Improving Predictions for Camber in Precast, Prestressed Concrete Bridge Girders

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Presenter:

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Boise, ID 9/24/2007

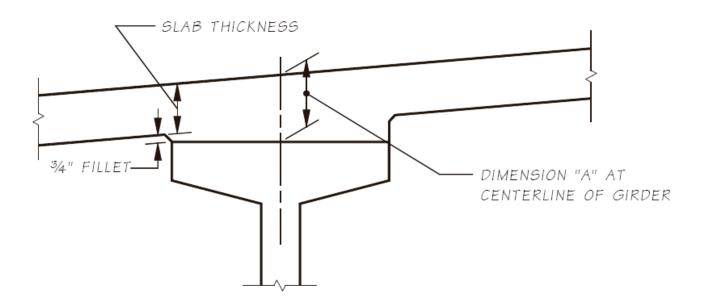




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Camber Prediction Challenges

- 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
- Increased material, labor and engineering costs



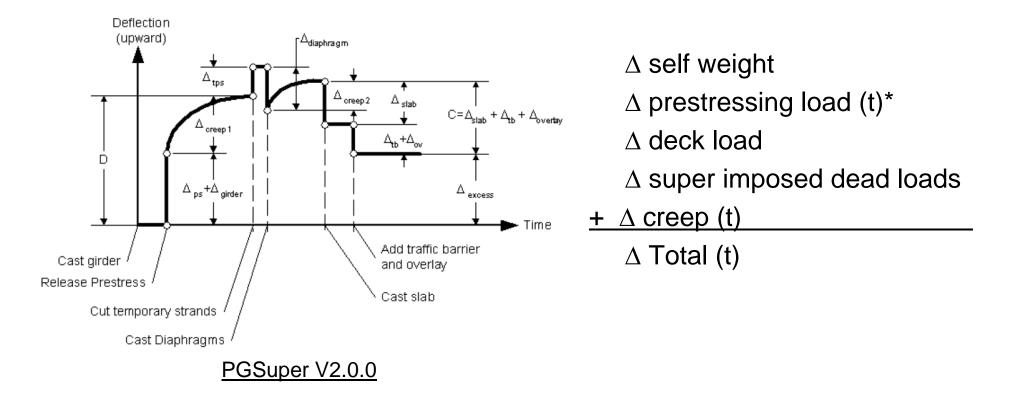
Outline

- 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

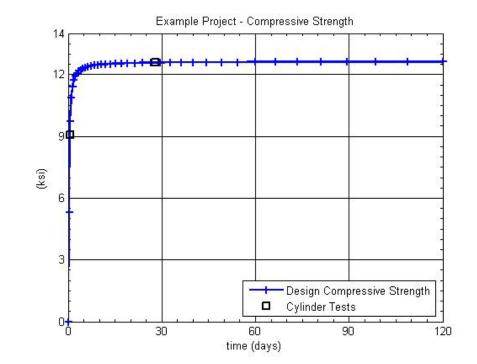


*Currently WSDOT does not include time dependent prestress losses in the prestress force deflection.

