STANDARD PRECAST PRESTRESSED TRAPEZOIDAL TUB GIRDERS IN WASHINGTON STATE

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ABSTRACT

Precast prestressed bridges compose the majority of bridges built in Washington State, and as the trend towards long-span girders continues, there is a greater need for efficient girder sections. The Washington State Department of Transportation (WSDOT) has recently developed standard precast trapezoidal tub girders to compete with typical single-web precast sections. With the cooperation of local precasters, WSDOT aims to make these girders a structurally efficient, architecturally pleasing, and cost effective system for precast prestressed bridge construction. This article presents a comprehensive review of span capability, design, details, shipping, and constructability issues with these new precast sections in non-post-tensioned design. Two recent state projects, in Spokane, Washington and Yakima, Washington, successfully utilized precast prestressed trapezoidal tub girders in both simple-span and live-load-continuous bridges.

Keywords: Bridge, Construction, Design, Detailing, Precast Concrete, Prestressed Concrete, Tub Girder, U Beam.

INTRODUCTION

Precast prestressed bridges compose the majority of bridges built in Washington State, and as the trend towards long-span girders continues, there is a greater need for efficient girder sections. The Washington State Department of Transportation (WSDOT) has recently developed standard precast trapezoidal tub girders to compete with typical single-web precast sections, and with the cooperation of local precasters, WSDOT aims to make these girders a structurally efficient, architecturally pleasing, and cost effective system for precast prestressed bridge construction.

WSDOT currently uses single web precast prestressed (PC/PS) sections for a large fraction of state-owned bridge designs for spans up to 175 ft. Historically, there are several generations of WSDOT-developed sections, and each generation has tended towards greater structural efficiency and improved constructability. The new tub girders can allow for longer spans while easily achieving depth-to-span ratios of 1/25. Therefore designers may span greater distances and avoid large grade separations for typical interchanges. Arguably, this can be done with greater aesthetic appeal, as tub girders have been selected for many projects with high aesthetic impact.

The new WSDOT tub girders include sections as deep as 82 in., and standard plans for the state developed sections are available publicly for other agencies and design firms. This article presents a comprehensive review of span capability, design, details, shipping, and constructability issues with these new precast sections. Two recent state projects, in Spokane, Washington and Yakima, Washington, successfully utilized PC/PS trapezoidal tub girders in both simple-span and live-load-continuous bridges. Each project has encountered both successes and lessons learned.

TUB GIRDER SECTIONS

The WSDOT standard tub girder sections are comprised of two sloping webs and one large bottom flange capable of holding over 100 of the 0.6" diameter prestressing strands with a 270 ksi tensile strength. Currently, the largest standard single-web WSDOT girders, with depths up to 95 in., can carry 70 of these prestressing strands. Figure 1 shows the nine 9 standard size tub girders with depths varying from 54 to 78 in. The webs and flanges of these sections may be varied in size to accommodate the required level of prestressing and bridge geometry much like cast-in-place (CIP) box bridge construction. With the increased prestress capacity of the tub girders, girder spacing can widen and girder lines may be removed. WSDOT's goal is to turn this ability into a financial economy.

