Designing Precast/Prestressed Concrete Bridge Girders for Lateral Stability

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ABSTRACT

Precast/prestressed girders in excess of 200 ft in length have become viable design options. The lateral stability of these girders is a serious concern. Initial lifting and transportation to the bridge site are often governing design cases. The Washington State Department of Transportation (WSDOT) has been designing precast/prestressed concrete bridge girders for handling and transportation for over 25 years. The Precast/Prestressed Concrete Institute (PCI) recently published recommendations for lateral stability of such girders. Additionally, PCI Pacific Northwest (PCI/PNW) and local heavy haulers approached WSDOT requesting updates to stability design practices to account for modern hauling equipment. This paper describes how WSDOT design practices accommodate the new PCI recommendations as well as the practical constraints of local fabricators and heavy haulers.

Keywords: Design, Long span girders, Stability, Software

INTRODUCTION

The span capability of precast, prestressed concrete bridge girders has been steadily increasing over the past two decades. This is due to new materials, better manufacturing processes and facilities, improved girder transport capabilities, and new engineering technology. Girders with lengths in excess of 200 ft have become viable options.

Washington State Department of Transportation (WSDOT) has refined design procedures, adapting to changes in the precast industry. Stability of long span girders has become a serious design concern. Lateral bending failures are sudden, catastrophic, costly, and pose a serious threat to workers and surroundings. Design of precast, prestressed concrete bridge girders has advanced from design for in-service conditions to designing girders for optimized fabrication and stability.

GIRDER DESIGN EVOLUTION

WSDOT has designed precast/prestressed girders for lifting and hauling for over 25 years. When spans were generally less than 120 ft in length, girders were not particularly deep, and stability was not a significant concern. The largest standard girder used by WSDOT was 74 inches deep with a span capability of 150 ft.

Handling design consisted of evaluating girder stresses during lifting from the form and hauling to the bridge site. Support locations during lifting and hauling are away from the girder ends by necessity. This reduces, or even reverses at the overhangs, the effectiveness of the dead load moment in counteracting the prestressing. The initial stresses in the girder are most severe when lifting the girder from the form. Uneven ground conditions cause a dynamic response in the girder during hauling. Stresses in the girder during hauling can exceed those experienced during other temporary construction conditions.

High performance concrete (HPC) became a standard material for the fabrication and construction of precast girders in Washington State at the end of the last the century[1,2]. Among many other advantages, HPC offered higher concrete strengths. Initial concrete strengths increased from 5.5 to 7.5 ksi and 28-day concrete strengths increased 7.0 to 9.0 ksi. Today, 28-day strengths of 10.0 to 15.0 ksi are achievable.

Higher initial concrete strength meant girders could accommodate a greater precompression force. To achieve the higher precompression force, 0.6” diameter strands replaced 0.5” diameter strand. The shape of the WSDOT W-series I-girder became a limiting factor. The geometry of the bottom flange did not permit enough strands, and thus enough precompression force, to take full advantage of the high early compression strength of the concrete.

WSDOT developed a new wide flange I-girder section, the WF-series girder, to take advantage of these new materials[2]. WF-series girders have a wider top flange to improve lateral stability and a larger bottom flange to accommodate more prestressing. Figure 1 compares the W and WF series girders. WF-series girder sections range from 36 to 100 inches deep. Theoretical span capabilities increased to 220 ft.

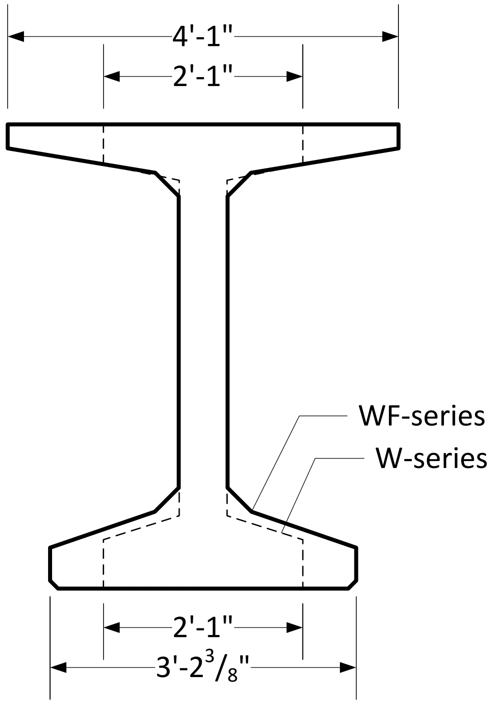


Figure 1 Comparison of W and WF series girders

Long span girders fabricated with HPC presented many new challenges. Of primary concern was the lateral stability of long slender girders and fabrication of these girders in existing stressing beds that were not design for the larger pretensioning forces and girder depths.

