken from Span 4, looking up the 7% slope towards Span 2. Note the four lines of plinth reinforcing that are embedded in the cast-in-place deck. In this photo, the concrete plinths have not yet been cast, or the rails placed.

Photo 3 Top of Deck During Construction

Several alternatives were considered to accommodate the crest vertical curve in Span 2. One option was detailing a varying depth haunch above each of the girders. The haunch would have been a minimum depth at the piers of about 1 inch, and 16 inches at midspan. This cast-in-place concrete haunch would have been applied to the PC PS girders in their noncomposite condition, and this quantity of weight was not structurally feasible. A second alternative considered varying depth of plinth concrete below the rails. Although this increase in load was similar to the varying haunch option, this concrete would be applied to the girders in their composite condition and was structurally feasible. The top-of-deck profile would have been nearly tangent, while the rail profile would have followed the crest vertical curve of the alignment. This option, though feasible, was not desirable. Aesthetically it would have significantly non-parallel visual lines of the girders and deck versus the rail profile. Investment into aesthetic design was incorporated into other aspects of this bridge including an ornamental concrete rail, architectural finish on retaining walls, and ornamental throw protection fencing. A bridge soffit with angled, non-parallel lines would have detracted from the site aesthetics.

THE SOLUTION

The design team contacted Knife River Corporation, a local precast concrete fabricator, to evaluate alternatives for constructing the PC PS girders in Span 2. Together we found a solution that details 13 inches of cast-in camber. PC PS girders typically have an upward camber in them prior to loading because of the prestressing steel eccentricity. However, in addition to this prestresssing camber, the concrete forms for the Span 2 girders were precambered, so that even if there had been no prestressing in the girders, they would have had 13 inches of camber.

The Span 2 girders were detailed with built-in camber varying along the span in a circular arc, with 13 inches specified at midspan (see Figure 5). Straight segments connected by angle points were allowed as long as the finished girder appeared to follow a smooth curve. The precast concrete fabricator assembled five 20-foot-long form segments with two 10-foot segments at each end, connected by side form wedges. The girder form was constructed of seven straight segments with angle points between each segment. The resulting girder appeared to follow a smooth curve.

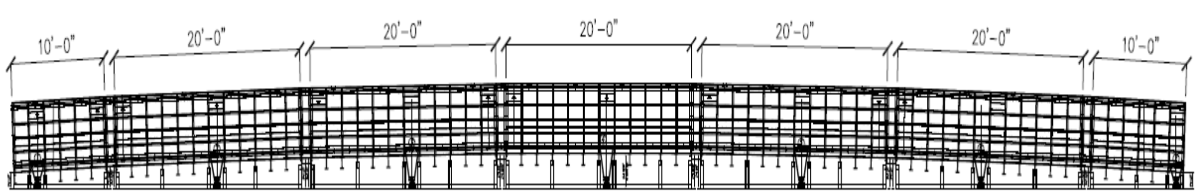

Fig. 5 Girder Form

The prestressing steel in these curved girders was unique. Initial design placed nearly half the strand in the bottom bulb, and half the strand in the web as harped strand. Later, the final design had a majority of the strand harped. See Figure 6 for a schematic of the girder stands. Of the 48 total strands, 36 are harped strands. Because of the varying location of the center of gravity of the section relative to a straight line between the bearing points of the girder, the harped strands are nearly level in the girder. The harped strands were only deflected downward 5 ¾ inches at the 4 tenths and 6 tenths points along the girder length. The remaining 12 "straight" strands in the bottom flange were detailed with a constant eccentricity from the bottom of the girder bottom flange. These "straight" strands were actually curved and required hold-ups at each of the form angle points to maintain the strand alignment during prestressing and casting.

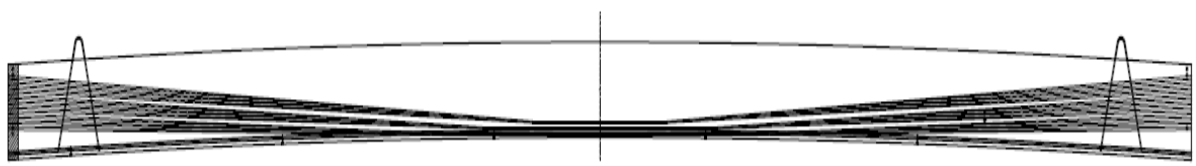

Fig. 6 Strand Pattern

Due to the downward force created by the straight strand turning small angles at each hold-up, unique stirrups were detailed on either side of these hold-ups to help resist the downward force of the straight strand at these angle points. The unique stirrups were single-piece U-stirrups that circled the entire bottom flange and extended up into the webs and bridge deck.

