# Precast Innovation in Washington State

**Richard Brice, PE**, WSDOT Bridge and Structures Office, Olympia, Washington

## ABSTRACT

The Washington State Department of Transportation (WSDOT) continuously innovates with precast solutions. This paper highlights recent innovations including an improved design technique, software solution, and the introduction of three new girder sections. WSDOT girder designs now consider installation options for temporary strand used to improve lifting and transportation stability. These options give producers more flexibility during fabrication while minimizing the adverse impact of altering the design camber. Our PGSuper software, which is jointly developed by the Washington State and Texas Departments of Transportation, has been enhanced to accommodate this new design technique and gives designers new bridge modeling and analysis capabilities. Working with our industry partners, 36", 66", and 100" deep wide flange girder sections have been developed to round out the Washington WF girder series. These new girders provide efficient and cost effective solutions for span lengths ranging between 60 and 210ft.

**Keywords**: Precast, Prestressed, Girders, Design, Optimization, Fabrication, Software

## Introduction

The Washington State Department of Transportation (WSDOT) has a strong collaborative relationship with its PCI industry partners. Working together, WSDOT and industry continuously refine practices and procedures and develop new and innovative solutions for mutually beneficial results. Recent innovations include the development of an improved precast-prestressed girder design technique, enhancements to precast-prestressed girder design software, and the development of three new girder sections.

The design procedure optimizes the girder design while taking into account the limitations of local fabrication facilities and the impact of various temporary top strand installation options a producer may elect to use. The design procedure and fabrication options account for and limit impacts to the predicted long term camber.

Software is required to design precast prestressed girders in a time efficient manner, and if properly managed, software solutions also provide the benefit of standardized and consistent designs throughout an owner's bridge inventory. WSDOT's girder design software, named PGSuper, has been updated to reflect the current AASHTO LRFD specifications, encapsulates the design procedure described in this paper, and provides designers with enhanced engineering capabilities.

Working with industry, 36", 66", and 100" deep wide flange girder sections have been developed for the Washington WF-series girders to provide efficient and cost effective solutions for span lengths ranging between 60 and 210ft. Each girder was developed for different and unique reasons as will be described in this paper.

## Designing for Fabrication Options

The use of high performance (HPC) and high strength concrete (HSC) and 0.6" diameter strand in the fabrication of precast, prestressed concrete girders has resulted in improved economy through the use of longer spans, increased girder spacing (or fewer girder lines), and shallower superstructures. However, the design of high performance precast-pretensioned concrete girders presents several issues with respect to challenges in fabrication, shipment, and erection of long, slender girders. Techniques to overcome many of these challenges, such as the use of temporary top prestressing to improve stability during shipment, are presented elsewhere.[6]

While most of the difficulties in fabricating long span HPC bridge girders have been overcome, some challenges remain. The primary issue is the capacity of prestressing plants. The stressing beds were not designed for the size of girders being constructed today. Modern long span HPC girders utilize more and larger strands, resulting in significantly larger jacking forces. These girders are much taller than other girders. The increased prestressing force and larger eccentricities at girder ends combine to produce overturning moments that quickly reach the capacity of most existing prestressing lines.

Fabricators are producing girders for many projects and many customers simultaneously. To produce these girders in the most efficient manner possible, flexibility is needed to schedule different girder sizes and stressing requirements on the available prestressing lines. It is extremely undesirable for a prestressing line to sit vacant because it does not have the capacity to produce a particular girder, when in fact it could if the design were optimized. This is clearly not productive for the fabricator and will adversely impact the customer's schedule.

The goal of optimizing for fabrication is to give fabricators the flexibility necessary to maximize the usage of their prestressing plant while reducing the time and labor required to produce girders. The benefits of optimization are reduced costs, improved schedule and enhanced quality. The more flexibility afforded to the fabricator equates to the lowest cost and the best schedule for all the girders being produced, whether it be for a single project or several projects at the same time.

## *Design Procedure*

The limiting capacity for most prestressing lines is either jacking capacity or overturning of the anchorages (stressing abutment). The magnitude and eccentricity of the prestressing force combine to cause the overturning moment as shown in Figure 1. Four factors contribute to the increased demand on stressing beds than have been experienced in the past: (1) girder sections that have been optimized for HPC contain more strands than have been traditionally used, (2) strand size has been increased from 0.5" to 0.6" diameter, (3) a greater total jacking force is required to stress these strands, and (4) long span HPC girders are notably taller than previous standard girders (6 to 8 feet in depth) resulting in larger eccentricities and harped strand exit locations that are well above the floor of the stressing bed. The combination of increased jacking force and larger eccentricities combine to tax the overturning capacity of casting beds.

Long span HPC girders tend to be laterally unstable during lifting and transportation. The use of temporary top strands to improve stability is a common and effective practice[2, 3, 4, 6.] The temporary top strands are well above the floor of the casting bed with an eccentricity that is approximately equal to the height of the girder. The jacking force in 4 to 6 temporary top strands is small compared to that of the permanent strands; however their large eccentricity produces a significant overturning moment.