WSDOT addressed the lateral stability concern by incorporating the analysis techniques developed by Mast[3,4] into design procedures. The stability design objective was to establish handling support locations and temporary top strand requirements for safe lifting and hauling while maintaining compliance with applicable criteria.

Many precasting plants responded to the challenge of fabricating larger girders by installing greater capacity stressing beds. However, fabricators frequently produce girders for many projects and customers simultaneously. Flexibility to schedule different girder sizes and stressing requirements on available stressing beds enable fabricators to produce these girders in the most efficient manner possible. Not utilizing a stressing bed because it does not have the capacity to produce a particular girder, when it could had the design been optimized, is highly undesirable.

Working with local fabricators, WSDOT updated its design methodology and detailing practices for optimized fabrication of precast, prestressed concrete bridge girders. The primary goal is to determine the least required concrete strength at release and lifting while simultaneously placing the least possible demand on the stressing bed and achieving adequate stability of the girder during lifting and hauling operations. Brice et al[5] gives a detailed description and numerical example of optimized fabrication design. Figure 2 gives a high-level look at the design procedure. Girder stresses and stability at initial lifting and hauling are integral elements of the design process. Lifting and hauling conditions often govern the design.

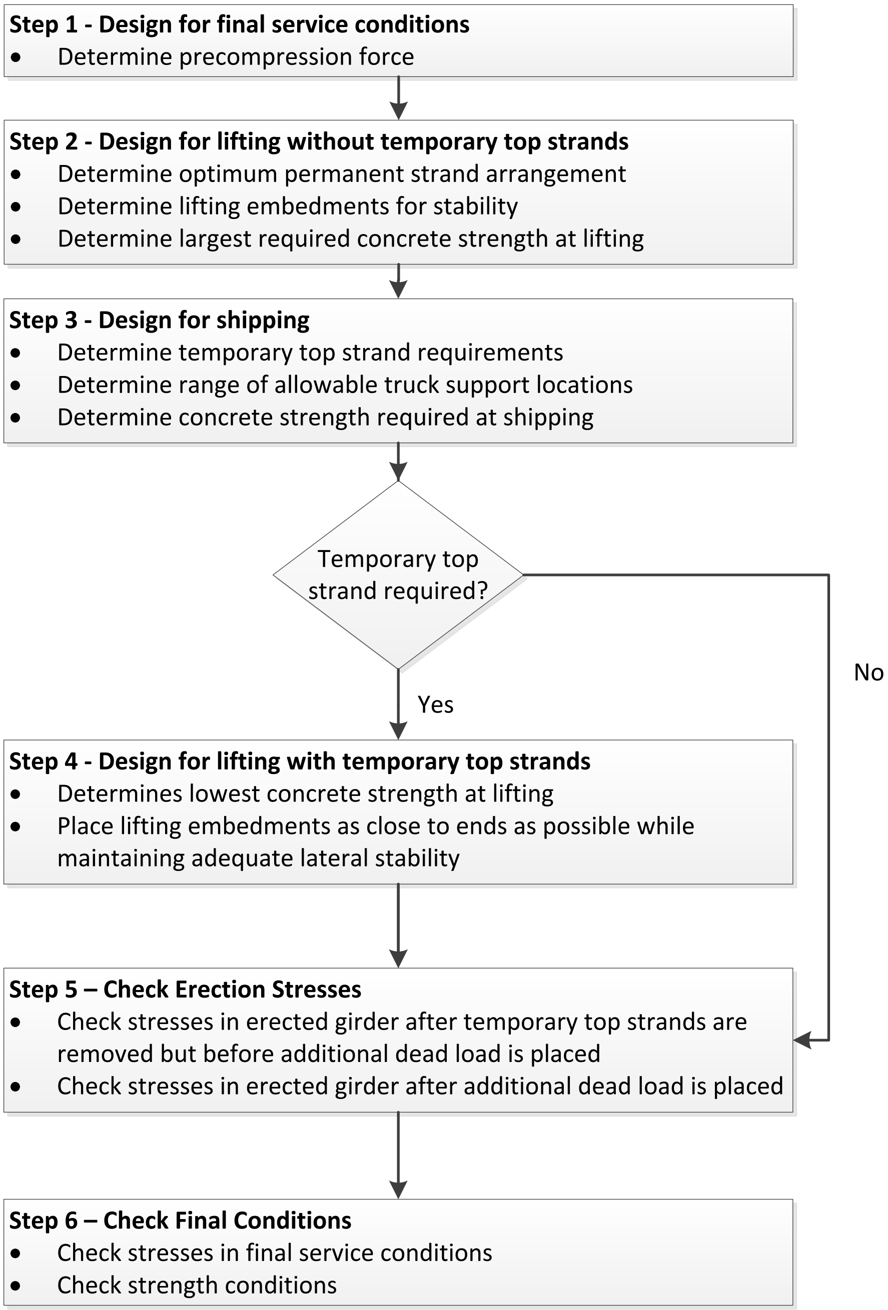


Figure 2 Girder design procedure for optimized fabrication

One key element of stability analysis is the recognition that girders are not always perfectly straight or supported exactly on their centerlines. This results in rotation about a roll axis until the girder is in an equilibrium configuration. WSDOT evaluates initial lifting stresses and stability for the girder in its equilibrium configuration. Table 1 lists the lifting stress and stability criteria used by WSDOT.

WSDOT evaluates three cases for hauling stresses and stability:

1. Stresses for girder in equilibrium configuration on a roadway with a normal crown slope of 2% subjected to a ±20% dynamic load allowance
2. Stresses for girder in equilibrium configuration on a roadway with a 6% superelevation and 0% dynamic load allowance
3. Stability of girder on a roadway with a 6% superelevation and 0% dynamic load allowance

Table 2 lists the hauling stress and stability criteria used by WSDOT.

Designing for stresses and stability does not include effects of wind or centrifugal forces. Contractors design the temporary bracing system as a means and methods item.

Table 1 Lifting stress and stability criteria

Allowable compression	$0.65f'_{ci}$
Allowable tension	$0.0948\lambda\sqrt{f'_{ci}} \leq 0.200ksi$
Allowable tension with sufficient bonded reinforcement	$0.24\lambda\sqrt{f'_{ci}}$
Factor of safety against cracking	1.0
