Improving Predictions for Camber in Precast, Prestressed Concrete Bridge Girders

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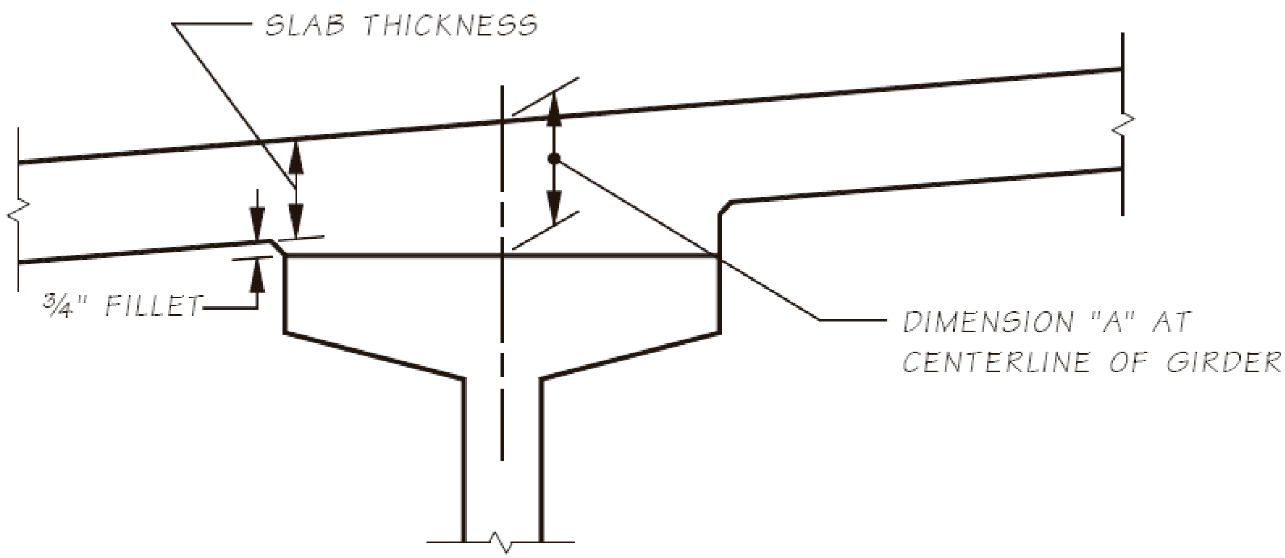
Camber Prediction Challenges

- Difficulty in accurately predicting camber
- Smaller measured camber then predicted
  - More concrete required in haunch to meet bottom of slab profile
- Larger measured camber than predicted
  - Interferes with deck reinforcement
- <u>Increased material, labor and engineering costs</u>



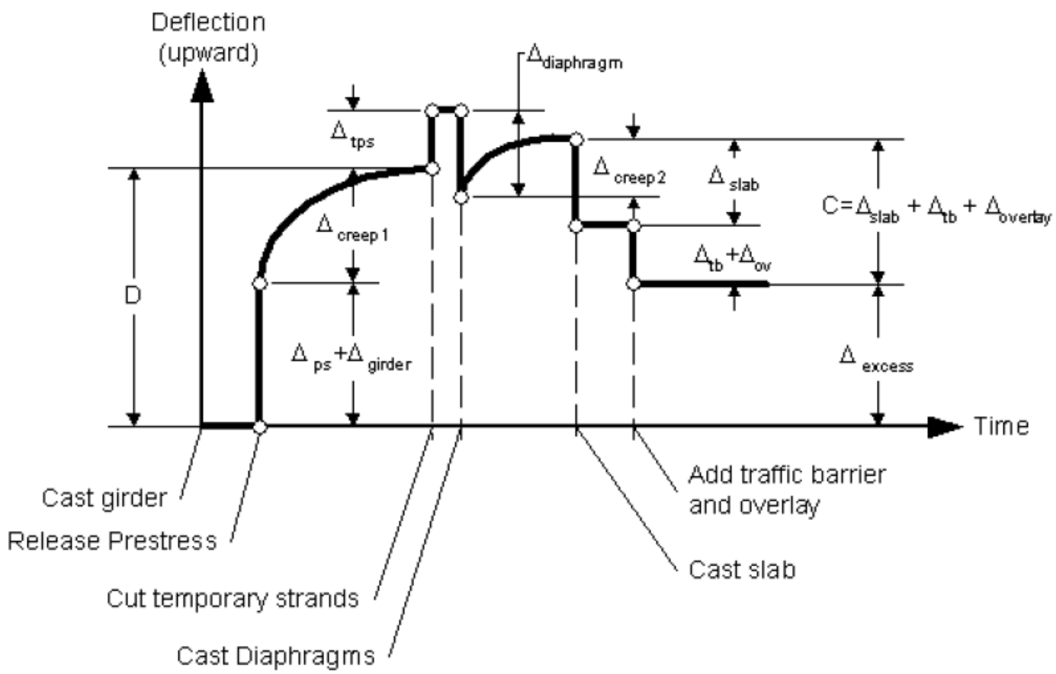
Outline

- Project Goals
- Current Camber Prediction Methods
- Camber Prediction Program
- Fabricator Data
- Materials Testing
- End Restraint/Roller Test
- Detailed Camber Monitoring – Keys Road Bridge
- Calibration of Camber Prediction Model
- Summary/Recommendations

Project Goals

- Determine the behaviors that most strongly influence camber.
- Develop a method for more accurate predictions of camber in prestressed concrete girders.
- Calibrate that method against measured data.
- Provide recommendations to improve current camber prediction methods

Current Methods of Prediction



PGSuper V2.0.0

Δ self weight

Δ prestressing load (t)*

Δ deck load

Δ super imposed dead loads

\+ Δ creep (t)

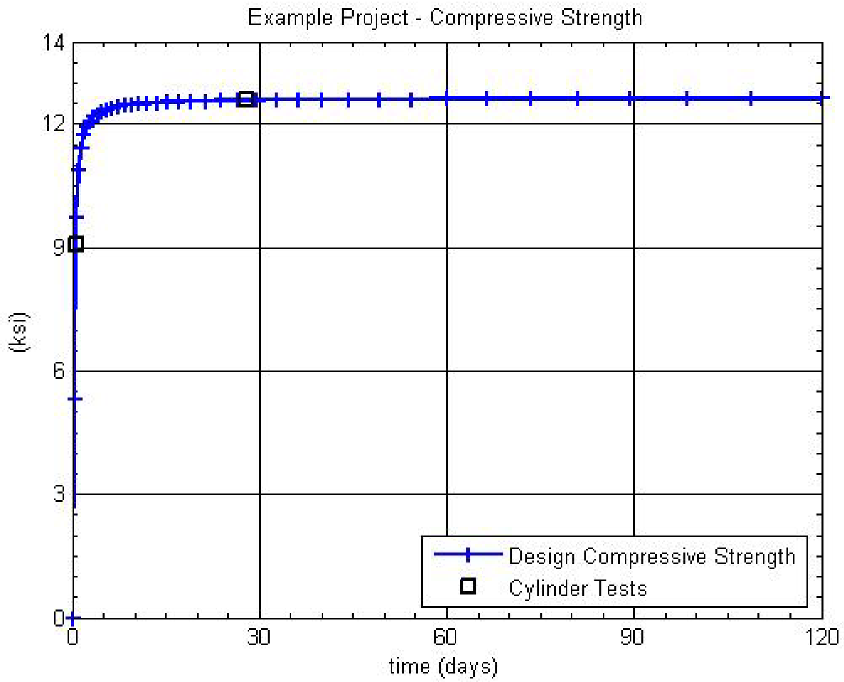
Δ Total (t)

*Currently WSDOT does not include time dependent prestress losses in the prestress force deflection.