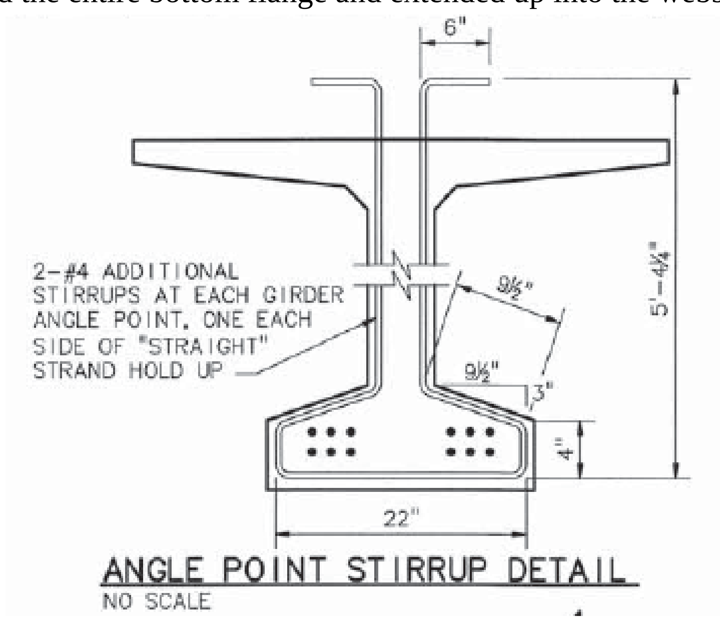

Fig. 7 Single-Piece U-Stirrups

FABRICATION

Although Knife River Corporation has produced other unique sections, prior to this project, a vertically curved girder of this nature had never been fabricated at their plant. A custom form was required for these girders. The form needed to accommodate multiple girder lengths, because the pier at one end of Span 2 was skewed, while the other end was not. The four girders in Span 2 had varied lengths from 113 feet to 117 feet. As discussed above, the form was constructed from 20-foot segments with custom wedges between each segment.

The precast fabricator designed a cast-in hold-up template that was embedded on the bottom flange of the girder at each of the straight strand hold-ups. This galvanized steel hold-up served to position the straight strands and hold them up in place. Figure 8 shows a detail of the steel hold-ups. The hold-up was supported by the bottom formwork, which was in turn braced against the casting bed. The maximum load to the hold-up device was 9 kips. Temporary angles were bolted to the side of the soffit during prestressing to keep the hold-up devices from moving. The angles were removed after final tensioning. Photo 4 was taken prior to stressing.