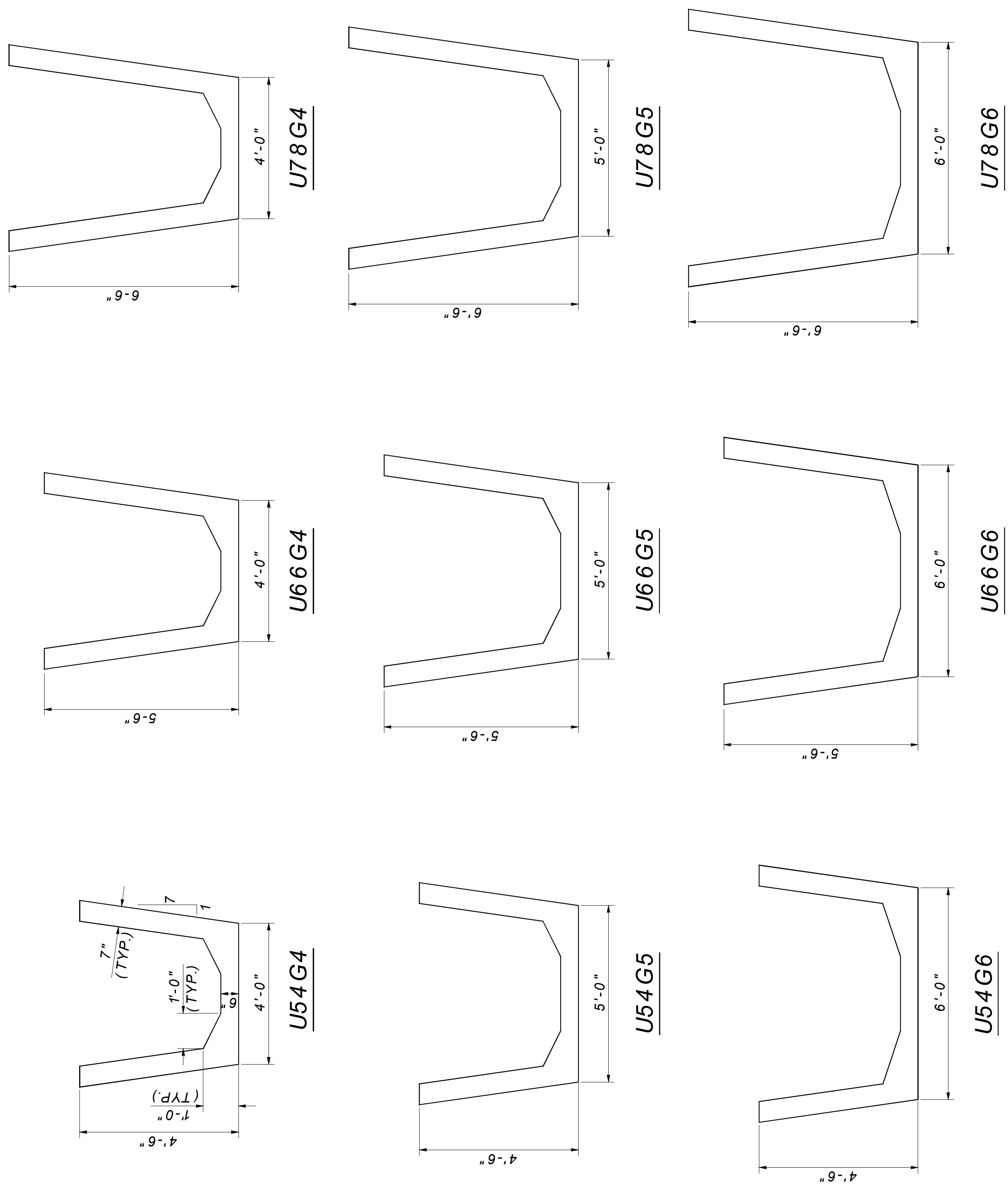

Fig. 1 Standard Precast Trapezoidal Tub Girders

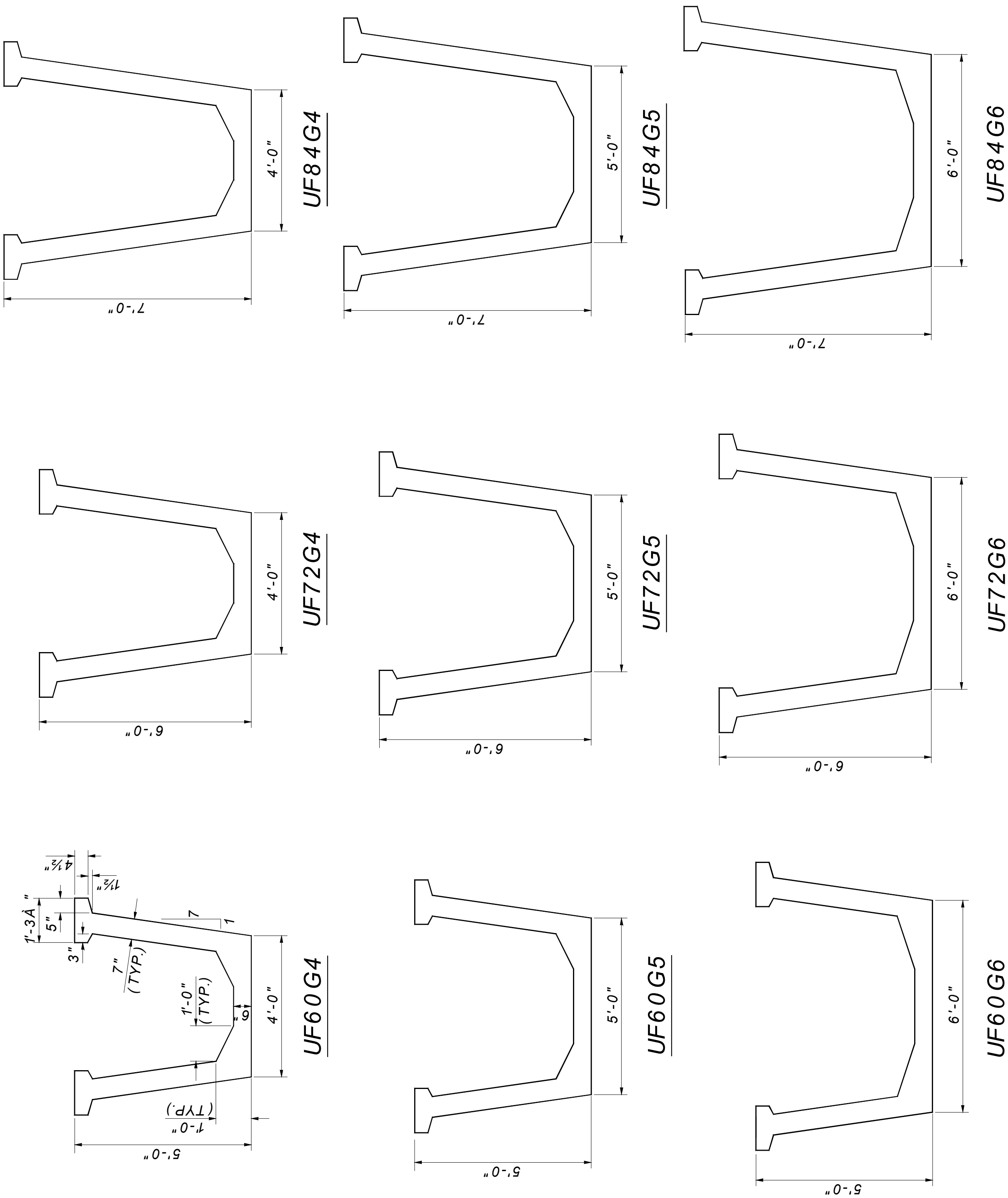

Fig. 2 Standard Precast Trapezoidal Tub Girders with Top Flanges

Along with the sections shown in Figure 1, WSDOT has also developed sections with flanges above each web; these sections are shown in Figure 2. The forms for these top flanges may be placed directly above the main web forms; consequently the flanged sections are 6 in. deeper than their straight-web counterparts. The addition of top flanges allows for the use of stay-in-place (SIP) deck panels as well as temporary top strands. Tub girders are particularly well suited to SIP deck panel construction methods because the tubs themselves act as an access platform for SIP panel placement. Figure 3 shows the end of a precast tub section without top flanges. WSDOT has also developed standard designs for post-tensioned tub girder design, though a review of those sections is beyond the scope of this paper.

Fig. 3 PC/PS Tub Girder

Although the fabrication of tub girders remains similar to single-web sections, the form details for bearing recesses do present an added complexity for precasters. This issue is particularly relevant for skewed sections. For skews larger than 15 degrees, WSDOT also designs polystyrene spacers at the acute angle corners for spall protection. Standard plans for the tub girder sections are included in the appendix. For further information, standard design details for prestressed tub girders sections can be found at:

http://www.wsdot.wa.gov/eesc/bridge/drawings/

Current WSDOT design standards do not include end diaphragms within the section; this is a practice that has been used in the past with similar designs. End-bearing forces are transferred directly through the webs. Although end diaphragms would also increase the torsional stiffness of the non-composite sections, WSDOT has not seen this to be a significant issue during handling or in the field. Contractors have had no problem lifting these sections with two cranes and spreader beams to accommodate the four lift points. Furthermore, these sections are much stiffer laterally than single web sections, and this simplifies design for transportation by allowing fewer temporary top strands.

PERFORMANCE OF TUB GIRDERS