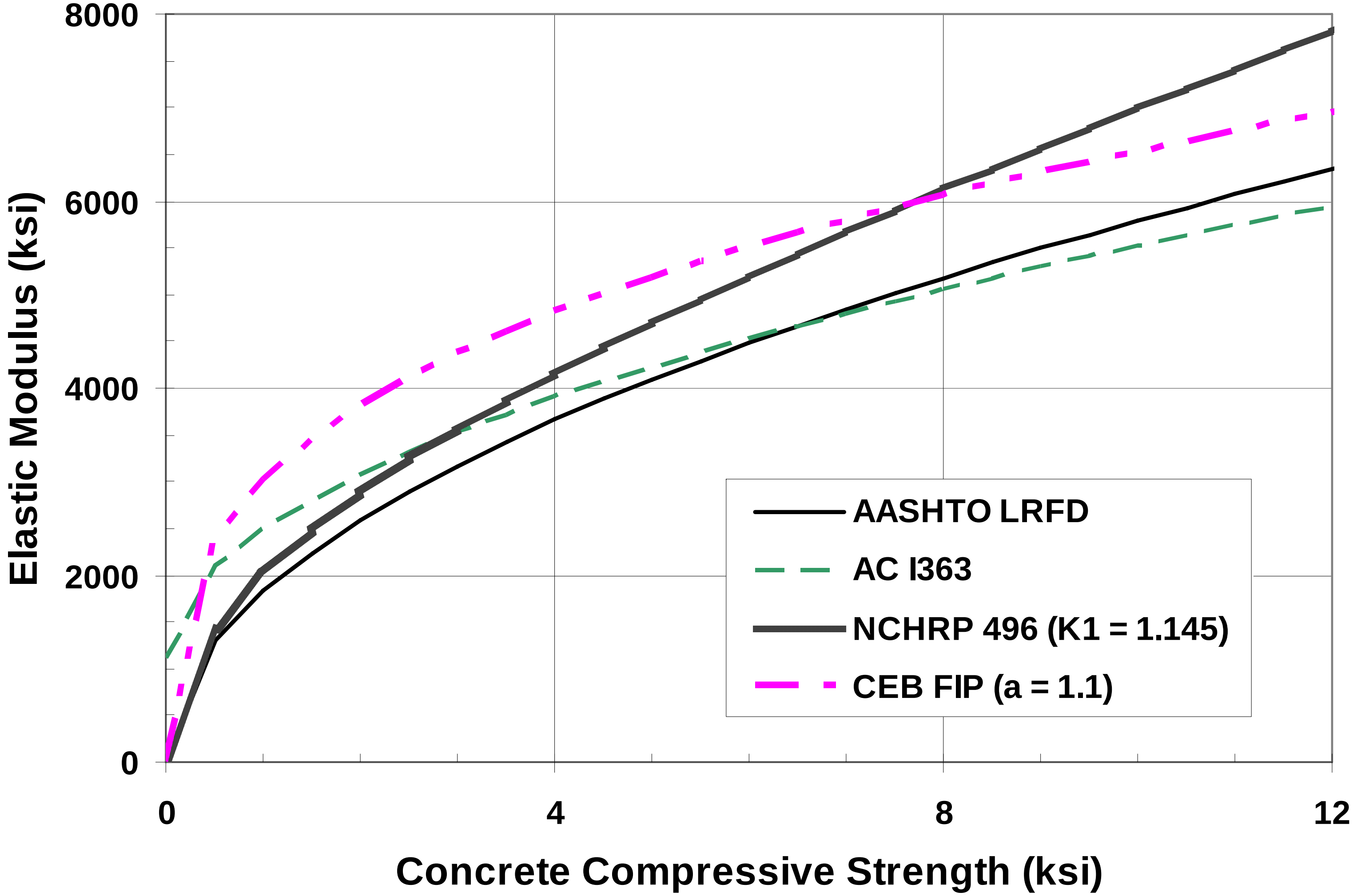
Concrete Compressive Strength

- Time dependent model
- WSDOT BDM Table 5.1.1-2
- Branson Equation
  - b and c calibrated based on measured strengths concrete compressive strength tests

$$f_c(t) = f_c(28)\frac{t_{str}}{b+ct}$$



Elastic Modulus



Shrinkage and Creep

- AAHSTO LRFD (2007)
  - Shrinkage

$$\varepsilon_{sh}(t) = -k_{vs} k_{hs} k_f k_{td} \, 0.48 \times 10^{-3}$$

  - Creep

$$\psi(t, t_a) = 1.9 k_{vs} k_{hc} k_f k_{td} t_a^{-0.118}$$

where:

- k_{vs} = factor for the effect of the volume to surface ratio
- k_{hs}, k_{hc} = humidity factor for shrinkage and creep
- k_f = factor for the effect of concrete strength
- k_{td} = time development factor
- t_a = age at loading

Prestress Losses

- AASHTO LRFD (2004)

$$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR2} + \Delta f_{pR1}$$

- AASHTO LRFD (2007)

$$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pLT}$$

$$\Delta f_{pLT} = (\Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1})_{id} + (\Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} + \Delta f_{pSS})_{df}$$

Prestress Losses

- AASHTO LRFD (2004)

$$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR2} + \Delta f_{pR1}$$

- AASHTO LRFD (2007)

$$\Delta f_{pT} = \Delta f_{pES} + \Delta f_{pLT} + \Delta f_{pR0}$$

$$\Delta f_{pLT} = (\Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1})_{id} + (\Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} + \Delta f_{pSS})_{df}$$

Elastic Deflection

- Self-Weight (changing support location)

$$\Delta_{SW} = \frac{\omega_{sw} L_c}{24 E_c I_g}\left[3L_c^{\ 2}\left(L_c + 2L_n\right) - L_n^{\ 3}\right] + \frac{\omega_{sw} L_n^{\ 2}}{384 E_c I_g}\left[5L_n^{\ 2} - 24L_c^{\ 2}\right]$$

- Additional Dead Load

$$\Delta_{DL} = \frac{5\omega_{DL} L^4}{384 E_c I_g}$$

- Prestress

$$\Delta_{ps} = \frac{PL^2}{8E_c I_g}\left[e_{mid} + \left(e_{end} - e_{mid}\right)\frac{4a^2}{3L^2}\right]$$

