Designing Precast, Prestressed Concrete Bridge Girders for Lateral Stability

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Introduction

- Lateral stability is a serious concern
- AASHTO LRFD BDS revised stability requirements (9th Edition, 2020)
- Designers should become familiar with stability requirements
- Overview of lateral stability theory
- WSDOT stability design practices

This is highly undesirable

Motivation

- Stability concerns are strongly emphasized by industry
  - PCI has published “*Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders*”

- Updates to the AASHTO LRFD BDS, 9th Edition

- Current trends
  - Girder lengths are increasing (220+ feet)
  - Stability is problematic at modest span lengths for I-Beams (AASHTO Type I-IV)
  - Issues
    - SAFETY
    - stability failure has occurred
    - re-design after bidding because girders can’t be lifted or transported
    - contractors and fabricators don’t want to be EOR for the girders
    - change orders, additional reviews, increased cost, schedule implications

Engineering Roles

- Design Engineering for Service
  - Engineering performed by the engineer-of-record to ensure the in-service structure is safe, durable, and meets all design requirements (AASHTO, BDM, etc.)

- Design Engineering for Constructability
  - Built-in allowances provided in the design (explicitly or implicitly) to ensure a precast girder is able to be constructed with available means and methods at a reasonable cost. Typically performed by the engineer-of-record as needed to minimize changes under contract

- Construction Engineering
  - Engineering performed by the contractor to ensure actual construction means and methods do not damage the bridge or otherwise prevent the bridge from functioning as intended

Current LRFD Specifications (8th Edition)

Specified since 1st Edition 1994

1.3.1—General

Bridges shall be designed for specified limit states to achieve the objectives of constructibility, safety, and serviceability, with due regard to issues of inspectability, economy, and aesthetics, as specified in Article 2.5.

2.5.3—Constructibility

Constructability issues should include, but not be limited to, consideration of deflection, strength of steel and concrete, and stability during critical stages of construction.

2.5.1—Safety

The primary responsibility of the Engineer shall be providing for the safety of the public. The Owner may require a design objective other than structural survival for an extreme event.

5.5.4.3—Stability

The structure as a whole and its components shall be designed to resist sliding, overturning, uplift and buckling. Effects of eccentricity of loads shall be considered in the analysis and design.

Buckling of precast members during handling, transportation, and erection shall be investigated.

Updated LRFD Specifications (9th Edition)

5.5.4.3—Stability
The structure as a whole and its components shall be designed to resist sliding, overturning, uplift and buckling. Effects of eccentricity of loads shall be considered in the analysis and design.

Buckling and stability of precast members during handling, transportation, and erection shall be investigated.

5.9.4.5 Temporary Strands

Temporary top strands may be used to alleviate tensile stresses in precast prestressed girders during handling and transportation. These strands may be pretensioned or post-tensioned prior to lifting the girder from the casting bed or post-tensioned immediately prior to transportation of the girder. Detensioning of temporary strands shall be shown in the construction sequence and typically occurs after the girders are securely braced and immediately before construction of intermediate diaphragms, if applicable.

C5.9.4.5 Temporary Strands

The stability of slender precast girders is improved when lifting and transportation support points are moved away from the ends of the girder. The consequence of having a shorter span between support points is reduced dead load stresses to balance the stresses due to pretensioning and thus excessive tensile stresses in the top flange and compressive stresses in the bottom flange may develop. Temporary strands placed in the top flange of the girder alleviate these excessive stresses and reduce the required strength at prestress transfer. Temporary strands in the top flange balance a portion of the primary prestressing and reduce camber and camber growth due to creep.

Updated LRFD Specifications (9th Edition)

5.12.3.2—Precast Beams

5.12.3.2.1—Preservice Conditions

The preservice conditions of prestressed girders for shipping and erection shall be the responsibility of the contractor.

Stability during handling, transportation, and erection can govern the design of precast, prestressed girders. Precast members should be designed such that safe storage, handling, and erection can be accomplished by the contractor using reasonable means and methods.

C5.12.3.2.1

AASHTO LRFD Bridge Construction Specifications place the responsibility on the Contractor to provide adequate devices and methods for the safe storage, handling, erection, and temporary bracing of precast members.

Lateral bending stability analysis may be based on the "Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders", Precast Concrete Institute, Publication CB-02-16-E. A detailed design example is presented in Seguirant, Brice, and Khaleghi, (2009).