Factor of safety against failure	1.5

Table 2 Hauling stress and stability criteria

Allowable compression	$0.65f'_c$
Allowable tension for normal crown slope	$0.0948\lambda\sqrt{f'_c}$
Allowable tension with sufficient bonded reinforcement for normal crown slope	$0.19\lambda\sqrt{f'_c}$
Allowable tension for superelevation slope	$0.24\lambda\sqrt{f'_c}$
Allowable tension with sufficient bonded reinforcement for superelevation slope	$0.24\lambda\sqrt{f'_c}$
Factor of safety against cracking	1.0
Factor of safety against failure and rollover	1.5

EXPERIENCE LEADS TO REFINEMENT

WSDOT has successfully delivered two projects with precast, prestressed girders with spans over 200 ft in length. The Alaskan Way Viaduct replacement project along State Route 99 in Seattle, Washington, used 205 ft long, 100 inch deep, WF100G girders. Designers, fabricators, and haulers communicated throughout the design process to ensure successful fabrication and delivery of these girders. A limited number of hauling vehicles capable of transporting these girders were available at the time. Designers had a high degree of certainty about the haul vehicle characteristics during design.

Figure 3 - Transport of 205 ft, WF100G Girder

Currently under construction, the Interstate 5, Northbound Puyallup River Bridge in Tacoma, Washington uses 203 ft long, 100 inch deep, WF100G girders. Designers assumed the same vehicle used to haul the Alaskan Way Viaduct girders would haul these girders. Based on this assumption, shipping support locations and temporary top strand requirements were determined.

The contract documents did not adequately communicate the design assumptions concerning girder hauling. Local haulers had invested in new equipment and needed to utilize it to meet the girder delivery schedule for the project. The new equipment has a lower rotational stiffness than assumed during design. As a result, the shipping support locations needed to be adjusted which would increase the required number of temporary top strands and the initial concrete strength requirement.

Changing the initial concrete strength and number of temporary top strands would alter initial and long term camber. Changes to camber will affect the required volume of concrete placed in the haunch between the top of the girder and the main deck slab. For girders with large flange widths, such as the WSDOT WF-series girders, this can add up to significant quantities of additional concrete for a large deck placement. Changes in camber could also affect bearing seat elevations and final profile grade. The confluence of camber and optimized design creates the issue that after advertising and bidding, it is a risky proposition to change any part of the design that will affect camber.

Adding temporary top strands was not a practical option for this project. Fortunately, refining the shipping analysis using measured properties, such as the actual concrete strength at the time of hauling and actual route conditions, showed shipping the girders as originally designed, with the less stiff equipment, was safe.