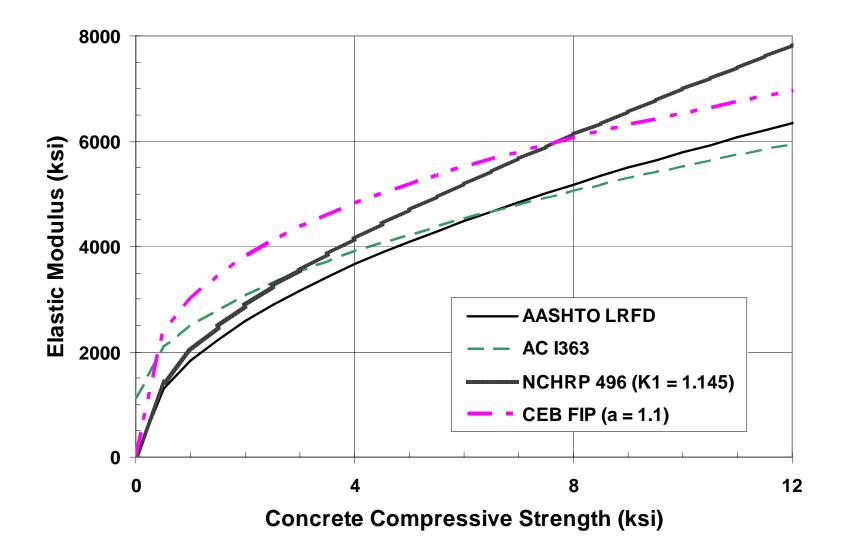
Concrete Compressive Strength

- 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



7

Shrinkage and Creep

- AASHTO LRFD (2007)
 - Shrinkage

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

Creep

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

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

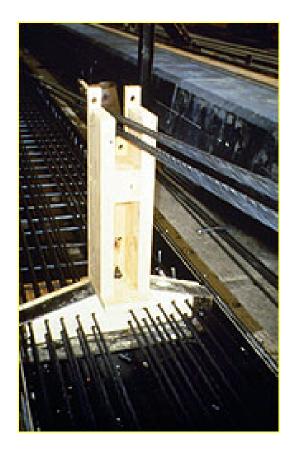
Prestress Losses

• AASHTO LRFD (2004)

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

AASHTO LRFD (2007)

$$\begin{split} \Delta f_{pT} &= \Delta f_{pES} + \Delta f_{pLT} \\ \Delta f_{pLT} &= (\Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1})_{id} \\ &+ (\Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} + \Delta f_{pSS})_{df} \end{split}$$



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)

$$\begin{split} \Delta f_{pT} &= \Delta f_{pES} + \Delta f_{pLT} + \Delta f_{pR0} \\ \Delta f_{pLT} &= (\Delta f_{pSR} + \Delta f_{pCR} + \Delta f_{pR1})_{id} \\ &+ (\Delta f_{pSD} + \Delta f_{pCD} + \Delta f_{pR2} + \Delta f_{pSS})_{df} \end{split}$$



Elastic Deflection

Self-Weight (changing support location)

$$\Delta_{SW} = \frac{\omega_{SW}L_c}{24E_cI_g} \Big[3L_c^2 (L_c + 2L_n) - L_n^3 \Big] + \frac{\omega_{SW}L_n^2}{384E_cI_g} \Big[5L_n^2 - 24L_c^2 \Big]$$

Additional Dead Load

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

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)