As of 2006, the longest span in which WSDOT utilized a tub girder design without post-tensioning is 148 ft, though the sections have the capability to span up to 190 ft without post-tensioning. The efficiency of tub girder sections is competitive with WSDOT's wide flange I-sections, and WSDOT's wide flange sections are already among the most efficient sections used in the industry. Table 1 shows the span capabilities of these sections for various girder spacings using the WSDOT-developed *PGSuper* software for prestressed concrete girder design. These figures are based on a 7.5 ksi concrete release strength; this is the maximum release strength that WSDOT specifies unless the designer can confirm a financial economy with higher strength concrete. The span capabilities also reflect WSDOT's design practice of simple-span design with no net tensile concrete stress allowed under service loads.

Girder	Girder Spacing (ft)	Span Capability (ft)	Hauling Limit (ft)	Light Weight* Hauling Limit (ft)
U54G4	8	130	N/A	N/A
U54G6	10	120	N/A	N/A
U66G4	8	155	149	N/A
U66G6	10	145	130	N/A
U78G4	8	170	131	167
U78G6	10	165	116	148
UF60G4	9	150	149	N/A
UF60G6	15	135	130	N/A
UF72G4	9	165	131	N/A
UF72G6	13	160	116	148
UF84G4	10	190	116	149
UF84G6	16	170	104	134

* Using a 0.125 kcf structural lightweight concrete

Table 1 Tub Girder Span and Shipping Limits.

Girder spacings up to 18 ft. are feasible with tub girders, and because the tubs have multiple webs per girder, the effects of shear lag are less than that of I-sections. Correspondingly, there is more deck formwork required, but in rapid construction situations, SIP deck panels could alleviate this issue. Early trials have shown that for wide spacings or short spans, noncomposite stage stress requirements may govern design. The flanged sections may be desirable in such cases because they are stiffer and they allow for the use of temporary top strands.

To display the competitiveness of tub girders, two designs for a 140 ft. span with a 50 ft. wide deck are compared using the *PGSuper* program. The designs compare a 60 in. deep flanged tub girder with a 58 in. deep WSDOT wide flange I-section as shown in Figure 4. Table 2 summarizes the results; the tub girder design has one-third fewer girder lines. While the total bridge weight is comparable, the tub girder design achieves a slightly higher total composite stiffness with slightly less prestress force. In cases where precast unit costs or shipping costs make up a substantial portion of superstructure costs, tub girder designs have potential to provide a less costly alternative to typical single-web girder designs.