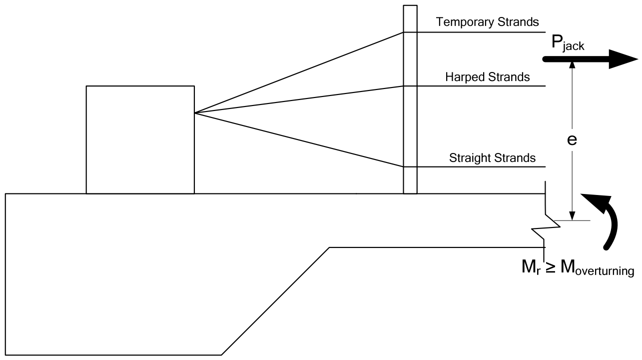


**Figure 1 Free Body Diagram of Critical Section of Prestressing Line**

Temporary top strands are used for stability of prestress girders during shipping and handling. These strands may be either pretensioned or post-tensioned. The timing and release sequence of temporary strands are important in both design and construction. Removal of the temporary top strands results in additional camber in the girder affecting the slab haunch depth and finished profile grade. Temporary top strands are removed after girders are erected and braced.

WSDOT is designing precast-prestressed girders with these fabrication challenges in mind. Overturning moment on prestressing lines is minimized by using as few harped strands as possible, selecting an optimum location for the harped strands to exit the girder while not interfering with other reinforcement, and using temporary top strands only when required for stability.

When temporary top strands are required for shipping it is most advantageous to pretension them along with the permanent strands. The use of pretensioned temporary top strands results in reduced release strength requirements, reduced long term camber, and reduced slab haunch requirements. However, the capacity of some prestressing lines is insufficient to withstand the overturning moment. Permitting the fabricator the option of post-tensioning the temporary top strands will reduce the demand on the prestressing bed.

Working in cooperation with industry, a new design procedure was developed. Each element of the design procedure is summarized below. It should be noted that, while this process is most critical for long, slender girders made of HPC, it is also beneficial to optimize girders of “normal” design. If temporary top strands are not required for shipping, steps 5 and 6 are simply skipped.

## Step 1 - Design for Final Service Conditions

Girders are designed for the final service condition. In this condition, the composite girder must carry its self-weight and the dead load of a cast-in-place deck on the non-composite section, and the superimposed dead load from traffic barriers, wearing surface, and appurtenances, and the live load on the composite section.

WSDOT Bridge Design Manual[7] limits the final tension in the Service III limit state to zero. Assuming a mid-span strand eccentricity, the required prestressing force, after all losses, can be computed using Equation 1 and the total number of prestressing strands can be estimated using Equation 2.

$$P = -\frac{f_{bottom}^{ServiceIII}}{\left(\frac{e}{S_b} + \frac{1}{A_g}\right)} \tag{1}$$

$$N = \frac{P}{a_{ps}\left(f_{pj} - f_{pT}\right)} \tag{2}$$

The required final concrete strength is then computed using Equation 3.

$$f_c' = \frac{\left(f_{top}^{ServiceI} + f_{top}^{prestresss}\right)}{0.6} \tag{3}$$

This brief process is for preliminary sizing of the prestressing. This estimate can be refined by computing the actual eccentricity and prestress loss using the required number of strands and iterating until the number of strands, prestress force, eccentricity, losses, and concrete strength all converge. Later in the design process, a full design check of all the LRFD requirements is performed.

## Step 2 - Design for Lifting without Temporary Top Strands

If temporary top strands are required for a design, it is most advantageous to pretension them along with the permanent strands. However, the temporary top strands increase the total jacking force and overturning moment the stressing bed must withstand. To reduce the demand on the stressing bed, temporary top strands may be post-tensioned prior to lifting, if required for stresses or lifting stability, or after the girder has been moved to a finishing station if required only for shipping.

There are three critical sections in the girder during lifting: the harp point, the lifting point, and the point of prestress transfer. The eccentricity of the strands at the harp point does not significantly change with changes to the harped strand exit location at the end of the girder and the proportioning of the total number of strands between straight and harped. For this reason, the harp point becomes the critical location for determining the required release strength to satisfy the allowable stress limits.

The design of this step is considered to be optimized when the stresses at either the lifting point or prestress transfer point are approximately equal to the stresses at the harp point. The stresses at these locations are manipulated by changing the proportion of straight and harped strands. Experience has shown that a good rule of thumb is to start with one harped strand for every two straight strands.

Starting at approximately 2 feet from the ends of the girder, move the lifting locations towards the center of the girder until lateral stability is achieved. Compute the stresses at the harping point and determine the required concrete release strength. This will be the largest required concrete release strength of all the fabrication scenarios; however it will also have the smallest overturning moment and prestress jacking demand on the stressing bed.

It is desirable to have the harped strands exit the girder as low as possible to minimize the overturning moment they cause. However, typical connection details require several reinforcing bars to protrude from the end of the girder. To avoid congestion and conflict between the harped strands and other reinforcement, the design is optimized by using as few harp strands as possible and having those strands exit the section without interfering with other reinforcement, violating any strand slope requirements, or causing the allowable stress limits to be exceeded.