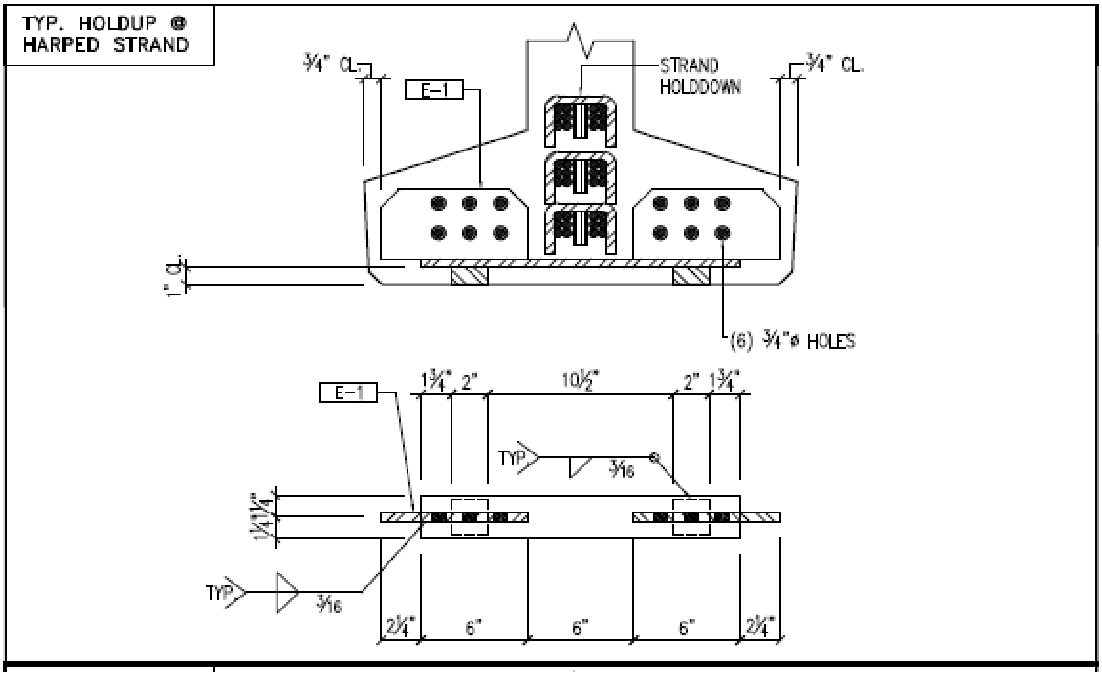

Fig. 8 Hold-ups

Photo 4 Hold-ups

At the ends of the girder forms, the straight strand went through a strand index hold-down in order to align the strand with the jacking bulk heads (Photo 5). The load to the strand index hold-down was 20 kips.

Photo 5 Strand Index Hold Down

Due to the stressing bed configuration, the form was centered in the middle of the jacking bulkheads. This meant that there was approximately 40 feet of strand between the bulkheads and the end of the girder. This created a non-typical stressing situation on the prestressing bed. Normally the form would be placed as close as possible to one stressing bulkhead, so that after the girder is cast, you can detention the strands on the long side with rams and cut them down live on the short side. It is not safe to cut down 40 feet of live strand. Instead, both ends were equipped with stressing rams. In this way, both ends could be detentioned simultaneously.

No unusual handling or shipping details were required. Since the girder is only 60 inches tall and has a 48 inch wide top flange, the section was quite stable during handling. See Photo 6 for handling of the girder in the casting yard. The girder profile was gradual enough that no special dunnage was required to temporarily support the girder in the yard. Additionally, no special bunking was required during shipping, because the slope did not conflict with any of the shipping equipment. Photo 7 shows a girder ready to be shipped from the yard.

Photo 6 Girder Handling

Photo 7 Girder Shipping

ERECTION

Erection of the girders was performed with two cranes. Photo 8 shows the bridge site during beam setting. The crane on the right side of the photo performed a walking pick that required to crane to move about 40 feet while lifting the girder. The Contractor attached the deck overhang brackets to the exterior girders prior to picking to minimize work over the railroad. On-site Union Pacific Railroad flaggers coordinated with the Contractor to identify windows of train-inactivity to work over the railroad. After the first girder was set and braced, the first train passed under the new crossing.