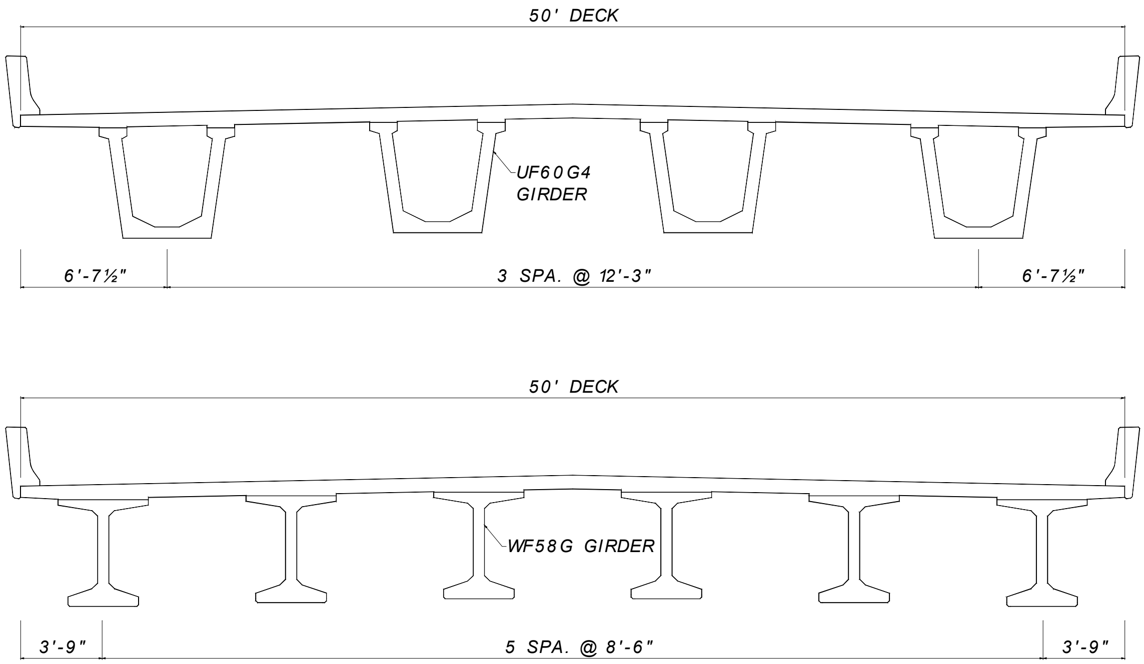

Fig. 4 Bridge Sections for Tub and I-Girder Spans of 140 ft.

	WF58G	UF60G4
Girder Lines (#)	6	4
Girder Spacing (ft)	8.5	12.25
Overhang (ft)	3.75	6.625
Depth-to-Span Ratio	1/25	1/25
Girder Area (ft^2)	5.69	8.38
Girder Unit Weight (lb/ft)*	910	1340
Girder Inertia Moment (in^4)	407000	483000
Straight Strands	38	32
Harped Strands	17	48
Total Strands	55	80
Temp. Top Strands	4	2
*Release Stresses**(ksi)*	-1.2/-4.3	-0.67/-4.2
Service III Stress (ksi)	-0.02	-0.03
Total Girder Weights (k)	764	750
Total PS Steel (# Strands)	354	328
Bridge Inertia Moment (ft^4)	219	228

* Based on a 0.160 kcf reinforced concrete density
** Stress measured at top and bottom of girder at harping point

Table 2 Design Comparison Between Tub and I-Girders

Under current WSDOT design practices, transportation unit weight is the major structural obstacle to utilizing tub girders in long-span precast superstructures without in-span splices. Due to trucking weight restrictions, WSDOT limits precast unit weight to 200 kips for typical bridge designs; generally the design of longer bridge spans with precast concrete superstructures requires post-tensioned spliced girder methods. Practically, this limits the standard tub girder sections to a range up to 150 ft. Thus for the U54G4, a 4'-6" deep section, only 75% of its span capacity can be achieved before the transportation weight restriction governs design. This percentage is even lower for the deeper sections. Even though tub girders have a large lateral capacity to withstand shipping loads, girder self-weight restricts them from span lengths where this factor would be of significant benefit. Figure 5 shows a large tub girder ready to be hauled to a WSDOT bridge site.

Fig. 5 Hauling of a Tub Girder

One issue that WSDOT and local precasters are discussing is the use of structural lightweight concrete in precast tub girder units. The reduction in self-weight of the precast units would allow several of the standard tub girder sections to reach their span capability without transportation weight restrictions governing design. Local precast plants currently have the ability to reach typical WSDOT concrete strength specifications up to 10,000 psi with structural lightweight concrete; this practice has previously been done by other agencies in state. Table 1 also shows the maximum hauling lengths of tub girders made from structural lightweight concrete. Currently, WSDOT is researching the properties and economics of lightweight concrete before it is used in precast girders. Lightweight concrete also has the added benefit of reducing seismic loads and therefore reducing substructure costs. Still, for precast concrete bridge spans up to 150 ft., tub girders are a competitive alternative to single-web units.

DESIGN CONSIDERATIONS

In general, the tub girders remain similar to other single-web precast units, though there are subtle differences. At the preliminary design stage, consideration should be given to the geometric requirements of having four points of bearing. Roadway superelevation will require either out-of-plumb placement, (which is not structurally significant for small superelevations), or larger haunches and increased bearing pad height. WSDOT has designed tub girders to be placed out-of-plumb for constant superelevations up to 6% without further analysis. Furthermore, either superelevation transitions or skewed piers on curved alignments force the four bearing points out of plane. These cases may require irregular crossbeam or bearing geometry in order to avoid twisting the noncomposite section.