Adjustments to the harped strand configuration alter the stresses at the transfer and lift points. Harped strands are converted to straight strands by decrementing the harped strand count by two and increasing the straight strand count by two. Strands are converted in pairs so that the total prestress force remains symmetrical about the vertical axis of the beam. The ratio of straight to harped strands is increased until either the straight strand pattern is full or converting one more pair of harped strand would cause the allowable stress limit to be exceeded. This establishes the optimal proportion of the straight and harped strands.

If the lifting stability requirements cannot be satisfied, lifting without temporary top strands is not an option during fabrication. Temporary top strand requirements are generally greater for shipping than lifting. The temporary top strands will be designed for shipping and later evaluated for lifting.

## Step 3 - Design for Release without Temporary Top Strands

Designing for release consists of computing the required release strength to strip the forms and impart the pretension force into the girder. Since the fabricator is given the option of either pretensioning or post-tensioning the temporary top strands, the designer does not know if they will be present when the prestress force is transferred to the girder and the forms stripped. The worst case for release strength, for the girder sitting in the form, is when the temporary top strands are not installed.

## Step 4 – Estimate Temporary Top Strand Requirement

Long, slender precast girders tend to be very flexible laterally and are transported on trucks with flexible supports. The flexibility of the truck supports, the superelevation of the roadway, and the lateral deflection of the girder combine during transportation to reduce the rollover stability of the truck. Reducing the distance between shipping support points will greatly reduce the lateral deflection of the girder, thereby increasing rollover stability. The lateral deflection is reduced by both the shortened distance between support points and the balancing effect of the longer girder cantilevers.

Moving the shipping support points closer together increases rollover stability; however it also increases the stresses at the harp point and support points. The stresses at the harp point increase because the dead load moment decreases. The stresses at the support points increase because the length of the cantilever overhang increases. Temporary top strands are added to the girder to keep the stresses within the allowable limits.

Starting at approximately 5 ft from the end of the girder, the truck support locations are moved toward the center of the girder until the stability requirements are satisfied. If they cannot be satisfied, temporary top strands are added and the support locations are investigated again.

## Step 5 - Design for Lifting with Pretensioned Temporary Top Strands

If temporary top strands are required for shipping, they will have a favorable influence on lifting. Temporary top strands improve girder stability permitting the lifting embedment to be moved closer to the ends of the girder. This in turn, increases the dead load moment at the harping point. The stress due to dead load serves to more effectively counteract the stress due to prestressing. The required concrete release strength under these conditions is computed. This scenario will require the lowest concrete release strength but will have the highest overturning moment demand on the stressing bed.

## Step 6 - Design for Lifting with Post-Tensioned Temporary Top Strands

Post-tensioned temporary top strands are used when the prestressing bed does not have the capacity to pretension them in addition to the permanent strands. There are three possible scenarios for the use of these strands:

1. If temporary top strands are required for shipping, but not for lifting, they can be added to the girder after it has been moved to the finishing area. This quickly frees the production line for the next girder to be constructed. The lifting locations are the same as for lifting without temporary top strands, which requires the highest concrete release strength. To minimize the impact on camber, the temporary top strands must be post-tensioned on the same day the permanent strands are released.
2. If, under scenario 1 above, the highest concrete release strength has not been achieved when the girder is ready to lift, the temporary top strands may be stressed before the girder is lifted. Since the lifting devices are located for lifting without temporary top strands, the calculated value of the concrete release strength will be intermediate to the cases of lifting without temporary top strands, and lifting with pretensioned temporary top strands. If this intermediate strength has been achieved, the girder can be lifted immediately after the temporary top strands have been stressed.
3. If the required concrete release strengths are high, but the prestressing bed cannot tolerate pretensioned temporary top strands, the fabricator can still pursue the minimum required concrete release strength by post-tensioning the temporary top strands prior to lifting. The same lifting locations for lifting with pretensioned temporary top strands are used in this case. The difference here is that the temporary top strands must be tensioned prior to lifting, or the lateral stability of the girder will be below the accepted factors of safety.

The advantage to post-tensioning, rather than pretensioning, the temporary top strand is that the overturning moment is not imparted into the stressing bed. This can make the difference between a production line being utilized or sitting vacant.

## Step 7 – Design for Shipping

Shipping long span precast girders is a delicate task. WSDOT considers two cases during shipping: plumb girder with 20% impact and an inclined girder without impact. The impact case represents the girder traveling the highway under normal conditions. There will naturally be a certain degree of vibration due to the roadway surface conditions. The inclined case represents the truck moving at a slow speed (or stopped) on a curve with superelevation or uneven ground at the construction site. In this case, the centrifugal forces are insignificant or nonexistent and impact is not present.