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

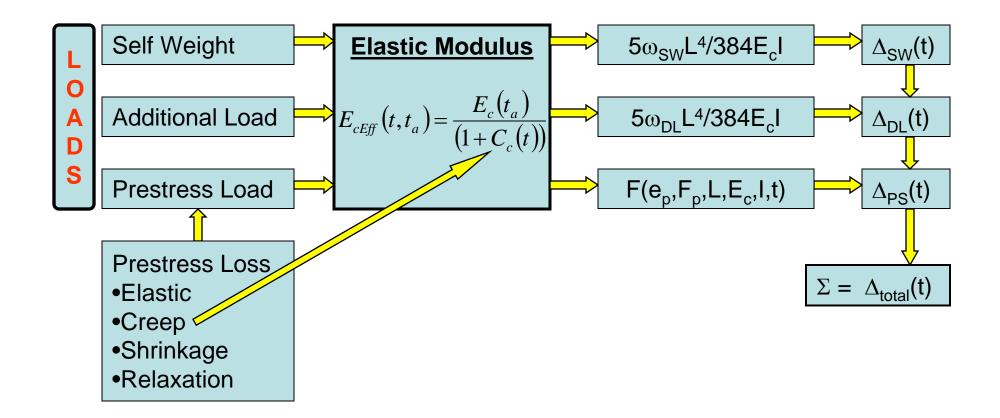
Additional Dead Load

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

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



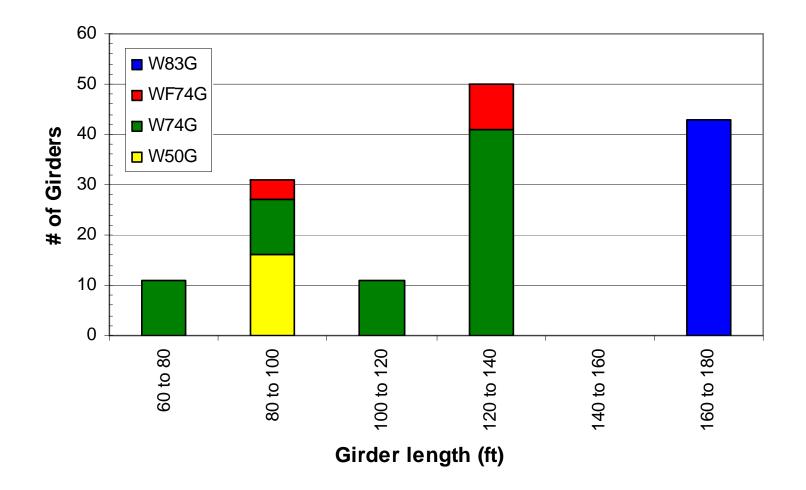
Camber Prediction Program

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

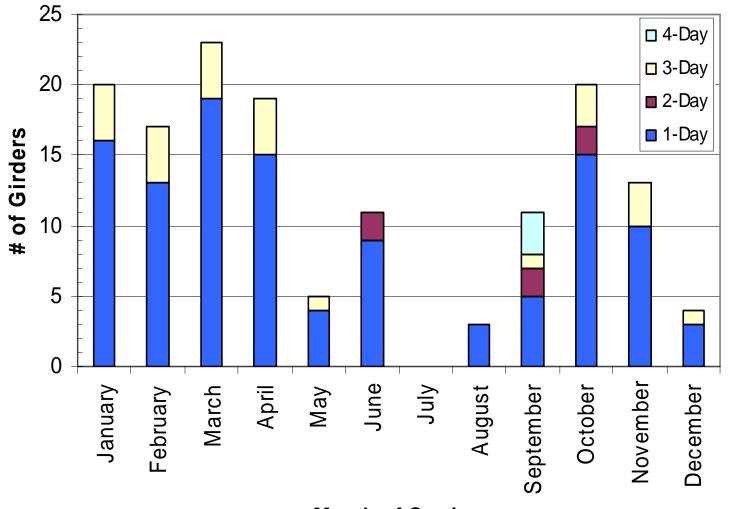
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Plots/Results Close Set Duplicate Default Delete Girder Funded by WSDOT, Developed by Michael Rosa/University of Washington	Piots/Results Close Set			v WSDOT. Developed by Michael Rosail Iniversity of Washington