The AASHTO LRFD Bridge Design Specifications are equipped to handle designs with general tub girder sections; however, live load distribution for these sections has not been studied as thoroughly as single-web precast concrete sections. As recent as the 2006 interim, the range of applicability for AASHTO live load distribution factors applies to spans under 140 ft. and for sections shallower than 65 in. In the absence of further studies, WSDOT practice allows the use of AASHTO live load distribution equations for all standard tub girder designs regardless of span or depth.

In general, the prestressing design for tub girder superstructures is treated identically to that of single-web girders; however the controlling load cases may follow different trends. Due to the relatively small noncomposite upper section modulus, compressive stress requirements in the top of the web may govern design during deck placement. This is particularly relevant in configurations with wide girder spacing. Generally, the flanged tub girder sections are better suited for wide girder spacing because they have a relatively larger upper section modulus during the noncomposite stage. Top flanged tub girders may also be beneficial when temporary strands are desired to control tensile stresses or deflections.

Currently, WSDOT practice omits the use of cast-in-place interior diaphragms between tub girder sections. Although the lateral stiffness of these sections provides the necessary stability for construction, the weight of the deck finisher may require additional load distribution at the non-composite stage in order to maintain a uniform deck thickness. Even though the omission of interior diaphragms reduces the superstructure dead load, the weight of lost forms within the girders must be considered. Like CIP box construction, precast tub girder webs are subject to out-of-plane flexural effects. The standard plans for the sloping webs of WSDOT standard tub girders are pre-designed for basic construction load effects.

After the girders are made composite for service loads, the tub girders may also be fully fixed at pier connections. WSDOT tub girders are capable of being used in live-load-continuous structures without the use of post-tensioning, as longitudinal deck steel is capable of developing the required negative moment capacity. Still, it remains WSDOT's practice to design prestressed girders for simple-span boundary conditions under live load. Rather than impose strict time requirements on contractors to control creep, which jeopardizes continuity under service loads, WSDOT designs for a simple-span distribution of loads. Additionally, straight prestressing strands in the bottom flange extend into the substructure to ensure connectivity and moment capacity under seismic loads. With tub girders, there is less congestion of extended strands than with single-web sections. Together these practices remove expansion joints, control seismic deflections and prevent cracking under service.

Also, given that the variable bottom flange width has little effect on overall span capability, the designer has freedom to select a cross section geometry that balances the deck flexural design as well as overhang design. With this adaptability, as well as lateral capacity and aesthetic appeal, tub girders are particularly well-suited for single-girder pedestrian bridges.

TUB GIRDER FABRICATION

In developing the standard tub girders, WSDOT met with local precasting companies to coordinate standard designs that the precasters could achieve with one adaptable steel form. Thus far, the precasters have not experienced major fabrication difficulties. Figures 6 and 7 show the two steel forms of a self-stressing bed for tub girder fabrication.

Fig. 6 Outer Steel Form

Fig. 7 Inner Steel Form

In order to place the concrete in a two-web girder, one local precast plant pours the majority of the concrete into one web. The concrete then flows up the opposite web through the bottom flange, and the opposite web is topped off afterwards. Initially there was concern that this procedure might lead to pocketing in the concrete, but in practice, the concrete flows through the bottom flange with no deficiencies.

One minor difference to typical single-web girders is that the bearing recesses for tub girders are more complicated to form in situations with asymmetric geometry. However, with the proper attention, this issue is easily managed by precasters. In addition, the handling of tub sections has not shown to be of any difficulty to precasters.

CASE HISTORIES

NORTH SPOKANE CORRIDOR

The North Spokane Corridor project was the first WSDOT project to utilize the new standard prestressed tub girder sections; this project used 54 in. and 66 in. deep sections up to 148 ft.

long in four simple-span bridges. Aesthetic impact drove many design decisions on this project, including the decision to use tub girders. Figure 8 shows one bridge upon completion of the bridge construction contract; roadway approach work fell under future contracts.

Fig. 8 Tub Girder Bridge near Spokane, WA

The largest bridge on this project, a 148-ft. span carrying a 37-ft. roadway on a 2% superelevation, required four U66G4 units spaced at 9 ft. Figure 9 shows the girder placement operation. In this case, the maximum shipping weight restriction of 200 kips precluded the bridge from spanning a larger distance. However, the high abutment walls on this project allowed for the limited span length while concurrently providing wingwalls as a medium for architectural designs.

Fig. 9 Tub Girders Being Placed near Spokane, WA

During construction, some complications arose due to the contractor's unfamiliarity with tub girder sections. The contractor shipped the girders to the site less than a month after casting, and this fact, combined with errors in field surveys, led the contractor to believe that the girders were failing under their own self-weight. Furthermore, there was concern that the webs would buckle out-of-plane due to self-weight and non-composite deck loads. After much debate, refined field measurements and further analysis proved these worries unwarranted. Still, the lack of camber did render the extended web stirrups too short for an ideal shear connection as designed.