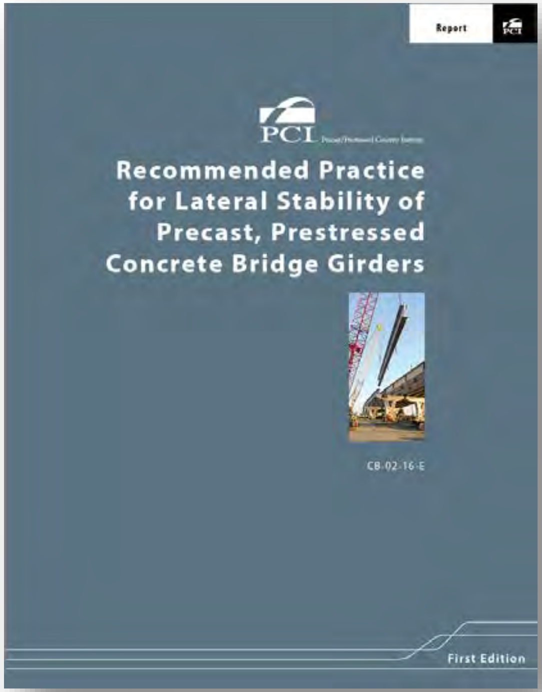
Stability analysis basics

- PCI – Recommended practices for lateral stability
  - Based on work of Robert Mast,
    PCI Journal Special Reports, Part 1 (1989), Part 2 (1993)

- Two primary cases of concern for bridge designers
  - Hanging girders (lifting)
  - Seated girders (hauling)

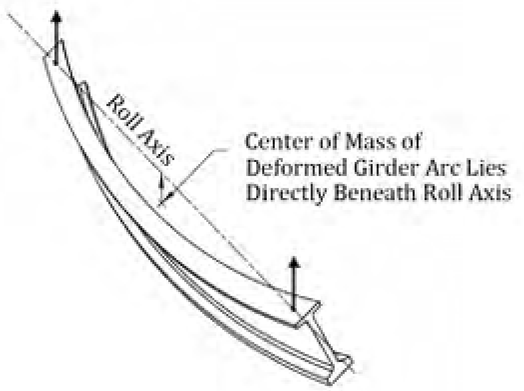
- Lateral **bending** stability
  - Girders assumed to be torsionally rigid

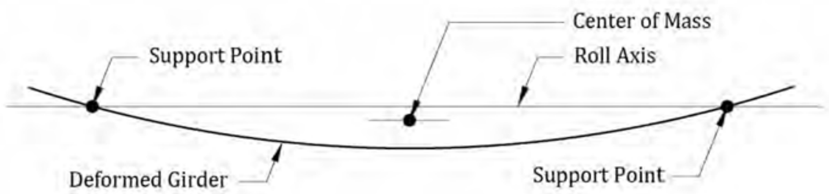
- Concerns
  - Statical equilibrium of the girder during handling
  - Ability of girder to resist lateral bending



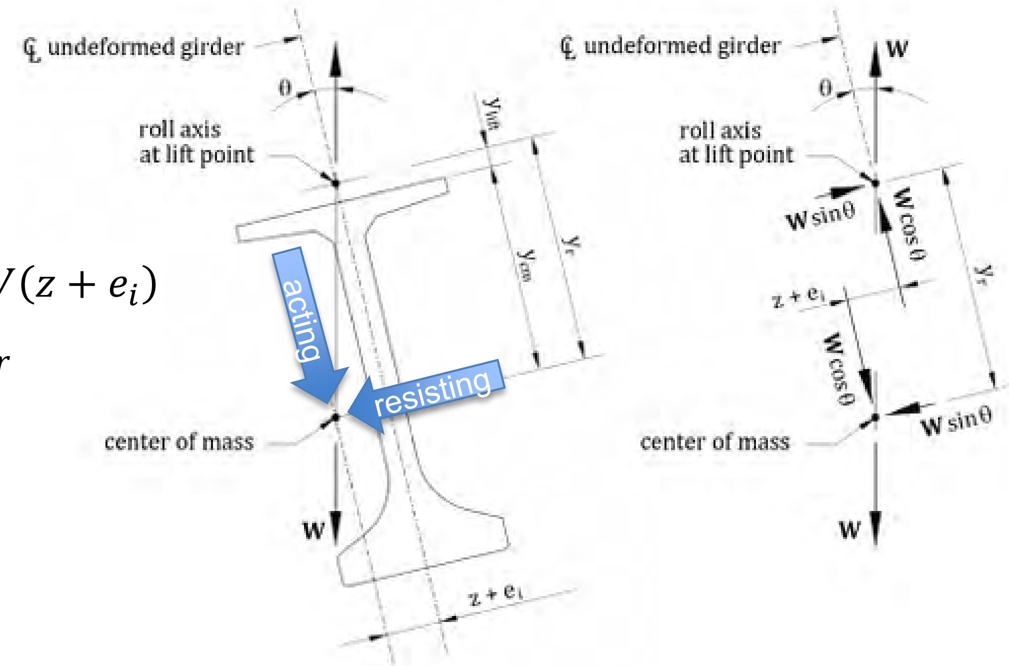
Hanging girders

- Parameters: Girder stiffness, lift device rigidity, pick point location, pick eccentricity, camber, sweep