Stresses are computed at the support and harping points. Using the WSDOT allowable stresses shown in Table 1, the required concrete strength at shipping is computed.

| | |
|---|---|
| Compression | $0.6 f'_c$ KSI |
| Tension in plumb girder with ±20% impact | $0.0948\sqrt{f'_c}$ KSI |
| Tension in plumb girder with ±20% impact in areas with bonded reinforcement sufficient to resist the tensile force in the concrete | $0.19\sqrt{f'_c}$ KSI |
| Tension in inclined girder without impact (inclined due to truck support flexibility and roadway superelevation) | $0.24\sqrt{f'_c}$ KSI |

**Table 1 Allowable stress during shipping**

## Step 8 - Check Final Service and Strength Conditions

The flexural design is finalized by ensuring the girder satisfies all of the applicable service and strength requirements defined by the AASHTO LRFD Bridge Design Specifications and WSDOT Bridge Design Manual. Minor adjustments to the strand configuration and concrete strength will generally suffice to satisfy any unmet allowable stress criteria. At the strength limit state, ultimate moment capacity is generally not an issue. The strength limit state is most likely to govern for shallow, short span girders, in which case stability is rarely a concern.

## Fabrication Options

The resulting fabrication options are summarized in the following example table. The table lists the various combinations of concrete release strength and lifting embedment location for the acceptable temporary top strand installation methods.

| Number of Temporary Top Strands | Jacking Force (kip) | Lifting with Pretensioned TTS | | Lifting with Post-Tensioned TTS | | Lifting without TTS* | |
|---|---|---|---|---|---|---|---|
| | | L (ft) | $f'_{ci}$ (ksi) | L (ft) | $f'_{ci}$ (ksi) | L (ft) | $f'_{ci}$ (ksi) |
| 6 | 263.7 | 9.50 | 7.0 | 12.0 | 7.1 | 12.0 | 7.4 |

* TTS must be installed the same day as prestress release to maintain design camber and losses

### *Impact on Camber*

Temporary top strands are employed to improve girder stability during handling and transportation. As mentioned earlier, they also have a favorable influence on release strength and camber. Pretensioned temporary top strands reduce the initial camber in the girder and limit the time dependent camber growth due to creep.

Choosing a fabrication option that significantly alters the design camber is very undesirable. When the camber is larger than the value predicted by design the top of the girder can interfere with the slab reinforcing and require changes to the roadway profile, bearing seat elevations, and adversely impacts ride quality. When the camber is less than the design value, the depth of the slab haunch must be increased to maintain the roadway profile. An increase in the slab haunch results in additional material costs and dead load demand on the structure.

The fabrication options presented above are selected such that they minimize impact on camber. WSDOT designs girders for the pre-tensioned temporary top strand case. This is the most effective design when temporary top strands are required. The post-tensioned options have approximately the same impact on camber as the pre-tensioned case. This is because the post-tensioned temporary top strand force is imparted onto the girder either immediately after form stripping or shortly after moving the girder from the stressing bed to a finishing station. The temporary top strand force is imparted on the girder while the concrete is at a very young age.

## Innovative Software for Precast Design

PGSuper™ is software for the design and analysis of precast-prestressed girder bridges. This program models simple and continuous span precast-prestressed girder bridge structures and designs in accordance with the AASHTO LRFD Bridge Design Specifications. PGSuper is jointly developed by the Washington State and Texas Departments of Transportation (WSDOT and TxDOT). The most recent version of PGSuper has an improved automated design feature, new analysis capabilities, and enhanced Bridge Information Modeling (BrIM) capabilities.

### *Automated Design*

The automated design feature in PGSuper determines the prestressing requirements, concrete strength requirements, and optionally, the lifting, transportation, and slab haunch requirements. WSDOT primarily designs precast-prestressed girders with harped strands. Early versions of the automated designer were limited to harped strand designs. One of the major contributions TxDOT has made to the PGSuper project is the development of algorithms to design debonded strands. The software can now determine the number and configuration of debonded strands required to satisfy debonding and allowable stress limits.

The automated design algorithm was also enhanced to including the design procedure described above. When temporary top strands are required for shipping, the resulting design is optimized for a girder constructed with pretensioned temporary top strands. A fabrication options analysis was also added to the software to assist engineers in evaluating an alternative temporary strand installation proposal submitted by a fabricator.

## *New Analysis Capabilities*

Several new analysis capabilities have been added to PGSuper. These features give engineers more flexibility in performing design calculations and automates several calculations that otherwise had to be done by hand. As will be described in the next section, PGSuper now has the capability of modeling flared girders, cross sections with mixed girder types, and bridges with a different number of girders in each span. These bridge configurations push the limits of applicability of the AASHTO LRFD approximate method of analysis described in LRFD Article 4.6.2.2. Additional methods for computing live load distribution factors have been added to the software. An engineer may now choose one of the following options:

- Compute distribution factors in accordance with LRFD 4.6.2.2. Halt the analysis if the bridge parameters are outside of the prescribed range of applicability
- Compute distribution factors in accordance with LRFD 4.6.2.2 ignoring the range of applicability requirements
- Compute distribution factors in accordance with LRFD 4.6.2.2. Compute distribution factors using the lever rule when the bridge parameters are outside of the range of applicability
- Compute all distribution factors by the lever rule
- Compute distribution factors outside of the PGSuper and input them into the software

Additionally, an engineer can specify that the software constrain the live load distribution factors so that they are not less than the number of lanes divided by the number of beams.

The global stability of girders that are placed with their top flange parallel to the roadway surface is evaluated. Stability of the girder can be an issue for deep deck bulb tee sections with wide top flanges used on curves with high superelevation. The software checks that the dead load reaction falls within the middle third of the bottom flange.