The deck placement operation did run into a notable constructability issue due to the lack of interior diaphragms in the framing plan. Though tub girders did not require the diaphragms for stability, the deck finishing truss loads on the exterior girders required further load distribution. The exterior girders exhibited differential vertical and torsional deflections under this construction load. In the future, WSDOT will include interior diaphragms in tub girder projects of sufficient length or width.

One small fabrication issue arose for the girders of a bridge that required a 6% superelevation. During the precast forming process it was realized that due to the skew, profile grade, large bearing size, and out-of-plumb girder placement, some corners of the bearing recesses broke the plane of the minimum cover requirement. WSDOT decided that the lack of environmental exposure warranted lenience on this issue.

I-82 UNDERCROSSING AT SR 24

The second state project to be constructed using WSDOT standard tub girders was an I-82 undercrossing in Yakima, Washington. This project replaced a four-span RC flat slab with a 158-ft. long two-span live-load-continuous structure in order to provide horizontal clearance for future interstate widening. The bridge was constructed in stages with a 112 ft. total roadway deck width, and the superstructure was comprised of 11 lines of 27-1/2 in. deep tub girders spaced at 10’-4”. The site required shallow tub girder sections due to the crest curve stopping sight distance requirements on the bridge and vertical clearance requirements under the bridge. WSDOT designs the majority state route bridges with 7.5” CIP decks for durability, therefore the bridge required a section capable of a 1/27 depth-to-span ratio for simple-span design. Figure 10 shows the selected tub girders in place during the first stage of construction.

Fig. 10 Tub Girder Bridge Prior to Deck Placement in Yakima, WA

Tub girders were an ideal section for this bridge because of their structural efficiency. Deck girders such as flat slabs are capable of similar span-to-depth ratios without the CIP concrete deck; however, the sacrifice would be reduced durability and a potentially more complicated connection between construction stages. The girder-pier connections of this bridge are also designed for full seismic loads, and this bridge is the first WSDOT bridge to demonstrate the tub girder's ability to be made continuous for live load by conventional deck reinforcement. In the past, WSDOT used post-tensioned spliced tub girders to achieve live-load continuity.

As of the summer of 2006, the first stage of construction is carrying traffic. With the exception of under strength CIP concrete in the deck and abutments, no major construction issues have arisen.

CONCLUSION

WSDOT developed tub girders have shown to be a structurally efficient alternative to single-web sections for a large range of spans up to 150 ft. for typical concrete strengths in Washington State. These sections also have a large composite section stiffness which allows for slimmer structures, and bridge projects with tight roadway geometry requirements have already taken advantage of this ability.

The major competitive hurdle for tub sections in the long span range of non-post-tensioned construction is the large shipping weight of multi-web sections. Aside from its post-tensioned standards, WSDOT and local precast facilities are considering structural lightweight concrete as a possible solution to this problem. With a lighter gross weight, WSDOT designs would utilize the full prestress capacity larger standard tub girders. As mentioned above, by reducing seismic loads, structural light weight concrete may also contribute to lowered project costs for bridge substructures.

As expected, the first projects to utilize WSDOT standard tub girders have witnessed large price premiums for girder fabrication. Precast facilities are recuperating the cost of their investment in tub girder forms, and as of 2006, the market competition for tub girder contracts lags behind that of typical WSDOT developed I-sections. It is not yet certain to what level tub girder prices will equilibrate relative to other PC/PS sections in the state.

Nevertheless, recent WSDOT projects have successfully used tub girders in PC/PS bridges with both stringent span requirements and aesthetic requirements. Along with the post-tension capable counterparts, the new WSDOT tub girder sections provide designers expanded options for the increasingly predominant method of prestressed concrete bridge construction.