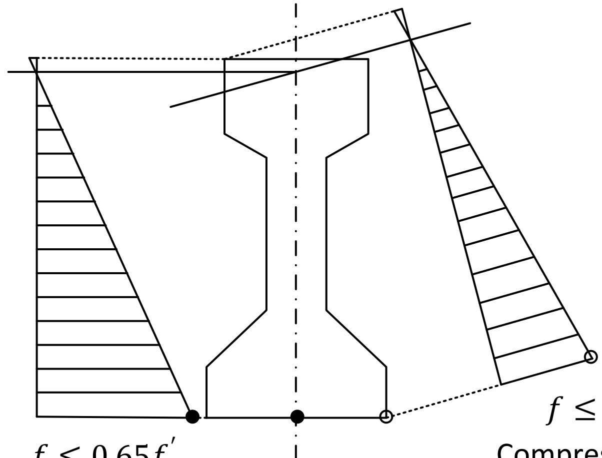
Stress Analysis



- Equilibrium
  - $M_{acting} = M_{resisting}$
  - $M_{acting} = W cos(\theta)(z + e_i) = W(z + e_i)$
  - $M_{resisting} = W sin(\theta) y_r = W\theta y_r$
  - Solve for θ
- Biaxial stresses
  - $f = \frac{P}{A} + \frac{(Pe+M)y}{I_x} + \frac{\theta M x}{I_y}$
- Lateral offset of center of mass, $z + e_i$
  - THIS IS NOT THE DEFLECTION OF THE CENTERLINE GIRDER
  - z computed as offset that would occur if 100% of the self-weight is applied laterally (z_o) times the tilt angle
  - $z = z_o\theta$
  - $M_{acting} = W(z_o\theta + e_i)$

Stress Limits

- Ensure stresses are within acceptable limits
  - Tension: $0.0948\lambda\sqrt{f'_{ci}} \leq 0.200\ ksi$
    $0.24\lambda\sqrt{f'_{ci}}$ (with bonded reinforcement)
  - Compression: $0.65f'_{ci}$ (plumb) $0.70f'_{ci}$ (tilted)

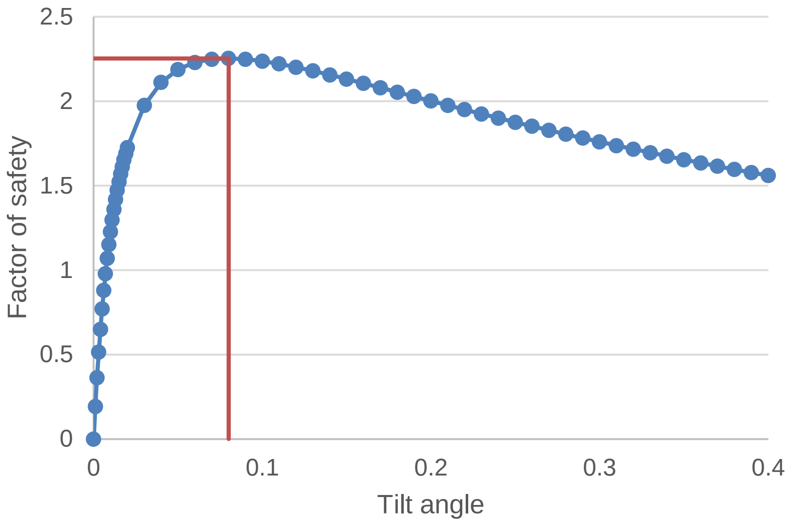


Cracking

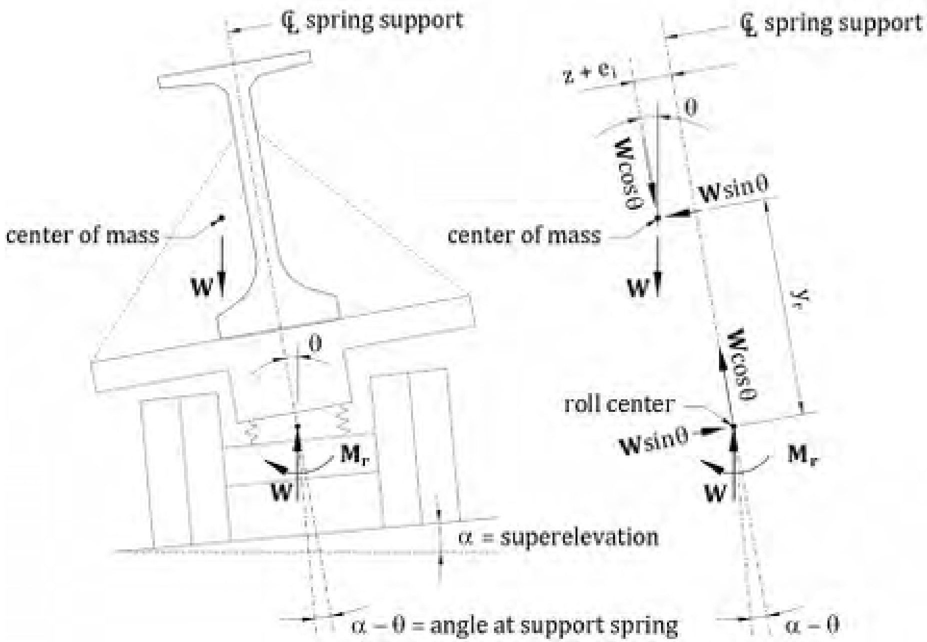
- At equilibrium, how close is the girder to cracking?
- M_{cr} cracking moment is the moment which gets $f = f_r$
- Compute tilt angle at cracking $\theta_{max} = \frac{M_{cr}}{M_x}$
- Compute acting and resisting moments at tilt which induces cracking
  - $M_{acting} = W(z_o\theta_{max} + e_i)$
  - $M_{resisting} = W\theta_{max}y_r$
  - $FS = \frac{M_{resisting}}{M_{acting}} \geq 1.0$