Fabricator Data

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



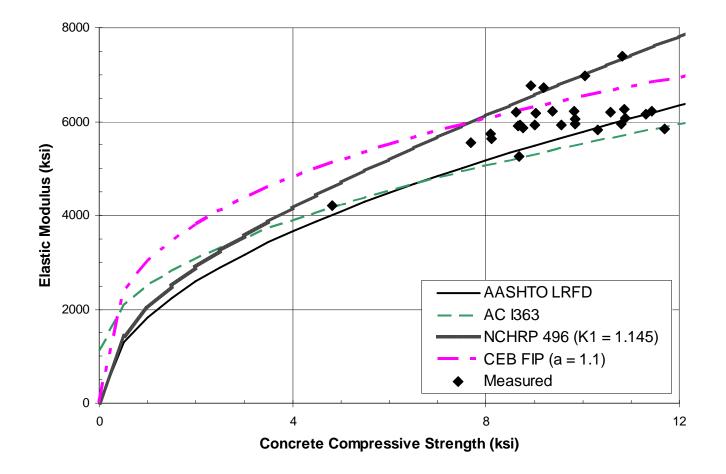
Fabricator Data



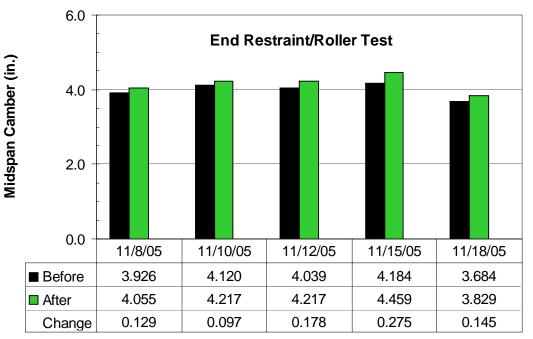
Month of Casting

Materials Testing

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



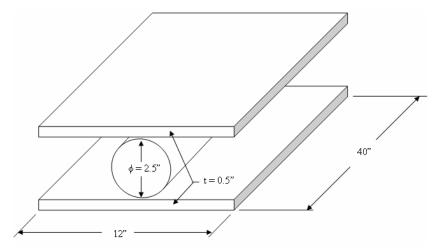
End Restraint/Roller Test



 Resistance of shrinkage and creep

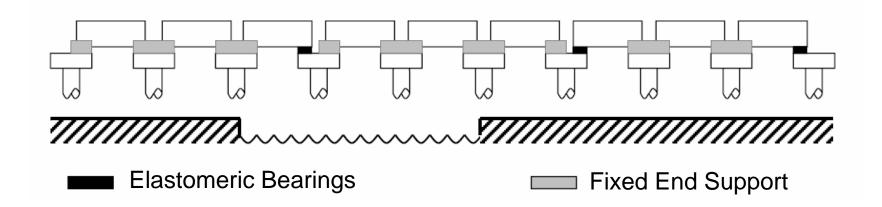
- Change in deflection when released
- Average Increase in Camber = 0.165 in.





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

		2 Ends Continuous		1 End Continuous	
$(\mu \pm \sigma)$		Exterior	Interior	Exterior	Interior
el.	$\Delta_{\rm m}$ (in.)	0.76 ± 0.16	0.73 ± 0.19	1.05 ± 0.28	1.05 ± 0.27
Temporary Strands Rel.	$\Delta_{\rm m}/\Delta_{\rm c}({\rm Design}\;{\bf f}_{\rm c})$	0.70 ± 0.15	0.68 ± 0.18	0.98 ± 0.26	0.98 ± 0.25
emp	$\Delta_m / \Delta_c (Actual \mathbf{f}_c)$	0.88 ± 0.19	0.84 ± 0.22	1.22 ± 0.31	1.21 ± 0.29
T. St					
nt	$\Delta_{\rm m} (\mu \pm \sigma) ({\rm in.})$	-1.54 ± 0.41	-1.13 ± 0.47	-1.79 ± 0.81	-1.96 ± 0.64
Deck Placement	$\Delta_{\rm m}/\Delta_{\rm c}({\rm Design}\;{\bf f}_{\rm c})$	0.57 ± 0.15	0.41 ± 0.17	0.66 ± 0.32	0.72 ± 0.25
De lace	$\Delta_{\rm m}/\Delta_{\rm c}({\rm Actual}\;{\bf f}_{\rm c})$	0.71 ± 0.20	0.51 ± 0.21	$0.82\pm\ 0.39$	0.90 ± 0.56
Ь					
	$\Delta_{\rm m} (\mu \pm \sigma) ({\rm in.})$	$\textbf{-}0.46\pm0.70$	$\textbf{-0.40} \pm 0.70$	$\textbf{-0.46} \pm 0.49$	-0.32 ± 0.56
Deck Creep*	$\Delta_{\rm m}/\Delta_{\rm c}({\rm Design}\ {\rm f}_{\rm c})$	0.40 ± 0.63	0.35 ± 0.62	0.42 ± 0.44	0.29 ± 0.51
Deck Creep*	$\Delta_m / \Delta_c (Actual \mathbf{f}_c)$	0.53 ± 0.86	0.45 ± 0.81	0.54 ± 0.56	0.36 ± 0.56
~	$\Delta_{\rm m} (\mu \pm \sigma) ({\rm in.})$	$\textbf{-}0.46\pm0.70$	$\textbf{-0.40} \pm 0.70$	-0.46 ± 0.49	-0.32 ± 0.56
Deck reep**	$\Delta_{\rm m}/\Delta_{\rm c}({\rm Design}\ {\rm f'}_{\rm c})$	0.72 ± 1.11	0.62 ± 1.11	0.74 ± 0.78	0.51 ± 0.90
Deck Creep**	$\Delta_{\rm m}/\Delta_{\rm c}({\rm Actual}\ {\rm f'}_{\rm c})$	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*Ig).