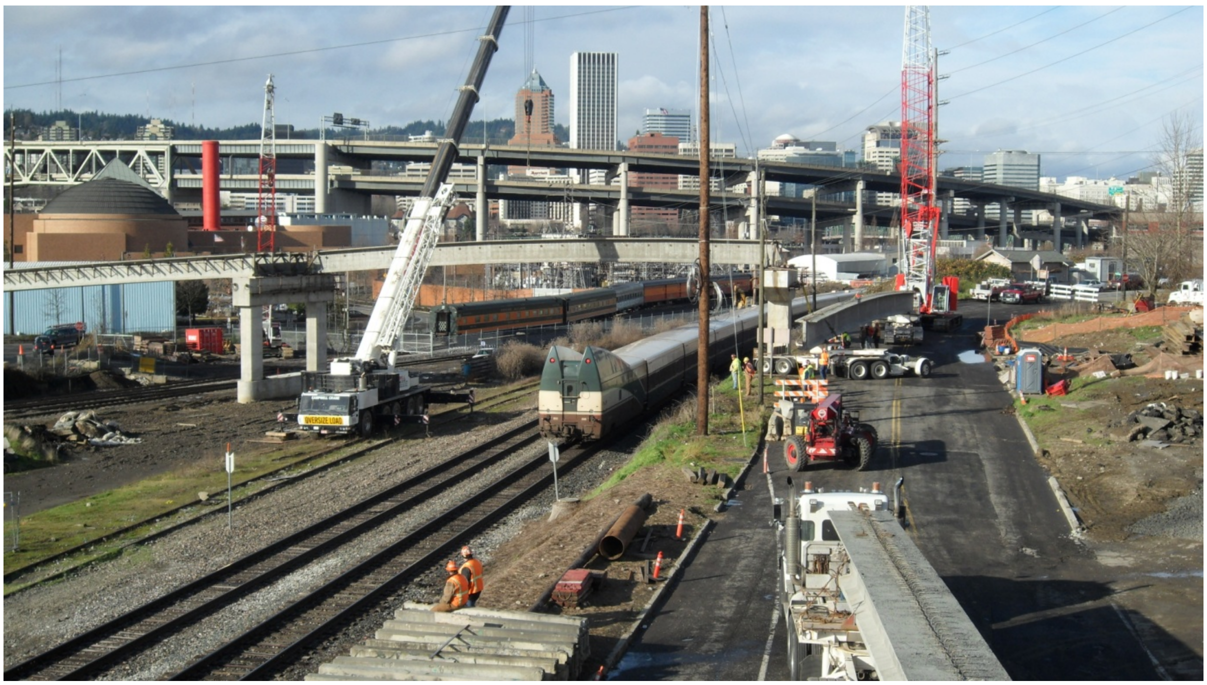

Photo 8 New Span over Railroad

CAMBER CALCULATIONS

Most calculations for the girder design were not unique compared to calculations performed for a girder without cast-in camber. However, the camber calculations were unique.

Consideration was given to the varying location of the concrete center of gravity. A global center-of-gravity point was identified and used in calculating the strand eccentricities. Both the harped strand and the "straight" strand produce two effects on the girder that contribute to its prestressing camber. The effects are the end eccentricity effect and the shape effect. The end eccentricity considers the strand location at the end of the girder relative to the center-of-gravity point of the girder. The shape effect for the harped strand considers eccentricity e'_H

defined as the location of the strand at the end of the girder minus the location of the strand at the harped points, from a global perspective. Similarly the shape effect for the straight stand considers eccentricity e'_S defined as the location of the strand at the end of the girder minus the location of the strand at the midspan of the girder, from a global perspective. Therefore both the e'_H and e'_S variables include consideration for the cast-in camber. See Figure 9 for the girder detail and prestressing free body diagram.