The live load analysis has been enhanced to accommodate user defined vehicles that can be applied to the typical strength and service limit states and the Strength II permit limit state. Live load reactions are computed with and without impact. Reactions without impact are used for substructure design.

All of the parameters required for elastomeric bearing pad design are computed and tabulated in a concise report.

Pedestrian and bicycle only bridges and bridges with pedestrian on sidewalk loading can now be modeled in PGSuper.

## *Enhanced Bridge Information Modeling*

Another area where WSDOT is innovating in its software is Bridge Information Modeling (BrIM). BrIM begins with modeling the real world data that describes a bridge and the parts of its surrounding environment that influence the structure. Since its inception, PGSuper has utilized bridge information including alignment data, vertical profile, and girder framing system definitions to build a robust model of a bridge.

There was a time when engineers made substantial efforts during the planning stage of a project to keep horizontal alignment transitions outside of the limits of a structure. Grade breaks were almost never permitted to occur on a bridge. Transitions and tapers within the limits of the bridge were avoided at seemingly all costs. Today we have to fit our bridges within the constraints of our existing infrastructure. Our bridges have to accommodate turn lanes at elevated intersections, transition into round-about traffic circles, accommodate merging traffic lanes, and support many other unique and interesting scenarios. New features have been added to PGSuper to facilitate the modeling of these complex bridge structures.

PGSuper can now model bridges with a different number of girders within a span, different spacing of girders at each pier, bridge decks with tapering edges, and a mix of girder types within a cross section. The number of girders within a span and the girder spacing can be used in conjunction with one other or separately to model flared or tapered structures. Mixing of girder types is typically done when adjacent members, such as voided slabs or box beams, are used to develop a specific bridge width. Mixed girder sections can also be used in widening situations where the existing structure uses girder types that are no longer available or geometric constraints require a shallower girder. Figure 2 shows a bridge modeled with several of the new geometric modeling capabilities.

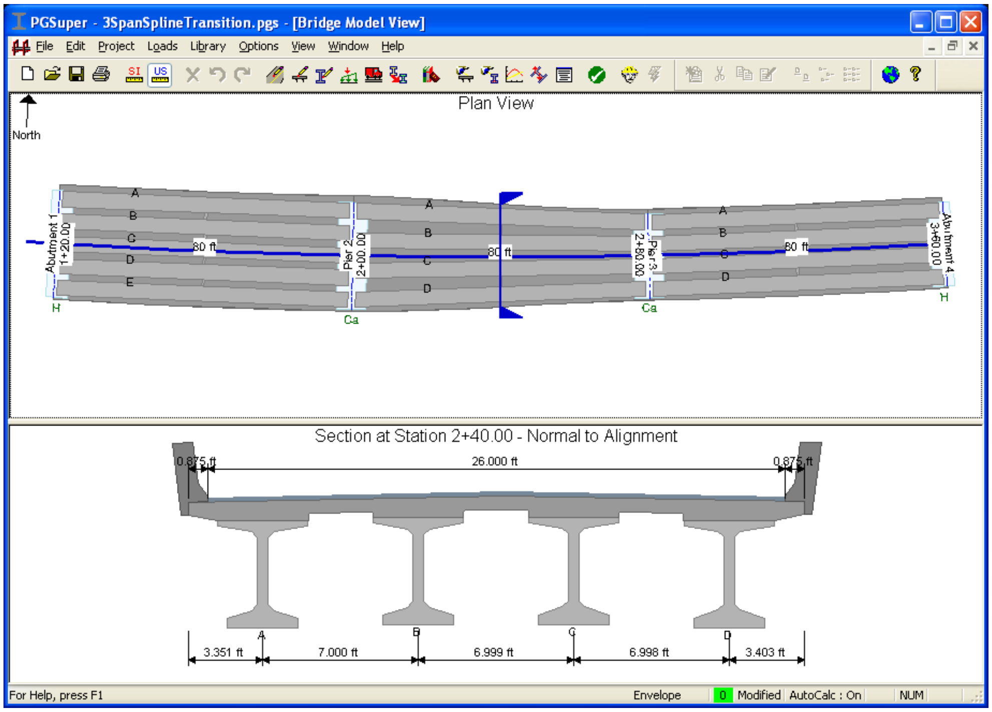


**Figure 2 Complex Bridge Modeled with PGSuper**

PGSuper can be downloaded free of charge from the WSDOT web site at http://www.wsdot.wa.gov/eesc/bridge/software.

## New Wide Flange Girder Sections

The WSDOT WF-series girder development began in 1996[5]. The objective of developing a new girder series was to improve economy by increasing span capabilities and allowable girder spacing over previous designs. High performance concrete (HPC) and 0.6" diameter prestressing strand make increasing the span lengths possible. The larger diameter strand can impart more prestressing force into a section than 0.5" diameter strand without changing the size of the section or the total number of strand. The higher strength of HPC balances the additional compressive force.

The WSDOT WF-series girders include the WF36G, WF42G, WF50G, WF58G, WF66G, WF74G, WF83G, WF95G, and WF100G girders. The numeric part of the designation represents the nominal depth of the girder in inches. The WF83G and WF95G were developed during the most recent attempt at adopting the SI system of units. Their depths were established with hard metric dimensions and thus do not represent their actual depth in inches. Figure 3 shows a typical section. Table 2 lists the geometric properties of the WF series girders.