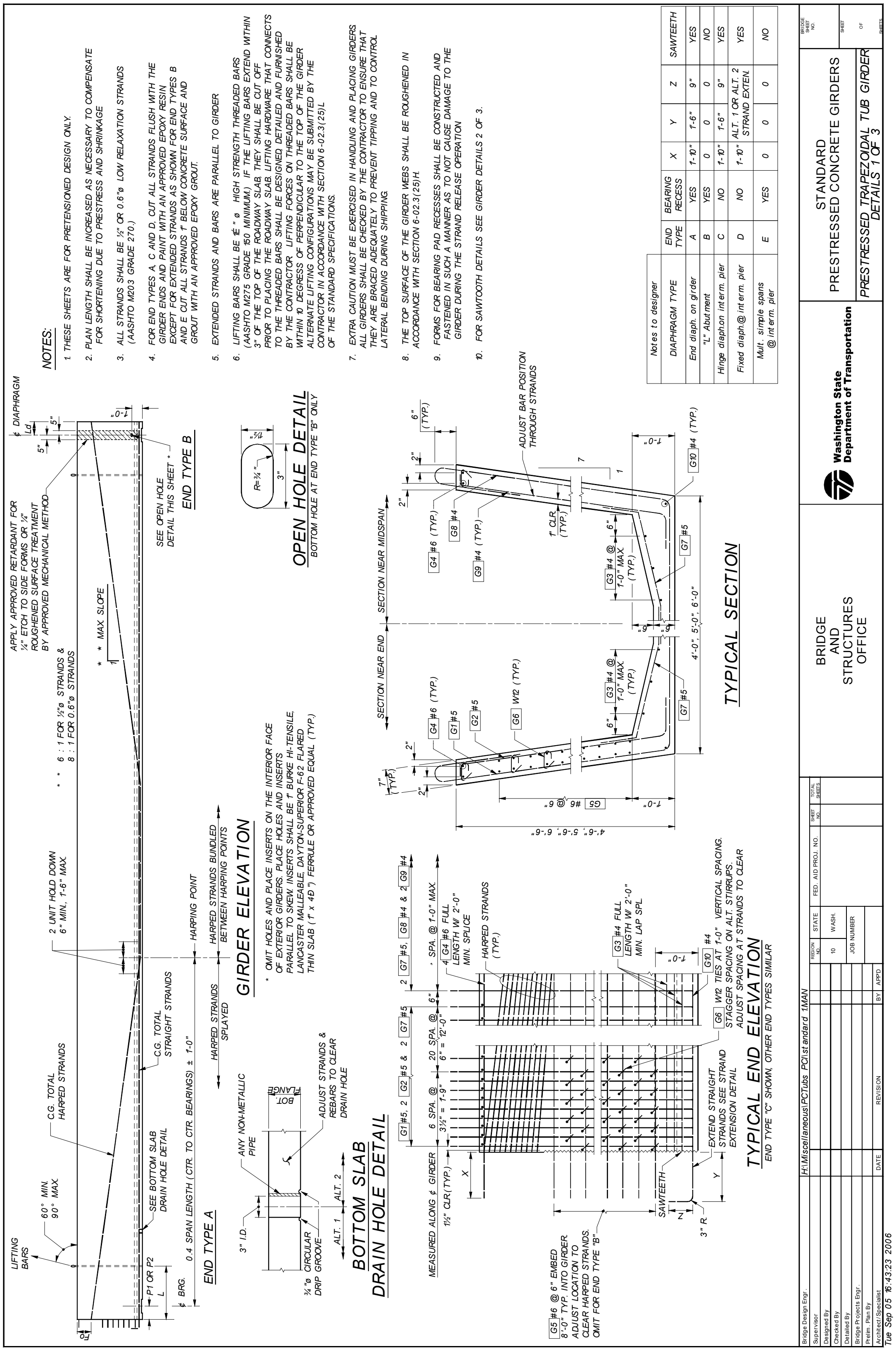

Fig. A1 Standard Drawing for Trapezoidal Tub Girder, 1 of 3

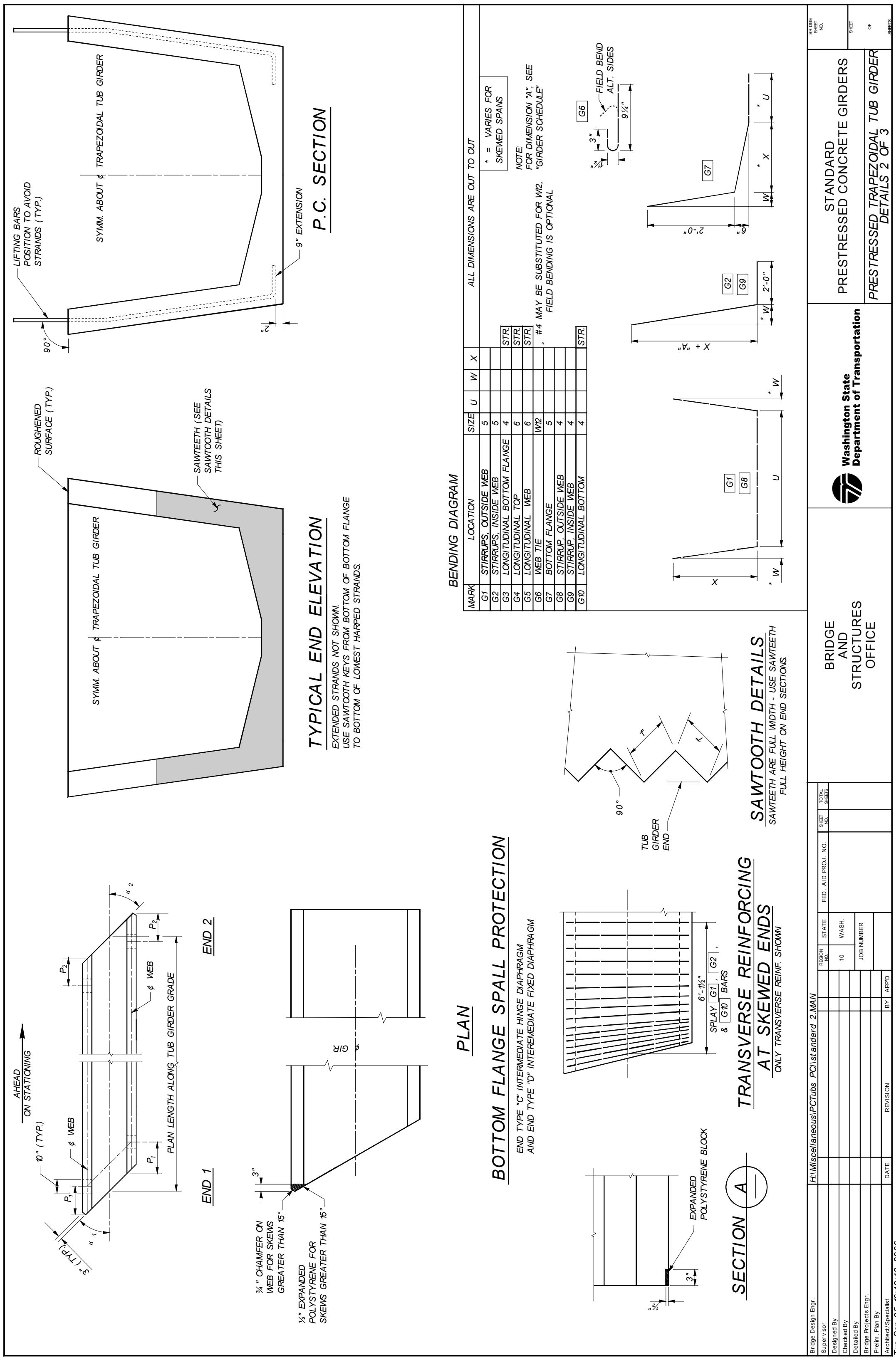