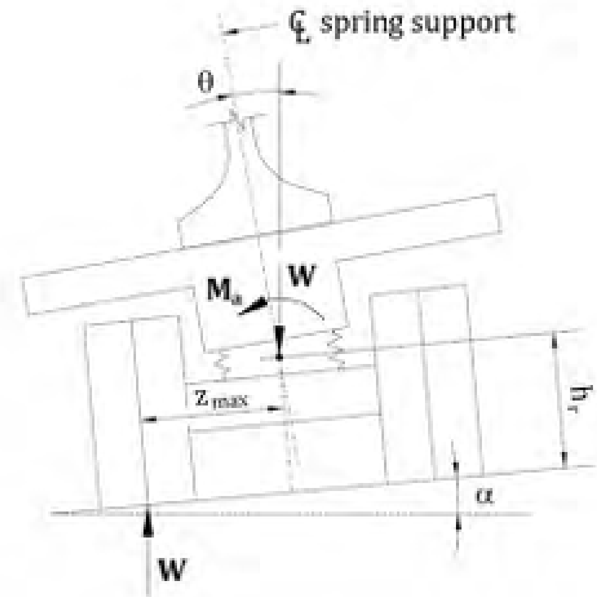
Failure

- Lateral deflection and rotation increases due to reduced post-cracking stiffness
- Ensure there is adequate lateral stiffness to avoid a lateral bending failure
- $EI_{eff} = \frac{EI_g}{1+2.5\theta}$
- Find tilt angle that maximizes the factor of safety
  - $\theta'_{max} = \sqrt{\frac{e_i}{2.5z_o}}$
  - $M_{acting} = W(z_o\theta'_{max}(1 + 2.5\theta'_{max}) + e_i)$
  - $M_{resisting} = W\theta'_{max}y_r$
  - $FS' = \frac{M_{resisting}}{M_{acting}} \geq 1.5$



Seated girders





Lateral bending

- Sum moments about roll center
- $M_{acting} = W\big((z + e_i)\cos\theta + y_r \sin\theta\big)$
- $M_{resisting} = K_\theta(\theta - \alpha)$
- $FS = \frac{M_{resisting}}{M_{acting}}$
- Stress, Cracking, Failure

Roll over stability

- Sum moments about roll center
- $M_{acting} = K_\theta(\theta - \alpha)$
- $M_{resisting} = W(z_{max}\cos\alpha - h_r \sin\alpha)$
- $FS = \frac{M_{resisting}}{M_{acting}}$

Hauling stability analysis

- Parameters: Girder stiffness, bunk locations, bunk eccentricity, superelevation, impact, **haul truck characteristics (wheel base and rotational stiffness)**, camber, sweep
- Case 1 – Normal crown slope – check stresses
  - 2% crown slope
  - ±20% vertical impact
- Case 2 – Max superelevation – check stresses and stability
  - 6% superelevation
  - No impact

Hauling stability analysis

- Ensure stresses are within acceptable limits
  - Tension: $0.0948\lambda\sqrt{f_c'}$
    $0.24\lambda\sqrt{f_c'}$ (with sufficient bonded reinforcement)
    Compression: $0.65f_c'$ (plumb) $0.70f_c'$ (tilted)

- Ensure resisting moment exceed acting moments
  - Minimum FS against cracking = 1.0
  - Minimum FS against failure = 1.5
  - Minimum FS against roll over = 1.5

Improving factors of safety

$$FS = \frac{M_{resisting}}{M_{acting}}$$

- **Increase resisting moment**
  - Lifting – use rigid lift hardware to increase elevation of roll axis
  - Hauling – use stiffer transport vehicle

- **Reduce acting moment**
  - Reduce lateral deflection and rotation by increasing girder stiffness (f_c', E_c) or providing lateral bracing
  - Increase distance from end of girder to lift/bunk points
    - Reduces eccentricity from center of mass to roll center
    - Overhangs reduce mid-span lateral deflections