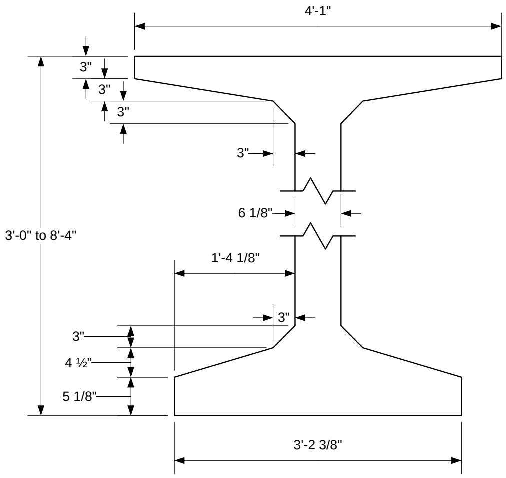


**Figure 3 Typical Section for the WF-Series Girder**

| **Girder** | **Depth (in)** | **Area ($in^2$)** | **$Y_t$ (in)** | **$Y_b$ (in)** | **I ($in^4$)** |
|---|---|---|---|---|---|
| WF36G | 36 | 692 | 18.5 | 17.5 | 125067 |
| WF42G | 42 | 728.5 | 21.7 | 20.3 | 184043 |
| WF50G | 50 | 777.5 | 25.9 | 24.1 | 283126 |
| WF58G | 58 | 826.5 | 30 | 28 | 407028 |
| WF66G | 66 | 875.5 | 34.2 | 31.8 | 557328 |
| WF74G | 74 | 924.5 | 38.4 | 35.6 | 735603 |
| WF83G | 82.625 | 977.4 | 42.8 | 39.8 | 960951 |
| WF95G | 94.5 | 1050 | 49 | 45.5 | 1331041 |
| WF100G | 100 | 1083.8 | 51.8 | 48.2 | 1527209 |

**Table 2 WF-Series Girder Geometric Properties**

The WF-series girders are some of the most efficient girders in use today. Figure 4 compares the Guyan[8] efficiency factors, computed as $\rho = \frac{I}{A_g Y_t Y_b}$ , for the WSDOT WF-series, WSDOT W-series, Nebraska NU, and AASHTO girders.