Elastic Deflection

- Self-Weight (changing support location)

$$\Delta_{SW} = \frac{5\omega_{sw} L_n{}^4}{384 E_c I_g}$$

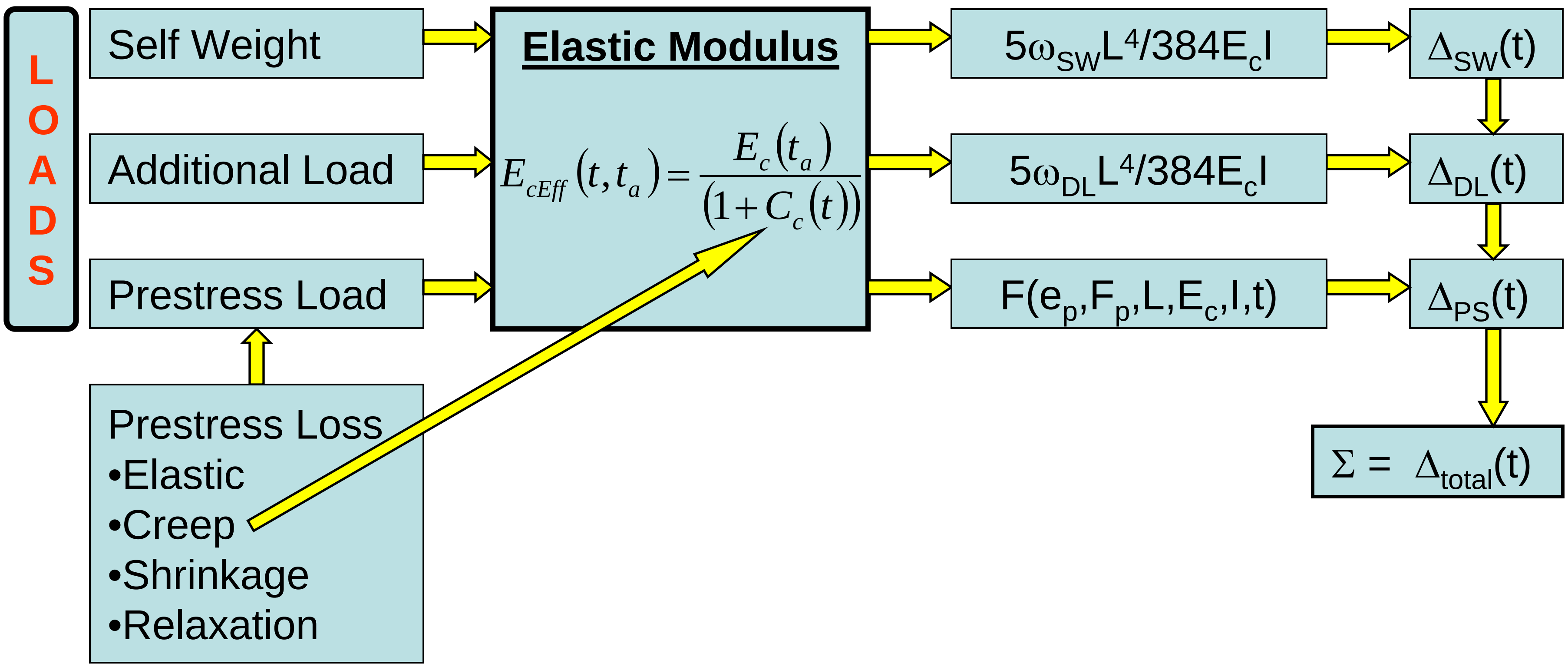
- Additional Dead Load

$$\Delta_{DL} = \frac{5\omega_{DL} L^4}{384 E_c I_g}$$

- Prestress

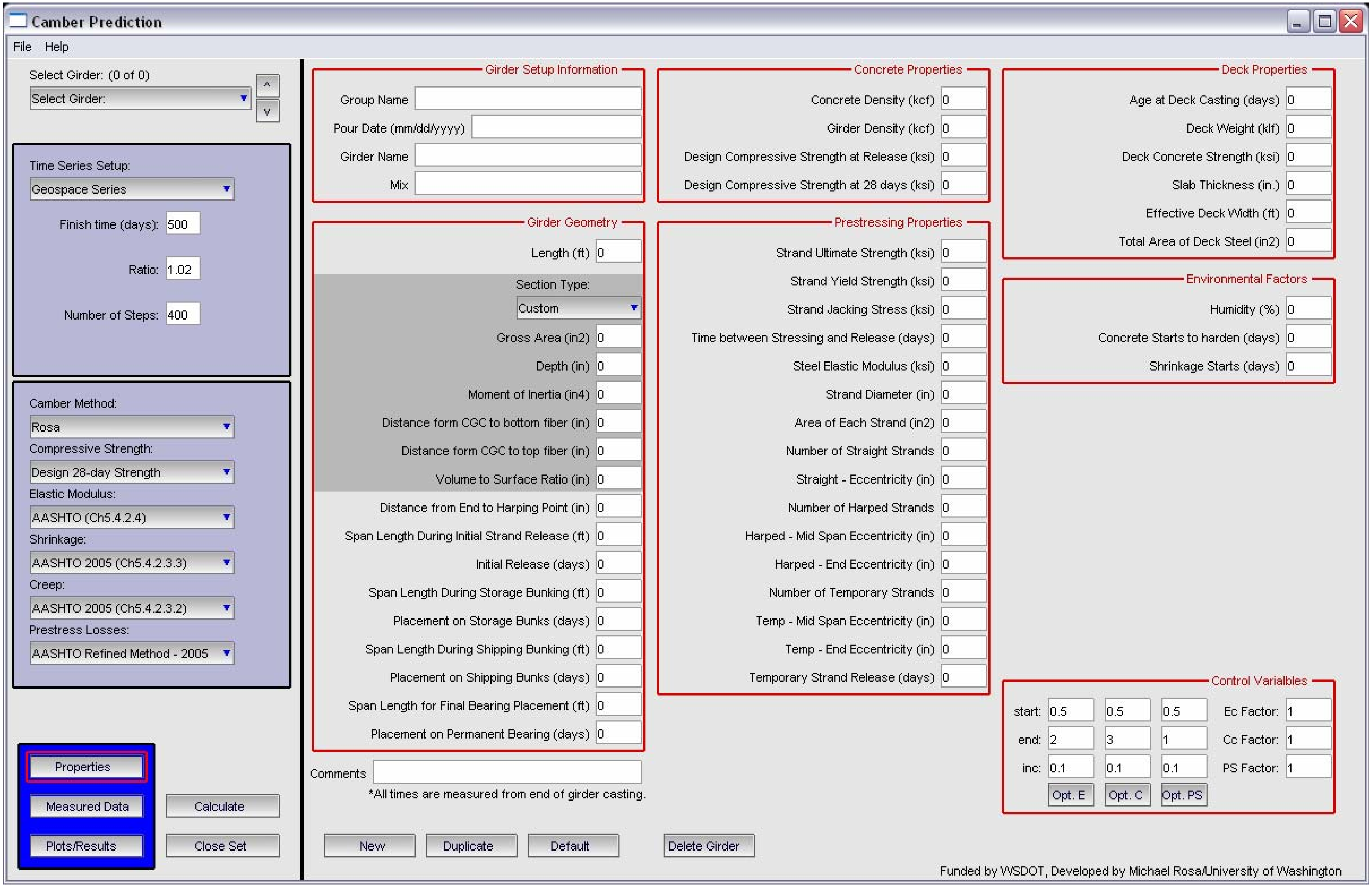
$$\Delta_{ps} = \frac{PL^2}{8E_c I_g}\left[e_{mid} + \left(e_{end} - e_{mid}\right)\frac{4a^2}{3L^2}\right]$$