    - *Reduces dead load moment that is balancing prestressing*
      - *Increases tension in top of girder*
      - **Temporary top strands** can mitigate excessive tensile stress

Stability design at WSDOT

- WSDOT design practices have adapted to changes in the precast industry
- See ASPIRE Magazine, Winter 2018 (Owner's Perspective)


PERSPECTIVE

Designing Precast, Prestressed Concrete Bridge Girders for Lateral Stability: An Owner's Perspective

by Richard Brice, Washington State Department of Transportation

The Washington State Department of Transportation (WSDOT) investigates initial lifting, hauling, and erection conditions during the design of precast, prestressed concrete bridge girders. The design engineer's objective, stated simply, is to be reasonably satisfied that safe handling of girders can occur at all stages of construction.

The following excerpts from the American Association of State Highway and Transportation Officials' *AASHTO LRFD Bridge Design Specifications*[1] show that constructability, safety, and stability must be considered by the design engineer.

> Article 1.3.1 Bridges shall be designed for specified limit states to achieve the objectives of constructability, safety, and serviceability, with due regard to issues of inspectability, economy, and aesthetics, as specified in Article 2.5.
>
> Article 2.5.1 The primary responsibility of the Engineer shall be providing for the safety of the public.
>
> Article 2.5.3 Constructability issues should include, but not be limited to, consideration of deflection, strength of steel and concrete, and stability during critical stages of construction. Bridges should be designed in such a manner that fabrication and erection can be performed without undue difficulty...
>
> Article 5.5.4.3 Buckling of precast members during handling, transportation, and erection shall be investigated.

The lateral stability of precast, prestressed concrete bridge girders is an important constructability and safety concern. Lateral bending failures are sudden, catastrophic, costly, and they pose a serious threat to surroundings and people, including the traveling public during transportation of girders from fabrication facilities to bridge sites. Investigation of potential instability conditions is well within the purview of the design engineer.

Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders contains state-of-the-art analysis techniques and best practices for lateral stability of precast, prestressed concrete bridge girders.

Lateral-Stability Design

WSDOT has designed precast, prestressed concrete girders for lifting and hauling for more than 25 years. When spans were generally less than 120 ft long, 120 ft long, bulb-tee and wide flange girder sections were not particularly deep, and stability was not a significant concern. Handling design consisted of evaluating stresses during lifting from the form and hauling to the bridge site.

10 | ASPIRE Winter 2018

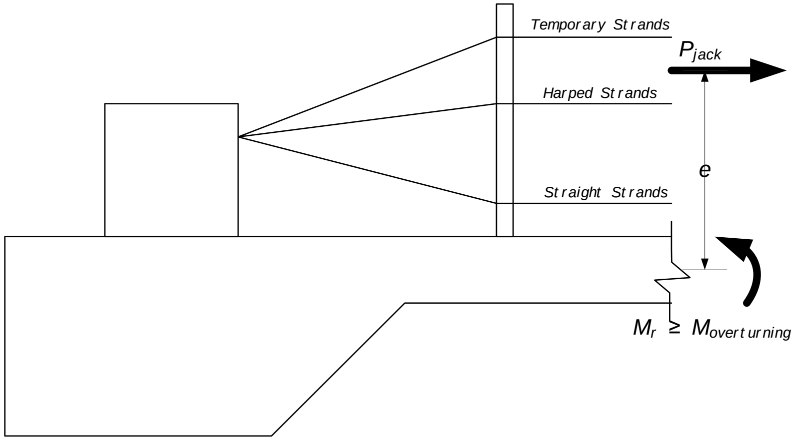
Goals

Engineer-of-record must be satisfied that girders can be safely fabricated, lifted, transported, and erected by available means and methods.

Avoid post-bidding design modifications.

Temporary top strands

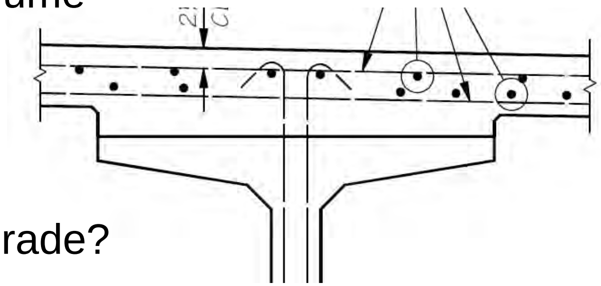
- (6) 0.6”ϕ strands are common
- Significant force at a high eccentricity above the stressing bed floor
- Tall girders, high prestressing, and TTS create fabrication challenges
- Girders need to be fabricated in existing facilities



TTS raise eccentricity and increase overturning moment on stressing bed

Post-design modifications

- **Design modifications after bidding are undesirable**
- Re-design required if capabilities of manufacturing facility are exceeded
- Changing prestressing arrangement (re-stranding and/or adding temporary top strands) effects initial concrete strength and camber
- Changes to camber effects haunch depth and concrete volume
  - This can be a significant quantity of material
  - Can the girders carry the extra dead load?
  - Who pays for the extra material?
  - What happens to bearing seat elevations and profile grade?