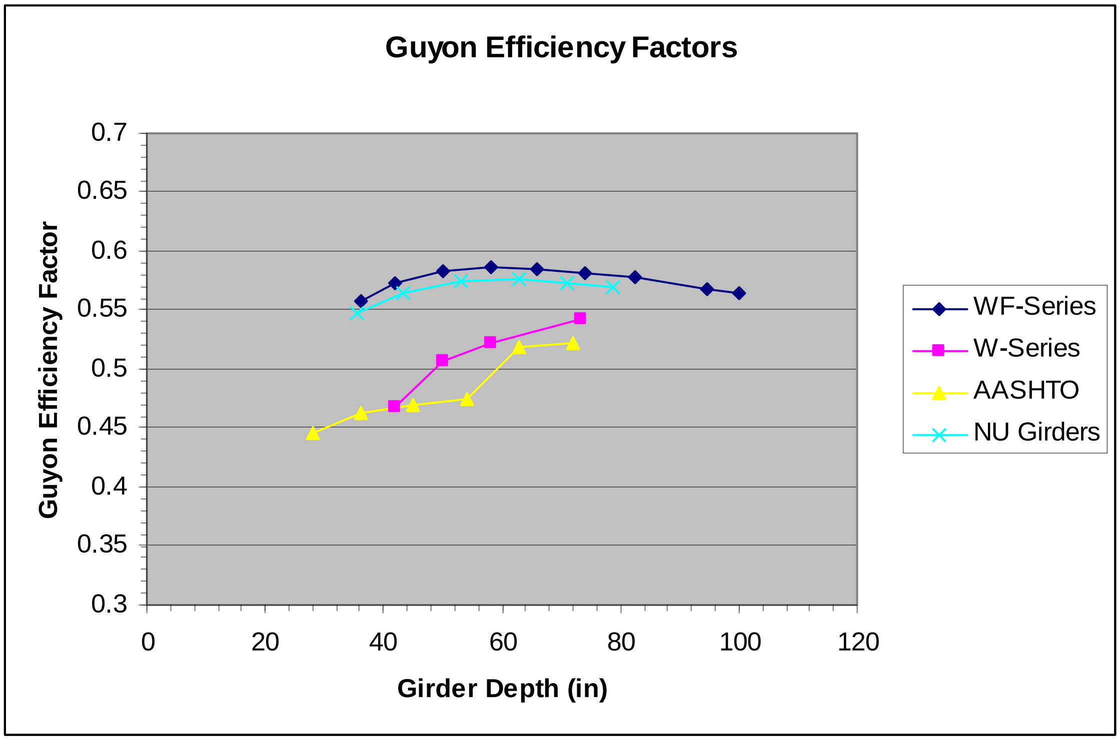


**Figure 4 Girder Efficiency Comparison (Ref. 8)**

The WF83G and WF95G girders were the first to be developed in this series. The goal was to exceed the span capabilities of WSDOT's then largest girder the W74G. The WF42G, WF50G, WF58G, and WF74G where developed next as replacements for the W42G, W50G, W58G, and W74G girders. For the same depth, the WF-series girders can easily span greater distances then their W-series counterparts. The W-series girders were optimized for normal strength concrete and 0.5" diameter strands. The capacity of HPC could not be fully realized in the W-series girders. The bottom flanges were simply too small for the number of 0.6" diameters strands required to balance the higher allowable compressive stress. The WF-series girders have a larger bottom flange that can accommodate up to 46 straight and 36 harped strands. This allows a much higher pre-compression force to be imparted on the section.

The WF36G, WF66G, and WF100G girders were developed for three separate and unique reasons. The WF36G girder provides an economic "long span" solution in low profile applications. The WF66G girder "fills the gap" in span capabilities for the WF-series girders. The WF100G girder takes advantage of technological advances in the local industry.

## *WF36G Girder*

WSDOT traditionally uses voided slab sections in low profile, short span applications. On a recent project, the span lengths of 26" deep voided slabs were extended into the 80 ft range. Relatively speaking, this is a "long span" application of a low profile member.

These were very flexible members with a span to depth ratio of 37. The camber of these members proved difficult to predict and was problematic during fabrication. A design policy decision was made to limit the span to depth ratio of voided slabs to 33. Industry proposed a 36" deep wide flange section for the WF-series for use in future low profile, "long span" applications. Compared to a 36" deep voided slab, the WF36G girder weighs half as much, has a greater structural efficiency, and is more economical to fabricate. The economy of the WF36G section coupled with the additional cost of forming a cast-in-place deck can be balanced against the costs and savings associated with manufacturing, transporting, and handling a heavier voided slab section that does not required a significant forming system for the cast-in-place deck.

## *WF66G Girder*

The WF66G girder was developed for a very simple reason. Analysis of the WF-series shows a "gap" in the span capabilities. This can be seen in Figure 5. For spans that are between 130ft and 150ft in length the larger WF74G girder could be used with a wide spacing or the smaller WF58G could be used with a more narrow spacing. The WF74G would require fewer girders however the larger spacing will require a thicker deck, larger bearings, larger equipment for transportation and handling, and have a deeper profile. The WF58G girder provides a lower profile and can be transported and handled with smaller equipment. However, more girders and related components would be required. The WF66G provides a balance between structure depth, equipment size, and the number of girder pieces. Designers can optimize the bridge configuration by balancing the costs associated with the number of girders, the impact girder depth has on the overall structure, and transportation and handling costs related to the size of the equipment, number of delivery trips, and number of crane picks.