Calculation Model



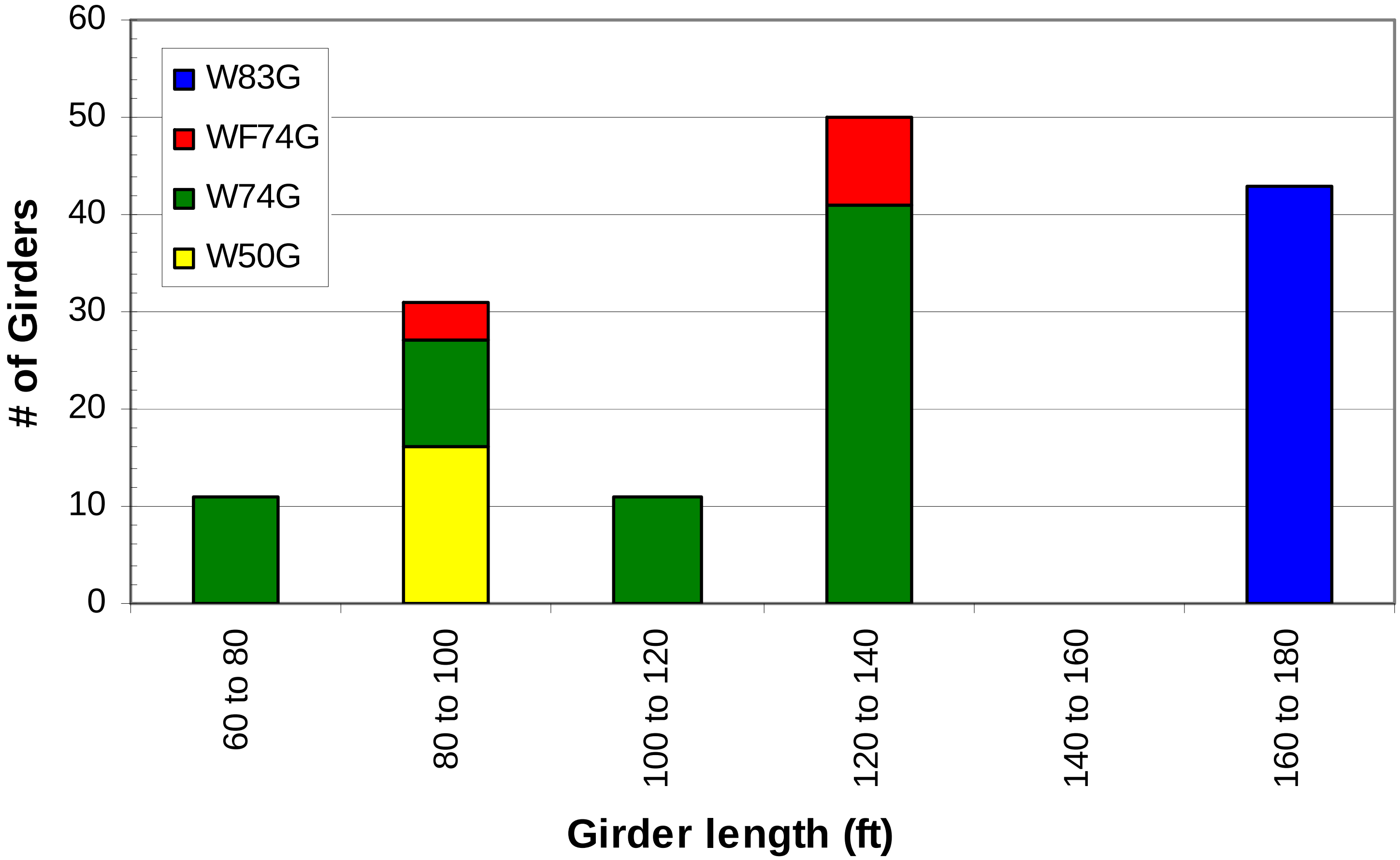
Camber Prediction Program

- Design Criteria
  - Select various prediction methods
  - Evaluate single or multiple girders
  - Produce plots to show behavior and compare sets
    - Utilize MatLAB Interface