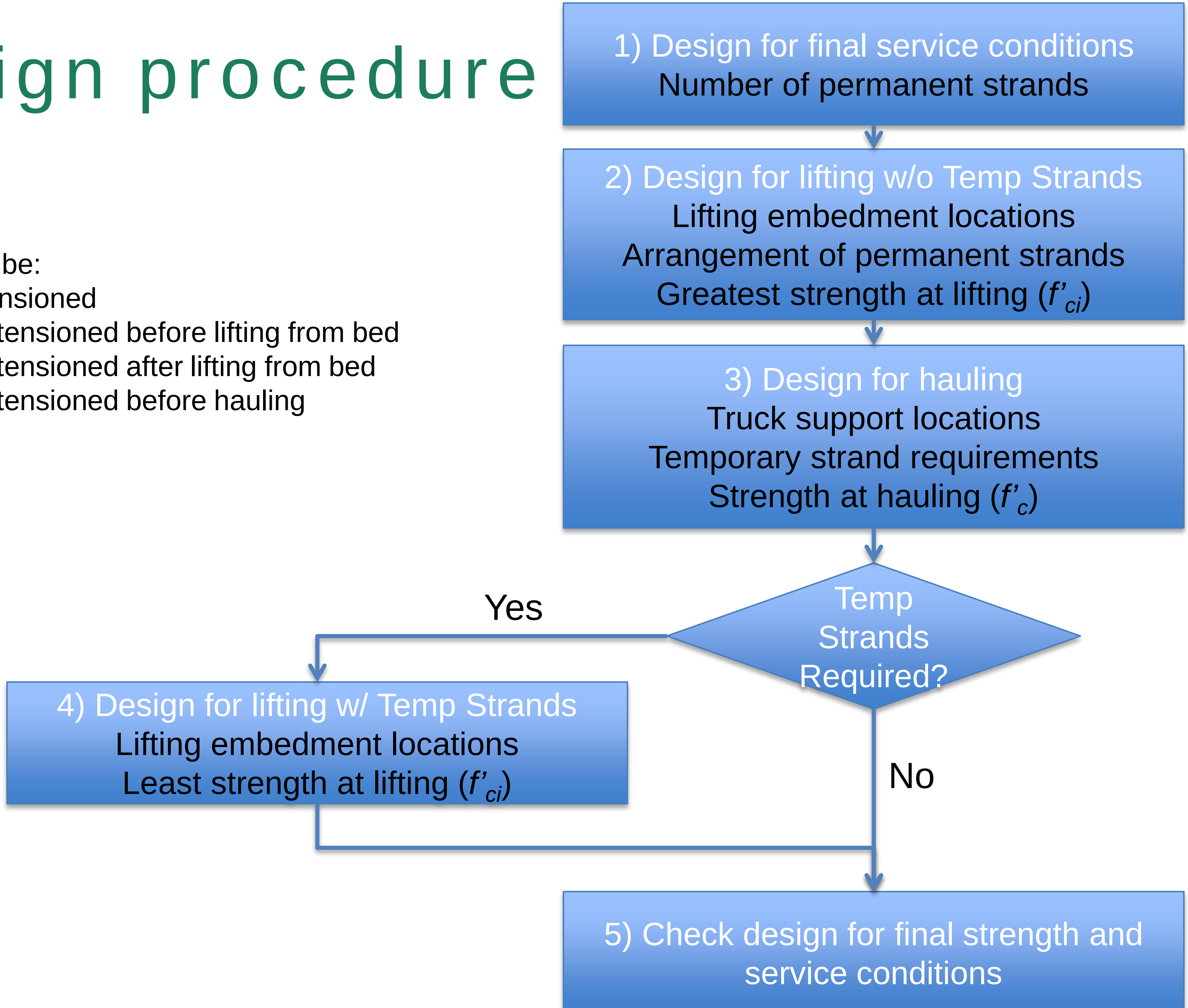
Optimized fabrication design

- WSDOT worked with local fabricators to develop a design methodology which includes flexibility for optimizing fabrication and addresses stability concerns
- Goal is to determine least f'_{ci} while simultaneously placing the least possible demand on the stressing bed – while achieving adequate stability
- "Design optimization for fabrication of pretensioned concrete bridge girders: An example problem", Brice, et. al. PCI Journal Fall 2009

Design procedure

TTS can be:

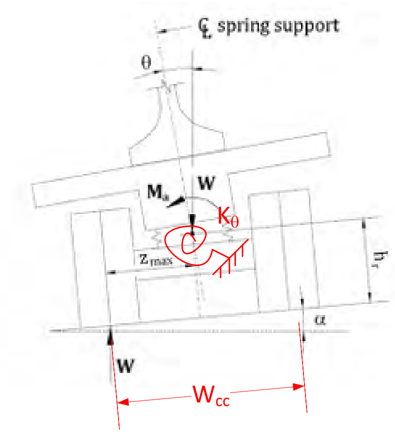
- pretensioned
- post-tensioned before lifting from bed
- post-tensioned after lifting from bed
- post-tensioned before hauling



Haul truck characteristics

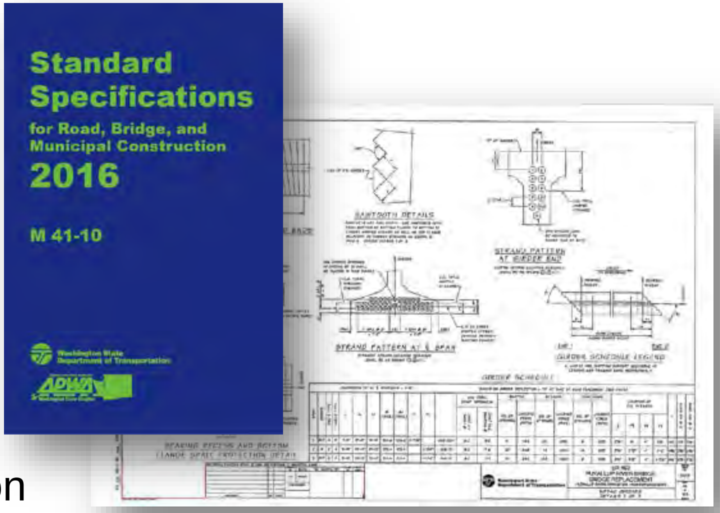
- Design to least capable haul truck
- Use least value of K_θ from the table below along with the corresponding W_{cc} that provides adequate stability

K_θ (k-in/rad)	W_{cc} (in)
40,000	72
50,000	72
60,000	72
60,000	96
70,000	96
80,000	96



- For Step 3 in design procedure, use parameters from row 1, then row 2, and so on, until stress and stability requirements are satisfied

Communicating assumptions



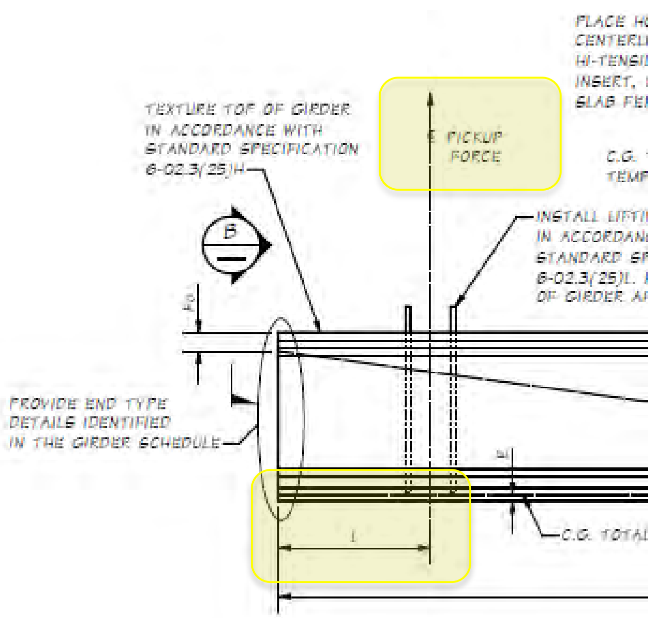
- WSDOT Standard Specifications provide
  - allowable stress and stability requirements
  - assumed parameters
  - tolerances

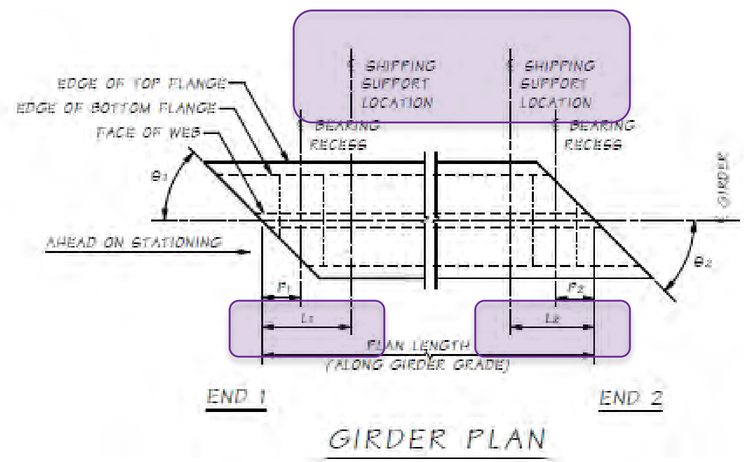
- Contract girder schedule lists job specific information