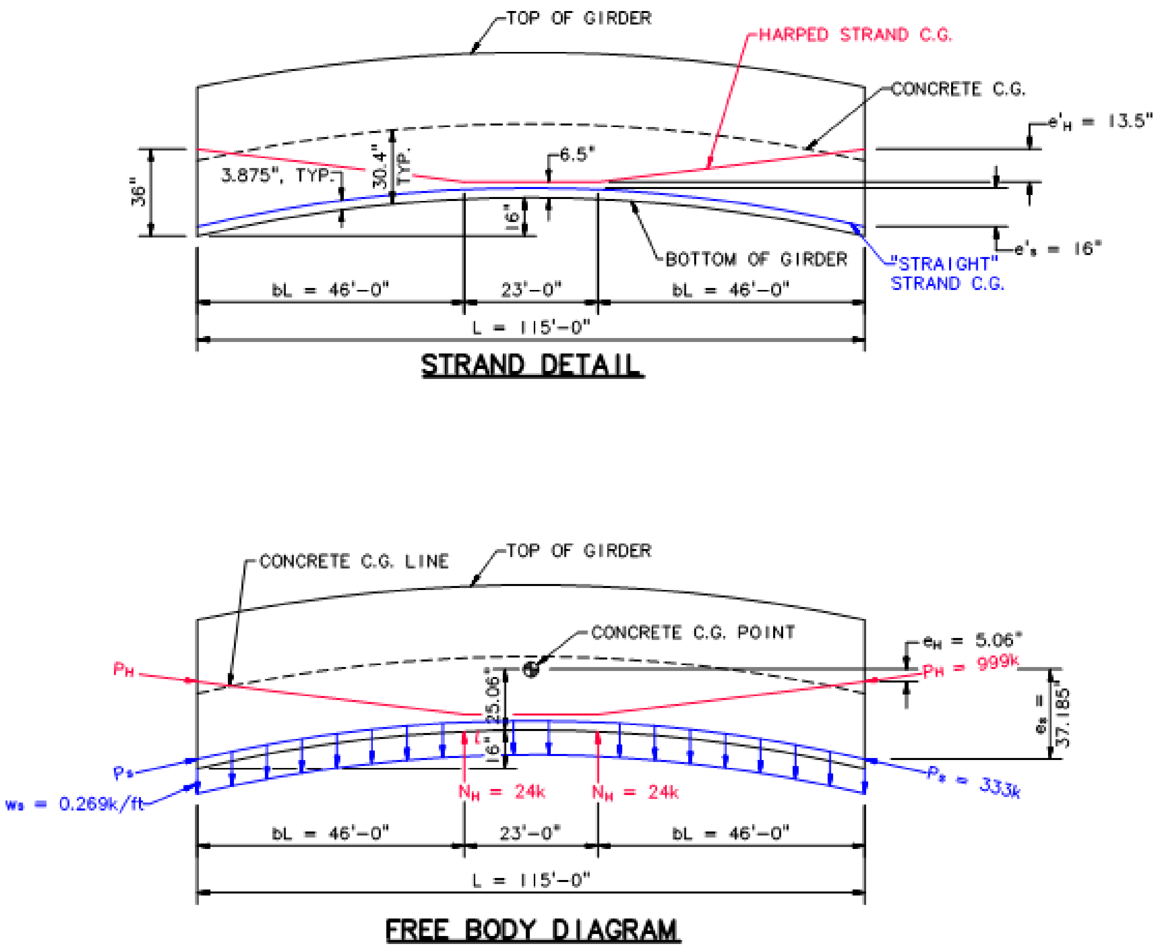

Fig. 9 Strand Diagram

HARPED STRAND

End Eccentricity Effect:

$$M_H = P_H e_H \qquad \text{Eqn. 1}$$

$$\Delta_{H,e} = \frac{M_H L^2}{8EI} \qquad \text{Eqn. 2}$$

Harped Shape Effect:

$$N_H = \frac{P_H e'_H}{bL} \qquad \text{Eqn. 3}$$

$$\Delta_{H,s} = \frac{b\,(3-4b^2) N_H L^3}{24EI} \qquad \text{Eqn. 4}$$

For the straight strand, the end effect considered the strand eccentricity to the center-of-gravity point of the girder. The shape effect of the straight strand looked at the cast-in shape and approximated it as a parabola. For these girders, the shape effect of the straight strand resulted in a downward deflection of about 0.7 inch.

STRAIGHT STRAND

End Eccentricity Effect:

$$M_S = P_S e_S \qquad \text{Eqn. 5}$$

$$\Delta_{S,e} = \frac{M_S L^2}{8EI} \qquad \text{Eqn. 6}$$

Parabolic Shape Effect:

$$w = \frac{8P_S e'_S}{L^2} \qquad \text{Eqn. 7}$$

$$\Delta_{S,s} = \frac{-5 w_S L^4}{384\,EI}$$

Eqn. 8

Variable Definitions:

$\Delta_{H,e}$ = Deflection due to harped strand end eccentricity
$\Delta_{H,s}$ = Deflection due to harped strand shape effect
$\Delta_{S,e}$ = Deflection due to straight strand end eccentricity
$\Delta_{s,s}$ = Deflection due to straight strand shape effect
b = Fraction of L at which the harped stand are held down
e_H = Eccentricity of the harped strand at end of the girder relative to the girder center of gravity point
e'_H = Eccentricity of the harped stand defined as the difference in the stand location at the end versus the strand location at the hold down points
e_S = Eccentricity of the straight strand at the end of the girder relative to the girder center of gravity point
e'_S = Eccentricity of the straight strand defined as the difference in the strand location at the end of the girder versus the strand location at the midspan of the girder
E = Modulus of elasticity of the girder concrete
I = Moment of inertia of the girder
L = Length of the girder
M_H = Moment due to the harped strand end eccentricity
M_S = Moment due to the straight strand end eccentricity
N_H = Equivalent point load due to the harped strand hold down point angles
P_H = Prestressing force due to the harped strand
P_S = Prestressing force due to the straight strand
w_S = Equivalent distributed load due to the straight strand shape

The total prestressing camber at release was calculated to be 3.7 inches upward. The self weight of the girder produced a 1.8 inch downward deflection. The net camber at release was 1.9 inches upward, not including the 13 inches of cast-in camber. With consideration for time effects, the predicted camber at the end of construction was 13 inches of cast-in camber plus 4.5 inches of prestressing camber minus 2 inches for dead loads, for a total of 15.5 inches. The designer's engineers and the precast fabricator's engineers found good agreement in each other's camber calculations, and the surveyed camber of the girders in the yard and at the bridge site were consistent. In Photo 9, taken during girder setting, the cast-in camber is noticeable.

Photo 9 Girder Setting

CONCLUSIONS

This innovative bridge provides a creative solution that increases the aesthetic of the structure by providing a smooth bridge profile that matches the Streetcar track profile. Both the design team and the precast fabricator were willing to try a concept with new challenges. Through teamwork and careful attention to detailing, the vertically curved girders were constructed and erected without issues. The result is a bridge that fits in with its surrounding and does not compromise the investment in improved aesthetics at the site.

REFERENCES

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3. *AASHTO Standard Specifications for Highway Bridges* 17th Edition, Washington DC, 2002.