This experience prompted local fabricators and haulers to approach WSDOT and request stability design practices be updated to include providing complete lifting and hauling design assumptions in contract documents and the adoption of new haul vehicle parameters to account for the modern fleet of hauling equipment.

HAULING VEHICLE ROTATIONAL STIFFNESS

The rotational stiffness of the hauling vehicle is an important parameter in evaluating the safety of girder transportation. Mast[4] shows that the factor of safety against cracking nearly doubles when rotational stiffness increases from 30,000 kip-in/rad to 60,000 kip-in/rad for a 136ft PCI BT-72 girder supported at 9 ft from the ends at a 6% superelevation.

WSDOT used the assumptions listed in Table 3 for hauling stability design.

Table 3 Assumed hauling vehicle parameters

Height of girder bottom above roadway	72”
Height of truck roll center above roadway	24”
Maximum expected roadway superelevation	6%
Maximum girder sweep at mid-span	1/8” per 10 ft of girder length
Support placement tolerance	1”
Center to center wheel spacing	72”
Rotational Stiffness	4,000 kip-in/rad per axle
Axle capacity	18 kip / axle

The basis for the rotational stiffness is the initial measurements reported by Mast[4] and subsequent measurements reported by Seguirant[2].

This method of estimating rotational stiffness has some inherent problems. The basic rotational stiffness and axle capacity represent the equipment of a single hauler. Very few rotational stiffness measurements establish the basis for design. WSDOT practice is to estimate the number of axles required to haul a girder, and from there, estimate the rotational stiffness of the haul vehicle. This approach does not reflect the reality of girder transportation. With the exception of “drop axles”, the number of axles available on any given piece of equipment is fixed. Haulers match their available equipment to the load and haul requirements.

Local haulers have invested in new equipment. Each piece has unique characteristics including rotational stiffness and center-to-center wheel spacing. In fact, the center-to-center wheel spacing is adjustable on certain pieces of equipment for improved rollover stability.

Haulers have the flexibility to mix and match various pieces of equipment to achieve a desired delivery schedule while providing adequate rotational stiffness and girder stability.

Working with local fabricators and haulers, WSDOT revised the method for estimating hauling vehicle parameters. The new approach is to design girders assuming the least stiff hauling configuration, chosen from a list of hauling configurations representative of the regional fleet of hauling equipment, for which stress and stability requirements are satisfied. The hauling vehicle parameters, with the exception of the rotational stiffness and center-to-center wheel spacing, are unchanged from those given in Table 3.

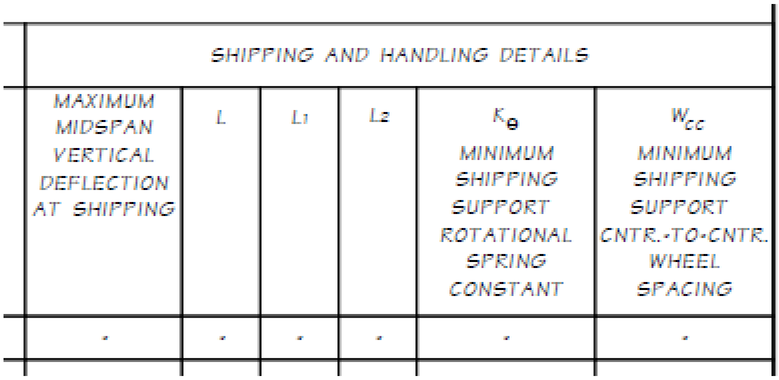
Table 4 lists the assumed rotational stiffness and center-to-center wheel spacing parameters. The hauling stability design procedure uses the parameters from the first row of Table 4 in Step 3 of the design procedure illustrated in Figure 2. If stress and stability requirements are not satisfied, use the parameters from the next row, and so on, until achieving an adequate design. In the rare case that an adequate stability design cannot be found, designers contact local fabricators and haulers for a more in depth investigation of hauling scenarios.

Table 4 Rotational stiffness and axle width parameters

Rotational Stiffness (kip-in/rad)	**Center-to-center wheel spacing (in)**
40,000	72
50,000	72
60,000	72
60,000	96
70,000	96
80,000	96

COMMUNICATING ASSUMPTIONS

The availability of new hauling vehicles creates a need to distinguish the set of characteristics parameters assumed in the hauling stability design of prestressed girders. Sections 6-02.3(25)L1 and 6-02.3(25)L2 of the WSDOT standard specifications[6] provide the girder stress and stability requirements and assumed parameters. WSDOT standard drawings for precast, prestressed concrete bridge girders include a girder schedule. Among other information, the girder schedule lists the estimated girder camber at shipping, lifting and hauling support locations (L, L_1, L_2), temporary top strands, assumed haul vehicle rotational stiffness (K_θ) and center-to-center wheel spacing (W_{cc}). Figure 4 shows the relevant portion of the WSDOT girder schedule.