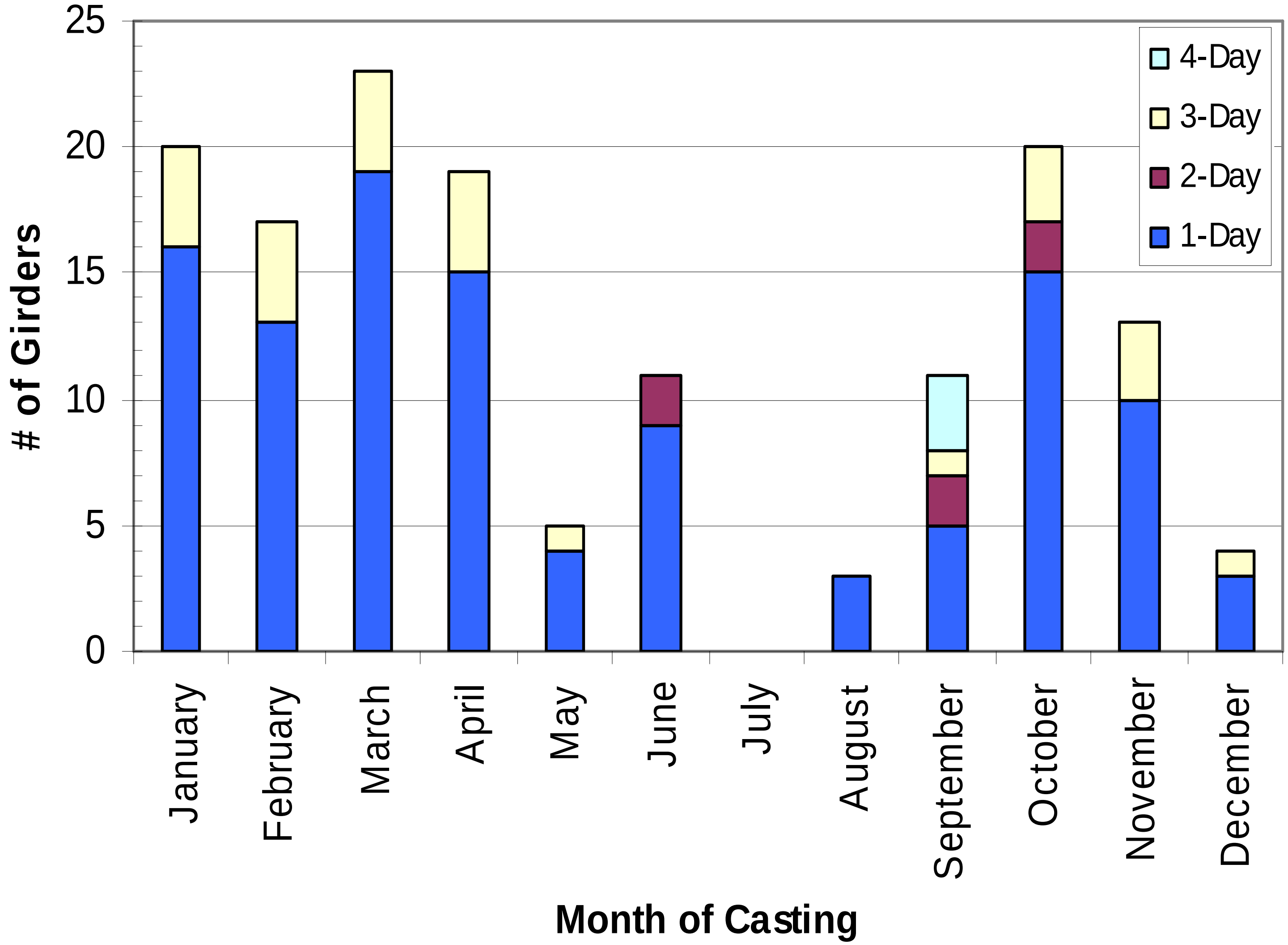

Camber Prediction
File
Help
Select Girder: (0 of 0)
Select Girder:
Time Series Setup:
Geospace Series
Finish time (days): 500
Ratio: 1.02
Number of Steps: 400
Camber Method:
Rosa
Compressive Strength:
Design 28-day Strength
Elastic Modulus:
AASHTO (Ch5.4.2.4)
Shrinkage:
AASHTO 2005 (Ch5.4.2.3.3)
Creep:
AASHTO 2005 (Ch5.4.2.3.2)
Prestress Losses:
AASHTO Refined Method - 2005
Properties
Measured Data
Plots/Results
Calculate
Close Set
Girder Setup Information
Group Name
Pour Date (mm/dd/yyyy)
Girder Name
Mix
Girder Geometry
Length (ft) 0
Section Type:
Custom
Gross Area (in2) 0
Depth (in) 0
Moment of Inertia (in4) 0
Distance form CGC to bottom fiber (in) 0
Distance form CGC to top fiber (in) 0
Volume to Surface Ratio (in) 0
Distance from End to Harping Point (in) 0
Span Length During Initial Strand Release (ft) 0
Initial Release (days) 0
Span Length During Storage Bunking (ft) 0
Placement on Storage Bunks (days) 0
Span Length During Shipping Bunking (ft) 0
Placement on Shipping Bunks (days) 0
Span Length for Final Bearing Placement (ft) 0
Placement on Permanent Bearing (days) 0
Comments
*All times are measured from end of girder casting.
Concrete Properties
Concrete Density (kcf) 0
Girder Density (kcf) 0
Design Compressive Strength at Release (ksi) 0
Design Compressive Strength at 28 days (ksi) 0
Prestressing Properties
Strand Ultimate Strength (ksi) 0
Strand Yield Strength (ksi) 0
Strand Jacking Stress (ksi) 0
Time between Stressing and Release (days) 0
Steel Elastic Modulus (ksi) 0
Strand Diameter (in) 0
Area of Each Strand (in2) 0
Number of Straight Strands 0
Straight - Eccentricity (in) 0
Number of Harped Strands 0
Harped - Mid Span Eccentricity (in) 0
Harped - End Eccentricity (in) 0
Number of Temporary Strands 0
Temp - Mid Span Eccentricity (in) 0
Temp - End Eccentricity (in) 0
Temporary Strand Release (days) 0
Deck Properties
Age at Deck Casting (days) 0
Deck Weight (klf) 0
Deck Concrete Strength (ksi) 0
Slab Thickness (in.) 0
Effective Deck Width (ft) 0
Total Area of Deck Steel (in2) 0
Environmental Factors
Humidity (%) 0
Concrete Starts to harden (days) 0
Shrinkage Starts (days) 0
Control Variables
start: 0.5 0.5 0.5
end: 2 3 1
inc: 0.1 0.1 0.1
Opt. E
Opt. C
Opt. PS
Ec Factor: 1
Cc Factor: 1
PS Factor: 1
New
Duplicate
Default
Delete Girder
Funded by WSDOT, Developed by Michael Rosa/University of Washington

Fabricator Data

- Concrete Technology Co. in Tacoma, WA (103).
- Central Pre-Mix Prestress in Spokane and Pasco, WA (43).

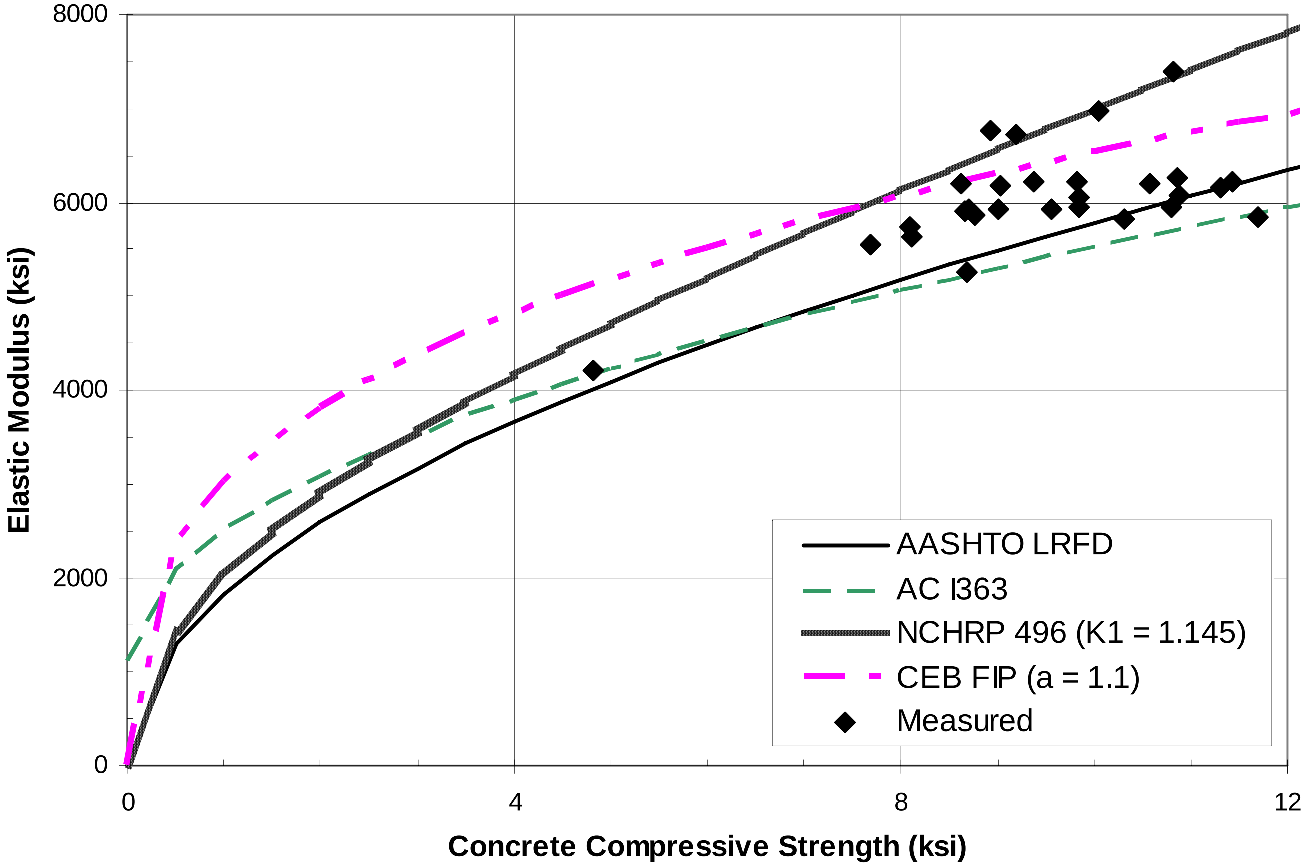


Fabricator Data



Materials Testing

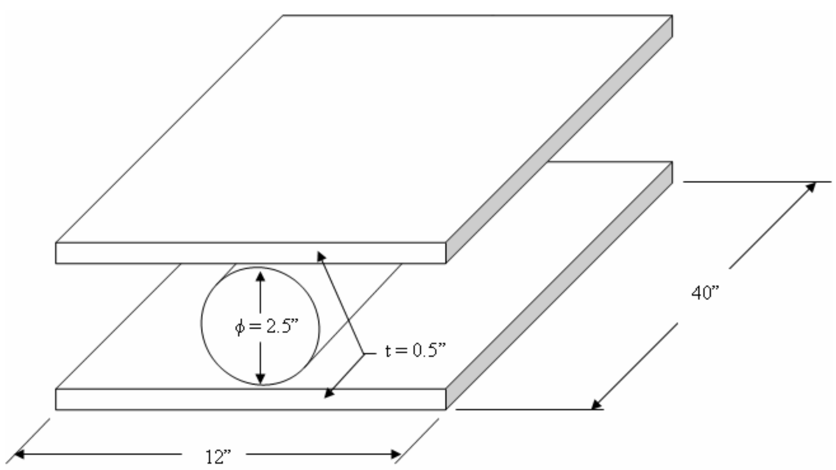
- 6 of 8 Snake Lake Bridge Girders at CTC
- Elastic Modulus Results