Keys Road Bridge Monitoring

		2 Ends Continuous		1 End Continuous	
$(\mu \pm \sigma)$		Exterior	Interior	Exterior	Interior
el.	$\Delta_{\rm m}$ (in.)	0.76 ± 0.16	0.73 ± 0.19	1.05 ± 0.28	1.05 ± 0.27
Temporary Strands Rel.	$\Delta_{\rm m}/\Delta_{\rm c}({\rm Design}\;{\bf f}_{\rm c})$	0.70 ± 0.15	0.68 ± 0.18	0.98 ± 0.26	0.98 ± 0.25
emp	$\Delta_m / \Delta_c (Actual \mathbf{f}_c)$	0.88 ± 0.19	0.84 ± 0.22	1.22 ± 0.31	1.21 ± 0.29
T. St					
nt	$\Delta_{\rm m} (\mu \pm \sigma) ({\rm in.})$	-1.54 ± 0.41	-1.13 ± 0.47	-1.79 ± 0.81	-1.96 ± 0.64
Deck Placement	$\Delta_{\rm m}/\Delta_{\rm c}({\rm Design}\;{\bf f}_{\rm c})$	0.57 ± 0.15	0.41 ± 0.17	0.66 ± 0.32	0.72 ± 0.25
De lace	$\Delta_{\rm m}/\Delta_{\rm c}({\rm Actual}\;{\bf f}_{\rm c})$	0.71 ± 0.20	0.51 ± 0.21	$0.82\pm\ 0.39$	0.90 ± 0.56
Ь					
	$\Delta_{\rm m} (\mu \pm \sigma) ({\rm in.})$	$\textbf{-}0.46\pm0.70$	$\textbf{-0.40} \pm 0.70$	$\textbf{-0.46} \pm 0.49$	-0.32 ± 0.56
Deck Creep*	$\Delta_{\rm m}/\Delta_{\rm c}({\rm Design}\ {\rm f}_{\rm c})$	0.40 ± 0.63	0.35 ± 0.62	0.42 ± 0.44	0.29 ± 0.51
Deck Creep*	$\Delta_m / \Delta_c (Actual \mathbf{f}_c)$	0.53 ± 0.86	0.45 ± 0.81	0.54 ± 0.56	0.36 ± 0.56
~	$\Delta_{\rm m} (\mu \pm \sigma) ({\rm in.})$	$\textbf{-}0.46\pm0.70$	$\textbf{-0.40} \pm 0.70$	-0.46 ± 0.49	-0.32 ± 0.56
Deck reep**	$\Delta_{\rm m}/\Delta_{\rm c}({\rm Design}\ {\rm f'}_{\rm c})$	0.72 ± 1.11	0.62 ± 1.11	0.74 ± 0.78	0.51 ± 0.90
Deck Creep**	$\Delta_{\rm m}/\Delta_{\rm c}({\rm Actual}\ {\rm f'}_{\rm c})$	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*Ig).

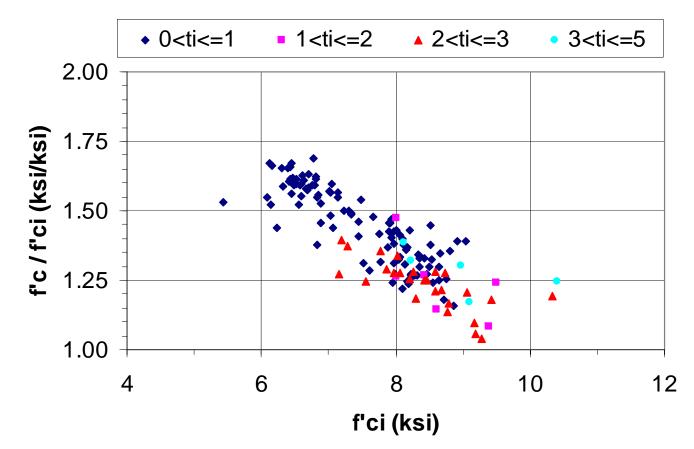
Calibration of Camber Model

- 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 <u>Sum of the Squares</u> of deflection error.