SHIPPING AND HANDLING DETAILS					
MAXIMUM MIDSPAN VERTICAL DEFLECTION AT SHIPPING	L	L1	L2	K_θ MINIMUM SHIPPING SUPPORT ROTATIONAL SPRING CONSTANT	W_{cc} MINIMUM SHIPPING SUPPORT CNTR.-TO-CNTR. WHEEL SPACING
-	-	-	-	-	-

Figure 4 Excerpt from WSDOT girder schedule

By specifying this information in the contract documents, contractors can more accurately bid the work. Bidders can plan alternative lifting and shipping schemes and account for costs associated with modifications to the prestressed girder and other bridge elements.

WSDOT standard specifications state clearly that the contractor is responsible for lifting, storing, shipping, and erected prestressed concrete girders. When the actual girder handling plans differ from those provided in the contract, contractors are required to demonstrate concrete stresses and factors of safety for stability will be within acceptable limits. Contractors accomplish this by providing WSDOT with handling plans that include professionally signed stability calculations.

To meet delivery and permitting requirements, it is likely that haulers will use somewhat different hauling setups than provided for in the contract. WSDOT permits minor deviations, within specified tolerances, from the assumed hauling plan to prevent the need for contractor submitted calculations on every job. The WSDOT standard specifications specify these tolerances, which ensure stresses and stability will remain within acceptable limits. For example, the specifications state that the hauling vehicle must have a rotational stiffness that is greater than or equal to that given in the contract documents (e.g. in the girder schedule). A contractor submitted hauling plan, including calculations, is required if the actual hauling vehicle has a lower rotational stiffness. If the contractor wants to transport the girder using a vehicle with a greater rotational stiffness, stresses reduce, stability improves, and calculations are not required.

ADOPTING PCI RECOMMENDATIONS

Throughout the country, bridge owners are developing new girder sections to take advantage of state of the art practices and materials. Longer, more slender girders are routinely used. Engineers should address stability concerns during design. However, the stability of earlier generation girders was generally not a concern and owners have little experience with stability analysis.

PCI recently published recommendations[7] to help engineers at all phases of a project, including design, fabrication, hauling, and erection, to understand and properly account for stability concerns. The work published by Mast[3,4] is the basis for the analytical procedures developed in the recommendations. The PCI recommendations revised the stability factors of safety to be ratios of resisting to overturning moments instead of ratios of moment arms. Additionally, the recommended stability analysis includes effects of wind, centrifugal forces, and inclination of lifting cables for hanging girders.

The analytical procedures for girder stability analysis developed by Mast[3,4] are the basis for WSDOT design practices. Adopting the PCI recommendations required only minor changes to the computation of stability factors of safety and inclusion of the equilibrium stability configuration for stress analysis. WSDOT standard specifications require that contractor submitted calculations conforming to PCI recommendations.

DESIGNING FOR STABILITY

Designing for girder stability and optimized fabrication utilizes complex iterative analytical procedures. With properly designed software, engineers can very quickly arrive at acceptable design solutions.

WSDOT's prestressed concrete girder design software, PGSuper for pretensioned girders and PGSplice for post-tensioned spliced girders, incorporates the analytical procedures necessary to design for optimized fabrication and girder stability. A new tool, called PGStable, to perform stress and stability analysis during initial lifting and hauling is also available. These software tools are part of the BridgeLink suite. BridgeLink is available for download from WSDOT's web site at http://www.wsdot.wa.gov/eesc/bridge/software.

SUMMARY

As bridge owners make use of longer and more slender girders, stability becomes a serious concern. Engineers should become familiar with these concerns and address them during design. Designs should propose plans for lifting and hauling of these girders.

Altering designs after bidding can lead to significant changes in material quantities and can negatively affect other aspects of bridge design including bearing seat elevations and final profile grade. Providing complete design assumptions enable prospective bidders, fabricators, and haulers to address possible changes to proposed lifting and hauling plans.

Girder stability design will be new to some bridge owners and engineers. Excellent design tools and resources are available. Stability design should become a routine part of precast prestressed concrete bridge girder design.

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