End Restraint/Roller Test

	11/8/05	11/10/05	11/12/05	11/15/05	11/18/05
Before	3.926	4.120	4.039	4.184	3.684
After	4.055	4.217	4.217	4.459	3.829
Change	0.129	0.097	0.178	0.275	0.145

Cast Date

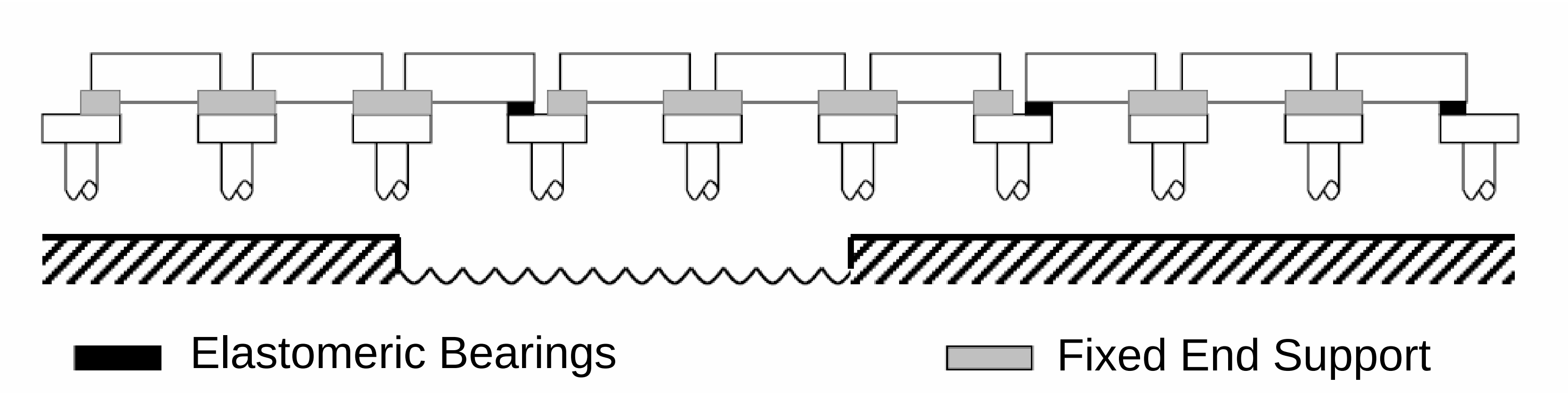


- Resistance of shrinkage and creep
- Change in deflection when released
- Average Increase in Camber

  = 0.165 in.

Keys Road Bridge Monitoring

- Effect of Temporary Strand Release
- Effect of Deck Placement – Non-Composite Section
  - End Restraint Conditions – partial diaphragm vs. elastomeric bearing
- Effects of Long Term Creep and Shrinkage – Composite Section



Keys Road Bridge Monitoring

	$(\mu \pm \sigma)$	2 Ends Continuous		1 End Continuous	
		Exterior	**Interior**	**Exterior**	**Interior**
Temporary Strands Rel.	Δ_m (in.)	0.76 ± 0.16	0.73 ± 0.19	1.05 ± 0.28	1.05 ± 0.27
	Δ_m/Δ_c(Design f'_c)	0.70 ± 0.15	0.68 ± 0.18	0.98 ± 0.26	0.98 ± 0.25
	Δ_m/Δ_c(Actual f'_c)	0.88 ± 0.19	0.84 ± 0.22	1.22 ± 0.31	1.21 ± 0.29
Deck Placement	Δ_m $(\mu \pm \sigma)$ (in.)	-1.54 ± 0.41	-1.13 ± 0.47	-1.79 ± 0.81	-1.96 ± 0.64
	Δ_m/Δ_c(Design f'_c)	0.57 ± 0.15	0.41 ± 0.17	0.66 ± 0.32	0.72 ± 0.25
	Δ_m/Δ_c(Actual f'_c)	0.71 ± 0.20	0.51 ± 0.21	0.82 ± 0.39	0.90 ± 0.56
Deck Creep*	Δ_m $(\mu \pm \sigma)$ (in.)	-0.46 ± 0.70	-0.40 ± 0.70	-0.46 ± 0.49	-0.32 ± 0.56
	Δ_m/Δ_c(Design f'_c)	0.40 ± 0.63	0.35 ± 0.62	0.42 ± 0.44	0.29 ± 0.51
	Δ_m/Δ_c(Actual f'_c)	0.53 ± 0.86	0.45 ± 0.81	0.54 ± 0.56	0.36 ± 0.56
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	Δ_m/Δ_c(Design f'_c)	0.72 ± 1.11	0.62 ± 1.11	0.74 ± 0.78	0.51 ± 0.90
	Δ_m/Δ_c(Actual f'_c)	0.94 ± 1.52	0.79 ± 1.43	0.95 ± 0.99	0.64 ± 1.16

m = measured, c = calculated

* Using girder section properties only.

** Using composite section properties ($1.6 * I_g$).

Keys Road Bridge Monitoring

$(\mu \pm \sigma)$		2 Ends Continuous		1 End Continuous	
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Temporary Strands Rel.	Δ_m (in.)	0.76 ± 0.16	0.73 ± 0.19	1.05 ± 0.28	1.05 ± 0.27
	Δ_m/Δ_c(Design f'$_c$)	0.70 ± 0.15	0.68 ± 0.18	0.98 ± 0.26	0.98 ± 0.25
	Δ_m/Δ_c(Actual f'$_c$)	0.88 ± 0.19	0.84 ± 0.22	1.22 ± 0.31	1.21 ± 0.29
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m = measured, c = calculated

* Using girder section properties only.