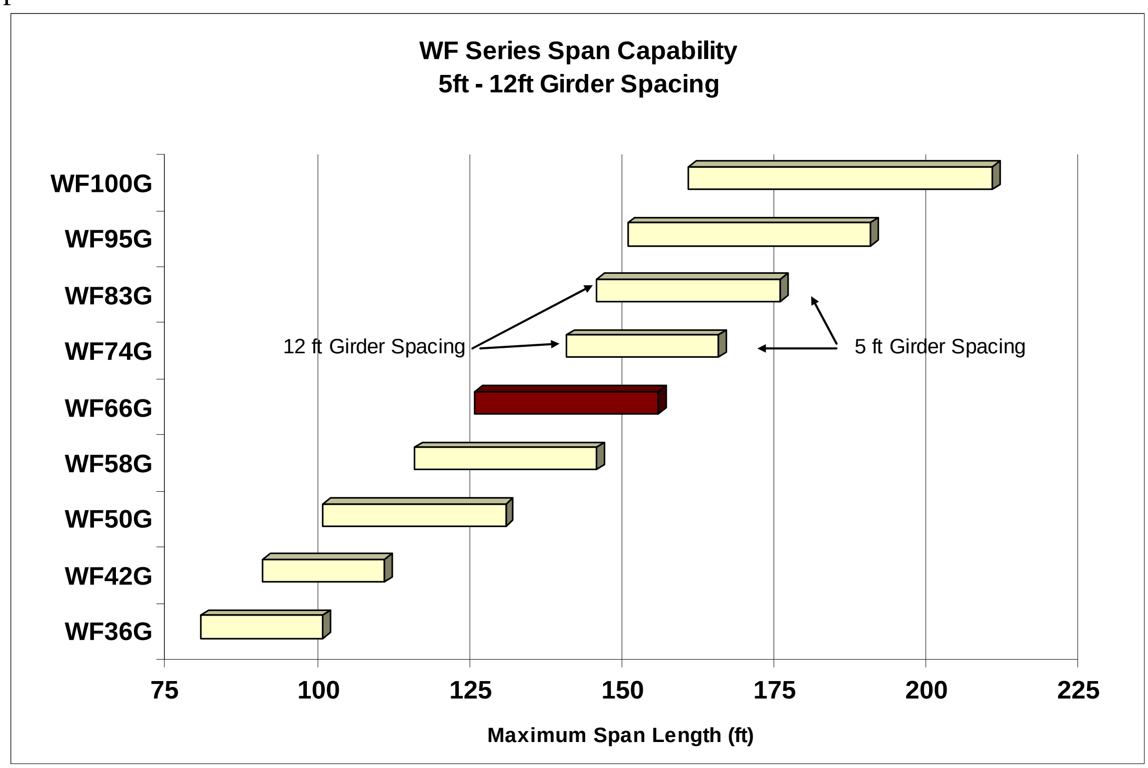


**Figure 5 Span Capabilities of the WF-series Girders**

## *WF100G Girder*

The WF100G girder has a depth of 8'-4" and can span up to 210ft at 5ft spacing using 70 permanent and 10 temporary 0.6" diameter pretensioned strands. Weighing in at 265,000 pounds, this massive girder requires 3.5 million pounds of pretension force, 7,100 psi concrete at release and 11,700 psi 28 day strength.

A girder of these proportions is only feasible if it can be fabricated and transported to the bridge site. The manufacturing and hauling capabilities available in Washington State have recently been upgraded. Concrete Technologies Corporation in Tacoma, WA has recently completed construction of their "Superbed" prestressing line. This stressing bed has parallel stressing lines and has the capacity to tension up to 100-0.6" diameter strands.

V. Van Dyke Trucking in Seattle, WA has recently purchased equipment capable of carrying loads up to 277,000 pounds. The axle width can be adjusted between to provide additional roll over stability.

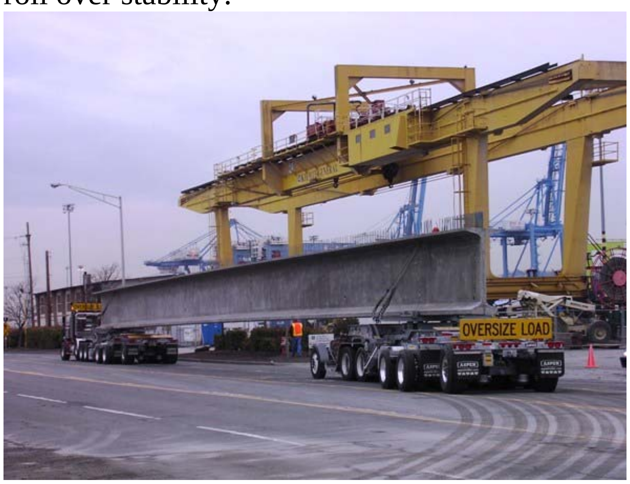


**Figure 6 WF-Series girder leaving casting yard**

**Figure 7 WF-Series girder at bridge site**

The WF100G girder at 210 ft and 265 kips is at the extreme upper limit for this girder. This configuration is only practical in special circumstances such as for bridge sites near the fabrication plant and at sites with transportation routes that do not require significant turning movements. The WSDOT Bridge Design Manual limits the size of girders based on shipping weight and hauling equipment. Table 3 summarizes these limits. In this table, "Old Equipment" refers to the standard equipment haulers have been using for decades. The "New Equipment" refers to the newly purchased equipment. The WF36G through WF66G girders are not shown because at their maximum span length the shipping weight is within the acceptable limits. Designers must estimate which equipment will most likely be used when selecting girder sizes.

| Leading End Equipment | Trailing End Equipment | Maximum Girder Weight (kips) | Span Length Limited by Weight (ft) | | | |
|---|---|---|---|---|---|---|
| | | | WF74G | WF83G | WF95G | WF100G |
| Old | Old | 170 | 160 | 152 | 140 | 135 |
| Old | New | 210 | | | 175 | 170 |
| New | New | 252 | | | | 200 |

**Table 3 WSDOT Shipping Weight Limits**

The WSDOT WF-girders have been recently adopted by the Utah DOT.

## Conclusion

An overview of recent innovations in the field of precast-prestress concrete bridges in Washington State has been presented. These innovations touch on many aspects of precast-prestressed girder bridge solutions. WSDOT has adopted an approach to girder design that accounts for the fabrication options and constraints for local fabricators. This design approach, as well as many other practices and policies have been standardized in a flexible software tool giving bridge engineers an efficient and effective means for designing precast-prestressed girder bridges. New girder sections have been developed to provide efficient and cost effective solutions for span lengths ranging between 60 and 210ft. The key to the success for these innovations is the cooperation between WSDOT and its PCI industry partners.

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# Appendix A – Notation

$P$ = Required prestressing force

$f_{bottom}^{ServiceIII}$ = Stress in the bottom flange at the Service III limit state

$f_{top}^{ServiceI}$ = Stress in the top flange at the Service I limit state

$f_{top}^{prestress}$ = Stress in the top flange due to prestressing

$e$ = Eccentricity of the prestressing strands

$S_b$ = Bottom section modulus

$A_g$ = Area of the girder

$N$ = Number of prestressing strands

$a_{ps}$ = Area of one prestressing strand

$A_{ps}$ = Total area of prestressing ($N \bullet a_{ps}$)

$f_{pj}$ = Stress in the prestressing strand at jacking

$f_{pT}$ = Total prestress loss