Fig. A2 Standard Drawing for Trapezoidal Tub Girder, 2 of 3

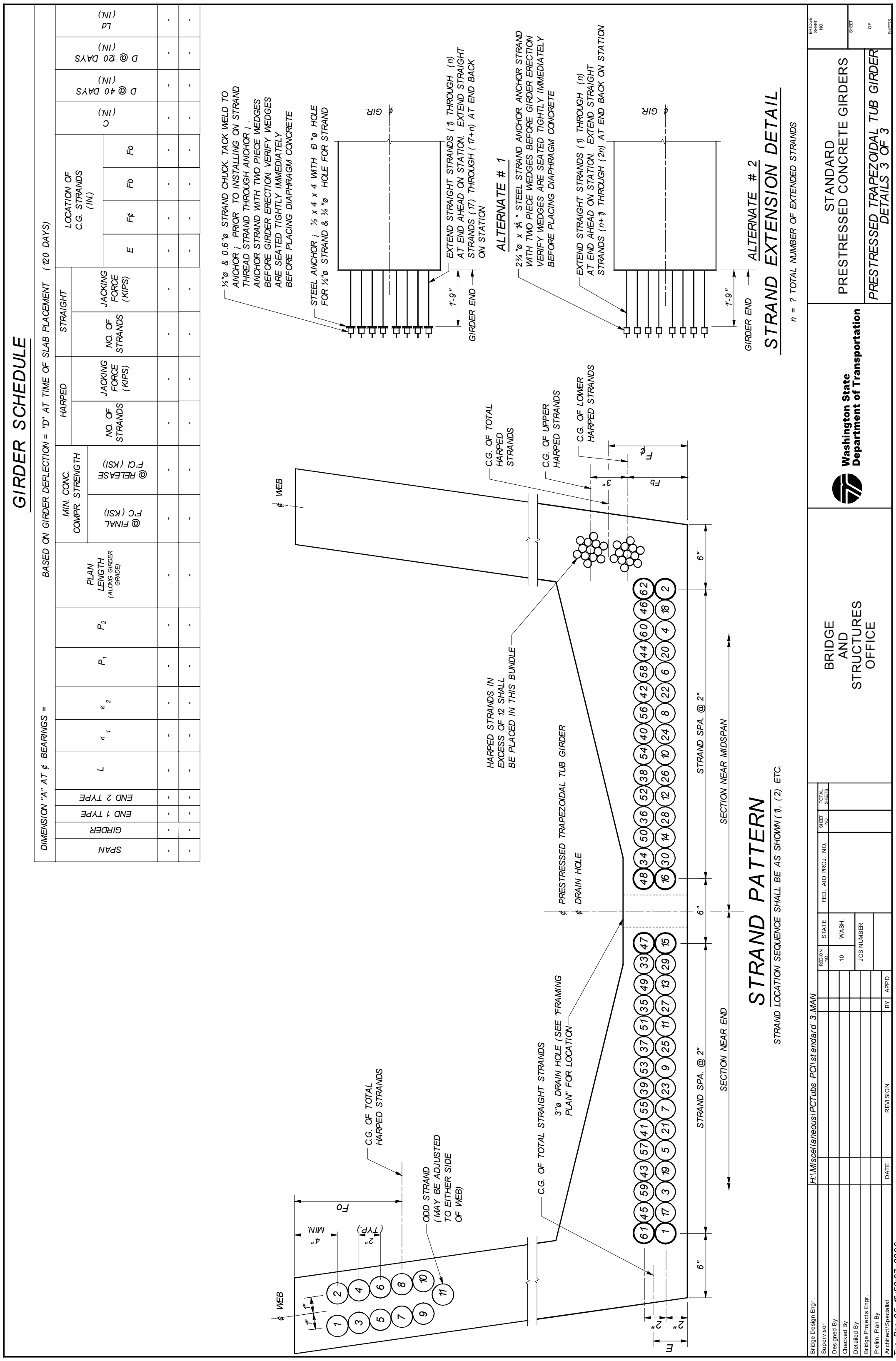

Fig. A3 Standard Drawing for Trapezoidal Tub Girder, 3 of 3