** Using composite section properties (1.6^*I_g).

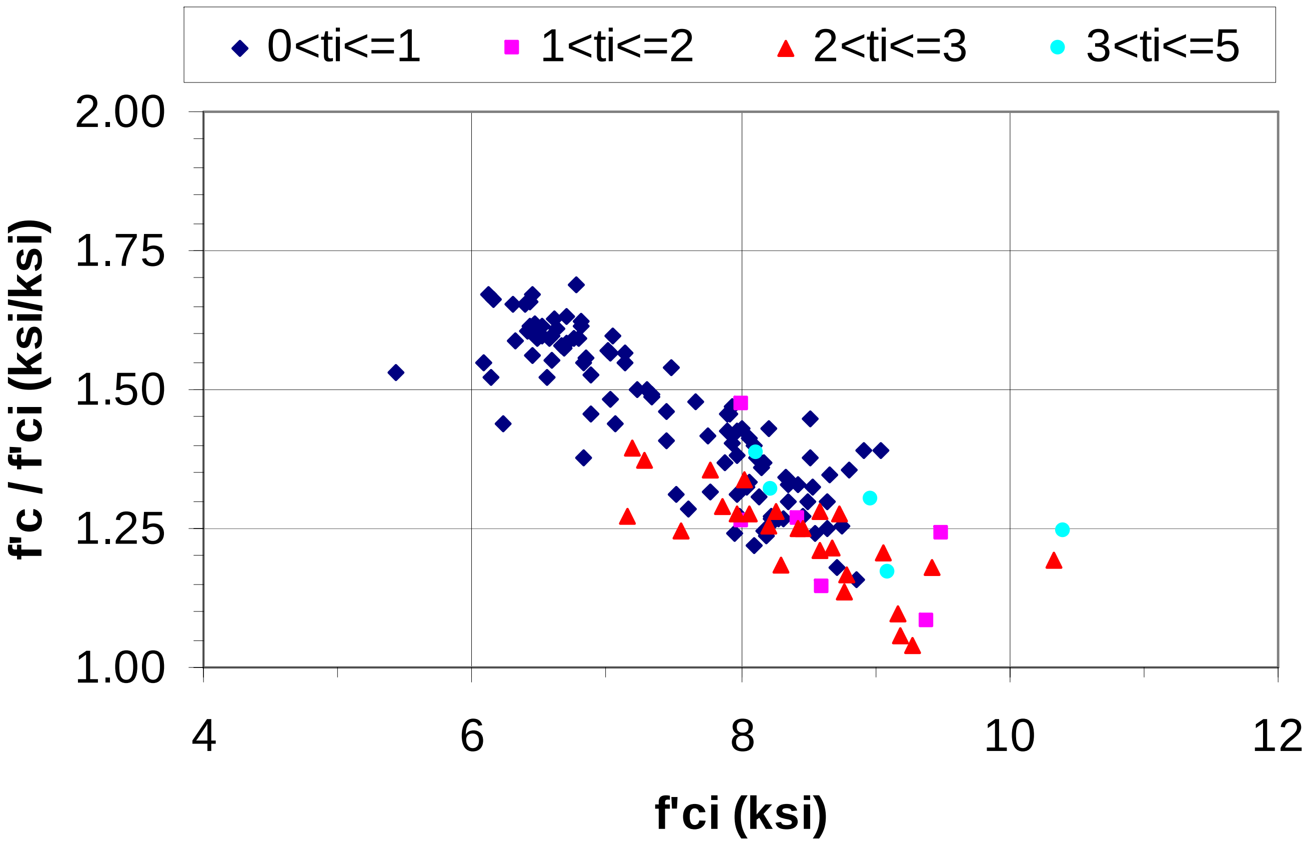
Calibration of Camber Model

- Current WSDOT Model
- Actual Concrete Strength vs. Design
- Effect of Prestress Loss on Deflection
- 2 Areas of Calibration Identified
  - Elastic Modulus
  - Creep Coefficient
- Optimized using the Sum of the Squares of deflection error.

$$\left|e_{ave}\right| = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(error_i^{\ 2}\right)}$$

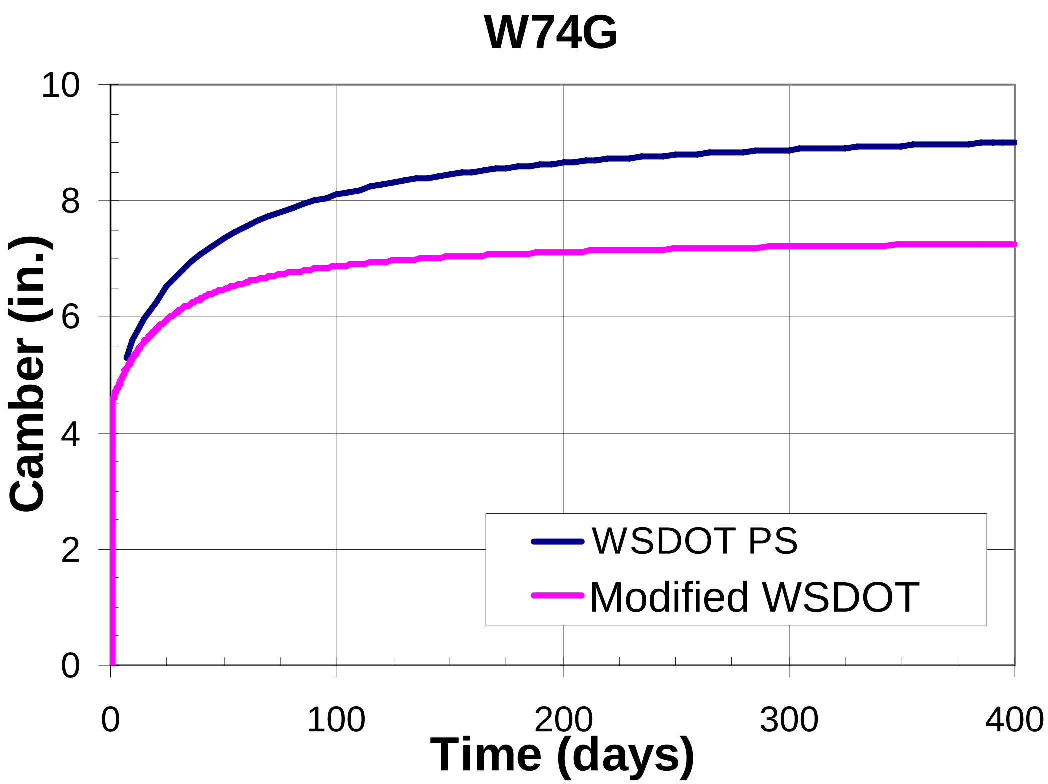
Actual Concrete Strength vs. Design

Measured / Design	Release	28-Day
All Girder	1.114	1.240
CTC Girders	1.058	1.119
CPM Girders	1.138	1.295