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

Actual Concrete Strength vs. Design

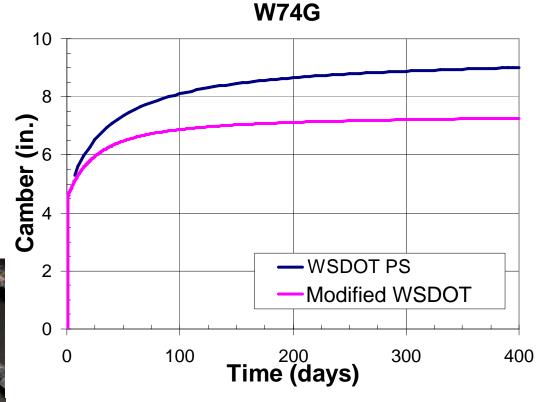
Measured / Design	Release	28-Day
All Girder	1.114	1.240
CTC Girders	1.058	1.119
CPM Girders	1.138	1.295



Effect of Prestress Loss

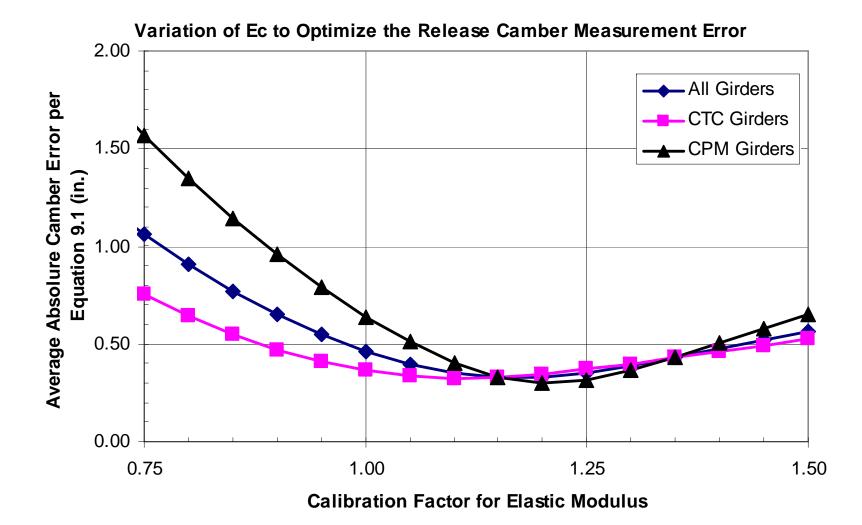
- Prestress Force is not Constant
- Creep deflection calculation can not be calculated the same way as self-weight deflection.





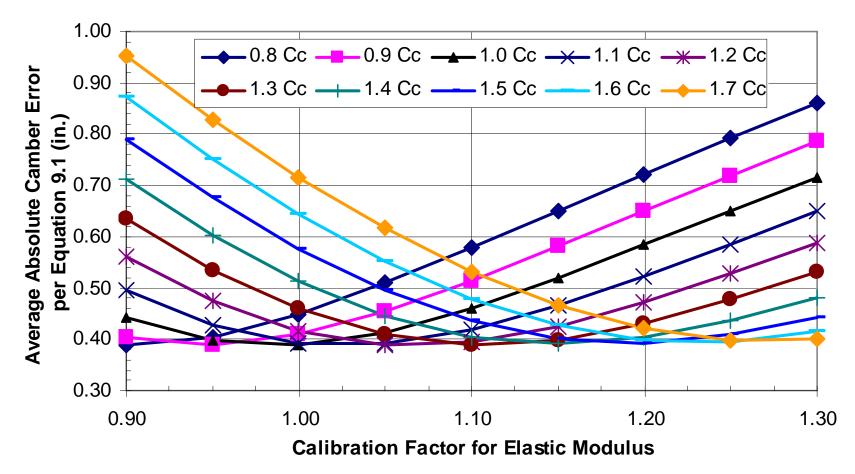
The Modified WSDOT Method includes prestress losses in the deflection calculation. Each change in prestress force is considered a new load with time dependent creep.

Elastic Modulus Calibration



Creep Coefficient Calibration

All Girders - 2nd Camber Measurement Error



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?