- Contractor must submit PE stamped handling plans when deviating from the contract
  - Calculations must follow PCI recommendations

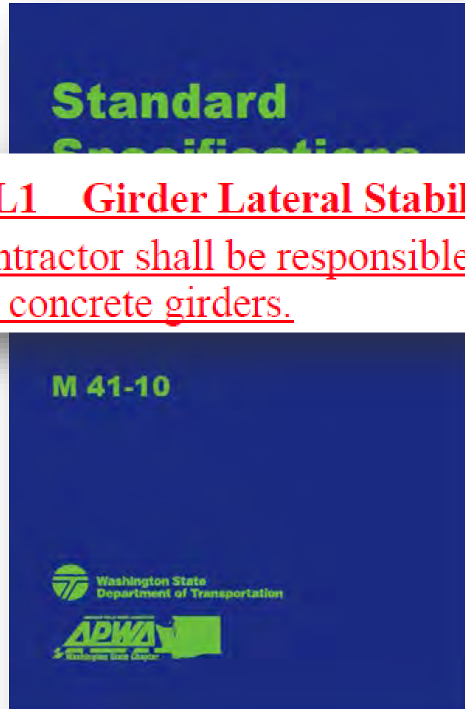
Job specific information

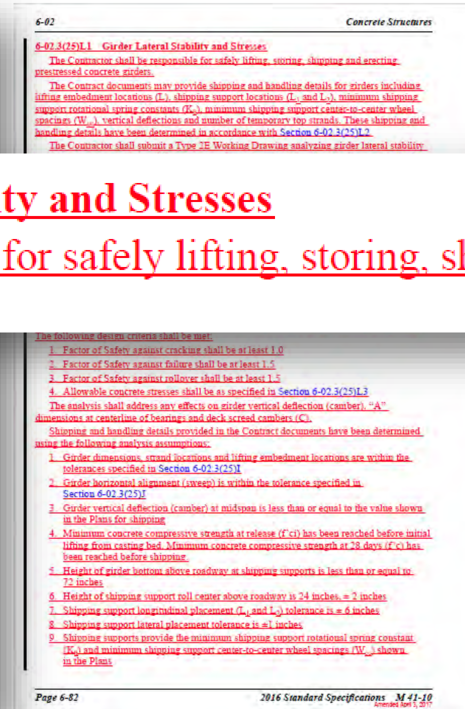
SHIPPING AND HANDLING DETAILS					
MAXIMUM MIDSPAN VERTICAL DEFLECTION AT SHIPPING	L	L_1	L_2	K_θ MINIMUM SHIPPING SUPPORT ROTATIONAL SPRING CONSTANT	W_{cc} MINIMUM SHIPPING SUPPORT CNTR.-TO-CNTR. WHEEL SPACING
-	-	-	-	-	-





Responsibility





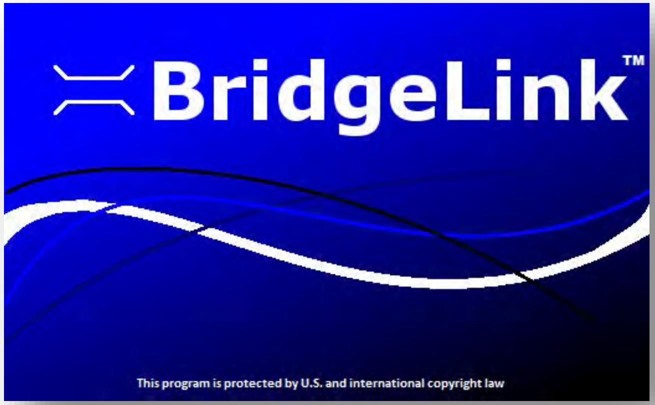
6-02.3(25)L1 Girder Lateral Stability and Stresses

The Contractor shall be responsible for safely lifting, storing, shipping and erecting prestressed concrete girders.

Designing for stability

- Designing for stability and optimized fabrication utilizes complex iterative analytical procedures
- Software can be used to quickly arrive at acceptable design solutions

- WSDOT design tools – part of the BridgeLink suite
  - PGSuper – precast/prestressed girder design with integrated stability analysis
  - PGSplice – precast spliced girder design with integrated stability analysis
  - PGStable – stand-alone girder stability analysis



https://www.wsdot.wa.gov/eesc/bridge/software

Additional Resources

- "Recommended Practice for Lateral Stability of Precast, Prestressed Concrete Bridge Girders", PCI, CB-02-16

Free download from PCI

- PCI eLearning (coming soon)
  - Introductory Material
  - Stability of Hanging Girders
  - Stability of Transported Girders
  - Seated Girders and Stability Issues from Bed to Bridge
  - Stability Calculations and Sensitivity Analysis

- PCI Stability Spreadsheet (coming soon)
  - Detailed stability calculations
  - User guide

Questions?

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