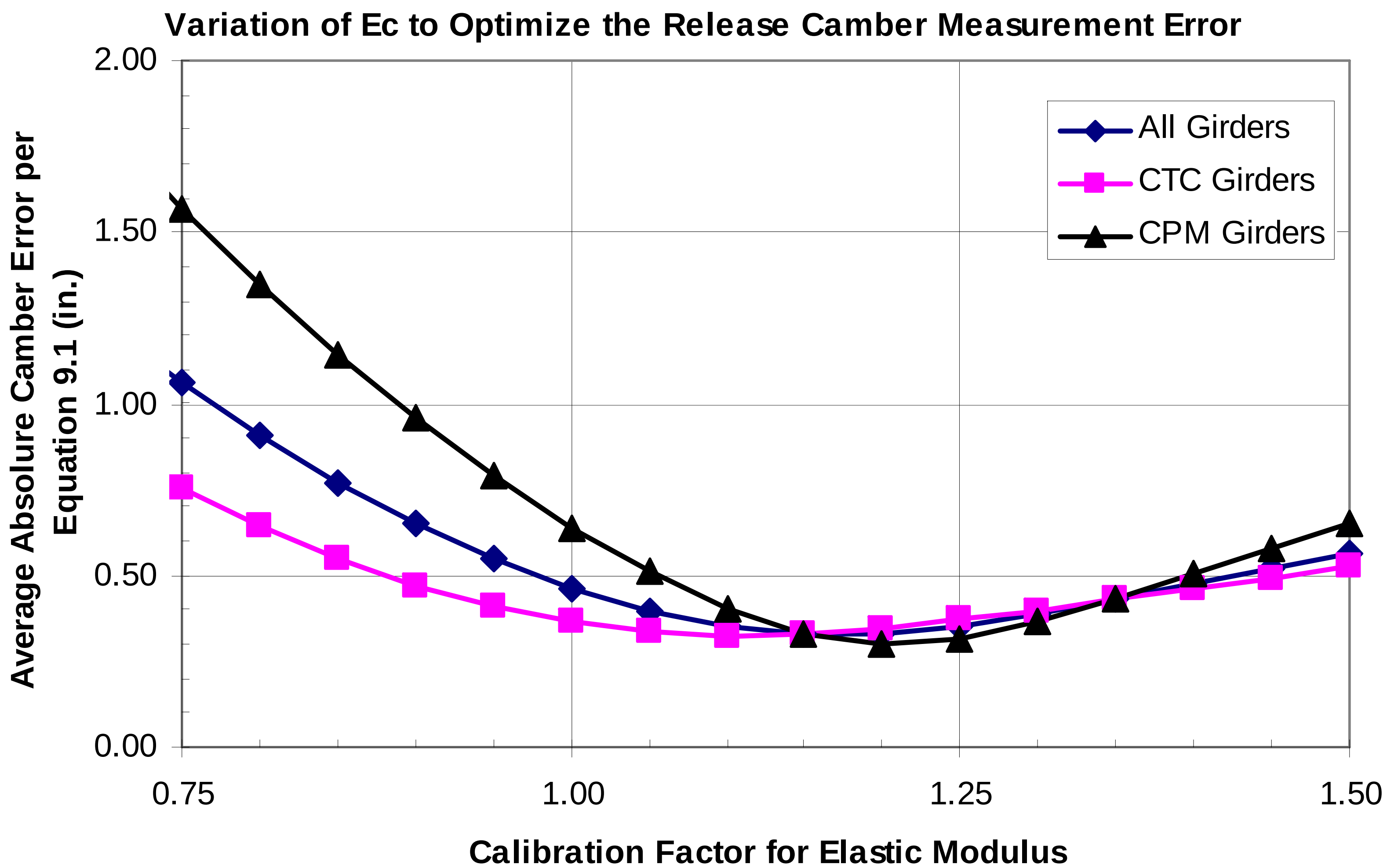
Effect of Prestress Loss

- Prestress Force is not Constant
- Creep deflection calculation can not be calculated the same way as self-weight deflection.

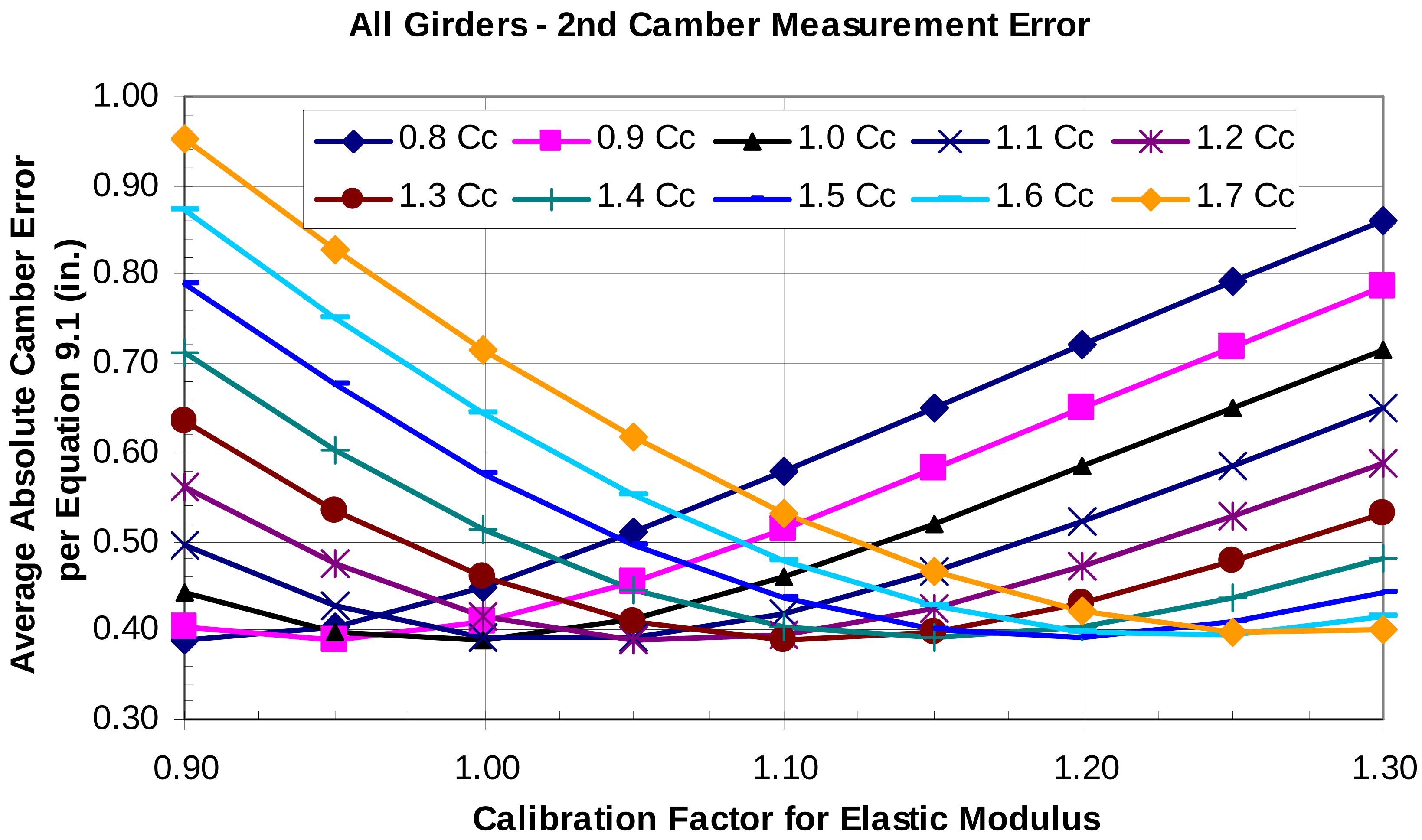


The Modified WSDOT Method includes prestress losses in the deflection calculation. Each change in prestress force is considered a new load with time dependent creep.

Elastic Modulus Calibration



Creep Coefficient Calibration



Summary

- **Research Findings**
  - WSDOT does not include prestress losses in camber calculations.
  - AASHTO LRFD 2007 predicts less "prestress loss due to creep" better than 2004 equations.
  - Actual Concrete Strength exceeded the design value by 10% at release and 25% at 28-days.
  - Optimization results
    - 15% higher Elastic Modulus than the AASHTO LRFD (corresponds to measured value, and recommended K1 value for Washington aggregate).
    - 1.4 factor on creep coefficient.
  - Keys Road Bridge
    - Possible End Restraint at temporary strand release and deck casting.
    - Large amounts of scatter after deck placement.

Summary

- **Design Recommendations**
  - Increase specified concrete strength by 10% at release and 25% at 28-days for deflection calculations.
  - Use 1.15 x the AASHTO LRFD 2007 equation for E_c.
  - Account for changes in long term camber due to prestress losses.
  - Continue to use the AASHTO LRFD 2006 equations for prestress loss.
  - Use 1.4 x the AASHTO LRFD 2007 calculated C_c.

Questions?